

**CEMENT-TREATED SOIL: A COMPARISON OF LABORATORY AND FIELD DATA
FROM FOUNTAIN SLIDE REMEDIATION DEEP MIXING PROJECT**

by

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Abstract

In order to better understand the influence of laboratory reconstitution methods on the strength of cement-treated soil, a laboratory program was undertaken to investigate the unconfined compressive strength of cement-treated specimens reconstituted from low plasticity soils. The laboratory program examines two soil types and two reconstitution methods. The soil samples were taken from a Cutter Soil Mixer [CSM] field improvement site in British Columbia. Two reconstitution methods were used: a saturated wet-mixing method and an unsaturated dry-mixing method. To assess the relevance of using laboratory results to guide design, a subsequent field component of this research compares the strength of test specimens cast from field-mixed cement-treated soil, with the strength obtained from laboratory-reconstituted specimens.

The strength of laboratory-reconstituted soil specimens is largely independent of the soil type and reconstitution method used. A standardized approach for determining cement content in uncured mixed soil-cement is evaluated. Results from the method allow for direct comparison between the strength of field-mixed versus laboratory-reconstituted specimens as a function of the cement content, and/or the water-cement ratio. Based on the simplicity of use and accuracy of results, it is recommended that the Heat of Neutralization method (ASTM 5982-07) be incorporated into the quality assurance program of deep mixing projects.

Preface

This thesis includes material presented at the 2012 New Orleans, Grouting and Deep Mixing International Conference (Lapointe, E., Fannin, R.J. and Wilson, B.W. 2012, Cement-Treated Soil: Variation of UCS with Soil Type, 4th International Conference on Grouting and Deep Mixing, Deep Foundation Institute, New Orleans, USA, 1-10.). The testing and data reporting required in putting this paper together was solely undertaken by Emilie Lapointe, while the analysis and presentation stemmed from a joint effort between Emilie Lapointe and Dr. Jonathan Fannin. Brian Wilson provided final review on the paper.

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To Luce:

Find your passion, work hard, and stay curious.

Chapter 1: Introduction

The increasing growth of urban infrastructure and the accompanying demand for supplies and energy has led to land shortages, increasing the cost associated with land usage every year. As a result, land with soft soil deposits, that was previously avoided, is now being considered for development. Solutions for development on these problematic sites involve either soil improvement techniques or deep foundation systems. One of the soil improvement methods that is increasingly being used is the deep mixing method.

Deep mixing technology was first developed in the late 1960s (Miura et al. (2001) and Larsson (2003)). The Japanese Geotechnical Society, the Japanese Port and Harbour Research Institute, the Swedish Deep Stabilization Research Center, and in general, engineers from Japan, Sweden, and Europe, all have contributed to the development of deep mixing technology. The technology involves the in-situ mixing of a wet or dry binder with soil, in an attempt to improve the properties of the soil— that is, by increasing the shear strength, decreasing the compressibility and/or decreasing the hydraulic conductivity (Porbaha (1998)). The binder that is used may be lime, cement, fly ash, slag or a mix thereof, although cement has been reported to be used the most to enhance the strength characteristics of soil. Since the early development, aside from improving the performance of soft soils, applications for deep mixing methods have now grown to include liquefaction mitigation, cut-off walls and slope stabilization. One of the Canadian example in this regards is the Nanaimo convention center that was built in 2006 over a waste-fill area. Cement-treatment of the soil using the Cutter Soil Mixer [CSM] deep mixing technology allowed for the soft contaminated soils to be treated in-situ and remediated against liquefaction potential while, at the same time, also rendering the soils capable of supporting the foundation for the heavy structure. More recently, deep mixing has been applied to a slope stabilization in Lillooet, BC, where panels of cement-treated soils were

mixed such as to intercept the slip surface and provide additional shearing resistance against sliding (Lapointe et al., 2012).

Given the wide variety of applications for cement-treatment of soil using deep mixing technology, there is a need for a standardized design methodology, as emphasized by Terashi (2003), Puppala and Porbaha (2004), and Bruce and Cali (2005). Even though it is recognized that strength and deformation properties, as determined in the laboratory, may differ considerably from those obtained in the field, the accepted industry methodology for deep mixing design of cement-treated soil projects relies on test results from laboratory reconstituted specimens of cement-treated soils. In the laboratory, soils collected from site are mixed with cement and water to reconstitute specimens for purpose of testing, in a manner that attempts to replicate field-mixing conditions. Unconfined Compressive Strength [UCS] is the most commonly performed test on these laboratory-reconstituted specimens. The results from UCS tests are used to guide the field mix design. Ultimately, it is required to select a binder factor, in the form of a mass of cement per volume of treated soil element, to be mixed with the in-situ soils in order to achieve the required design parameters. Understanding the main factors influencing the strength of a cement-treated soil, with reference to the strength of specimen reconstituted in the laboratory and elements mixed in the field, is a challenge for which most designers and contractors, in deep mixing projects, have little information upon which to base decisions.

This study aims to inform the decision making process for deep mixing projects. It originates from a university-industry collaboration where Golder Associates Ltd, the industry partner, provided access to a deep mixing project site. The deep mixing project, which is described in further detail in Chapter 3, involves the stabilization of an active landslide, the Fountain Slide near Lillooet, BC (herein referred to as the Site), by creating cement-treated soil panels using the Cutter Soil Mixer [CSM] deep mixing technique.

1.1 Organisation of the Thesis

In the following section, Chapter 1.3, existing methods for reconstitution of laboratory specimens are reviewed. Consideration is given to their relative merits in replicating the field mixing conditions of deep mixing projects. Test methods available to determine the quantity of cement present in a cement-treated soil sample are also reviewed and discussed.

A major component of this thesis research is the laboratory study and the companion field project involving cement-treatment of soil, which are presented in Chapters 2 and 3, respectively. First, the manner in which the laboratory testing portion of this research was performed is presented, and the main findings reported. Thereafter, the CSM field project is described. The field results are presented along with a discussion on the quantity of cement mixed in the soil, at the project location, as determined from production records. The suitability of a test method, capable of determining the cement content of uncured cement-treated soil, is examined in Chapter 3 with test results, obtained on field-mixed samples then presented. An analysis and discussion of the results, including comparison to the published literature, is undertaken in Chapter 4. Finally, Chapter 5 presents the main conclusions and recommendations arising from the research findings.

1.2 Literature Review

Many factors are known to influence the strength of cement-treated soil specimens, as reconstituted in the laboratory, and the study of them has been the focus of many previous investigations, see for example: Filz et al. (2005), Merrigi et al. (2005), Babasaki et al. (1997), CDIT (2002), and Lewsley (2008). The intent of this study, however, is to concentrate on: (i) characterizing the relation between soil type and reconstitution method on the strength of cement-treated soil specimens; and (ii) to provide a basis for comparing the strength of specimens cast from grab samples of field-mixed soil to the strength of laboratory-reconstituted specimens. As such, this literature review focuses on

understanding the different existing laboratory reconstitution techniques and their suitability for use in this research. Additionally, to allow for a reliable comparison of field and laboratory data, it is necessary to know the quantity of cement present in field-mixed specimens. This section provides an overview of current test methods believed appropriate for establishing the quantity of cement present in cement-treated soil, and describes the method that was chosen to be use in this research.

To allow for clarity in comparisons between different projects and research studies, as recommended by Bruce and Cali (2005), a standardisation of terms used in reporting quantity of cement is undertaken. Table 1.1 presents the nomenclature, or terms, that will be used in this study and the corresponding terms used by others in the published literature.

Table 1.1 Cement Quantity Terms

| This Study | | | Description | |
|---|----------------------|-------------------|---|------------------------|
| Index Name | Symbol | Unit | Publication | Referred Name |
| Field Binder Factor | α_r | kg/m ³ | Mass of Cement/Volume of Treated Soil | |
| as commonly agreed upon by : Filz (2011). | | | Omine et al. (1999) | Cement Content |
| | | | Nicholson (1999) | Cement Usage |
| | | | Maher et al. (2007) | Dose of Cement |
| | | | EN 14679:2005 | Binder Content |
| | | | Kasama et al. (2006) | Cement Amount |
| | | | Madhyannapu et al. (2010) | Dosage Rate |
| Lab Binder Factor | c | kg/m ³ | Mass of Cement/Volume of Test Specimen | |
| as commonly agreed upon by : Bhadriraju et al. (2007) | | | Lewsley and Fannin (2011) | Initial Cement Content |
| Cement Content | C_c | % | Mass of Cement/Mass of Dry Soil | |
| as commonly agreed upon by : Babasaki et al. (1997) | | | Kitazume et al. (2003) | Cement Factor |
| Filz et al. (2005) | | | EN 14679:2005 | Binder Factor |
| Horpibulsuk et al. (2006) | | | Bhadriraju et al. (2007) | Binder Content |
| Merrigi et al. (2008) | | | Consoli et al. (2007) | Cement Percentage |
| Sariosseiri et al. (2009) | | | Muhunthan et al. (2008) | Percent Cement |
| Viana da Fonseca et al. (2009) | | | Al-Aghbari et al. (2009) | Stabilizer Percentage |
| PCA (2009 and 2010). | | | | |

1.2.1 Reconstitution Methods for Cement-Treated Soils

Rather than providing data that are directly applicable to a field project, laboratory tests of cement-treated soil specimens improve the understanding of the mechanism governing the field behavior of the treated soil element (Terashi (2003)). Historically, laboratory reconstitution methods have often been developed by a research and/or construction group attempting to simulate the field-mixing conditions of a specific deep mixing technique. Thus, each tends to be developed locally, often in isolation from work undertaken elsewhere because of limited dissemination of project findings. This literature review intends to clarify the main principles, and identify the differences, among the various existing laboratory methods for reconstituting cement-treated soil specimens.

To replicate the field mixing procedures of deep mixing equipment for soil improvement in loose and/or soft marine deposits, practitioners and researchers from Japan first developed laboratory reconstitution procedures in the late 1960s (Hodges et al. 2008). During the 1970s, in Europe, emerging mostly from Sweden and Norway, deep mixing technology designed to improve the geotechnical properties of marine silt and clay deposits were also developed. Binders in a dry form (lime and/or cement) were incorporated to the soil by pressure injection. Laboratory reconstitution methods replicating the field mixing process involved dry mixing of the binder with soil and application of static compaction to the specimen as per the EuroSoilStab (2002) standard. These methods were used by practitioners and researchers such as Schwarz et al. (1994), Al-Tabba et al. (1999), Janz and Johansson (2002), and Larsson (2003).

Concurrently, in the United States, field mixing methods for cement-treatment of soils were also being developed for the purpose of sub-base treatment of embankments, roadways, and/or airways. These methods involved shallow mixing and compaction of cement-treated soils to improve the bearing capacity and shear resistance of in-situ soils. Laboratory reconstitution methods were developed to generally replicate these field mixing conditions as the American Society for Testing of Material [ASTM] D558, ASTM D1632, and PCA (2011). The main differences between those methods and the Japanese or

European standards for specimen reconstitution are twofold: dynamic compaction is used to reconstitute a specimen in a series of layers, and specimens are reconstituted at, or around optimum moisture content. These techniques have been widely used by various research groups such as: Bhadrirajue et al. (2007), Muhunthan et al. (2008), Sariosseri et al. (2008), Consoli et al. (2007, 2009, 2010), and Al-Aghabi (2009).

Later, in the early 2000s, deep mixing projects were gaining in use in North America, notably with the New Orleans levee improvement work (DFI (2011)). Different reconstitution methods, not involving standard mixing energy or reconstitution at optimum moisture content, were developed in the USA and in Canada, see for examples: Hodges et al. (2008) and Lewsley and Fannin (2011), and which were used by Jacobson et al. (2003) and Lewsley (2008) respectively.

Among all the existing methods for laboratory reconstitution of cement-treated soil specimens, the main differences relate to the mixed soil conditions (density, moisture content and saturation level), binder type, binder state at mixing time (dry or slurry), specimen dimensions, compaction energy per unit volume, and curing procedures. The soil and cement can be combined dry or wet, with either the dry soil from site mixed with cement prior to the addition of water (dry mixing) or the soil, at in-situ moisture content, mixed with a cement slurry (wet mixing). The mixing is typically achieved through mechanical means (dough mixer or drill), but hand mixing might also be recommended based on the soil type and the ease of mixing. The cement-mixed soil specimen is then cast with or without compaction energy, and curing is most often carried out in a moist environment.

For the purposes of this research, the field mixing characteristics of the Cutter Soil Mixer [CSM], which will be described in Chapter 3, were to be replicated by the laboratory reconstitution method. Accordingly, cement and water were to be mixed with the soil, and the resulting cement-treated mixture cast without any compactive effort. From among the reconstitution methods outlined in the previous paragraphs, it is believed the field mixing

method of the CSM can best be replicated by: the dry-mixing without compaction method as per CDIT (2002) yielding unsaturated specimens; the wet-mixing method applicable to the wet method of deep mixing as per Hodges et al. (2008), yielding specimens of varying saturation level; the standard published by EuroSoilStab (2002), which also yields specimens of varying saturation level; the wet-mixing method as per Lewsley and Fannin (2011), yielding saturated specimens. Simplified descriptions of these specimen reconstitution methods are included below.

1.2.1.1 Dry-Mixing (Unsaturated)

According to the method, translated from the original Japanese and presented in CDIT (2002), an oven-dried mass of soil (pulverized for cohesive soil) is combined with a predetermined mass of cement in a bowl, by hand mixing, until it becomes homogeneous in color. A mass of water (fresh or salted, according to which will be used in the field project), including the mass of water found in the in-situ soil and the mass of water found in the cement slurry, is mixed in with the soil and dry cement. The mixing is performed using a domestic dough mixer with a hook-type paddle, for a minimum of 10 minutes, at about 200 revolutions per minute, until the mixture is deemed homogeneous. The resulting mixture is then placed in a mold of 50 mm diameter and 100 mm height. Using rodding and light tamping, the mixture is placed in the mold in three lifts. The specimen is subsequently stored, with ends sealed, in a room at constant temperature (20 °C) and relative humidity (95 %) for the intended curing period. This method is referred to herein as the dry-mixing (unsaturated) method because of the manner in which the soil and cement are combined prior to mixing.

1.2.1.2 Wet-Mixing (Unsaturated)

The reconstitution method presented by Hodges et al. (2008) differs from the previous dry-mixing method in two ways. First, the specimen is reconstituted from wet soil, sampled from site, which has been stored so as to retain its natural moisture content (as compared

to dry soil used in section 1.3.1.1). The soil is mixed into a homogeneous state, using a commercial dough mixer, set at the lowest setting (revolution of less than 100 cycle/minute) for about 3 minutes. If additional water is to be mixed in the soil at site, then a corresponding mass of water can be added to the mixing soil at this stage. Second, the cement is introduced to the homogeneous soil as a slurry. The slurry is prepared separately, at a water-cement ratio equal to that of the field project (in contrast to a dry cement powder added in the dry-mixing technique). The slurry is introduced to the wet soil, while ensuring continuous mixing action using the same commercial dough mixer. The mixing lasts, on average, 10 minutes, from the time the total amount of binder is added to the soil mixture. The specimen is cast in a mold of 50 mm diameter and 100 mm height. Casting proceeds in 3 lifts using rodding and/or light tapping of the mixture after each lift to remove air bubbles, while ensuring no segregation. Specimens are then stored, in their molds and with sealed ends in a constant temperature (as specified by the project), moist (100 % relative humidity) room, for the designated curing time.

1.2.1.3 EuroSoilStab Standard (Unsaturated)

Given that this method was used as a starting point from which the wet-mixing (unsaturated) method was developed, the EuroSoilStab standard is very similar to the method described in section 1.3.1.2. The standard addresses the sampling method for obtaining soil sample from site in greater detail. The soil, at its natural moisture content, is first mixed into a homogeneous state. The binder (in dry or wet slurry-form) is then added to the homogeneous soil and mixing proceeds using mechanical means. The standard does not specify the type of mixing machine, power or rotation speed required for mixing, but instead instructs the user to choose a machine based on experience. The main differences between this standard and the wet-mixing (unsaturated) method relate to the casting of the specimen. The EuroSoilStab standard requires the mixture to be placed in 25 mm thick layers, using a fork to eliminate bubbles of liquid or air. A compaction tool consisting of a circular steel stamp, with a level or inclined base, mounted on a steel rod or a press, is used on each layer. A pressure of about 100 kPa is exerted on the surface of each layer, 3 times,

for about 2 seconds, with rotation of the tool each time. The resulting cast specimen is then sealed and stored at constant temperature and humidity, as specified by the project, until it is ready for testing.

1.2.1.4 Wet-Mixing (Saturated)

Lewsley (2008) used a different approach to reconstitution, choosing to work with soils closer to their in-situ state. Recognizing that improvement sites are often located where the soil is saturated, Lewsley developed a novel reconstitution method that is intended to yield saturated cement-treated specimens of silt and sand. Detailed reconstitution procedures are presented in Lewsley and Fannin (2011). Herein, the method is referred to as the wet-mixing (saturated) method.

In this method, first, the soil sand and fines fractions are brought to a saturated state, separately, by boiling in water. The sand fraction is then water-pluviated in a mold with a diameter of 71 mm and a height of 142 mm. The fine saturated slurry is then poured over the sand in the mold. Once the soil settles, excess standing water is removed and dry cement powder is added.

Apart from the soil being in a saturated state, another difference between the preceding methods of reconstitution and the wet-mixing (saturated) method is that, in this method, the mixing is done in the mold. The mold is built from clear acrylic, with a removable bottom and collar attachment. With the cement on top of the saturated soil, a top cover plate (with a mixing vane passing through it) is fixed to the collar extension. A vacuum pressure is then applied to the mold. A $\frac{3}{4}$ " commercial drill attached to the mixing vane allows for mixing, which rotates at about 1150 rpm. While rotating, the vane is lowered and raised at a rate equal to 6 m/min along the vertical axis of the mold. The mixing process lasts about 5 minutes, until the specimen is deemed homogeneous by visual inspection. The reconstituted specimen is then allowed to rest, until it attains sufficient strength to permit trimming. Trimming proceeds by first uncoupling the collar extension from the mold and then, using a wire saw, cutting the specimen to a target height of 142 mm. The specimen is

then placed in a moist, temperature-controlled room (high relative humidity and 23 °C), for an initial 1 day of curing. Thereafter, it is extruded from the mold, wrapped in plastic film and, returned to the moist room for the remainder of the intended curing period.

In summary, the wet-mixing (saturated) method incorporates two significant variations on other commonly-used methods. First, the soil is reconstituted in a saturated condition, while attention is paid to prevent entrainment of air during cement-mixing that would otherwise yield an un-saturated specimen. Second, the mixing process occurs in the mold and no external compaction energy is imposed while casting the soil-cement mixture.

With reference to the intent of comparing laboratory and field strength data, in an effort to bound the likely conditions on site, where the degree of saturation in the soil varies and no compaction energy is imparted to the treated soil, two methods are deemed relevant to this research: the dry-mixing (unsaturated) method, after CDIT (2002), and the wet-mixing (saturated) method, after Lewsley and Fannin (2011). Accordingly, the two methods, which rely on self-weight consolidation of the specimen after mixing (similar to the process experienced by an element of cement-treated soil in the field), were selected for use in the laboratory study portion of this research, presented in Chapter 2.

1.2.2 Determining Cement Quantity

The degree of improvement that is attained in a deep-mixed soil project is a function of many factors. In addition to choosing the appropriate equipment for mixing, the most important factor is to specify the binder type (for example, cement) and the quantity of binder (for example, binder factor in kg/m³) to be mixed with the soil, in order to achieve the desired geotechnical properties. A major focus of quality assurance and control [QA/QC] during construction is document field records (for example B-Reports for the CSM, which report depth, wheel-torque, slurry injection rate, and cutting time) to ensure the binder factor, specified in design, is achieved in field mixing.

The field binder factor is subjected to some uncertainty. Factors such as binder loss in the surrounding soil, precision of the operator when observing readings, and uneven binder distribution cannot be reflected accurately in α_r . Since α_r is calculated from the total quantity of binder (for example, kg of cement) mixed in a given element of treated-soil, averaged over the element volume (m^3), factors listed above might yield an overrepresentation of the actual binder per unit volume of treated soil to be present, or homogeneously mixed, in the element of cement-treated soil. Additionally, as noted and discussed by Larsson (2005), Bruce and Cali (2005), and Madhyannapu et al. (2010), it is common for soil to bulk-up during mixing and not only is it difficult to measure the volumetric increment, it is also impossible to determine reliably the amount of binder lost in the bulked-up soil. To address these legitimate concerns, consideration is given in this thesis to forensic testing for cement content of grab samples collected from cement-treated soil elements in the field. Knowing the quantity of cement in a given element is often required for QA/QC purposes, but it also serves another important purpose. It allows the strength of specimens obtained from the field to be reported as a function of the water-cement ratio. On this basis, a comparison can then be made with the strength of laboratory reconstituted specimens.

Note that there are many factors that should be considered when sampling field treated elements, such as spatial variation in material properties, representative sampling locations, method of sampling, and the potential for disturbance of the sample. Larsson (2005) and Kitazume et al. (1997) provides a comprehensive statement on the challenges faced when sampling. Despite the limitations listed in their work, wet-grab sampling of freshly mixed elements of cement-treated soil, using sampling tools attached to the cutter head of the CSM, is deemed to be an acceptable method for obtaining representative samples in this research.

The methods that are currently available to determine the quantity of cement present in a sample are now reviewed in this section. Approaches available to determine the quantity of cement present in cement-treated soils, either in the form of reported field binder factor

$[\alpha_r]$ or cement content $[C_c]$, are taken from the concrete industry. Each relies on one of the following three principles: i) the difference in density between cement and aggregate-soil which is being treated; ii) the difference in grain size distribution between cement and aggregate-soil which is being treated; or iii) the chemical reaction of the calcium oxide $[CaO]$ present in the cement. Methods under principles i) or ii), although appropriate for concrete, are unsuitable for integration in a QA/QC program for most deep mixing cement-treated soils, because of the potential fines content present in the soil which has a density and grain size close to that of the cement particles. However, with reference to principle iii), there exist several methods that have already been adapted to cement-treated soil. These methods include STP479-EB (1970), Nagële and Hilsdorf (1980), Scavuzzo and Kunzer (1998), ASTM D806-06, and ASTM D5982-07. They are reviewed in the following section based on their main characteristics.

