Guidelines for Chemically Stabilizing Problematic Soils

Task Report for Task 5
August 2017 to Feb 2018

Prepared for:
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### METRIC (SI*) CONVERSION FACTORS

#### APPROXIMATE CONVERSIONS TO SI UNITS

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#### APPROXIMATE CONVERSIONS FROM SI UNITS

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Note: Volumes greater than 1000 L shall be shown in m³
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1 Introduction

The aim of this project is to develop a chemical stabilization guideline for problematic soils incorporating the needs of the Montana Department of Transportation (MDT). The guideline will be based on the problematic soils encountered in the State of Montana. In the process of developing this guideline, Task 1 (Current Practices Survey) focused on literature review of current chemical stabilization guidelines of several states, federal agencies, along with stabilization practices of Departments of Transportation (DOTs) of Montana’s neighboring states. This task revealed that many states surrounding Montana do not have much experience with chemical stabilization of subgrade soils. Thus, the stabilization guideline developed through this study will help MDT and provide a reference to the nearby states as well. The next step in this project (Task 2 Material Selection) was to study the various problematic soils experienced by MDT to help target stabilization. Since a wide variety of problematic soils exist across the state of Montana including low bearing capacity soils, expansive soils, high sulfate bearing soils and high organic content soils, it is important that the selected soils represent these problematic soils. Hence, based on interactions with MDT personnel, six different locations were chosen from different regions of Montana. The goal was to obtain different problematic soil types from various geological conditions to ensure that the stabilization guideline at the end of this project will address diverse problematic soils. These soils were then stabilized using existing guidelines (Task 3 Evaluate Chemical Stabilizer) to determine the type and the amount of additive needed for soil stabilization. To better tailor the stabilization to Montana specific soils, we studied the chemical and mineralogical changes between treated and untreated soil samples (Task 4). A combination of task reports 2, 3 and 4 was submitted in March 2018. After discussing this report with the technical panel, it was decided that the strength target for subgrade treatments to be 50 psi for both lime and cement treatments and also base treatments is not a target. The current task (Task 5) of this project is to establish curing and moisture conditioning protocols that can help minimize the time needed for curing. Permanency of the stabilized soil against freezing/thawing cycles and wetting/drying cycles will be assessed and discussed as a part of Task 6 (Assess the Permanency of Chemical Stabilization). Results of Task 5 and Task 6 can be used to determine suitable type and amount of chemical stabilizer for a given type of problematic soil from the State of Montana. Furthermore, Task 7 - Life Cycle Cost Analysis (LCA) will be done that would help engineering managers in making informed decisions on adopting appropriate stabilization alternatives. The final stage (Task 8) will summarize all the previous protocols and propose a protocol for chemical stabilization of problematic soil specific to the State of Montana.

This report presents discussion and results of laboratory tests as part of Task 5. It starts with an introduction to curing and moisture conditioning methods. Traditional curing and moisture conditioning methods discussed and a new moisture condition method – Humidity Controlled Accelerated Curing (HCAC) developed as part of this project. All of the tests were done in the Sustainable and Resilient Geotechnical Engineering (SuRGE) laboratory at Boise State University. The test results then were compared against conventional curing and moisture conditioning methods, and a final recommendation is made.
2 Material Selection (Task 2)

Since a wide variety of problematic soils exist across the state of Montana including low bearing capacity soils, expansive soils, high sulfate bearing soils and high organic content soils, it is important that the selected soils represent these problematic soils. Hence, based on interactions with MDT personnel, six different locations were chosen from different regions of Montana. The goal was to obtain different problematic soil types from various geological conditions to ensure that the stabilization guideline at the end of this project will address diverse problematic soils. These soils consisted of two high-plasticity clays, two low plasticity clays, one low plasticity silt and one sandy subgrade. The sampling locations along with the nearest highway and reference post information are presented in Table 1. The naming convention for these soils was as per the notation on the sample bags in which they were delivered.