1.2.2.1 Methods to Determine Cement Content

A method of cement content determination for freshly mixed specimens of soil-cement relates to the titration, or volumetric analysis, of the cement carbonate content present in the material. More specifically, it relates the amount of disodium tetra-acetate dehydrate $[EDTA]$ required for reaching a determined color endpoint when mixed in a fresh cement-treated soil to a predetermined laboratory calibration curve of the cement content versus EDTA. The accuracy of the method is unclear, and it was never published as a standard ASTM method following the initial work of Nagële and Hilsdorf (1980). It can be inferred, that since never published, this method is complex to use and as such, it is deemed impractical to use on field DM projects.

The heat of neutralization method, in which the carbonate content of the cement present in a freshly mixed sample reacts exothermically with a buffer solution, was first reported by the Australian Main Roads Department in 1978. The method has successively evolved and was first refined by the Bureau of Reclamation (Scavuzzo (1991)) and then in Scavuzzo and Kunzer (1998). It was formulated as a standard test method, ASTM D5982-07, and calls for

a representative sample of fresh soil-cement to be obtained. The temperature of the soil-cement sample is recorded. Then, a buffer solution, made from sodium acetate and acetic acid, is mixed and its temperature adjusted to be within $\pm 2^\circ$ Celsius of that of the soil-cement sample. The pre-reaction temperature is taken to be the average value of the measured temperature of the soil-cement sample and the temperature of the adjusted buffer solution. Upon combining the soil-cement sample and buffer solution (vigorous mixing for 4 minutes), the post-reaction mix temperature is recorded after 1 minute, to the nearest 0.1° Celsius. Finally, the heat of neutralization is calculated as the difference between the post-reaction mix temperature and the pre-reaction average temperature. The cement quantity, as a mass ratio of the cement over the entire specimen mass and hence different from C_c presented earlier, is obtained with reference to a previously established calibration curve. The heat of neutralization method has been successfully reported as an easy, reliable, and accurate method to determine the cement content of a freshly mixed soil-cement sample, see for example Scavuzzo and Kunzer (1998). It is believed that, based on its ease of use, this method is currently the most promising for determination of cement quantity in freshly mixed cement-treated soil. This method is discussed in further detail in Section 3.2.2.2, and reported in Appendix C.

1.3 Research Need

For a soil improvement project to be effective, the main factors influencing the strength of a cement-treated soil need to be understood. Although soil conditions (grain-size distribution, in-situ moisture content and in-situ density) and mixing parameters (mixing energy, binder type and binder quantity) are known to influence the strength of field-mixed cement treated soils, as touched upon in the previous section, the individual effect of each change in parameters has not, to this day, been methodically studied. This study, using soils from a field project, investigate the effect of grain size distribution on the strength of cement-treated soil specimens. It also investigates the effect of binder content on the strength results.

Given that tests on laboratory reconstituted specimens are used as a guide to design, it is foremost important to understand the influence of the various reconstitution parameters on specimens' strength. Out of the many reconstitution methods described earlier, this study used two different laboratory reconstitution methods. Additionally, results from the literature are brought in to further investigate the influence of the reconstitution method on the strength of cement-treated soil. By combining all of the laboratory test results, a database is created that provides insight to the influence of reconstitution method on the strength of laboratory reconstituted specimens of cement-treated soil.

Finally, a soil improvement design requires the understanding of the relation between laboratory results and field results. This study attempts at correlating the strength of cement-treated soil as mixed in the field with the strength of cement-treated soil specimens as reconstituted in the laboratory. It is believed that, by providing a basis for comparing laboratory and field strength data, the study will provide meaningful information that a design engineer, working on a deep mixing project can rely on for purpose of decision support in mix-design.

Chapter 2: Laboratory Study

A program of laboratory tests was undertaken (i) to investigate the influence of soil type and reconstitution method on the unconfined compressive strength [q_u] of cement-treated soil specimens and (ii) to create a database that would allow comparison of q_u between laboratory-reconstituted cement-treated soil specimens and specimens cast from samples of field mixed elements.

Materials used in the laboratory testing program are presented below, followed by a reporting of the two reconstitution techniques used in this research: the wet-mixing saturated method (Lewsley and Fannin 2011) and the dry-mixing unsaturated method (CDIT 2002). Next, the UCS testing procedure is described. Results from the laboratory study, with their respective variables, are presented at the end of this chapter in the form of graphs for the stress-strain relation and for the variation of q_u with final laboratory binder factor [C_f]. Data for specimen reconstitution, and the test results, are tabulated in Appendix D.

2.1 Materials

The specimens used in laboratory testing were reconstituted from a mix of soils sampled from the Site, cement that was used at the Site, and water. These materials are described in the following sections.

2.1.1 Soil

The soils used in the laboratory portion of the study were sampled from the Fountain slide remediation project, herein referred to as the Site. The Site is located 16 km north-east of Lillooet, 270 km north-east of Vancouver, along Highway 99 (formally Highway 12B) in the Squamish-Lillooet Regional District of British Columbia, Canada.

Geotechnical investigations, reported in Golder Associates (Bosdet 1989, 1990 and 1991), reveal that the Site is underlain by a mixture of soils: predominantly sand, with varying content of silt, clay and gravel. All boreholes encountered a zone of fine-grained soil and mixed sandy, gravelly clay within the sand strata (see borehole logs (Bosdet 1991), along with the site plan, presented in Appendix A-1). Slicken-sided surfaces were identified within the fine-grained soils. Slope inclinometers installed in 1990, and monitored until the end of 1991 (Bosdet 1992) confirmed that the slope shear zone is located within the fine-grained soil deposits (see Inclinometer results in Appendix A-2).

Atterberg limits reported on the borehole logs, presented in Appendix A-1, on the fraction less than 0.420 mm of the fine-grained soils, established the plastic limit to vary from 16 % to 19 %, and the liquid limit range to vary from 24 % to 44%. The fines, located at the shear zone of the slide classify as either CL or ML, and as such, is defined as a low plasticity fine-grained soil.

After review of the geotechnical reports, presented in Bosdet (1989, 1991 and 1992), soils used for the laboratory testing portion of this study were obtained from surficial exposures and visually deemed representative of the Fountain slide deep mixing site project, before being transferred to the UBC laboratory for index testing, as described in the following sections. More specifically, grab samples were taken at each end of the Site, at the Fountain Creek and Gibson Creek locations, as represented on the Site photograph (see Figure 2.1).



Figure 2.1 Physical Setting of Fountain Slide Project

2.1.1.1 Fountain Creek

The Fountain Creek [FC] sample location is on the uphill, northeast shoulder of Highway 99, about 200 m west of the Site, as illustrated on Figure 2.1. Soil collected at the Fountain Creek location was sieved to remove the gravel fraction, which was found to be less than 10 % by weight, in order to facilitate specimen reconstitution in the laboratory, a practice reported in reconstituting cement-treated specimen (EuroSoilStab 2002). A combined sieve and hydrometer analysis, performed on the fraction smaller than 4.75 mm of the sampled Fountain Creek soil, is presented in Figure 2.2. From the grain size distribution, it can be observed that Fountain Creek soils have a sand and silt matrix with a trace of clay size particles. More specifically, the Fountain creek sample contains 38 % sand and 62 % fines [$\sim 40\text{S}:60\text{M}$]. Atterberg limits performed on the fraction finer than 0.420 mm yielded a plastic and liquid limit of 19 % and 28 %, respectively, and, as such, the fine fraction of the sampled Fountain Creek soil classifies as low plasticity silt.

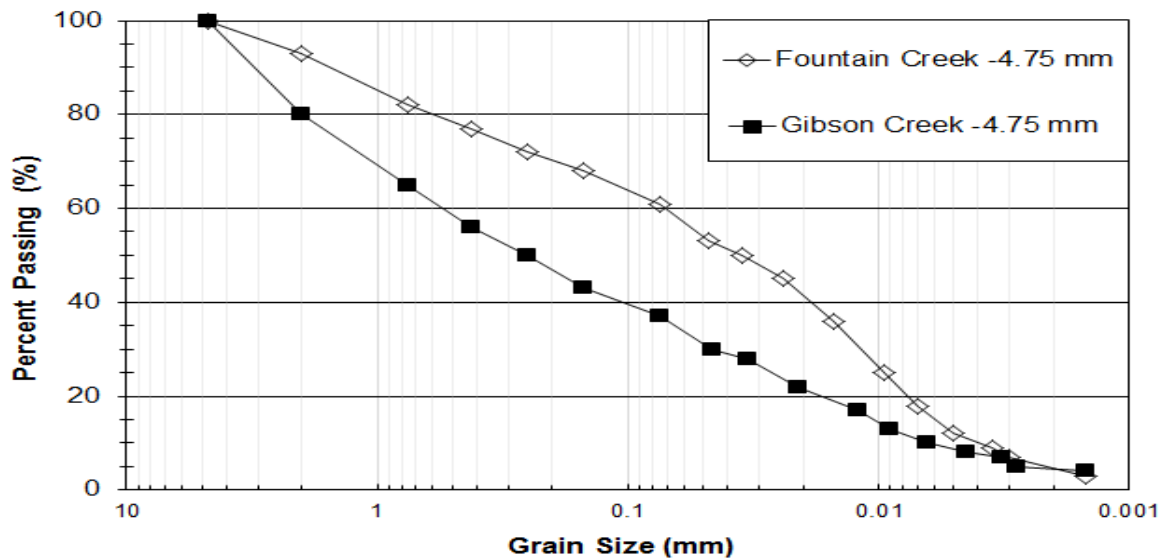


Figure 2.2 Grain Size Distributions

2.2.1.2 Gibson Creek

The Gibson Creek [GC] sample location is on the uphill, northeast shoulder of Highway 99, about 100 m east of the Site, as illustrated on Figure 2.1. Soil collected at the Gibson Creek location was also sieved to retain the fraction finer than 4.75 mm. Combined sieve and hydrometer analysis revealed that the Gibson Creek soil matrix is a silt and sand with a trace of clay- size particles. The grain size distribution curve is presented together with the Fountain Creek data in Figure 2.2. The Gibson Creek sample contains 61 % sand and 39 % fines [$\sim 60\text{S}:40\text{M}$] and the fine fraction also classifies as a low plasticity silt, given a plastic limit of 18 % and a liquid limit of 26 %.

It can be observed that the range in grain size distribution (i.e. from 38 % to 61 % sand and from 39 % to 62 % non-plastic fines) is in good agreement with that reported in earlier geotechnical investigations at the Fountain Slide location (see Appendix A-1). The two samples of soil, used in the laboratory study, bound the range of reported grain size distribution for the sliding mass of soil, as established in those prior geotechnical

investigations (Golder 1991). As such, Fountain Creek and Gibson Creek soil samples are considered representative of the soil present at the slide location.

2.1.2 Cement

Cement used in the laboratory study was obtained from Lafarge North America Inc. at a Vancouver-based branch. It was a General Use, Type 1-Portland cement, supplied in 40 kg bags, with a reported specific gravity of 3.15 (Lafarge 2011). The cement meets all applicable chemical and physical requirements of ASTM C150 and CSA A3000-03.

2.2 Laboratory Testing

The first objective of this laboratory test program is to investigate the sensitivity of the Unconfined Compressive Strength [q_u] to the soil gradation of cement-treated soil specimens using two different soils (namely, Fountain Creek and Gibson Creek soil), using the wet-mixing saturated reconstitution method to yield the cement-treated specimens. A second objective of the test programs is to study the influence of the reconstitution method on the q_u of cement-treated soil specimens, by using two different reconstitution methods (namely, the wet-mixing saturated and the dry-mixing unsaturated methods) on one of those soils, namely the Gibson Creek soil.

2.2.1 Specimen Reconstitution Techniques

As discussed earlier, from among the existing reconstitution methods presented in Section 1.2, the two selected for use in this study are i) the wet-mixing saturated method after Lewsley (2008) and, ii) the dry-mixing unsaturated method of CDIT (2002). These two methods are described in a step by step manner in this section.

2.2.1.1 Wet-Mixing (Saturated) Method

The reconstitution method first used in Lewsley (2008) and presented in Lewsley and Fannin (2011) was followed exactly, to yield homogeneous, saturated cement-treated soil specimens. The following are the main steps that were used:

An oven dry mass [M_s] of site soil, on average about 1000 g, was separated into sand and fines fractions, through wet-sieving over the sieve #200. The fractions were then brought to a fully saturated state by boiling in de-aired water for 30 minutes in a conical flask, and for 60 minutes in a beaker, for the sand and fines, respectively. Following the boiling process, the beaker containing fines was placed in a desiccator to further boil under vacuum for about 15 minutes (in order to remove residual entrapped air). Meanwhile the flask containing sand was left to cool at room temperature. The cooled saturated sand was then water-pluviated in a mold with a removable collar and bottom. The mold dimensions are 71 mm in diameter and 142 mm in length, plus the removable collar height of 126.5 mm. Mold characteristics and dimensions are presented in Figure 2.3. Upon cooling at room temperature, the fines slurry contained in the beaker was poured over the sand that was already in the mold. Once the majority of the soil fractions had settled (~ 1 hour for the Gibson Creek soil and ~ 3 hours for the Fountain Creek soil) the excess water was removed using a syringe, while leaving a thin film of water on top to inhibit re-entrainment of air.

At this stage, the mass of water contained in the mold was determined by subtracting M_s from the mass of the mold containing the saturated soil. The predetermined mass of cement [M_c] was then air-pluviated on top of the soil in the mold to a target laboratory binder factor [c]. Knowing the total mass of soil and cement, de-aired water was added to a target mass of water [M_w] in the mold, thereby achieving an initial water content [w_i] of about 30 %, as defined in Equation 2.1:

$$w_i = \frac{M_w}{(M_s + M_c)} * 100 \quad (2.1)$$

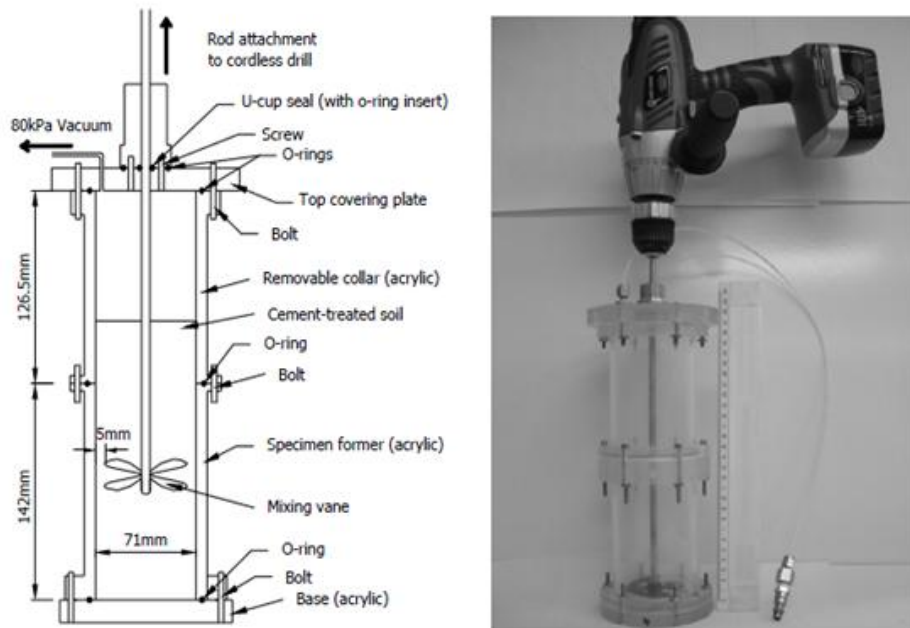


Figure 2.3 Saturated Mixing Apparatus (after Lewsley (2008))

The mold was then sealed off with a mixing vane passing through the lid and a vacuum pressure of 60 kPa applied (see Figure 2.3). The vane was connected to a 14.4 V commercial drill, operating at a speed of about 1150 rpm. The mixing vane was lowered and raised at a rate of about 3 seconds per cycle while rotating. The cement-treated soil specimen was mixed until visual observation confirmed homogeneity, which was approximately 5 minutes. The resulting saturated specimen phase diagram is schematically presented in Figure 2.4. Once mixing was completed, the vacuum was released and the lid removed, with the specimen still inside the mold and the collar attached. It was then placed for initial curing in a moist room with a constant temperature of 23 °C and relative humidity of 95 %.

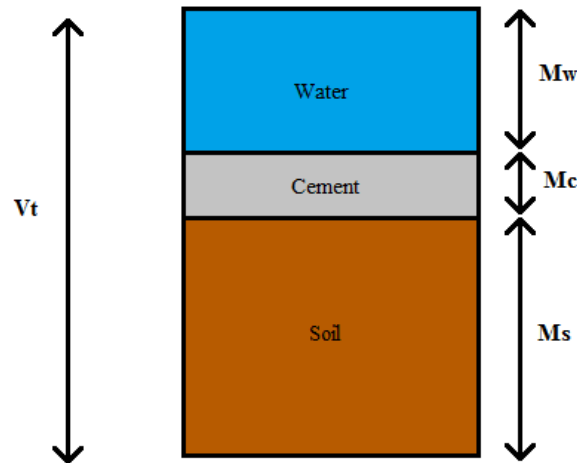


Figure 2.4 Saturated Specimen Phase Diagram Schematic

2.2.1.2 Dry-Mixing (Unsaturated) Method

The second reconstitution method used in this study followed the no-compaction mixing method presented in CDIT (2002), herein referred to as the dry-mixing unsaturated method, and yielded unsaturated specimens of cement-treated soil. The CDIT method was followed throughout, with the exception that the mixing energy was imparted by the same mixing vane as used for the wet-mixing (see Figure 2.3), as opposed to a dough mixer as recommended by CDIT. The following paragraph describes the step by step procedure followed to reconstitute unsaturated dry-mixed specimens.

An oven dry mass of soil [M_s] was placed in an aluminum bowl to which a pre-weighed mass of cement, to the target c , was added [M_c]. The soil and cement were mixed together using a mixing vane operated by a commercial drill until the color of the dry mix looked uniform, which was approximately 1 minute. This step differs from the wet-mixing saturated method in that the soil condition was dry using this method. A pre-determined mass of water [M_w] was then added to the dry mix to achieve an initial water content [w_i] of about 30 % (i.e. the same w_i as used for the wet-mixing saturated method). Using the mixing vane attached to the drill, the specimen was again mixed until homogenous. Once

the mixture was deemed homogeneous in color and consistency (after approximately 5 minutes of mixing — since the same equipment and same mixing time yields about the same mixing energy per volume as the wet-mixing saturated method), it was poured into the same mold described earlier, using a funnel. The bowl and funnel were then oven-dried to allow for correction of as-mixed masses of soil, cement, and water in the specimen, taking into account the dry residual solids remaining on the bowl and funnel. The mold containing the cement-treated soil specimen was placed in the moist room for initial curing. The resulting unsaturated specimen phase diagram is schematically presented in Figure 2.5.

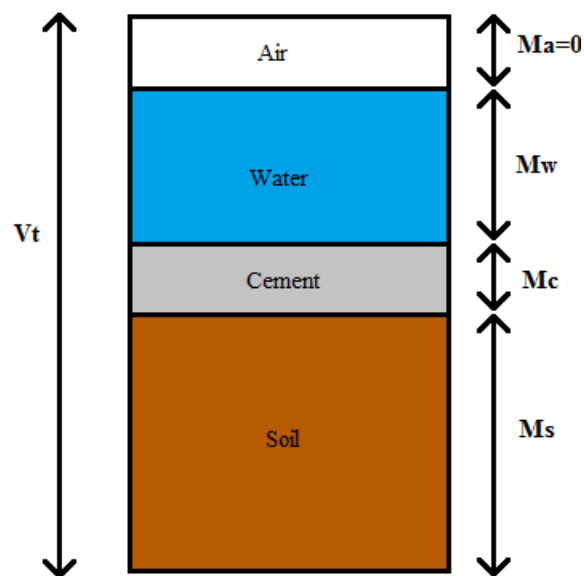


Figure 2.5 Unsaturated Specimen Phase Diagram Schematic

2.2.2 Specimen Preparation

Once the saturated and unsaturated cement-treated soil specimens were reconstituted as described in sections 2.2.1.1 and 2.2.1.2, respectively, they were left in the moist room for about 2 hours for initial curing of the cement. This allowed the cement-treated soil to attain a consistency similar to that of a soft clay, prior to being trimmed and cured in preparation for UCS testing.

If bleed water formed on top of the specimen during the setting phase of 1 to 3 hours, it was removed prior to separating the collar extension and trimming the excess material using a wire saw. This was done to obtain a specimen length equal to that of the specimen former (mold). Excess material was trimmed off, then oven dried.

The as-cured moisture content was determined using the trimmings, from which the as-cured mass of water could be calculated. The mass of cement contained in the trimmed specimen, referred to as the as-cured mass of cement $[Mc_c]$, can be obtained from a mass fraction of the original, as-mixed mass of cement $[Mc_m]$ of the as-cured specimen mass $[M_c]$ (once trimmed) divided by the mass of the specimen as mixed $[M_m]$ (including the trimmings) according to the following Equation:

$$Mc_c = \frac{M_c}{M_m} * Mc_m \quad (2.2)$$

The as-mixed cement content $[Cc]$, which is taken to be equal to the as-cured cement content, assuming that the cement to soil ratio in the trimming is the same as in the entire specimen, is defined in equation 2.3 below, as per the definition presented in Table 1.1. The mass of soil mixed $[Ms_m]$ is taken as the actual recorded mass of dry soil used in the mixing, around 1000 g as presented in section 2.2.1.1.

$$Cc = \frac{Mc_m}{Ms_m} * 100 \quad (2.3)$$

Once trimmed, the specimen is covered with a plastic film and returned to the moist room for further curing. The specimen has usually gained sufficient strength for extraction after an additional day of curing, at which time, the base of the mold is removed (see Figure 2.3). The specimen is extracted using a piston which is mounted vertically and moves upward. The piston has a diameter slightly smaller than that of the specimen to ensure even

pressure distribution, while still allowing for the smooth passage of the piston in the mold. The specimen is then wrapped in plastic film and returned to the moist room for the remainder of the intended curing period. The final dimensions of the reconstituted cement-treated soil specimen are approximately 71 mm in diameter and 142 mm in length, as required by ASTM D1633-00.

2.2.3 Unconfined Compressive Strength [q_u] Testing

The cement-treated soil specimens are now reconstituted, cured, and ready to test for Unconfined Compressive Strength [UCS]. If visual inspection reveals slight unevenness, ends are smoothed using 60 grit sanding paper. Specimen mass, length, and diameter are recorded prior to it being mounted on the loading frame to calculate the volume of the specimen at time of testing, the final volume specimen [V_f]. The loading frame consists of a 49.8 kN capacity Wykeham-Farrance compression machine, modified to fit two plates, which hold the specimen in place. Output voltages from a load cell (measuring axial force) and from a LVDT (measuring axial displacement) are recorded by a data acquisition system, such that stress-strain curves can be obtained. This system comprises of: a signal conditioning unit which amplifies the output signals; a 12 bit resolution DAS board with digital input/output; and a computer with the Labtech data acquisition software. The data are recorded at a frequency of 10 Hz by the software and stored as an output file by the computer software where further plots can be generated.

The specimen is mounted between the plates and loaded to failure at a constant rate of displacement of 1 mm/minute with automated measurements of stress, or axial force (over the specimen area) and displacement as per ASTM D1633-00. Once failed, the maximum stress value is taken as the unconfined compressive strength [q_u]. The failure shear plane is inspected and the entire specimen oven-dried to obtain the final moisture content. The water-cement ratio at failure [$(w/c)_f$], presented in Equation 2.4, can then be obtained knowing the mass of water in the specimen at failure [M_{w_f}], divided by the mass of cement in the specimen at failure [M_{c_f}], which is taken to be the same as the as-cured mass of

cement $[Mc_c]$. The final laboratory binder factor $[c_f]$, in kilogram of cement over volume of specimen, is calculated from parameters established earlier, as per equation 2.5.

$$(w/c)_f = \frac{Mw_f}{Mc_f} \quad \text{where: } Mc_f = Mc_c \quad (2.4)$$

$$C_f = \frac{Mc_f}{V_f} \quad \text{where: } Mc_f = Mc_c \quad (2.5)$$

2.3 Test Results

The following section presents the test variables and the plots (axial stress versus axial strain $[\epsilon_a]$ and q_u versus C_f). The original findings are presented, and the results discussed within the context of the objectives of the laboratory study.

2.3.1 Test Program

A total of 28 Unconfined Compressive Strength tests, and 9 duplicates, were performed to meet the two objectives stated above. Reconstitution method, soil type, as-mixed laboratory cement content $[Cc]$ (where VLC, LC, MC, and HC refer to very low, low, moderate, and high value of Cc respectively) and curing time were examined as variables in this study. A summary of the test program is given in Figure 2.6. All of the test data are reported in Appendix D.

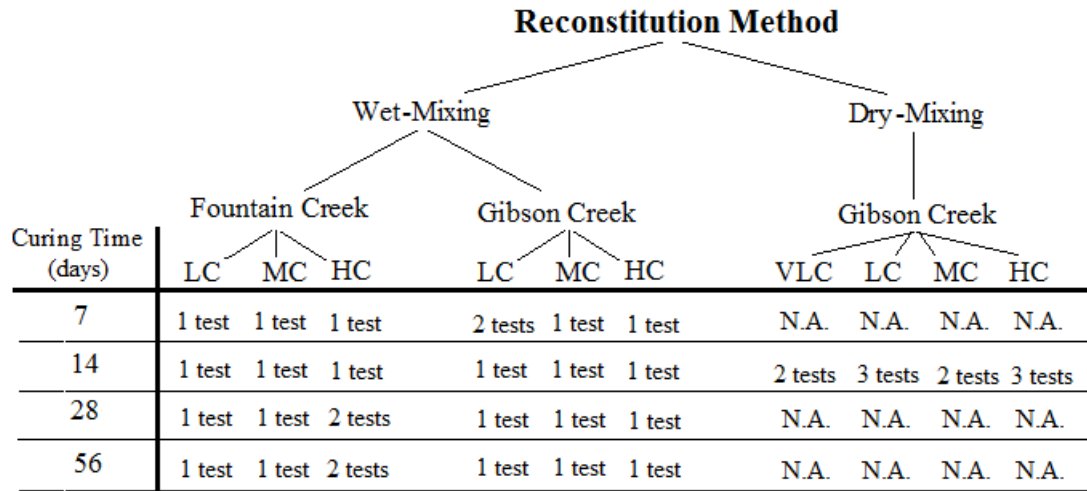


Figure 2.6 Summary of the Test Program on Laboratory Specimens

2.3.2 Saturated Test Specimens

Following are the test results from the 27 saturated specimens reconstituted using the method of wet-mixing for Fountain Creek soil and Gibson Creek soil, and their UCS test results.

2.3.2.1 Variation of Strength with Axial Strain

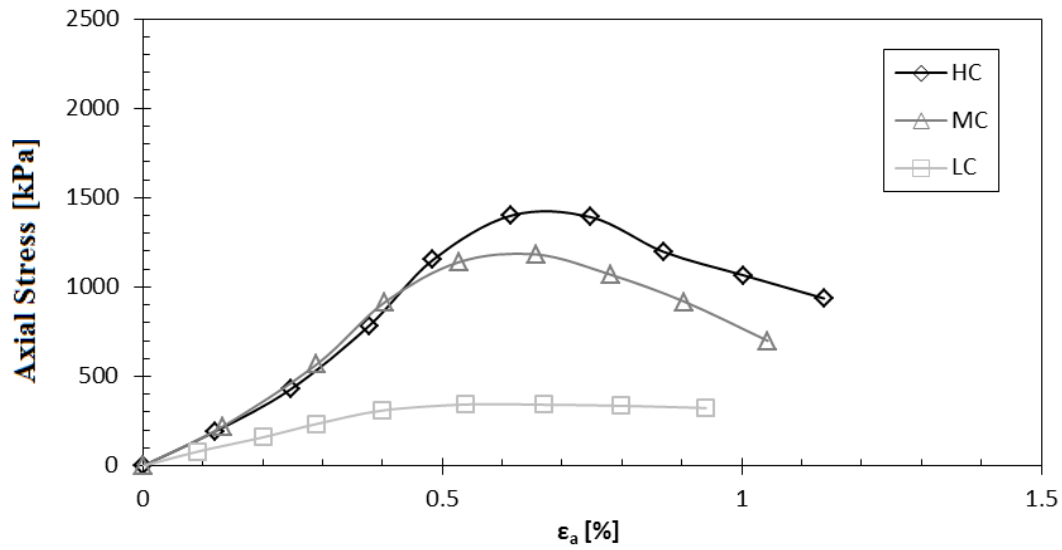
The influence of curing time on the stress-strain behavior of cement treated-soil specimens is evident from the results presented in Figures 2.7 to 2.10. Note that LC, MC, and HC refer to specimens reconstituted at a laboratory cement content [Cc] that is low ($\approx 8\%$), moderate ($\approx 14\%$), and high ($\approx 18\%$), respectively. For precise values of Cc, refer to Table D-1, in Appendix.

Inspection of the results (Figure 2.7 to 2.10) presenting stress-strain curves for the two types of soils, shows that the axial stress increases with axial strain $[\epsilon_a]$, up to a maximum value of strength $[q_u]$. Beyond the maximum value of q_u , the stress either diminishes sharply with increasing ϵ_a , signifying the specimen has failed in a brittle manner, else it

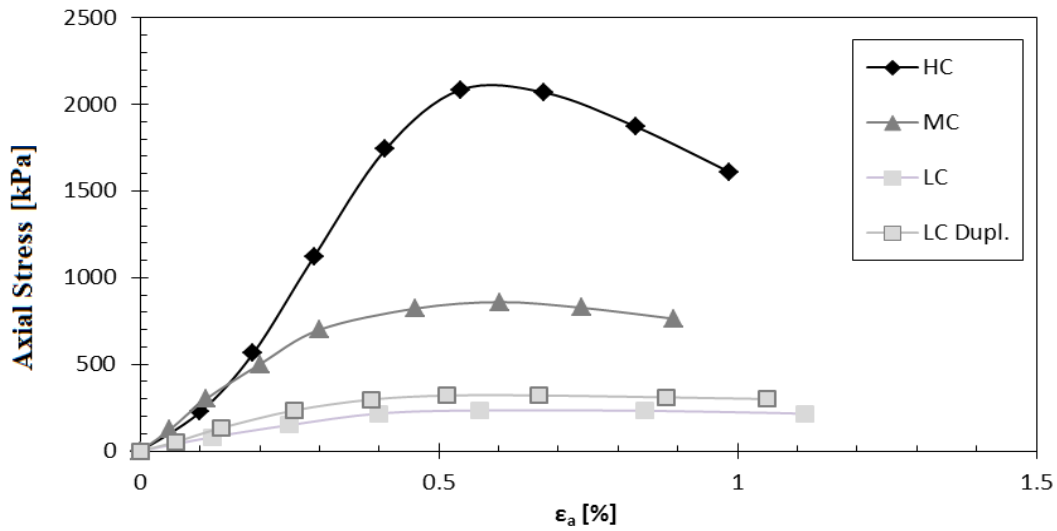
decreases very slowly, indicating the specimen behaved in a ductile fashion. Brittle failure was observed for all saturated specimens reconstituted at high laboratory cement content [Cc] while ductile behavior was observed for all of the saturated specimens with low Cc, irrespective of the soil type. The loading behavior post-failure of the specimens with moderate Cc appears unclear, as it sometimes resembles a brittle behavior (see, for example, Figures 2.7a, 2.9a, 2.10a, and 2.10b), and sometimes behaves in a more ductile fashion (as observed in Figures 2.7b and 2.9b).

In terms of the mobilized stiffness, it can be observed that, independent of soil type or specimen age, the slope of the curve up to failure increases with greater Cc. Similarly-shaped loading curves, hence loading behavior, are observed from duplicate tests on Gibson Creek specimens with low Cc at 7 days (Figure 2.7b), the Fountain Creek specimens with high Cc at 28 days (Figure 2.9a), and the Fountain Creek specimens with high Cc specimens at 56 days (Figure 2.10a). The finding suggests very good repeatability in the test results. The tests were stopped once the maximum strength was achieved, at no more than 1 % axial strain [ϵ_a]. Typically, the specimen failure occurred at an axial strain between 0.5 % and 0.7 %, irrespective of the cement content, soil type, or specimen age.

Inspection of data for the 7 day curing period, on Figure 2.7, reveals that specimens mixed at low laboratory cement content [Cc] exhibit peak strength in the range $0.25 < q_u < 0.36$ MPa. Moderate and high Cc specimens exhibit peak strengths of $0.88 < q_u < 1.22$ and $1.46 < q_u < 2.14$ MPa, respectively. In the case of the 14 day curing period, presented on Figure 2.8, peak strengths vary within the ranges of $0.28 < q_u < 0.37$ MPa, $1.03 < q_u < 1.4$ MPa, and $2.0 < q_u < 3.0$ MPa for low, moderate, and high Cc, respectively. From the 28 day results (presented on Figure 2.9), peak strengths vary within the ranges of $0.48 < q_u < 0.58$ MPa, $1.48 < q_u < 1.84$ MPa, and $2.29 < q_u < 3.49$ MPa for low, moderate, and high Cc, respectively. Inspection of the 56 day plots on Figure 2.10 reveals that peak strengths vary within the ranges of $1.21 < q_u < 1.26$ MPa, $2.64 < q_u < 3.88$ MPa, and $4.88 < q_u < 5.99$ MPa for low, moderate, and high Cc, respectively.

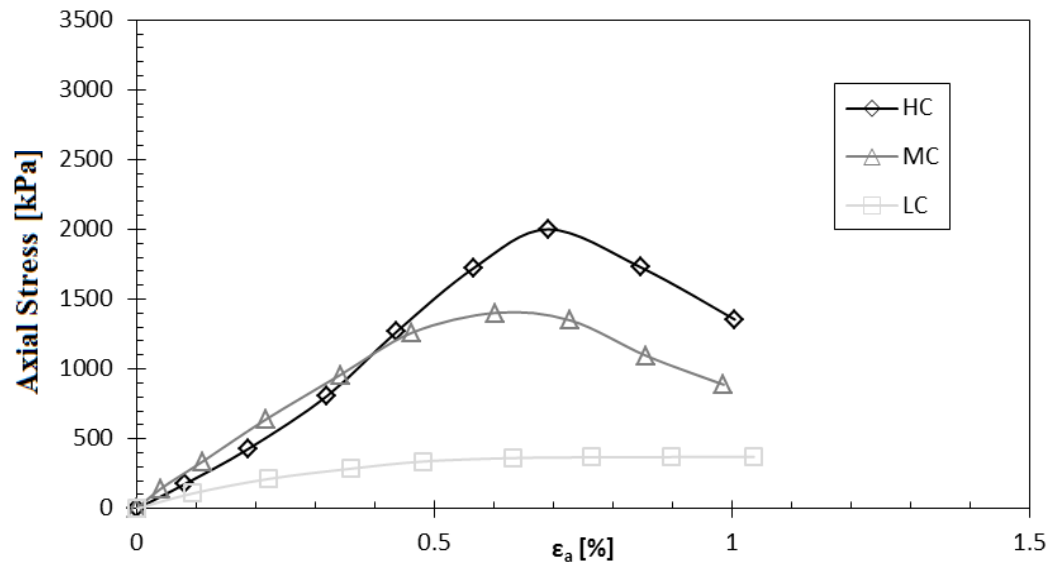


a) Fountain Creek

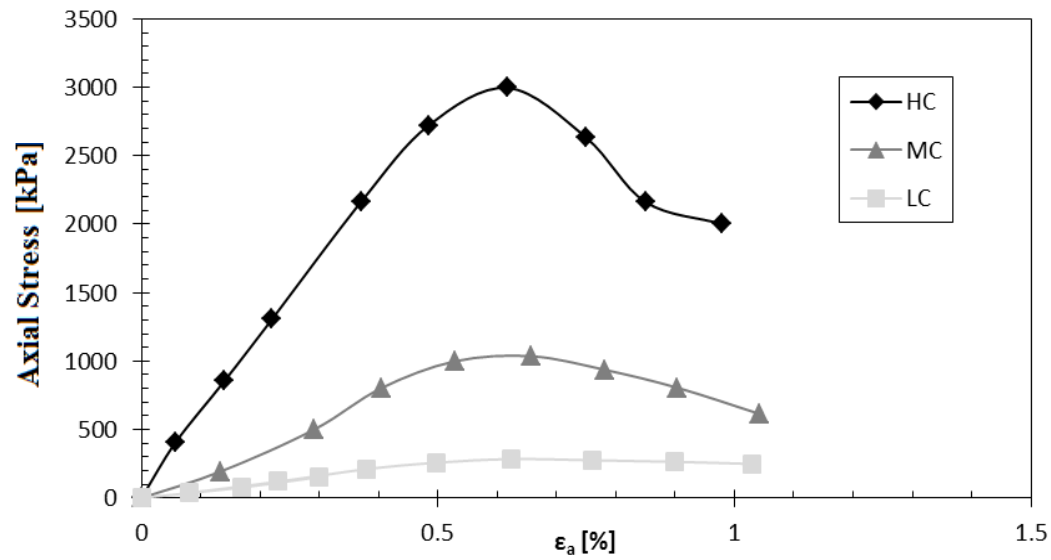


b) Gibson Creek

Figure 2.7 Stress vs. Strain Relation (Saturated Specimens, 7 days)

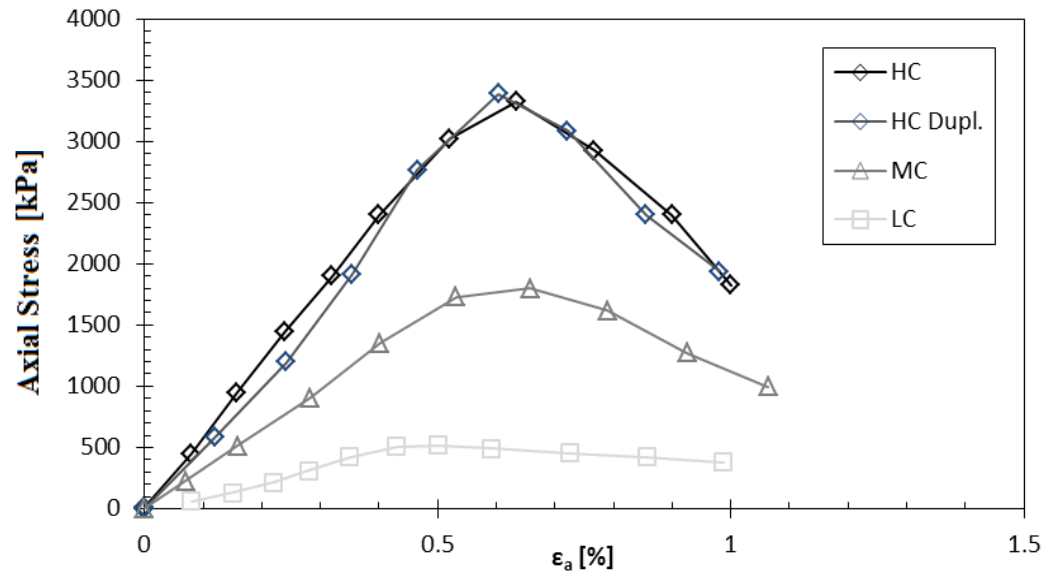


a) Fountain Creek

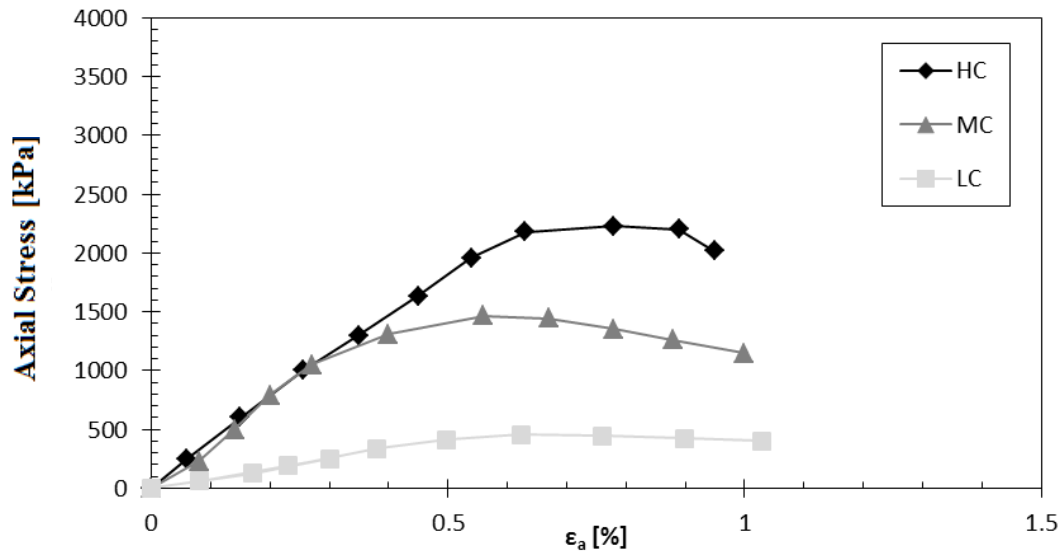


b) Gibson Creek

Figure 2.8 Stress vs. Strain Relation (Saturated Specimens, 14 days)

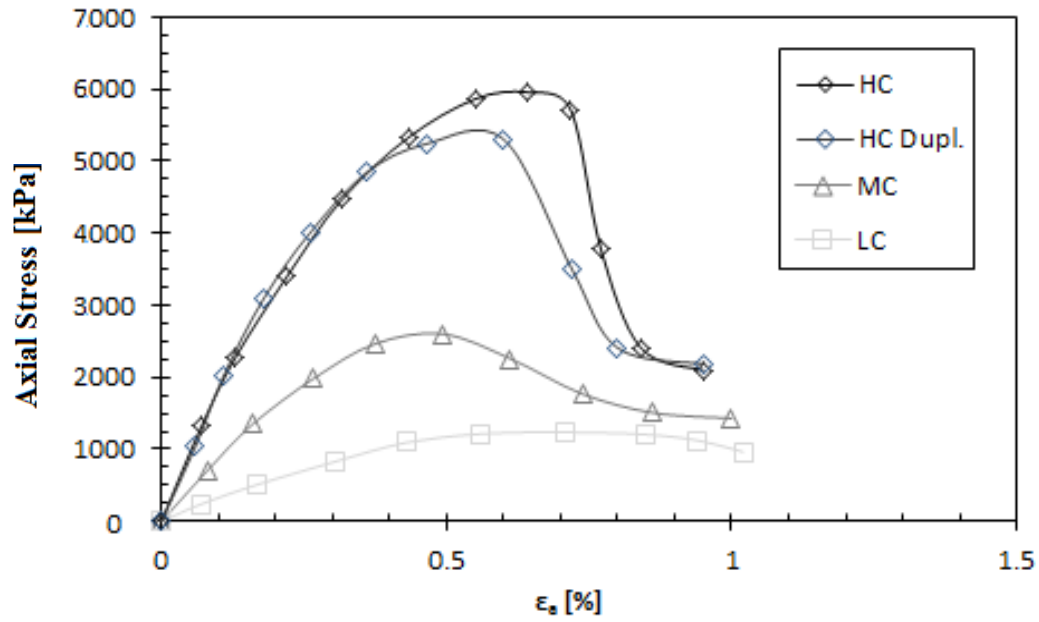


a) Fountain Creek

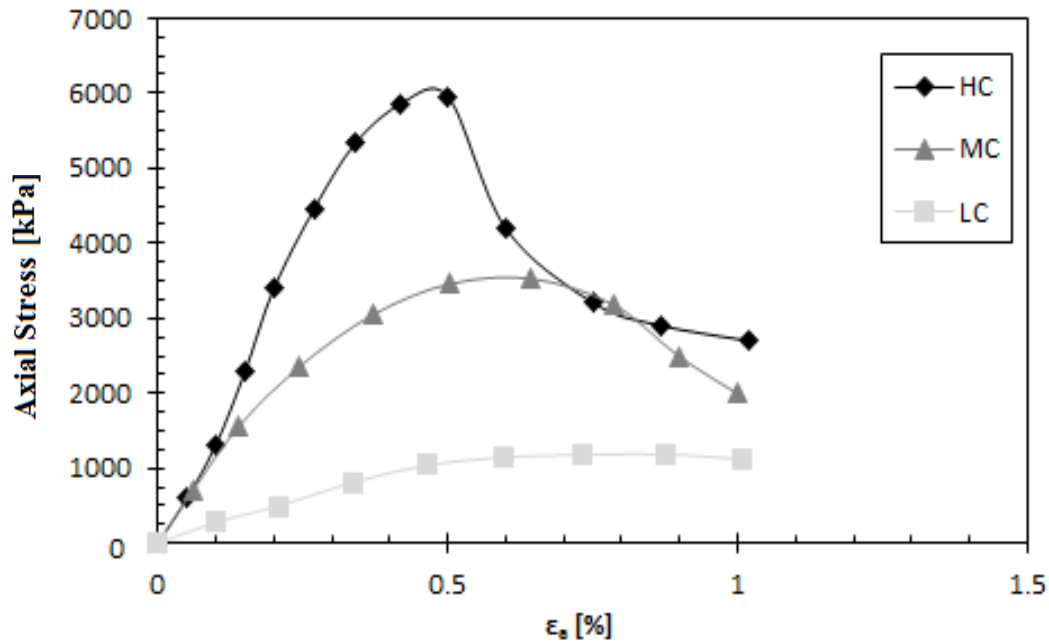


b) Gibson Creek

Figure 2.9 Stress vs. Strain Relation (Saturated Specimens, 28 days)



a) Fountain Creek



b) Gibson Creek

Figure 2.10 Stress vs. Strain Relation (Saturated Specimens, 56 days)

From inspection of the strength relations, it can be observed that the magnitude of q_u increases with cement content and with curing time. However, there does not appear to be a systematic difference in q_u with soil type.