Table 1: Summary of soil sampling locations

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<td>US287</td>
<td>RP 105.9</td>
</tr>
</tbody>
</table>

The lime used for stabilization was high Calcium Quick Lime from Graymont Western US Inc., Townsend, Montana. The cement used for stabilization was Type II/V, from Ash Grove Cement, Montana City Plant, Clancy, Montana. Approximate location of these plants is shown in Figure 1.

Figure 1: Location of lime and cement plant
3 Introduction to Curing and Moisture Conditioning

The success of soil stabilization is dependent on the proper selection of type/amount of stabilizer with appropriate curing and moisture conditioning that yields an acceptable strength and durability characteristics (Mitchell, J K, Hooper 1961 & Celaya et al. 2011). These strength and durability characteristics of stabilized soil are dependent on duration and temperature of curing of the specimen as well as the type of moisture conditioning of the specimen. The goal of this section is to develop such curing and moisture conditioning methods for stabilized soil that accelerates the laboratory mix design process while maintaining similar strength characteristics and also can be implemented comfortably in a typical geotechnical laboratory. Therefore, an attempt was made to shorten the duration of curing by elevating the curing temperature to produce similar Unconfined Compressive Strength (UCS) as that of typical 7-day strength. In the following section, some of the commonly used curing methods, as well as novel methods proposed by this study, are discussed.

3.1 Conventional curing method

Conventionally cemented soil samples are cured at 25°C at 100% humidity. This procedure removes the need for moisture conditioning as the moisture is not allowed to escape from the sample and hence no need to test its susceptibility to it. All soils tested in this research were first subjected to the conventional curing method to establish a baseline of target strengths to be compared to the newly developed curing protocols. For this purpose, cylindrical samples of height 5.6 in. and diameter 2.8 in. were prepared at optimum moisture content (OMC) and maximum dry unit weight (MDUW) for various percentages of lime and cement. The samples were then wrapped with impermeable wrapping material making it airtight to avoid the loss of moisture during curing (See Figure 2). In addition to wrapping, the samples were placed inside a chamber with 95%±5% humidity and temperature of 23°C (±2°C). This insured a minimum loss of moisture during curing. The setup used for this process is shown in Figure 3.

The percentages of lime and cement used were selected based on the recommendations of established stabilization guidelines reviewed as a part of Task 1 while targeting a cut-off strength of 50 psi – as decided (in consultation with technical panel) at the end of task 4. All the soil samples except CNK, which is silty sand, were treated with lime. Although GF (high plastic clay) and DC (low plastic clay) only qualified for lime treatment (as per literature review done in Task 1), BR (low plastic clay), NTF_LP (silt), and NTF_HP (high plastic clay) were treated with a minimal quantity of lime (i.e., 2%) to evaluate the strength gain.

Please note that CNK soil is a Silty Sand with 14% fines as a result conducting UCS tests on these samples was challenging and may not be representative of the true strength improvements in this soil. Hence, California Bearing Ratio (CBR) test as per ASTM D1883-07 was conducted on these soils samples in addition to UCS to better represent the strength characteristics. The untreated and treated CNK specimens were tested in the un-soaked condition with standard energy of compaction. For treated sample, the sample was cured with CBR mold inside a chamber with 95% (±5%) humidity and temperature of 23°C (±2°C). The strength and stiffness
data of these samples are presented in section 3.2 and were used as baseline data to evaluate other curing and moisture conditioning techniques.

**Figure 2:** Sample wrapped in cellophane sheet to ensure no loss of moisture

**Figure 3:** Samples wrapped in cellophane (red boxes) being cured in an airtight container at 95% (± 5%) humidity and 23°C (± 2°C).