2.3.3 Unsaturated Test Results

The following are test results for the four cement-treated specimens of Gibson creek soil and 6 duplicates, reconstituted using the dry-mixing unsaturated method. The maximum unconfined compressive strength [q_u] was determined in all specimens at a curing period of 14 days, as per Figure 2.6. All of the test results are reported in Appendix D.

2.3.3.1 Variation of Strength with Axial Strain

Figure 2.11 shows the variation of stress as a function of the axial strain, for the unsaturated cement-treated soil specimens prepared in this laboratory study. Three specimens were reconstituted and tested at relatively high [HC1-HC3] and low [LC1-LC3] laboratory cement content, while two specimens were reconstituted and tested at moderate [MC1 and MC2] and very low [VLC1 and VLC2] cement content.

Beyond the maximum value of compressive strength, q_u , two situations are observed. For specimens HC-1, HC-2, HC-3, and MC-2, the Stress diminishes with increasing ϵ_a , signifying the specimen failed in a brittle manner. In contrast, the decrease in stress is more subtle for specimens LC-1, VLC-1 and VLC-2, indicating that these specimens behaved in a ductile fashion post-failure. The loading behavior post-failure of the moderate Cc specimens is not well defined.

The attempt to replicate tests yielded some scatter for all of the laboratory cement content [Cc] at which specimens were reconstituted. Unsaturated specimens reconstituted at high Cc and tested at 14 days have a peak strength, q_u , between 3.1 and 4.41 MPa, while the range is 2.16 to 2.19 MPa for moderate Cc, 0.74 to 1.24 MPa for low Cc, and 0.15 to 0.25 MPa for very low Cc. The scatter appears to increase in magnitude for increasing Cc.

The stiffness of the specimen, from general inspection of the slope of the stress-strain curve, increases with cement content. This finding is consistent with previous observations for saturated specimens. It can be further observed that unsaturated specimens failed at an axial strain varying between 0.4 % and 0.65 %, which is comparable in magnitude to that found in testing the saturated specimens (see Figures 2.7 to 2.10). Likewise, the shape of the stress-strain curves for unsaturated specimens is similar to those of the saturated specimens.

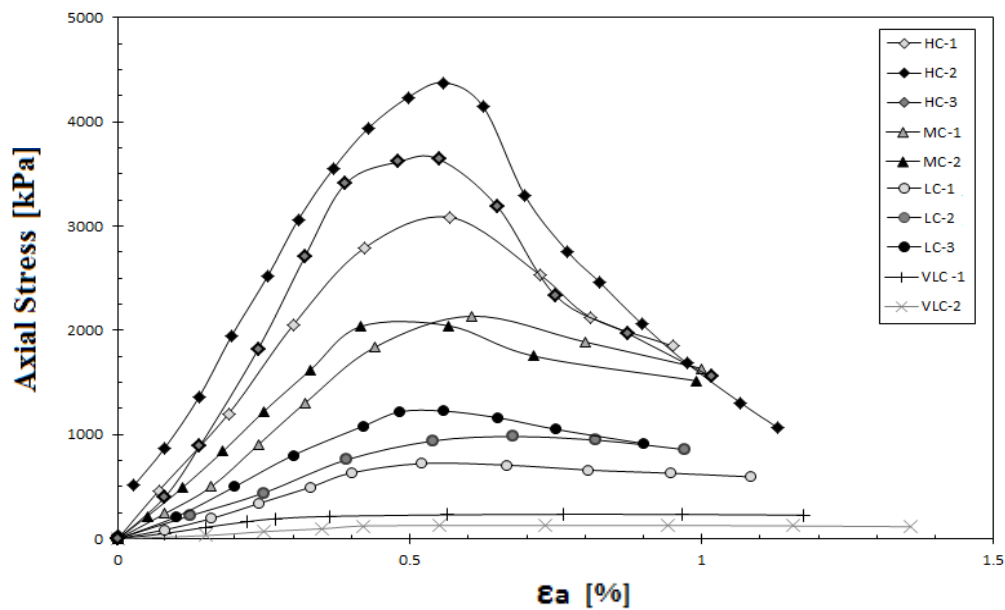


Figure 2.11 Stress vs Strain Relation (Unsaturated Specimens, 14 days)

Chapter 3: Field Study

A main goal of this research is to compare the strength of cement-treated soil specimens that are reconstituted in the laboratory with the strength of the same soil type when mixed with cement in-situ, using deep-mixing equipment, and then sampled for testing in the laboratory. The laboratory test data were reported in Chapter 2. The field site is now described together with details of the project requirements. Strength data are also reported for specimens reconstituted from wet-grab samples. These strengths data are related to the cement quantity (reported binder factor and cement content) of the cement-treated soil. Finally, results of the Unconfined Compressive Strength [UCS] testing and the ultimate unconfined compressive strength [q_u] data are presented for the specimens from the field. A comparison to the companion laboratory obtained results is also attempted.

3.1 Site Location and Description

The Fountain Slide remediation project is located in the Fountain Valley, 16 km northeast of Lillooet, or 270 km northeast of Vancouver, along Highway 99 (formally highway 12B) in the Squamish-Lillooet Regional District of British Columbia, Canada. The valley is known to have been the location of an earth flow during the Holocene period (Bosdet 1989). With the passage of time a slide has developed over a portion of the ancient earthflow. Movement of the Fountain Slide, located in the middle of the Fountain Valley, was first recorded in the mid-1980s. At that time, movement was estimated to be in the order of millimetres per year, and periodic maintenance was required on road, electricity and railway infrastructure traversing the slide location (see Figure 2.1).

Geotechnical investigations revealed the slide to be composed of a mix of silty sand, sandy silt, containing some sand and traces of gravel, as described in Section 2.1. Sample borehole information, retrieved from Bosdet (1991), is presented in Appendix A-1. The slide was the object of several studies from 1988 to 1992 (Bosdet 1992). Although the exact slide

mechanism remains a subject of discussion within the geotechnical community (MOTI 2006), the sliding surface was identified in 1990, from inclinometers installed within the moving mass. Inclinometer readings, reported from Bosdet (1992) and with a sample presented in Appendix A-2, revealed that the sliding zone is at about 9 to 12 meters below the roadway elevation of 1990.

Despite efforts to improve the slope stability, through unloading of the slide area, sealing of tension cracks, and collecting and discharging surface drainage outside the zone of infiltration above the slide, the slide had not stabilized in 1991 (Bosdet 1992). Recorded slope movements were noted to accelerate significantly between November 1989 and January 1991 (Bosdet 1992). At that time, potential remedial options were investigated, including the use of concrete shear pins, tension anchors and/or relocation of the highway. A full-time monitoring program of the slope movement was implemented by the owner, and maintenance of the infrastructure scheduled into regular interval, requiring more intense effort in the spring (MOTI 2006).

In the spring of 2010, the slide movements were noted to accelerate. The resulting ground displacements are causing severe disruption to services in the utility and transportation corridors crossing the slide location. The section of Highway 99 within the slide is now unpaved and requires monthly re-grading. As the scarp of the slide lies just above the railway, the depth of the slide is limited at that location. An H-pile wall was constructed to support the rail-track, with trains now operating at a lower speed while traversing the slide area, and an automated system install to monitor track deviations. Hydropower poles, originally located within the sliding zone, were relocated on either side of the slide, with cables being unsupported over a longer span (Golder 2011). Given the cumulative impact of ground displacement on Highway 99 at the slide location, the owner initiated a trial deep-mixing project in order to mitigate the slope movements.

3.2 Ground Treatment Procedure

The first portion of the soil mixing stabilization work, the pilot phase, is to be constructed using the Cutter Soil Mixer [CSM] technology, so as to yield rectangular panels of cement-treated soil. The pilot phase comprised about 60 panels, perpendicular to the slide along the highway alignment, each of which is intended to provide shear resistance against sliding. The panels, 2.8 m. by 1.0 m. in plan area, extend below the postulated slip surface and be embed 1 m. into the underlying competent till layer. The pilot phase aims at investigating the potential for remediation of the entire slide by measuring any change in rate of movement of the slide after panels are installed.

For the remediation project, design engineers set a target binder factor [α_i], measured in kilograms of cement per cubic meter of in-situ soil [V_s] to be improved, at 300 kg/m³. The target was set to achieve contract strength requirements of 2 MPa after 14 days of curing time, while accounting for uncertainties in ground conditions, variation of soil type, and mixing energy distribution.

3.2.1 Cutter Soil Mixer [CSM] Method

The CSM technology involves the mixing of binder slurry with in-situ soil at depth to yield panels of cement-treated soil. The slurry is obtained from combining water with a dry binder --cement in the case of this pilot phase, at a given suspension ratio [w/c]. The field set-up required for a CSM project is presented on Figure 3.1. The slurry mixing is carried out at a mobile batch plant, located within pumping distance to the CSM rig. The batch plant is automated and used calibrated scales to weight in the slurry constituent as they are added to the mixer. The cement gets delivered to the mixer from the cement silo using a screw auger. The mixing energy is then imparted to the cement and water through a high shear action in the mixer. Once mixed, the cement slurry is transferred to the agitator for a short time. A delivery pump then transfers the slurry from the agitator pump to the CSM where it will be mixed in panels.

To mix a panel, the CSM is positioned over the panel location. The soil at the panel location is first put into a liquefied mode, with the cutting wheels penetrating the soil to the required depth (referred to as the base layer). To help during the cutting action, water, or a mix of water and bentonite in low ($\sim 1\text{-}2\%$ by weight) suspension ratio, is injected as needed. The CSM mixing energy is provided by two rotating cutting wheels (see Figure 3.2), operated at a given rpm, mounted on a vertical shaft guided by a Kelly bar (Bauer 2011) which provides a pushing crowd force. The mixing tool is referred to as the CSM cutting and mixing head. The cutting and mixing head can be energised by different types of rig and for the pilot phase, a Bauer RG 19 T rig was used. The CSM operator has control over the shaft crowd force, the wheel rotation direction and rpm as well as the vertical location of the cutting and mixing head. The slurry injection flow, supplied by the delivery pump from the batching plant, is also controlled by the operator.

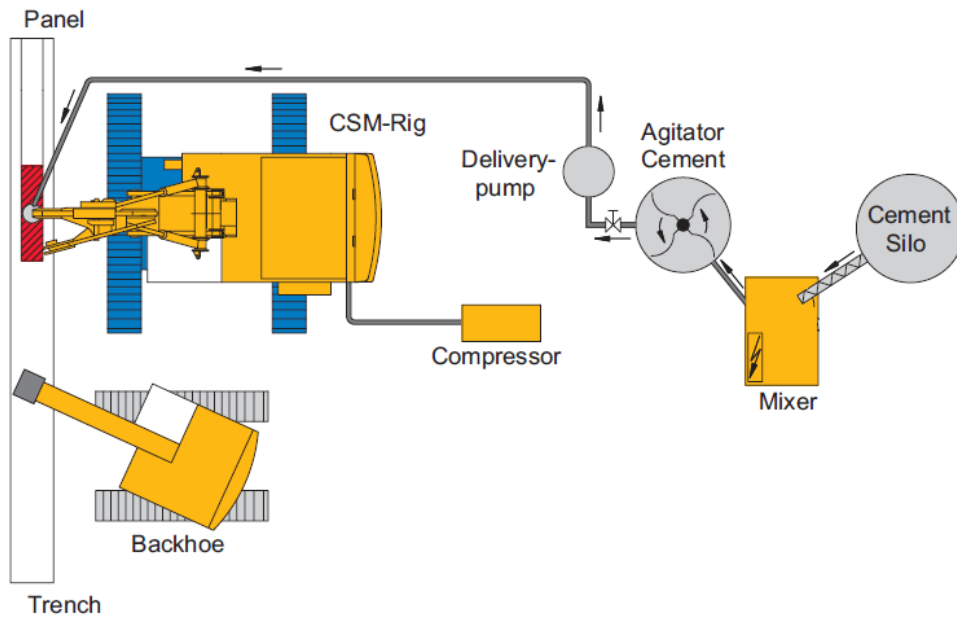


Figure 3.1 CSM System (Bauer, 2011, adapted by permission)

Once the cutting of the panel is done and the base layer is reached, the shaft is raised while a predetermined amount of cement slurry $[V_{cs}]$ is injected at each meter depth interval of the panel $[V_p]$. Using the target binder factor $[\alpha_i]$, hence mass of cement $[m_c]$

per volume of soil [V_s], and w/c of the cement slurry, V_{cs} can be determined as per Equation 3.1. Note that the cement slurry density [ρ_{cs}] is obtained using w/c and its constituent's respective density (ρ_w for water and ρ_c for cement).

$$V_{cs} = \frac{(1+w/c) * m_c}{\rho_{cs}} \quad (3.1)$$

$$\text{where: } \rho_{cs} = \frac{(w/c * \rho_c) + \rho_w}{(1 + w/c)}$$

The CSM wheels rotation provides sufficient mixing energy to yield a homogeneous cement-treated soil material, when retracting the cutting and mixing head. The cutting and mixing actions of the CSM are represented in Figure 3.2 with a diagram of the site soil phases before and after treatment. Here, V and M stand for volume and mass, respectively, while i stands for initial state of the soil prior to mixing and f for final state after mixing.

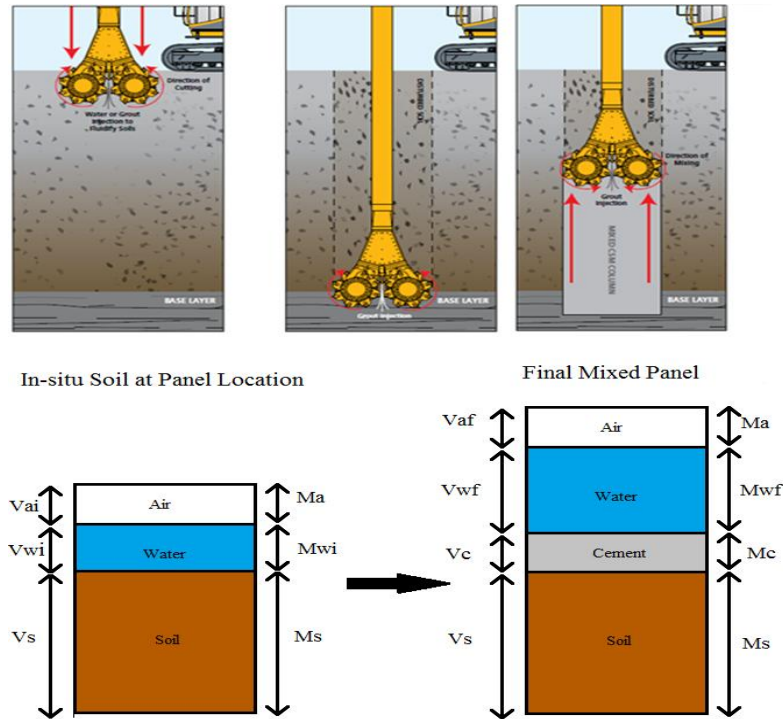


Figure 3.2 CSM Cutting, Mixing and Resulting Specimen Schematic

After mixing of a given panel, instrumentation from the CSM allows for volume of pumped slurry to be tracked as a function of depth. The total volume of slurry pumped in a panel [V_{cs}], the wheel torque, panel mixing time, final depth, and surveyed location, are stored in the construction records –see for example sample CSM B-report presented in Appendix B.

3.2.2 Pilot Phase

The existing soil deposits at Fountain slide were described in details in section 2.1.1. Overall the pilot phase subsurface consists predominantly of sand containing varying amount of silt, clay and gravel. The soils in their natural state are dense to very dense and have relatively low natural moisture content (~ 3 to 12% as per Appendix A.1). The CSM was judged adequate to cut and mix the existing soils into cement-treated soil panels. During the cutting phase, water was injected to help liquefy the soil. To reach the base layer, located at about 12 to 13 meters below highway 99 at its 2011 elevation, it took, on average, 40 minutes, at a penetration speed of about 30 cm/min. During the cutting phase, the wheels typically cut at 24 rpm and use about 200 bar of hydraulic pressure.

Cement used in the field project was General Use Type 1 Portland cement, manufactured and supplied by Lafarge and delivered in bulk from trucks having a 40 tons capacity. Lafarge Canada reports a relative density or specific gravity of 3.15 for the cement. Based on this information, it is believed that the cement used in the laboratory study is the same as the cement that is used in the field project

For the pilot phase, it was determined that a cement slurry w/c of 0.6, with corresponding ρ_{cs} of 1806 kg/m³, was optimal for pumpability and mixing quality. Once the base layer reached, the cement slurry injection rate [$V_{cs}/\text{min.}$] was set at 0.4 m³/min., while the retrieval rate was set at about 0.8 m/min., for a V_{cs} of about 0.5 m³ per linear meter of panel. At Fountain slide, each panel was mixed with about 6 000 to 7500 liters of cement slurry [V_{slurry}], or 6.0 to 7.5 m³. On average the slurry pumping and mixing action took 15 minutes from the bottom of the panel to surface. During the mixing phase, the wheels still rotated at about 24 rpm, but the hydraulic pressure required is only about 100 bar.

For the field study, wet-grab samples were obtained following EN14679:2005 specifications. A sampling box attached to the CSM which was inserted into a mixed panel immediately after the completion of the panel, prior to the cement setting in. The sampling box is about 10 litres in volume and has a hinged bottom that allows for un-cured soil-cement to flow through the box when the cutter head is pushed down into the panel. This same hinged bottom closes when the cutter head is retrieved from the panel. Figure 3.3 presents the installation of the sampling box onto the CSM cutting and mixing head, the insertion of the sampler into the freshly-mixed panel, the retrieval of the wet-grab sample and the transport of the wet-grab sample for casting into specimens on site, respectively. Circled in red in the two first images of Figure 3.3, is the empty sampler box. The orange circles, presented on Figure 3.3c and 3.3d, identify the wet-grab sample retrieved from a given CSM panel.

Wet-grab samples, retrieved from the predetermined depth at which the operator stops the downward pushing, were obtained from two different freshly mixed panels, labelled 4B and 5B respectively. Panel 4B is located 25 m. from the east end of the Fountain Slide remediation project, about 125 m. west of the Gibson Creek location (see Figure 2.1). Sample 4B was obtained at 7.5 m. depth, relative to the existing road surface. Panel 5B is immediately next to Panel 4B, 5 m. west, when measured centre to centre. The wet-grab sample, obtained at Panel 5B location, was from a depth of 10 m. Laboratory tests were carried out on the two samples of cement-treated soil, as obtained from CSM field-mixed panels. Test procedure and results are described in the next section.



a) Mounting of the Sampler Box



b) Insertion of Sampler Box



d) Retrieval of Wet-grab Sample



c) Wet-grab Sample

Figure 3.3 CSM Sampling

3.3 Laboratory Testing

This section describes the tests performed on the samples of cement-treated soil, as retrieved from the pilot phase of the field project. First, a portion of the sample was used to test for cement content, then the remainder of the sample was used to cast field-mixed cement-treated soil specimens for UCS testing.

3.3.1 Determination of Cement Quantity

As discussed in Chapter 1, there are different methods for reporting or testing the quantity of binder present in a given specimen of cement-treated soil. This section presents one reporting method, using information provided by the CSM records, and one testing method [ASTM D5982-07], used on the field-mixed samples 4B and 5B.

3.3.1.1 Production Records

Recall that the CSM is a wet-mixing deep mixing method, and as such, the predetermined mass of cement required to be mixed-in a given panel volume of soil, to achieve α_i , is introduced in the soil in a slurry form, mixed at a batch plant and pumped to the CSM head. From α_i , a target injection rate, was set up for the CSM operator to meet. The actual amount of binder that ends up in the panel is described as the reported binder factor [α_r] and can be calculated from construction reports (B Report for actual pumped V_{cs} and information from the batching plant for ρ_{cs}) as described in Equation 3.2. The volume of soil, which is mixed using the CSM, is taken as equal to the panel volume [V_p], or the section of panel for which α_r is calculated.

$$\alpha_r = \frac{V_{cs} * \rho_{cs}}{V_p} \quad (3.2)$$

For the sampled panels, the reported binder factors were calculated to be 313 kg/m³ and 288 kg/m³ for panels 4B and 5B, respectively.

3.3.1.2 Heat of Neutralization

The actual Cement Content [Cc], as defined in Equation 2.3 by the mass of cement over the mass of dry soil in a given cement-treated soil, was used on the field-mixed samples. The method is based on the heat of neutralization between the carbonate content of the cement mixed in the soil and a buffer solution. The heat of neutralization method [ASTM D5982-07] was performed using soil from the Site and is described in detail in Appendix C. In general, the method relies on a calibration curve, which is obtained in the laboratory from

the temperature difference between fresh cement-treated soil specimens, mixed at known C_c , and the fresh specimen reacting with an acidic buffer solution.

The wet-grab samples, obtained from the field project, were tested using the heat of neutralization method. Tested samples from panel 4B and 5B, yielded temperature differences of 20.3 and 18.1 °C, which are plotted on the calibration curve from Appendix C. From Figure 3.4 the Cement Content [C_c] can be inferred to be 10.8 and 9.9 % for sample 4B and 5B respectively.

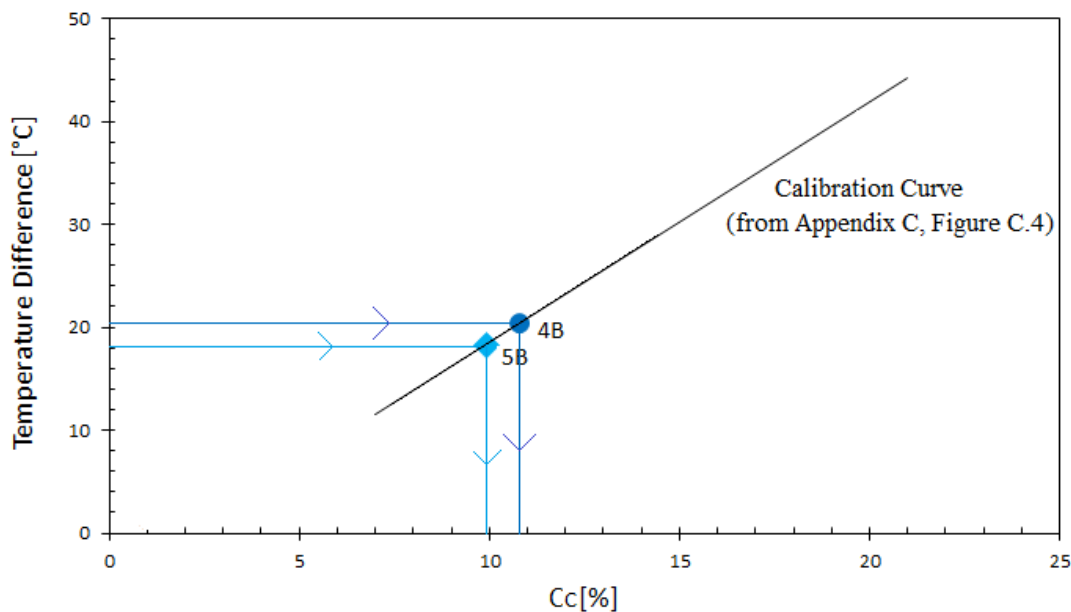


Figure 3.4 Cement Content Calibration Curve with Field Sample Results

3.3.2 Specimen Preparation

From each sample, four cylinders were cast in the same type of mold as used for the laboratory study, minus the collar attachment, so as to yield specimens of 71 mm in diameter and 142 mm in length. To remove entrapped air, the wet-grab sample was poured through a funnel into the mold in three layers, each of them rodded, using a 19 mm diameter smooth steel rod. The top of the reconstituted specimen was levelled flush with the top of the base mold. The mass of the specimen was recorded and the initial density [ρ_i]

determined. A portion of the sample was oven-dried to determine the moisture content and, hence, the mass of water in the sample [M_{wf}], as illustrated on Figure 3.2. Once the specimens were cast, they were covered with a plastic film and placed in a cooler (20 ± 4 °C), with wet burlaps, for initial curing at the Site. After 2 days in the cooler, initial setting allowed for the specimens to be transported to UBC laboratory, without excessive disturbance. Once in the laboratory, the specimens were extracted from the molds, using the piston sampler that was used in the laboratory study. The specimens were then wrapped in plastic film and placed in the moist room for the remainder of the intended curing period of 14 days. The final dimensions of the field-mixed specimens were approximately 71 mm in diameter and 142 mm in length, as required by ASTM D1633-00.

Once cured, the specimens were tested using the same equipment and procedure as described in Section 2.2.2.2.

3.4 Test Results

The following section presents the test variables with their respective q_u and associated plots (Stress versus Axial Strain [ϵ_a]; α_r versus α ; and q_u versus C_c , as reported or deduced). The field findings are presented and the results discussed with comparison to the laboratory test data in accordance with the study objective.

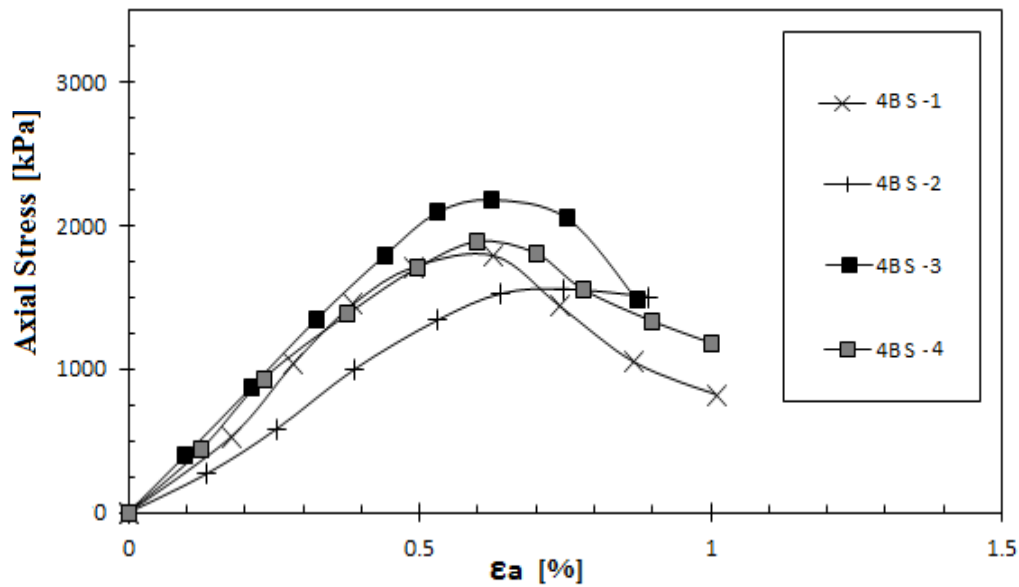
3.4.1 Test Program

A total of 8 specimens were cast from the two samples taken from the panel 4B and 5B locations at the Site. The specimens were tested for UCS at 14 days. Reported binder contents [α_r] were obtained from the values in Golder Construction field records (2011), as reported in section 3.3.1.2. The complete data set, from the field-mixed specimens, is presented in Appendix D.

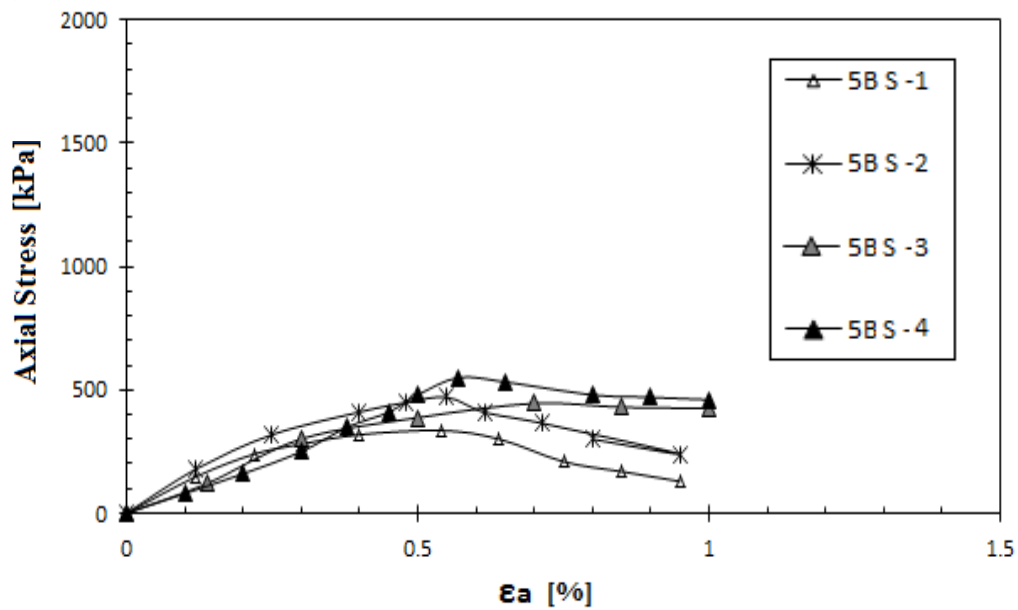
3.4.2 Variation of Strength with Axial Strain

The stress-strain curves for field-mixed specimens of cement-treated soil, from the two sampled panels, are presented in Figure 3.5. From the curves, it can be observed that the stress increases with axial strain [ϵ_a] up to a maximum value of Unconfined Compressive Strength [q_u]. The four stress-strain curves of the specimens from panel 4B, presented in Figure 3.5a, are very similar to each other in shape. The well-defined q_u with sharply decreasing strength post failure indicates they are behaving in a brittle manner, except for specimen 4B S-2, which exhibits a more ductile behaviour post-failure. Duplication of results is deemed satisfactory for specimens from panel 4B, since 3 out of 4 specimens behave in a similar manner. Inspection of the data reveals that specimens cast from 4B sample exhibit a peak strength in the range $1.58 < q_u < 2.22$ MPa.

Specimens from panel 5B, also have stress-strain curve shapes that are similar to each other, with a ductile behaviour post failure. However specimens from 5B have a distinctly lower q_u than those from 4B, with peak strengths observed to be in the ranges of $0.35 < q_u < 0.55$ MPa. Overall the strains at failure for 4B and 5B specimens, ranging from $0.55 < \epsilon_a < 0.75\%$, are of the same magnitude as those observed from laboratory-reconstituted specimens, as presented earlier in Chapter 2.



a) 4B Panel Location



b) 5B Panel Location

Figure 3.5 Stress vs. Strain Relation (Field-Mixed Specimens, 14 days)

3.4.3 Variation of Strength with Quantity of Cement

In order to compare the reported binder factor to the forensically determined, or deduced, cement content [Cc], the later was converted into a deduced binder factor [α], in kilogram of cement per volume of specimen. Equation 3.3 presents α , using the specimen initial density [ρ_i] as defined earlier in Section 3.3.2.

$$\alpha = \frac{C_c * \rho_i}{100} \quad (3.3)$$

Figure 3.6 compares the reported binder factors [α_r] to the deduced cement content, expressed in kilograms per cubic meter [α]. It can be observed that the deduced values obtained from the ASTM heat of hydration method, range from 187 to 198 kg/m³ for panel 4B specimens, and from 172 to 182 kg/m³ for panel 5B specimens. The reported binder factors are 313 kg/m³ and 288 kg/m³ for panels 4B and 5B, respectively. The deduced values are about 60 % of the reported ones.

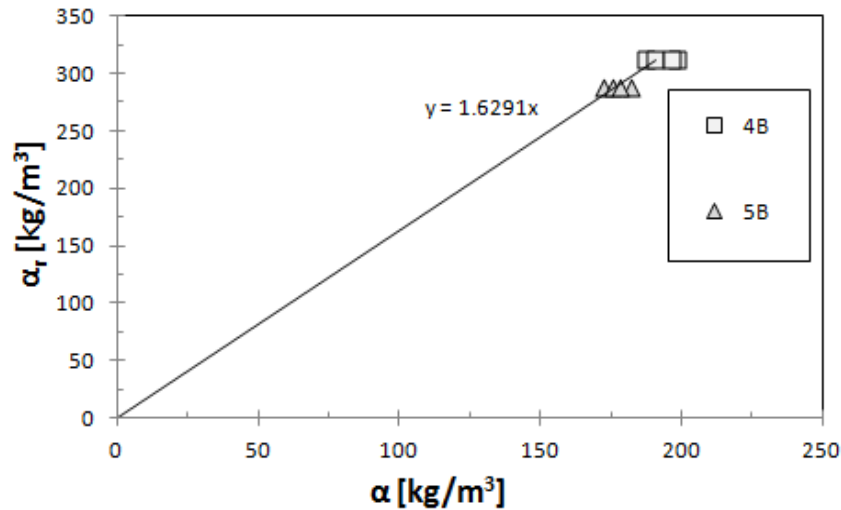


Figure 3.6 Reported versus Deduced Binder Factor

In Figure 3.7, the Unconfined Compressive Strength [q_u] of each field-mixed specimen is presented as a function of both α_r (Equation 3.2) and α (Equation 3.3). It can be observed that results for specimens of the same panel locations tend to cluster, and the overall difference between reported binder factor and deduced binder factor is consistent for both samples. The reported binder factor for panel 4B sample was 25 kg/m³ more than that of panel 5B sample, representing an increase of about 8.6%. On average, the deduced binder factor was 13 kg/m³ more for panel 4B sample than for the sample of panel 5B. The deduced binder factor was 7.3% more for panel 4B than panel 5B.

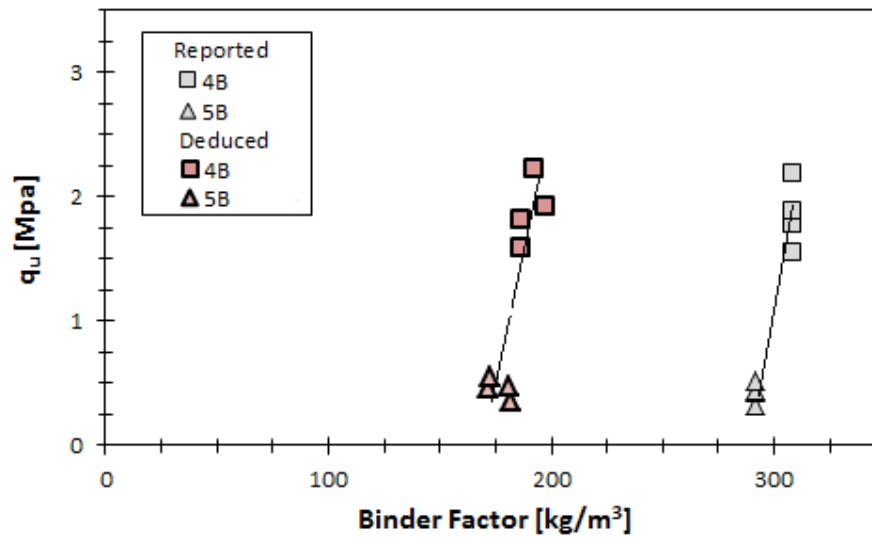


Figure 3.7 Unconfined Compressive Strength vs. Binder Factor (Field-Mixed Specimens, 14 days)

Chapter 4: Analysis and Discussion

In this chapter, consideration is first given to the results of Unconfined Compressive Strength [q_u] tests on specimens that were reconstituted in the laboratory.

Following the laboratory test results, the q_u data for specimens cast from wet-grab samples of field-mixed soil panels at the Fountain Slide project are compared to the strength of companion specimens reconstituted in the laboratory. The utility of testing for the cement content of field-mixed specimens is also discussed.

4.1 Laboratory Reconstituted Specimens

This section investigates the effects of water-cement ratio and curing time on the strength of cement-treated soil specimens that have been reconstituted in the laboratory. Next, these results are compared to existing data from Lewsley (2008) to examine the influence of soil type on strength. Results from this study using two different reconstitution methods are then compared to investigate the influence of specimen saturation on the strength. Finally, data from Filz et al. (2005) and Merrigi et al. (2008) are presented to further examine the effect of soil type and reconstitution method on the strength of cement-treated soil.

4.1.1 Variation of q_u with Water-Cement and Curing Time

Water-cement ratio has been used to describe the combined influence of water and cement content on the q_u of cement-treated soil specimens. The water-cement ratio $[w/c]$, as defined by Equation 2.4 in section 2.2.3, was previously determined to be a useful index when describing the strength of cement-treated soil by Miura et al. (2001), Janz and Johansson. (2002), Filz et al. (2005), and Lewsley (2008). As such, the q_u results from the saturated specimens of cement-treated soil presented in Section 2.3.2, are now presented

as a function of their respective final water-cement ratio $[w/c]_f$, or their w/c at time of testing.

For a curing time of 7 days, the strength ranges from a maximum unconfined compressive strength $[q_u]$ of 2.14 MPa at $(w/c)_f = 1.9$ to a minimum q_u value of 0.25 MPa at $(w/c)_f = 4.8$. There is excellent agreement for FC and GC data, yielding $R^2 = 0.97$. 14 days specimens $(w/c)_f$ values increased with respect to the 7 days results, specifically they ranged from $1.9 < (w/c)_f < 5.9$. The R^2 value for the 14 days specimens, equal to 0.90, is lower than for 7 days data.

At 28 days curing time, q_u of FC and GC specimens appear to be fitting a power relation nicely when expressed as a function of the specimen $(w/c)_f$ with a goodness of fit of 0.96. For GC specimens, $0.48 < q_u < 2.29$ MPa while for FC specimens, $0.54 < q_u < 3.50$ MPa. The range of $(w/c)_f$ appears to be similar for both soils reconstituted specimens and ranged from $2.0 < (w/c)_f < 5.1$.

It can be observed that the q_u data for 56 days specimens plots very closely, $R^2 = 0.99$, around the power trendline with no distinct difference between the GC and FC specimens. The strength ranges from a maximum q_u of 5.99 MPa at $(w/c)_f = 1.6$ to a minimum q_u value of 1.21 MPa at $(w/c)_f = 3.4$. It is noted that the goodness of fit of the q_u data, when presented as a function of $(w/c)_f$, is better, at each curing time interval, than when q_u data are presented as a function of final laboratory binder factor $[C_f]$ alone, which was presented on Figures 2.7 to 2.11. This implies that $(w/c)_f$ is a better indicator than C_f for predicting q_u — an observation that is in agreement with previous related studies (Babasaki et al. (1997), Lewsley (2008) and Consoli et al. (2007 and 2009). It can also be noted that the trend observed between q_u and $(w/c)_f$ gets distinctly steeper with additional curing time, a trend that is consistent with the increase in q_u with additional curing time, observed in Chapter 2.

Additionally, the close fit of all the data points presented on the four Figures 4.1 suggests that, for the two soils tested, recall that GC and FC ranged from 40 to 60 % sand

respectively, the sand-fines ratio does not appear to be a driving factor in the strength generation for specimen of cement-treated soils, as reconstituted in a saturated manner in the laboratory. To further investigate this hypothesis, the next section incorporates data from previous research carried out at UBC and using the same reconstitution method.

It should be noted that the w/c index is valid only if there is sufficient water present in the specimen to hydrate all cement particles. A study by Horpibulsuk et al. (2006) revealed that the relation between q_u and w/c for cement-treated soil is similar to that of moisture-density relation for soil—that an optimum water content exists. On the dry side of the optimum, there is not enough water available for optimum hydration of the cement, while on the wet side, water is in excess of the cement hydration demand and keeps the particles further away (void ratio $[e]$ increases), hence inhibiting the cementation process and reducing q_u . Horpibulsuk et al. (2006) concluded that within 80 to 120 % of the optimum moisture content, enough water was present within the cement-treated soil pores to allow functional hydration of the cement particles. Although no moisture curves were prepared within this study, it is expected that the saturated reconstitution technique used yields specimens with moisture contents close to, but slightly above 100% of the optimum moisture content.

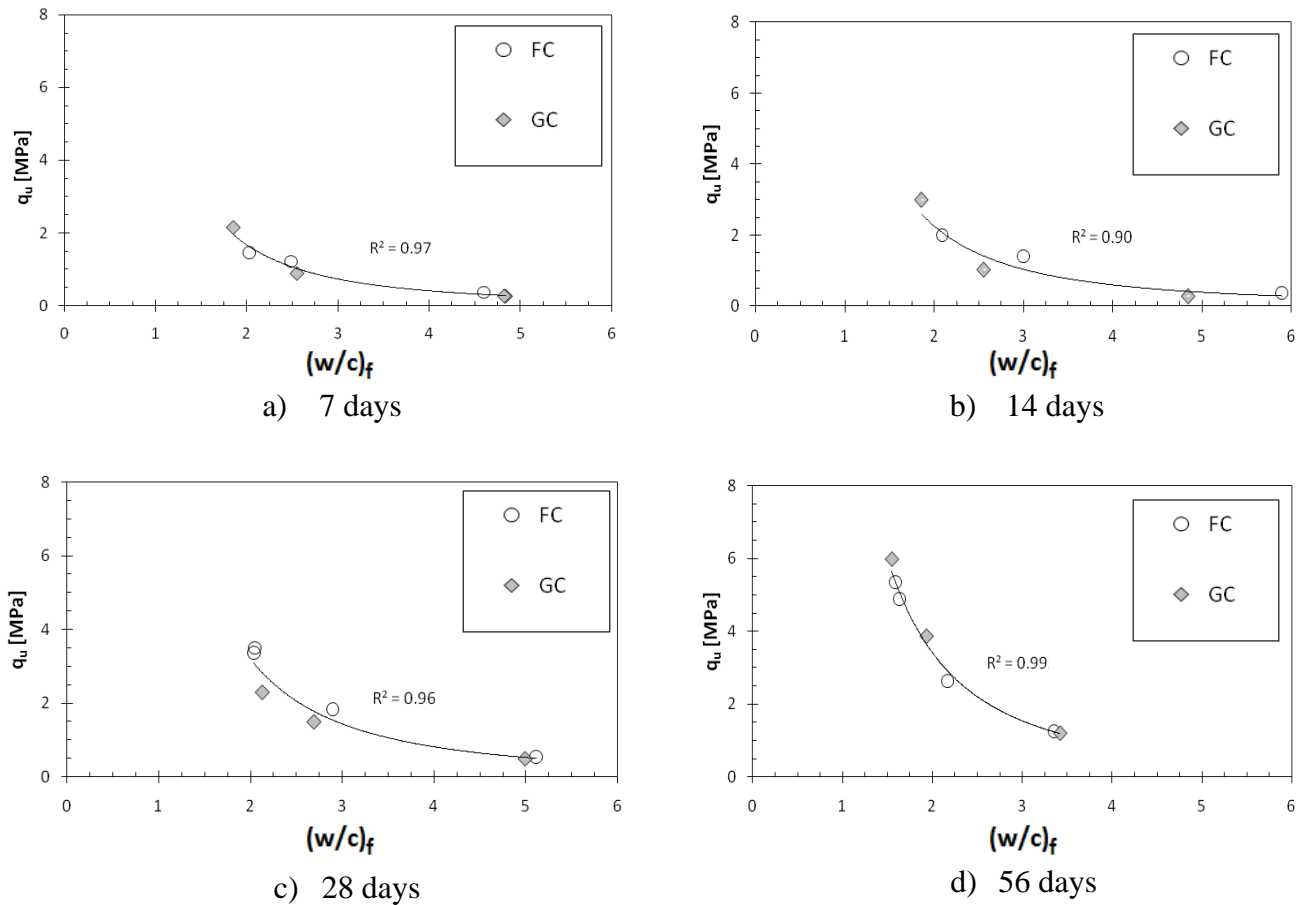


Figure 4.1 Unconfined Compressive Strength vs. Final Water to Cement Ratio for Saturated Specimens

4.1.2 Variation of q_u with Soil Type

In Lewsley (2008), the influence of a wider range of sand to fines ratio was studied for cement-treated soil specimens. Lewsley developed the wet-mixing saturated method, described and used in this study, and applied it to reconstitute specimens of cement-treated soil. To reconstitute his specimens, Lewsley used four fabricated soils of distinctly different gradation. Fraser River Sand [FRS] and Kamloops Silt [KS] were mixed at four sand-fines weight ratio to yield specimens with sand [S] to fines [F] ratio varying from 90S:10F to 25S:75F (Lewsley 2008). Figure 4.2 shows Lewsley's q_u results for laboratory

reconstituted saturated specimens, tested after 7 day's curing time. To show how this study results compare with Lewsley's, 7-day data from Figure 4.1a are plotted again in Figure 4.2, with results from specimens reconstituted from GC soil presented using their sand-fines ratio (60S:40F) and same for FC soil data (40S:60F).

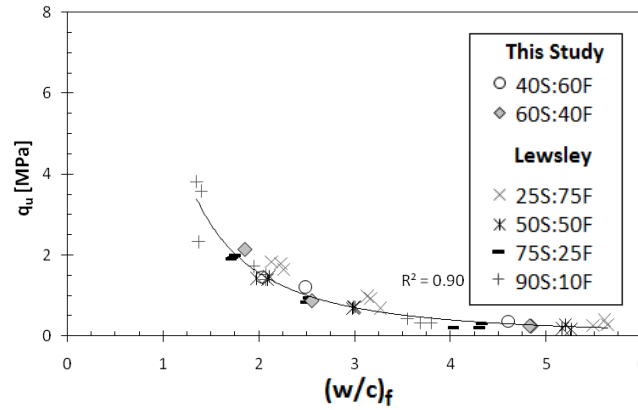


Figure 4.2 Variation of q_u with Final Water-Cement Ratio for Saturated Specimens ($t = 7$ days)

It can be observed that the range of $(w/c)_f$ for which the power trendline fits q_u results is larger than the range presented on Figure 4.1a. More specifically, specimens reconstituted $1.2 < (w/c)_f < 5.7$ yielded $0.3 < q_u < 3.8$ MPa. The goodness of fit, R^2 , for the combined FC, GC and blended mixes of FRS and KS soils, is 0.90.

From Figure 4.2, it can be noted that 25S:75F data points from Lewsley (2008) yield q_u results which plot slightly higher on the graph than the remaining points. By recognizing that this blend soil behaviour is slightly different than that of the rest of the tested soil, Figure 4.3 presents an improved way of plotting q_u as a function of $(w/c)_f$ for all soil types. For specimens reconstituted from soil having a sand-fine ratio from 90 % sand (90S:10F) to 40 % Sand (FC at 40S:60F), the relative change in sand to fines ratio has no apparent effect on the q_u : see Figure 4.3 lower trend line.

It can be observed from Figure 4.3 that the two trendlines bound the observed specimen behaviour. The R^2 value for trendline representing all the data, minus 75S:25F, is 0.97. The R^2 value of the trendline describing q_u data for 75S:25F, is also 0.97. Similarly, q_u data for the same soils, tested after 14, 28 and 56 days of curing, are presented on Figure 4.4.

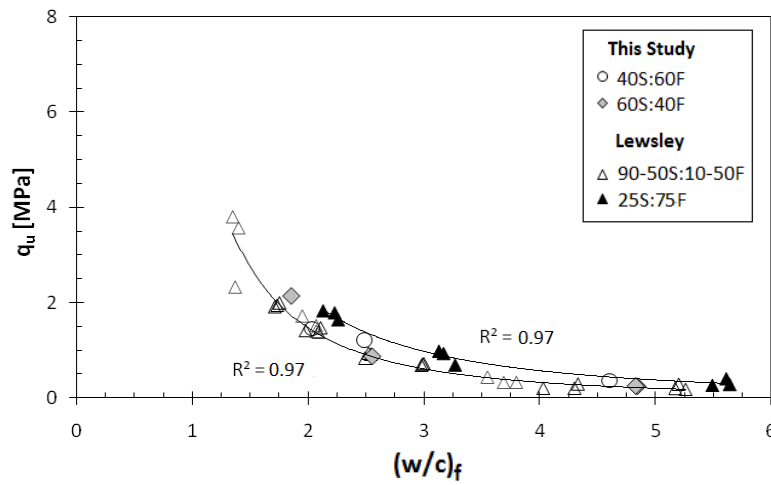
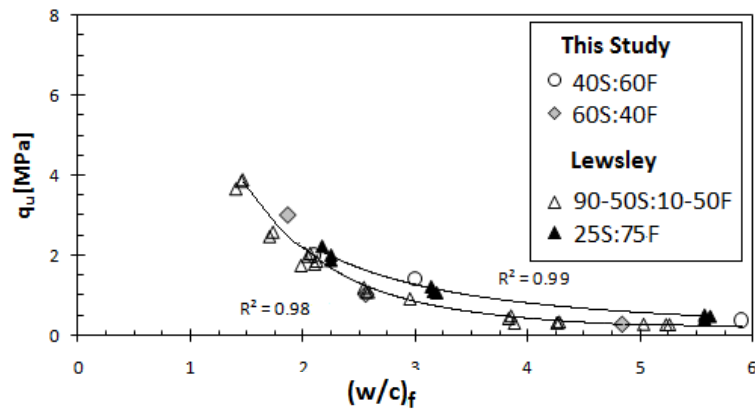
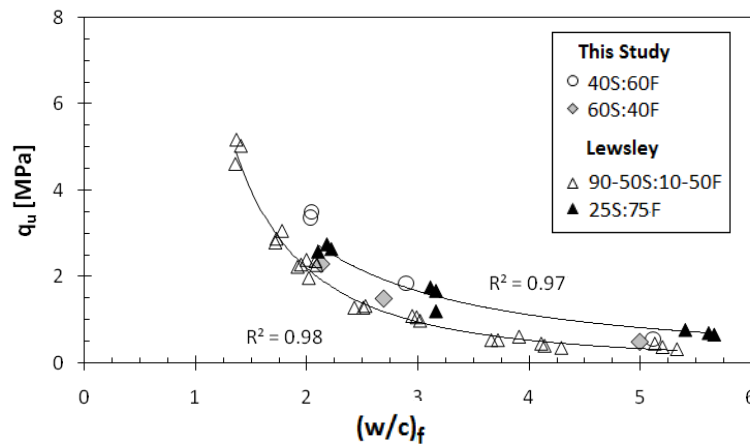


Figure 4.3 Variation of q_u with Final Water-Cement Ratio for Saturated Specimens-Bounded ($t = 7$ days)

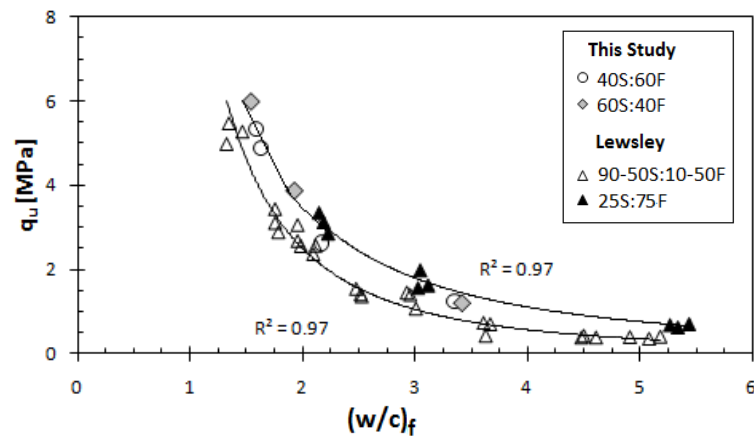
From Figure 4.4a, presenting q_u data at 14 days of curing, a trend similar to that observed from Figure 4.3, is established for mostly sand and mostly fines soil blend. Q_u data range from 4.0 MPa down to 0.5 MPa for $(w/c)_f$ varying from 1.5 to about 6.0 respectively. It can be observed that the goodness of fit of the two power-trendlines is better than for the 7 days q_u data, and stands at $R^2 = 0.98$. It can be observed that for the 28 days data, $5.0 < q_u < 0.4$ MPa for 1.5 to 5.8 values of $(w/c)_f$. The goodness of fit is judged excellent. Finally, Figure 4.4c presents data for specimens tested after 56 days of curing. The upper and lower trends are again, judged excellent ($R^2=0.97$).



a) All 14 days with Distinct Soil Behaviour



b) All 28 days with Distinct Soil Behaviour



c) All 56 days with Distinct Soil Behaviour

Figure 4.4 Variation of q_u with Final Water-Cement Ratio for Saturated Specimens-Bounded

For the saturated, cement-treated specimens reconstituted from non-cohesive soil, such as those tested so far at UBC (i.e. Fraser river sand; Fountain Slide sandy silt and silty sand; and Kamloops silt), there exist a unique relation, with an upper and lower trendline, defining q_u data with respect to $(w/c)_f$ of tested specimens. It can be observed that the strength of cement-treated specimens is highly insensitive to the sand-fines ratio of the soil used in the reconstitution, for the 6 non-plastic soil tested at UBC.

4.1.3 Variation of q_u with Reconstitution Method

Unconfined Compressive Strength [q_u] results from cement-treated Gibson Creek [GC] soil specimens, reconstituted in an unsaturated manner ($S < 1$) and tested after 14 days of curing, are presented as a function of final water-cement ratio $[(w/c)_f]$ in Figure 4.5. It can be observed that $(w/c)_f$ varies from about 1.0 to 5.2 and its relation to q_u follows a power trendline ($R^2 = 0.95$). The resulting q_u vary from 7.8 to 0.3 MPa.

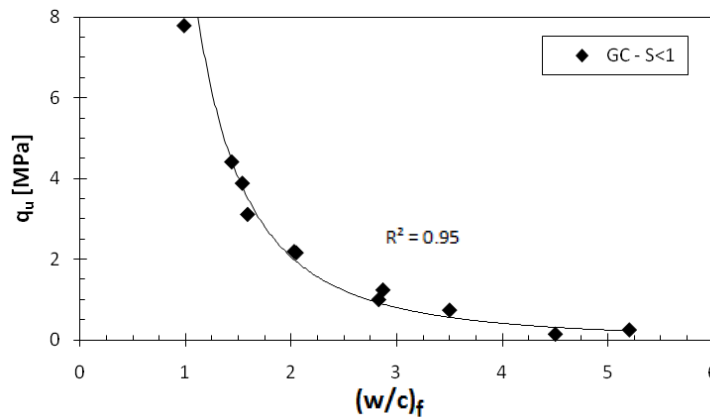


Figure 4.5 Variation of q_u with Final Water-Cement Ratio for Unsaturated Specimens ($t = 14$ days)

The general shape of the relation between q_u and $(w/c)_f$, that was established for *saturated* specimens of cement-treated soil reconstituted in the laboratory also describes *unsaturated* specimens, as can be observed from Figure 4.6.

Accordingly, the data from Figure 4.1b and 4.5, namely at a curing time of 14 days, for the two reconstitution methods used in the laboratory testing program, are presented in Figure 4.6.

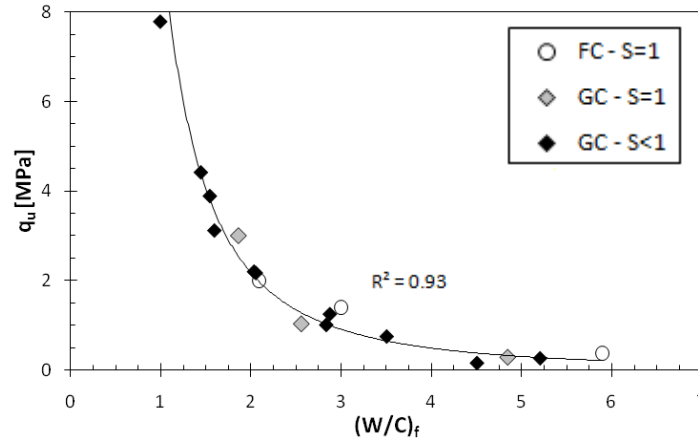


Figure 4.6 Variation of Strength with Water-Cement ratio ($t=14$ days)

The range of $(w/c)_f$ for which the power relation fit the q_u results is now extended from about 1.0 to 6.0. The resulting q_u values are in the range 7.6 to 0.25 MPa. Although the R^2 value is slightly lower than for the unsaturated data above (as per Figure 4.5), it is nonetheless good at $R^2=0.93$.

Given the generally excellent agreement, it appears that the strength of the cement-treated soil specimens is insensitive not only to the two types of soils tested, which vary in sand content from 40 to 60%, but also to the reconstitution method used in testing. This finding implies that the rigorous but time-consuming saturated wet-mixing is likely unnecessary for purpose of characterizing the strength of cement-treated soil using the CSM device. Instead, the relatively quick dry-mixing (unsaturated) method, presented in CDIT (2002) should be used, when reconstituting cement-treated soil specimens for strength testing in the laboratory.

4.1.4 Comparison with Other Studies

In order to investigate further the influence of soil type and reconstitution method on the strength of cement-treated soil specimen reconstituted in the laboratory, results from other studies that are reported in the literature are compared with the findings from this study.

More specifically, Filz et al. (2005) report test results for two soils, termed Light Castle Sand [LCS] and Vicksburg Silt [VS]. LCS is a poorly graded fine sand consisting entirely of sand size particles while VS contains only particles finer than 75 μm . VS has a liquid limit of 27 % and a plastic limit of 22 % and classifies as a SP soil. The reconstitution method used in Filz et al. (2005) follows exactly the wet-mixing (unsaturated) process, presented in Section 1.3.1.2, yielding unsaturated specimens ($S < 1$). The method differs from the dry-mixing (unsaturated method) used in this study, in that it uses soil at natural moisture content and that the binder is introduced in a slurry form for the mixing.

Merrigi et al. (2008) report test results for a washed quarry silt [S]. Soil S comprises of 7 % sand, 80 % silt and 13 % clay size particles and is described as a low plasticity silt. Its fine fraction classifies as a CL soil with a liquid limit of about 25 % and a plastic limit of about 6 %. Merrigi used a reconstitution method for his specimens which relies on initial dry mixing of the soil and cement before water is mixed in and the mix compacted for optimal density in the curing mold –as per ASTM D1632 method presented in section 1.3.1. The reconstitution method yields unsaturated specimen at unknown saturation level ($S < 1$). It should be noted that the main difference between this reconstitution method and the two methods used in this study is the use of compaction energy during casting of specimens. Merrigi et al. (2008) uses a standard proctor energy delivered by a falling weight hammer on each of the 3 layers of the reconstituted specimens.

The format of the data published in Filz et al. (2005) and Merrigi et al. (2008) allows for the reported strength [q_u] data to be plotted as a function of the Water-Cement ratio at beginning of curing [$(w/c)_c$] (as defined in Chapter 2). All of the data are for the same

curing time of 28 days. Data from the current study are also plotted as a function of $(w/c)_c$ in Figure 4.7. It is important to note that, although three of the reconstitution methods, for which data is presented, yielded unsaturated specimens, the actual level of saturation of the specimens is unknown.

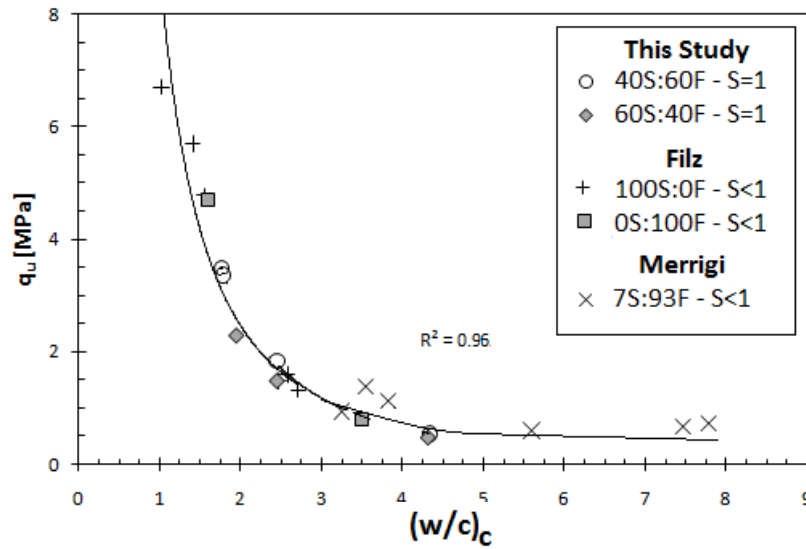


Figure 4.7 Variation of Strength with Water-Cement Ratio ($t = 28$ days)

It is observed that the shape of the relation between q_u and $(w/c)_c$ is as previously established. The range of $(w/c)_c$ for which the relation holds true is larger, $1.0 < (w/c)_c < 7.9$. The goodness of fit for data from 3 different studies and for 5 soils is $R^2=0.96$, for combined sandier and finer soil material. The close fit of all the data in Figure 4.7 offers yet more evidence to support that q_u versus w/c is independent of (i) the sand/fines ratio in non plastic soils and of (ii) the method of reconstitution used.

4.2 Field Sampled Specimens

This section attempts at comparing the q_u results obtained from field-mixed specimens of cement-treated soil with that of laboratory reconstituted specimens, using the water-cement as an index. Recall that two samples, 4B and 5B, were obtained from the Fountain

Slide CSM project. Following sampling, 8 specimens were cast from the two wet-grab samples and tested after 14 days of curing. The goal of this analysis is to determine if such a comparison is first practical and second brings in any value for deep mixing project.

In order to analyze the strength of field-mixed specimens in the same manner as that of laboratory mixed specimens, it is first necessary to quantify the mass of cement present in the grab sample taken from the field-mixed panel of soil. As previously discussed in Chapter 3, two methods of accounting for quantity of cement were used in this study, the reported binder factor $[\alpha_r]$ –as obtained from the Construction Records and the cement content $[Cc]$ –as tested and deduced from ASTM D5982-07.

Recall that the reported binder factor $[\alpha_r]$ was calculated from construction records (B-report as presented on Appendix B) while deduced binder factor $[\alpha]$ was forensically determined from the heat of neutralization method. From these two methods, a final water-cement ratio $[(w/c)_f]$ could be determined using the following equations, with M_f and V_f measured at time of testing:

$$\text{Reported } (w/c)_f = \frac{M_w}{\alpha_r / 1000 * V_f} \quad (4.1)$$

$$\text{Deduced } (w/c)_f = \frac{M_w}{[Cc * (M_f - M_w)] / [1+Cc]} \quad (4.2)$$

$$\text{where: } M_w = \omega_f * M_f$$

Figure 4.8 shows q_u as a function of both reported, on 4.8a, and deduced, on 4.8b, $(w/c)_f$. It can first be observed that the data points for each group of sample specimens plot close to each other, which confirms the homogeneity of the samples collected.

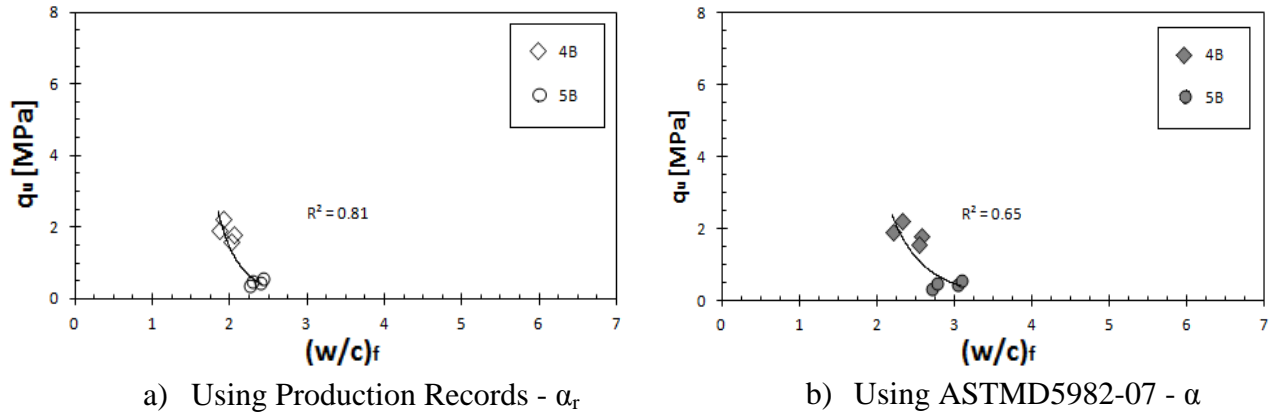


Figure 4.8 Variation of strength with Final Water-Cement Ratio for Field-Mixed Specimens (t=14 days)

From Figure 4.8a, reported $(w/c)_f$ value range from 1.75 to 2.5 with corresponding strength values of $2.2 < q_u < 0.5$ MPa. From Figure 4.8b, deduced $(w/c)_f$ value range from 2.2 to 3.2 with corresponding q_u values equal to that of presented on Figure 4.8a. Recall that they were only 4 specimens cast from Panel 4B sample and 4 specimens cast from Panel 5B sample. The only difference between Figure 4.8a and b is that the specimen strength is presented as a function of $(w/c)_f$ calculated from two different means, using production records and using ASTM D5982-07. There is significantly more scatter in the data obtained from the ASTM method, $R^2 = 0.65$ versus $R^2 = 0.81$ when data is from the production records. The denominators of Equations 4.1 and 4.2, calculating the mass of cement in a specimen, are the variables leading to the different plotting between Figure 4.8a and 4.8b. The scatter observed on Figure 4.8b, can then be explained by the influence a given specimen mass [M] has when compared to the other specimens casted from the same sample. It is also noted that the mass of cement contained in a given specimen when obtained from reported cement factor is higher than when it is obtained from the ASTM D5982-07 method. Using the reported cement factor, instead of the deduced cement content, to determine $(w/c)_f$, yields a 20 % to 30 % decrease in the $(w/c)_f$ value. To that extent, this study indicate that relying on the reported cement factor from the DM contractor can yield an unconservative estimate of the strength of cement-treated soil.

Also noted is that the relative plotting arrangement for each Figure's 4B and 5B data conglomerate in two scatters. Data from panel 4B specimens are of higher q_u and lower water-cement content than those from panel 5B. A potential explanation for this might reside in the spatial variation between the panel and the highly variable geology at the site — recall that the panels were constructed within a sliding area. Although not common, clays were found in localized areas within the field project, and they were potentially present at panel 5B location. Notwithstanding that the deduced binder factors were about 60 % of the reported binder factor for both samples, it is interesting to note that the heat of hydration method was capable of capturing the ~8% cement increase, reported by the CSM instrumentation, between samples 5B and 4B.

Figure 4.9 compares results from field-mixed specimen with results from Gibson Creek [GC] unsaturated laboratory data ($S < 1$) from this research, reproduced from Figure 4.5.

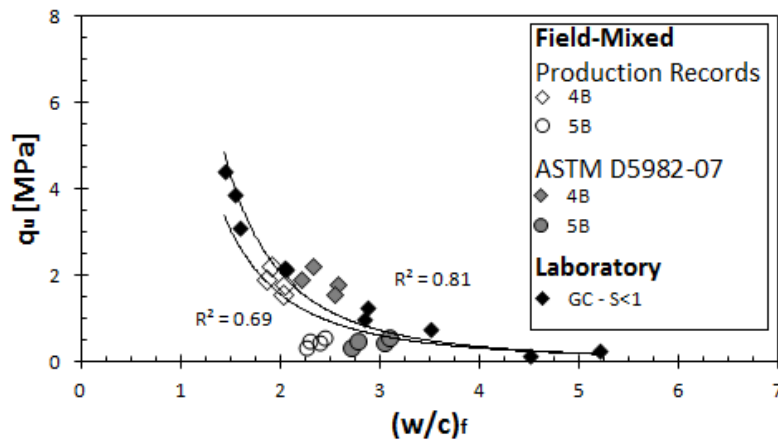


Figure 4.9 Variation of strength with Final Water-Cement Ratio for Unsaturated and Field-Mixed Specimens ($t=14$ days)

It can be observed that overall, the strength from field-mixed specimens appear to be exhibiting a behaviour similar to that of the laboratory-mixed specimens, when plotted as a function of their $(w/c)_f$. Additionally it can be observed that the field-mixed specimens fit the laboratory unsaturated dataset better when $(w/c)_f$ is calculated from the deduced α ,

using ASTM D5982-07—with a R^2 value of 0.81 as opposed to a R^2 value of 0.69 when using α_r , from the production record.

There are many different factors — mixing energy, time lapse before casting the specimen, and disturbance of the specimen when transported to the laboratory — that could have influenced the q_u of field-mixed when compared to laboratory reconstituted specimens. However, based on the current knowledge of factors affecting the strength of cement-treated soil specimens, as per Porbaha (1998) and CDIT (2002), all of these factors would have decreased q_u for field-mixed specimens as compared to laboratory reconstituted specimens. The relatively close fit of the field data to the laboratory data gives confidence in the use of a laboratory database to estimate the strength of field-mixed soil. It can also be noted that the field-mixed specimen strength have a better fit with the laboratory reconstituted specimens when $(w/c)_f$ is obtained from ASTM D5982-07 as opposed to when it is obtained from production records.

A case can therefore be made that simply relying on reported cement quantity from the soil-mixing equipment instrumentation is less than ideal. Rather, it is important to incorporate the cement content determination test (using the heat of neutralization method, ASTM D5982-07) into the quality-assurance program for deep mixing project.

Chapter 5: Conclusions

In general, the Cutter Soil Mixing [CSM] technology is used to create cement-treated soil panels for the purpose of ground improvement. At the site of the Fountain Slide, CSM panels were installed to intercept the slip surface, and thereby provide additional shearing resistance in order to reduce ground movement. In such an application, it is necessary to understand the influence of soil conditions and mixing conditions on the strength of the cement-treated soil element. Additionally, when the design process relies on strength data from laboratory-reconstituted specimens of cement-treated soil to guide the selection of a field binder factor, the relation between laboratory and field obtained strength must be understood.

This study comprises two components: (i) a program of laboratory testing and (ii) a companion body of field work. In the laboratory component, two samples of soil taken from the Fountain Slide site were reconstituted to obtain a series of cement-treated specimens. Testing established the variation of Unconfined Compressive Strength [q_u] over time. In the field component of the study, samples of field-mixed cement-treated soil were obtained from two CSM panels, immediately after mixing. These samples were cast into specimens and then similarly tested to determine values of q_u .

One objective of the laboratory program was to establish the influence of soil type on the strength of cement-treated specimens. A second objective was to investigate how strength is influenced by the method of specimen reconstitution through comparison of the wet-mixing, saturated method (after Lewsley and Fannin 2011) with the dry-mixing, unsaturated method (after CDIT 2002). The intent of the field component of the study was to compare the strength of cement-treated soil specimens mixed in-situ with the strength of those reconstituted in the laboratory, using the Water-Cement ratio at failure $[(w/c)_f]$ as the basis for comparison.

5.1 Experimental Findings

Based on the data, results and analysis of the current study, the following conclusions are drawn:

- For the range of low plasticity soils examined in testing, the unconfined compressive strength $[q_u]$ appears mostly insensitive to the soil type used in reconstituting saturated cement-treated specimens in the laboratory, when expressed as a function of Water-Cement ratio at failure $[(w/c)_f]$. This finding, for the two soils sampled from the Fountain Slide location, is consistent with the data of Lewsley (2008), on a wider range of non-plastic and low plasticity soils.
- For a given soil and range of $(w/c)_f$ examined in testing, laboratory reconstitution methods do not influence the value of q_u for cement-treated specimens. This finding is consistent with test results published in Filz et al. (2005) and Merrigi et al. (2008).
- Good agreement is found between the strength of cement-treated specimens reconstituted in the laboratory and those mixed in-situ at the Fountain Slide location using the Cutter Soil Mixer [CSM], when $(w/c)_f$ for the field-mixed specimens is calculated using a cement content deduced from the ASTM D5982-07 Heat of Neutralization method.

5.2 Limitations of the Study

These findings are believed generally applicable for the types of soil tested, namely a sandy silt to a silty sand, and for curing times varying from 7 to 56 days. Although there is some scatter in the dataset compiled, findings are based on a comparison of 9 different soils and 4 independent studies. Accordingly, the dataset offers useful guidance on the selection of a field binder factor, with reference to gain of strength with time in cement-treated sands and silts. More research is required to fully understand the influence of plasticity, as found in naturally occurring clays, on the strength of cement-treated soil.

The correlation between laboratory and field results presented in Chapter 4 is believed to require more insight and research before a unique, solid relation can be established. In particular, mixing energies and in-situ, natural, moisture contents of soil are believed to play crucial roles in the strength generation of cement-treated soil.

5.3 Recommendations

Based on the findings of this research study, the following recommendations are made:

- The wet-mixing (saturated) method for reconstituting cement-treated specimens requires considerable effort. In contrast, the dry-mixing (unsaturated) reconstitution methods, such that described in CDIT (2002) and in Hodges et al. (2008), are relatively easy to use. Given the finding that strength appears independent of reconstitution method established in this research, the saturated reconstitution method does not appear necessary, and a simpler reconstitution method is likely adequate for purposes of design guidance; and,
- Given that a standard method for determining the cement content of a soil-cement mix exists, in the form of ASTM D5982, it is recommended that serious consideration be given to including the method in the Quality Assurance program of Deep-Mixing projects.

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Appendix A-1: Sample Fountain Slide Borehole Log

(Bosdet, 1991, by permission)

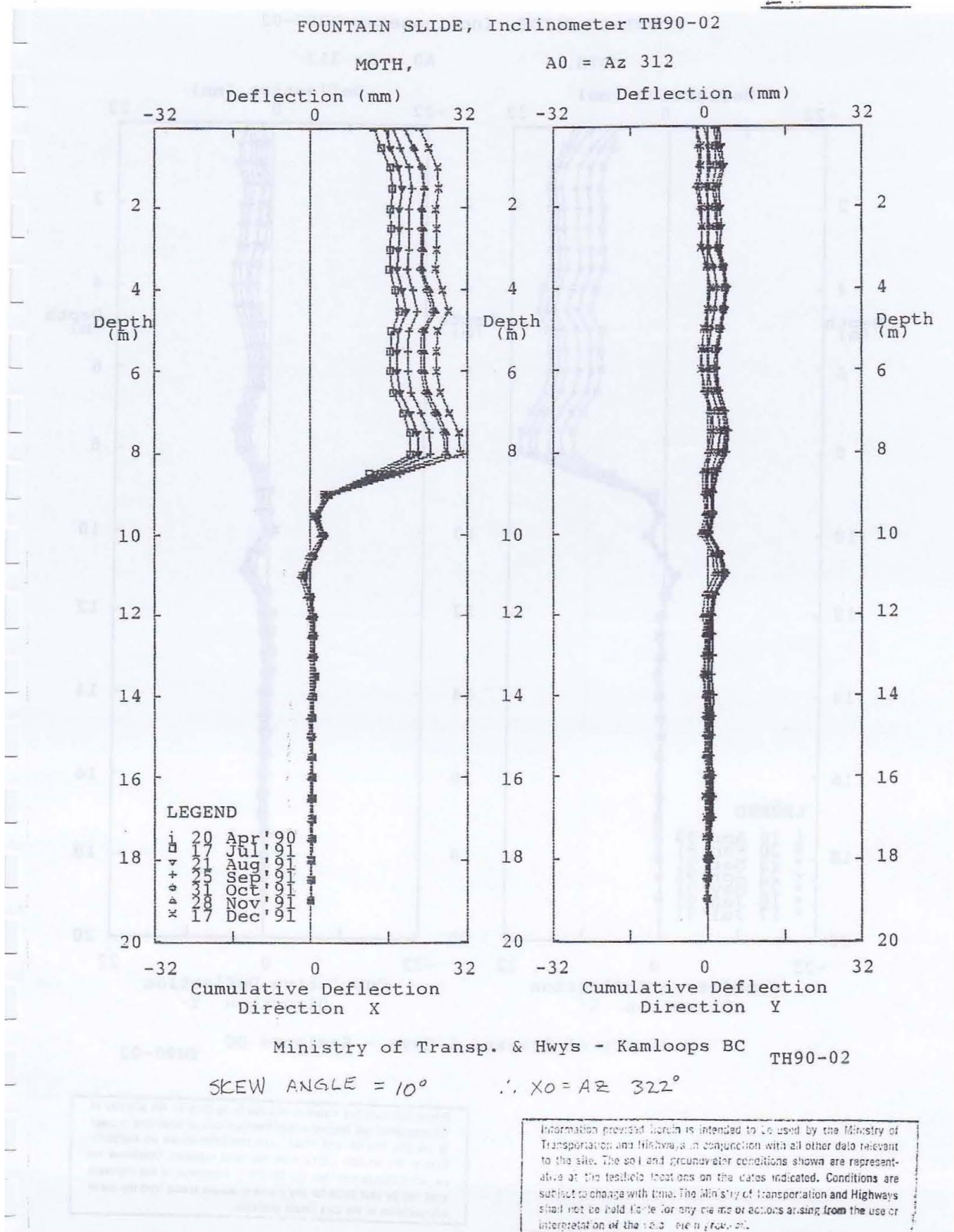
| Ministry of Transportation and Highways | | TEST HOLE LOG | | | | | | | | | | Geotechnical and Materials Branch | | TEST HOLE No. 90-04 | |
|--|-----------|---------------------|-----------|--------------|-------------------------|-------------|------|-------|---------------------|----------------|------|--------------------------------------|---|------------------------|------|
| Project 05791, FOUNTAIN SLIDE, HWY 12 | | | | | | | | | | | | Elevation 333.674m | | | |
| Location Sta. 0+098 o/s 50m Rt. | | | | | | | | | | | | Dates 90-05-1/10 | | | |
| Driller C. SLEASMAN | | Method ROTARY HW HQ | | | | | | | | | | | | | |
| Drilling Details | Depth (m) | Sample Type | Blowcount | Recovery (m) | Shear Strength (kPa) | Gradation % | | | Index Properties | | | Classification | Description | Other Tests | |
| | | | | | | Gravel | Sand | Fines | W _L | W _p | W | | | | |
| SI | 1 | S | 24 | .25 | | 10 | 37 | 53 | - | - | 14.6 | ML(CL) | Hard, grey-brown, SILT and sand, some gravel. Gravel size to 30mm. | 2.0 | |
| | 2 | | | | | | | | | | | | | | |
| | 3 | S | 31 | .25 | | 5 | 76 | 19 | - | - | 3.1 | SM ₁ | Dense, grey SAND, some silt, trace gravel. Gravel size to 25mm. | | |
| | 4 | S | 38 | .25 | | 10 | 13 | 77 | - | - | 5.6 | ML | Hard, light orangy brown SILT with some dark brown clay seams, some gravel. | 4.1 | |
| | 5 | | | | | | | | | | | | | 4.9 | |
| | 6 | S | >100 | .25 | | 5 | 14 | 81 | - | - | 8.4 | CL | Hard, medium to dark orangy brown CLAY, some sand, trace gravel. Gravel size to 25mm. | | |
| | 7 | S | >100 | .20 | | 1 | 9 | 90 | - | - | 8.7 | | | | |
| | 8 | | | | | | | | | | | | | | |
| | 9 | S | >100 | NIL | | - | - | - | - | - | - | | | | |
| | 10 | S | >100 | NIL | | - | - | - | - | - | - | | | | 10.5 |
| | 11 | | | | | | | | | | | | | | |
| | 12 | S | >100 | .20 | | 15 | 51 | 34 | - | - | 3.8 | SM ₃ | Very dense, greenish grey with orange and dark brown seams of silty SAND, some gravel. Gravel size to 25mm. | | |
| | 13 | S | >100 | NIL | | - | - | - | - | - | - | | | | |
| | 14 | | | | | | | | | | | | | | 14.0 |
| | 15 | S | 48 | .25 | | 12 | 31 | 57 | - | - | 6.6 | CL | Hard, grey-dark brown, sandy CLAY, some gravel. Gravel size to 30mm. | | |
| | 16 | | | | | | | | | | | | | | |
| | 17 | | | | | | | | | | | | | | |

| | | | | | | |
|--|--|--|--|---|------------------------------|------------------------------|
| SAMPLE TYPE A - Auger C - Core D - Denison S - Split Spoon T - Shelby Tube W - Wash | | SHEAR STRENGTH kPa U - Unconfined Compression Fv - Field Vane Lv - Lab Vane R - Remoulded | | TESTS M - Mechanical Analysis Q,R,S - Triaxial Compression C - Consolidation DS - Direct Shear W _L , W _p - Liquid, Plastic Limits W - Moisture Content | | FILE No. 2M6-30-32 |
| | | | | | DRAWN BY: DGS | |
| Blowcount - Standard Penetration Test (ASTM 1956) | | | | | SHEET 01 of 05 | |


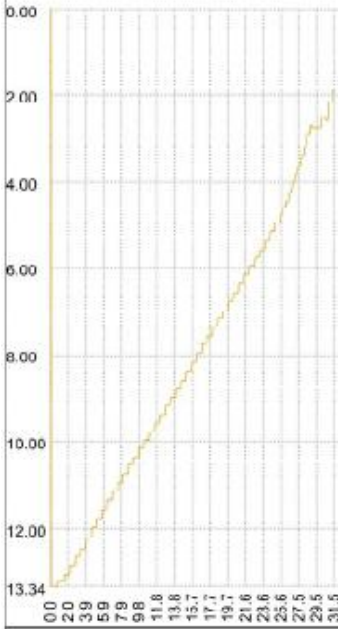
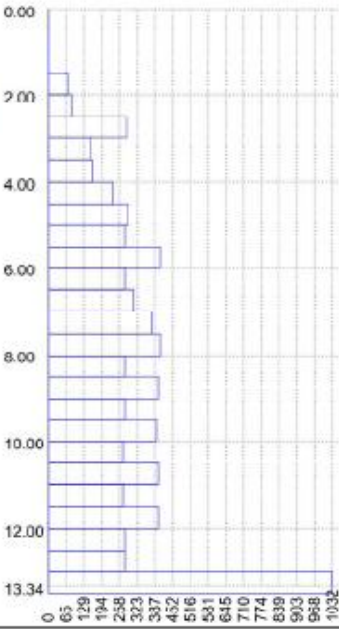
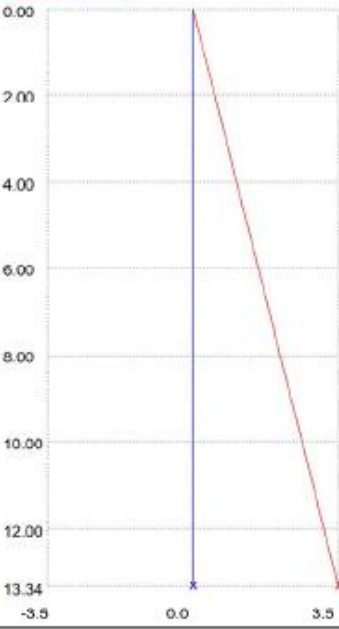
ACAD No. 632-9004

Appendix A-2: Sample Fountain Slide Movement Monitoring Log

(Bosdet, 1992, by permission)



Appendix B: Sample B-Report

| PRODUCTION LOG, CSM | |  | |
|---|-----------------------|---|--------------|
| Jobsite: | Fountain Slide CSM | Project No.: | 1070040055 |
| Client: | British Columbia MOTI | | |
| Operator: | Tristan Hulley | Cut: | 8AR |
| Drilling Rig: | RTG RG 19T | Date: | Mar 29, 2011 |
| I-No.: | | Wall thickness/Dia.: | 1.0 m |
| | | Width of cut: | 2.8 m |
| | | Drilled depth: | 13.34 m |
| | | Nom. Inclination: | 0 ° |
| CSM recipe: | | | |
| Cement: | 300kg/m3 | Additives | |
| | | Quantity: | |
| | | Grout density:- | |
| Start: | 9:59:12 AM | Actual grout con... | 7.684 m³ |
| End: | 10:38:12 AM | | |
| Total time: | 00:39:00 | | |
| Depth progress [min]  | | Grout [l/0.50m]  | |
| | | DeviationX [cm] DeviationY [cm]  | |
| Comments | | | |
| supervisor: | | Client: | |

Appendix C: Test Method for Cement Content Determination

This Appendix presents results from a test that was performed in the laboratory and in the field immediately after mixing of cement-treated soil, in order to determine the cement content of the sample. The test method followed the standard presented in ASTM D5982-07 – Determining Cement Content of Fresh Soil-Cement (Heat of Neutralization Method).

C.1 Background

The reporting of quantity of cement field-mixed in a soil is challenging. The effect of uneven mixing, segregation, and/or loss of binder slurry through voids or through an adjacent coarser soil matrix cannot be accurately represented when using construction records to determine a sample particular cement content. Neville (1994) concluded that “there exists no test for the composition of fresh concrete that is convenient and reliable enough to be used as a preplacement acceptance test”. Subsequently, ASTM refined a method originally developed in 1978 by the Australian Main Roads Department. The method evolved through the years, and the current ASTM D5982-07 method was chosen in this study to be investigated for usefulness and ease of use in a QA program. The method is used to establish a relation between heat of neutralization of the carbonate content of the cement-treated specimen, in reaction with an acidic buffer solution, and the cement content of the specimen.

The following section presents the materials, the test method used, the results and a discussion on the implications from the results for the deep mixing industry.

C.2 Materials

C.2.1 Soils

Samples, that are believed representative of the soil at the project site, were obtained for testing according to ASTM D5982-07. Two samples were obtained: (i) a grab sample of soil

from surface exposures at a road cut in the vicinity of what is known locally as Gibson Creek [GC] and (ii) an auger sample from mixed cuttings at panel 17C location [17C]. GC sample was obtained about 1 meter above the existing highway 99 elevation (EL~350m) while the sample from panel 17C was mixed cuttings from the existing highway 99 elevation to about 12 meters below existing ground. The sampling locations are shown on Figure C.1. The two samples were brought back to the UBC lab for identification through sieve analysis and Atterberg limit and testing using the Heat of Neutralization method.



Figure C.1 Locations of Samples

The Gibson Creek soil sample is a silty sand with a trace of clay. Atterberg test, carried out on GC soil fraction passing the sieve #40 ($< 425 \mu\text{m}$), yields a plastic limit of 21.3 % and a liquid limit of 25.8 %, hence classifying the fine fraction as a low plasticity silt (ML). 17C soil is a well graded sand, some silt, some clay. The soil fraction finer than $425 \mu\text{m}$ from 17C soil classifies as low plasticity clay (CL) when tested for Atterberg limits with a 16.0 % and 32.0 % plastic and liquid limit, respectively. Grain size distribution curves for the two soils are presented in Figure C.2.

C.2.2 Cement

The cement used to establish the calibration curve was General Use Type 1 Portland Cement, manufactured and distributed by Lafarge North America Ltd. This is the same supplier that was used at the Cutter Soil Mixer [CSM] ground improvement site.

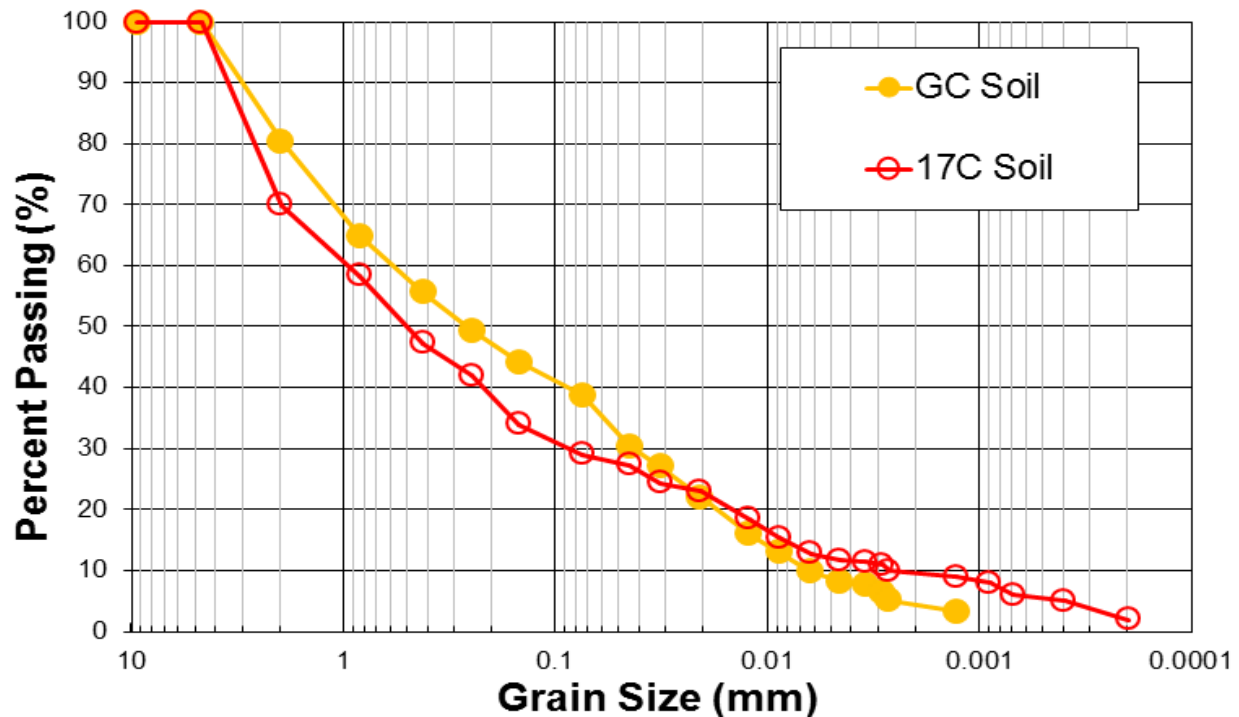


Figure C.2 Grain Size Distribution Curves

C.3 Test Method

The Heat of Neutralization method relies on the exothermic reaction of the carbonate content, present in the cement, with an acidic buffer. The heat of hydration standard (ASTM D5982) is a method from which the cement quantity [%C], mass of cement over total mass of sample -as defined in Equation C.1, of a soil-cement sample can be determined. The method uses a calibration curve relating the cement quantity of a sample to the temperature expelled when the sample reacts with an acidic solution. The method is based

on the proportionate relationship between the temperature a given sample reaches, when mixed with an acidic buffer, to the amount of carbonate in that given sample [Main Road Department, 1978]. The cement, contained in a sample, is the main source of carbonate content in a cement-treated soil and as such, the above relation can be extended to relate the temperature of a given sample of cement-treated soil, reacting with an acidic solution, the sample cement content.

$$\%C = \frac{m_c}{(GC_d + m_c + m_w)} * 100 \quad (C.1)$$

In this research, ASTM D5982-07 was followed exactly except for the reporting of cement quantity, which was instead reported as cement content [Cc] was defined in Equation C.2.

$$C_c = \frac{m_c}{GC_d} * 100 \quad (C.2)$$

Two calibration curves were obtained in the laboratory using dry soil from Gibson creek and cuttings from panel 17C to reconstitute cement-treated soil samples at different Cc. To generate the calibration curves presented on Figure C.3, a buffer solution was first obtained. To prepare the buffer solution, Sodium Acetate was diluted in distilled water, to which was added glacial acetic acid and more distilled water. Then, 15 specimens of cement-treated Gibson creek soil and 15 specimens of cement-treated panel 17C soil were mixed. Gibson creek specimens were reconstituted at 3 different Cc varying from 10 to 19% while cuttings from panel 17C were also reconstituted at 3 distinct Cc which varied from 8 to 17%. A dry mass of soil, taken as GC_d , was mixed with a predetermined mass of dry cement, m_c , and a mass of water, m_w , so as to achieve the target cement content, as per equation C.1 and C2, and reconstitute one cement-treated specimen.

The temperatures of the cement-treated specimen and of the buffer solution were recorded separately and, as required, the temperature of the buffer solution heated or cooled to be

within 2°C of that of the specimen. 1.35 kg of the buffer solution and 1.5 kg of a cement-treated specimen were then combined and mix together for 4 minutes. The subsequent temperature increase, due to the exothermic reaction of the cement carbonate with the acid, was recorded 1 minute after the end of mixing. As such, temperature difference refers to the difference between (i) the average temperature of the two separate materials prior to combining them together and $\%C = \frac{C_c}{GC_d + C_c + W_c}$ (ii) the mix temperature 1 minute after

finishing the mixing of the cement-treated soil specimen together with the buffer solution.

The temperature difference was calculated and plotted as a function of the C_c at which the given specimen of cement-treated soil was reconstituted. Each distinct cement content point, presented as 1 data point in Figure C.3, is the averaged results from the three separate tests at a given C_c , with error bars representing the extreme obtained values.

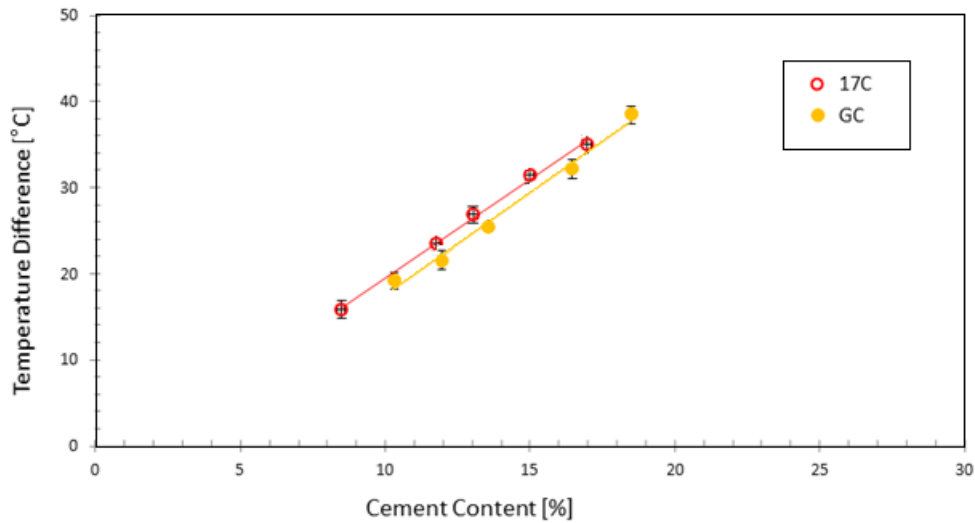


Figure C.3 Cement Content Calibration Curves

After the curves, presented on Figure C.3, were created, freshly field-mixed samples of cement-treated soil were obtained from CSM panels at the Fountain Slide site. Samples

were obtained from 10 and 11 meters depth at the Panel 4B and 5B locations, respectively (see Figure C.1 for sample location). Following sampling, both were immediately mixed with the buffer solution, their mix temperatures were recorded, and the temperature differences were calculated. The obtained temperature difference for the Panel 4B sample was 21.1 °C while a temperature difference of 18.0 °C was obtained for Panel 5B field-mixed sample. Those temperature differences are plotted on Figure C.4, from which the cement content could be inferred to be 10.8 and 9.9% for Panel 4B and 5B respectively.

It is important to note that the soil present at the Panel 4B and 5B locations was not sampled prior to the CSM work, but is believed to be similar to the soil sampled at Gibson creek soil and at the Panel 17C location. The tested temperature differences for samples of cement-treated soil at the Panel 4B and 5B locations are plotted on a calibration curve built by combining all the data points from the Gibson Creek and Panel 17C soil calibration curves, as presented on Figure C.4.

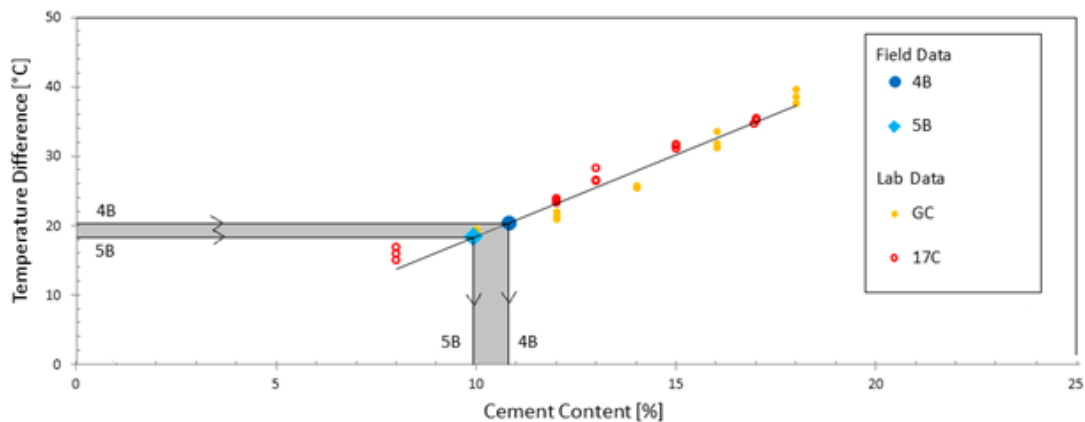


Figure C.4 Best Fit Calibration Curve with CSM Mixed Specimens Cement Content

C.4 Discussion

From Figure C.3, it can be observed that the two different soils tested yield both a linear relation between the cement content and the temperature difference. As seen in Figure C.4,

the relatively tight plotting location of the data points for each given C_c from the two different soils seems to indicate that the presence of a higher clay content in a soil only has a subtle influence on the heat generation pattern. This could either be due if the two soil had a slightly different carbonate content, or to the fact that the coarser matrix of the soil sampled from the Gibson creek location has a higher heat capacity than the soil from the Panel 17C location. This finding corroborates the ASTM recommendation that a calibration curve is required every time a different soil is to be used in field mixing project.

Reported binder factors $[\alpha_r]$, as mixed in the lower portions (from 5 to 13.5 meters below existing ground surface) of Panels 4B and 5B, were 313 kg/m^3 and 288 kg/m^3 , respectively, as reported in Chapter 3 of this thesis. Cement contents of samples from Panels 4B and 5B, as determined by the heat of neutralization method and presented in Figure C.4, were 10.8% and 9.9 % for sample 4B and 5B respectively. It can be observed that a 9 % relative increase in binder factor (from 288 kg/m^3 up by 25 kg/m^3 to 313 kg/m^3) from panel 5B to 4B was also captured by the cement content determination method (from 9.9 % up by 0.9 % to 10.8%).

C.5 Remarks

The Heat of Neutralization method for determining the cement content of fresh soil-cement was successful in this investigation. The method captured the difference in binder factor, measured as cement content, of two field-mixed element of cement-treated soil. This implies there is utility in using the ASTM as a Quality Assurance measure for forensically determining the cement content of a fresh soil-cement specimen.

Appendix D: Data

Table D.1 Test Data for Laboratory Wet-Mixing (Saturated) Specimens

| Plotting Code | Soil Origin | Mixed | | | | Cured | Tested | | | | |
|---------------|----------------|---------|------------------------|---------------------|-------------------------------------|--------------------|-------------|---------------------|-------------------------------------|--------------------|-----------------------|
| | | Cc % | C kg/m ³ | ω _i % | ρ _i kg/m ³ | (w/c) _c | Age days | ω _f % | ρ _f kg/m ³ | (w/c) _f | q _u MPa |
| HC | Fountain Creek | 18.0 | 237.2 | 32.9 | 2066.4 | 2.15 | 7.1 | 30.2 | 2021.4 | 2.03 | 1.46 |
| MC | Fountain Creek | 14.0 | 198.5 | 26.9 | 2048.7 | 2.16 | 7.1 | 32.2 | 2016.5 | 2.49 | 1.22 |
| LC | Fountain Creek | 8.1 | 115.9 | 30.0 | 2020.2 | 3.90 | 7.1 | 38.4 | 1991.2 | 4.60 | 0.36 |
| HC | Gibson Creek | 18.0 | 250.5 | 26.8 | 2078.8 | 1.75 | 7.1 | 27.8 | 2044.2 | 1.86 | 2.14 |
| MC | Gibson Creek | 14.1 | 194.5 | 29.1 | 2035.3 | 2.34 | 7.1 | 30.8 | 2019.3 | 2.56 | 0.88 |
| LC | Gibson Creek | 8.0 | 111.5 | 32.5 | 1989.5 | 4.29 | 7.1 | 36.7 | 1992.5 | 4.84 | 0.25 |
| LC Dupl. | Gibson Creek | 8.0 | 114.0 | 31.3 | 2018.1 | 4.14 | 7.1 | 35.3 | 1971.8 | 4.83 | 0.26 |
| HC | Fountain Creek | 19.2 | 250.0 | 30.7 | 2025.0 | 1.89 | 13.9 | 27.7 | 1975.0 | 2.09 | 2.00 |
| MC | Fountain Creek | 14.4 | 191.8 | 31.5 | 2006.3 | 2.49 | 13.9 | 28.7 | 1968.3 | 3.00 | 1.40 |
| LC | Fountain Creek | 7.2 | 98.5 | 33.8 | 1956.0 | 4.96 | 13.9 | 29.7 | 1926.6 | 5.89 | 0.37 |
| HC | Gibson Creek | 18.0 | 250.5 | 26.8 | 2078.8 | 1.75 | 13.9 | 22.4 | 2044.2 | 1.86 | 3.00 |
| MC | Gibson Creek | 14.1 | 195.3 | 28.1 | 2034.3 | 2.31 | 14.0 | 24.4 | 2018.2 | 2.55 | 1.03 |
| LC | Gibson Creek | 8.0 | 111.4 | 32.5 | 1989.5 | 4.29 | 14.0 | 27.1 | 1992.5 | 4.84 | 0.28 |
| HC | Fountain Creek | 19.7 | 255.5 | 29.8 | 2015.1 | 1.79 | 27.9 | 25.8 | 2013.8 | 2.03 | 3.37 |
| HC Dupl. | Fountain Creek | 18.3 | 248.4 | 27.4 | 2049.0 | 1.76 | 27.9 | 24.7 | 1976.5 | 2.04 | 3.49 |
| MC | Fountain Creek | 13.5 | 185.6 | 29.5 | 2018.2 | 2.45 | 27.9 | 26.6 | 1987.1 | 2.90 | 1.84 |
| LC | Fountain Creek | 8.2 | 113.2 | 33.6 | 1996.9 | 4.34 | 27.9 | 29.0 | 1952.2 | 5.11 | 0.54 |
| HC | Gibson Creek | 18.2 | 235.6 | 30.3 | 1992.9 | 1.95 | 27.9 | 25.2 | 1978.5 | 2.13 | 2.29 |
| MC | Gibson Creek | 14.2 | 189.6 | 30.8 | 1991.7 | 2.45 | 27.9 | 25.6 | 1978.5 | 2.69 | 1.48 |
| LC | Gibson Creek | 8.2 | 111.8 | 33.2 | 1970.0 | 4.31 | 28.0 | 28.3 | 1993.4 | 4.99 | 0.48 |
| HC | Fountain Creek | 18.3 | 251.2 | 28.4 | 2086.6 | 1.84 | 56.2 | 23.6 | 2086.6 | 1.59 | 5.34 |
| HC Dupl. | Fountain Creek | 18.8 | 253.3 | 29.0 | 2065.6 | 1.83 | 56.2 | 25.1 | 2065.6 | 1.63 | 4.88 |
| MC | Fountain Creek | 14.2 | 193.3 | 30.6 | 2034.2 | 2.45 | 56.2 | 25.9 | 2034.2 | 2.17 | 2.64 |
| LC | Fountain Creek | 8.1 | 120.6 | 26.9 | 2043.4 | 3.58 | 56.2 | 24.7 | 2043.4 | 3.35 | 1.26 |
| HC | Gibson Creek | 18.4 | 250.5 | 27.2 | 2049.8 | 1.75 | 56.2 | 23.3 | 2049.8 | 1.55 | 5.99 |
| MC | Gibson Creek | 14.1 | 202.0 | 25.9 | 2062.8 | 2.10 | 56.2 | 23.3 | 2062.8 | 1.93 | 3.88 |
| LC | Gibson Creek | 8.1 | 118.6 | 27.4 | 2026.1 | 3.60 | 56.2 | 25.0 | 2026.1 | 3.42 | 1.21 |

Table D.2 Test Data for Laboratory Dry-Mixing (Unsaturated) Specimens

| Plotting Code | Soil Origin | Mixed | | | | Cured | Tested | | | | |
|---------------|--------------|---------|------------------------|---------------------|-------------------------------------|--------------------|-------------|---------------------|-------------------------------------|--------------------|-----------------------|
| | | Cc % | C kg/m ³ | ω _i % | ρ _i kg/m ³ | (w/c) _c | Age Days | ω _f % | ρ _f kg/m ³ | (w/c) _f | q _u MPa |
| HC-1 | Gibson Creek | 18.0 | 248.1 | 25.9 | 2048.3 | 1.66 | 13.7 | 19.5 | 1695.5 | 1.59 | 3.11 |
| HC-2 | Gibson Creek | 18.0 | 257.1 | 22.2 | 2056.1 | 1.45 | 13.7 | 18.2 | 1725.2 | 1.44 | 4.41 |
| HC-3 | Gibson Creek | 18.0 | 257.0 | 23.7 | 2079.4 | 1.53 | 14.0 | 18.6 | 1714.7 | 1.54 | 3.88 |
| MC-1 | Gibson Creek | 14.9 | 212.2 | 26.1 | 2059.7 | 1.96 | 14.1 | 20.7 | 1662.9 | 2.03 | 2.19 |
| MC-2 | Gibson Creek | 13.1 | 191.7 | 23.1 | 2038.1 | 1.99 | 14.0 | 19.6 | 1673.0 | 2.05 | 2.16 |
| LC-1 | Gibson Creek | 10.5 | 149.0 | 32.6 | 2076.7 | 3.43 | 13.9 | 19.3 | 1708.7 | 3.50 | 0.74 |
| LC-2 | Gibson Creek | 8.0 | 124.4 | 22.2 | 2044.4 | 2.97 | 14.0 | 18.5 | 1697.6 | 2.83 | 1.00 |
| LC-3 | Gibson Creek | 6.8 | 113.7 | 19.7 | 2136.7 | 3.09 | 14.0 | 16.9 | 1785.2 | 2.87 | 1.24 |
| VLC-1 | Gibson Creek | 5.6 | 78.4 | 24.1 | 2101.2 | 2.91 | 13.9 | 19.5 | 1720.4 | 5.20 | 0.25 |
| VLC-2 | Gibson Creek | 5.4 | 75.6 | 22.0 | 2029.5 | 2.95 | 13.9 | 15.1 | 1727.3 | 4.50 | 0.15 |

Table D.3 Test Data for CSM Mixed Specimens

| Plotting Code | CSM Mixed and Sampled | | | | Tested | | | | | |
|---------------|-----------------------|---------------------------------|---------|-------------------------------|--------|-------------------|------------|-----------|-----------|-------|
| | ω_i | Amount of Cement | | | Age | ρ_f | ω_f | $(w/c)_f$ | $(w/c)_f$ | q_u |
| | | Reported | Deduced | | | | | | | |
| | % | α_r kg/m ³ | Cc % | α kg/m ³ | day | kg/m ³ | % | Reported | Deduced | MPa |
| 4B S -1 | 38.1 | 234.9 | 10.8 | 186.9 | 13.9 | 1730.4 | 38.4 | 2.04 | 2.57 | 1.81 |
| 4B S -2 | 38.0 | 234.9 | 10.8 | 187.1 | 13.9 | 1732.0 | 37.8 | 2.02 | 2.54 | 1.58 |
| 4B D -1 | 38.0 | 234.9 | 10.8 | 193.2 | 13.9 | 1789.1 | 33.4 | 1.91 | 2.32 | 2.22 |
| 4B D -2 | 38.1 | 234.9 | 10.8 | 197.9 | 13.9 | 1832.7 | 31.2 | 1.85 | 2.20 | 1.91 |
| 5B S -1 | 33.7 | 218.5 | 9.9 | 182.1 | 14.0 | 1839.9 | 36.5 | 2.25 | 2.70 | 0.35 |
| 5B D -1 | 33.7 | 218.5 | 9.9 | 172.1 | 14.0 | 1738.5 | 43.0 | 2.39 | 3.04 | 0.46 |
| 5B S -2 | 39.1 | 218.5 | 9.9 | 180.8 | 14.0 | 1826.5 | 37.8 | 2.29 | 2.77 | 0.48 |
| 5B D -2 | 39.1 | 218.5 | 9.9 | 172.6 | 14.0 | 1742.9 | 43.8 | 2.43 | 3.08 | 0.55 |