3.2 Results from the conventional curing method

3.2.1 Cement treated Samples

The initial amount of stabilizer used in case of cement treated soil was per recommendations of various standard guidelines from federal and state agencies as discussed in Task 1 and Task 2, 3, & 4 reports. These recommended amounts correspond to the maximum additive percentage used for each soil in this study as it resulted in high UCS values. Other treatment dosages were examined to find a suitable amount that will result in a UCS value of 50 psi, and these results are presented in Table 2. The UCS and secant moduli are illustrated in Figure 4, and Figure 5 respectively. It can be noted from these Figures that high plastic soil such as GF showed the low improvements with cement treatment while DC, BR, and NTF_LP, which are low plastic
clays/silts, showed a strong increase in strength with increase in stabilizer content. For these soils, addition of a minimal percentage of cement was sufficient to increase the UCS value to 50 psi.

Table 2: Summary UCS and secant moduli for cement treated samples cured at 100% humidity and 23°C (± 2°C)

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>USCS</th>
<th>AASTHO</th>
<th>Stabilizer Content (%)</th>
<th>UCS (psi)</th>
<th>% Change (compared to untreated soil)</th>
<th>Secant Modulus (psi)</th>
<th>% Change (compared to untreated soil)</th>
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<tr>
<td>GF</td>
<td></td>
<td>CH</td>
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<td></td>
<td></td>
<td>3</td>
<td>27.45 19</td>
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<td>97</td>
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<td>96.42 80</td>
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<td>13</td>
<td>440.68 1158</td>
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The CBR values for 0.1 in. and 0.2 in. penetration are given in Table 3. A treatment of 2% cement to the CNK soil increased the CBR value by 3 fold which suggests a high suitability of cement stabilization for silty sands. CNK soil treated with 3% cement has very high CBR value for 0.1 in. penetration. The same for 0.2 in. penetration couldn’t be determined, as the device capacity was reached before the 0.2 in. penetration.
3.2.2 *Lime stabilized samples*

The strength characteristics in the form of UCS and secant modulus (@ peak strength) for lime treated samples are presented in Table 4. Graphical representation of UCS and secant modulus of lime treated soils are shown in Figure 6, and Figure 7 respectively. For GF soil, which is a high plastic clay, 7% of cement was required to increase the strength above 50 psi whereas 2% lime was sufficient for a similar amount of improvement. GF had the least increase in UCS value as well as secant modulus upon treatment with cement. This further confirms that lime is more suitable additive for treating GF soil than cement. Furthermore, in the case of lime stabilized soils, the maximum increase in the strength of GF and DC soils was observed with addition of 4 percent lime. Further increase in the amount of lime led to a decrease in the strength of these soils, it happens when the amount of lime being more than a threshold called lime fixation point. Lime fixation point represents an optimum point at which the amount of lime required for the pozzolanic reaction is equal to the available lime. Beyond this point, any excessive amount of lime reduces the strength as lime does not have appreciable friction and cohesion (Bell, 1996). A1-Rawi (1981) noted that at times this decline in strength exceeds 30%, it is associated with considerable decrease in dry unit weight.

The value of secant modulus also followed a similar trend to UCS. BR and NTF_HP soils have very high sulfate, and NTF_LP has very low plasticity which didn’t qualify them for lime treatment. Although, a small quantity of lime, i.e., 2%, increased the strength of NTF_LP and NTF_HP above 50 psi. BR had the least increase in UCS after treatment compared to other soils as seen in Figure 6. Also, the secant modulus of this soil seems to decrease after treatment, this could be due to the presence of lower amounts of reactive alumina and silica in BR soil compared to other soils. Please note that the reactive alumina and silica data was reported in the task report summarizing Tasks 2, 3, and 4 which was submitted in March, 2018. Lime reacts with alumina and silica to form pozzolanic compounds which contribute to an increase in strength, when the reactive alumina and silica of a soil are low, the excess lime cannot form pozzolanic compounds and the overall strength of the soil sample reduces. Therefore, the amount of reactive alumina and silica play an essential role in the performance of lime stabilization. It should be noted that none of the strength of the lime treated soils reached 150 psi which would a target for a base/subbase application as per TxDOT (2005).
Table 4: Summary of UCS and secant moduli for lime treated samples cured at 100% humidity and 23°C (± 2°C)

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>USCS</th>
<th>AASTHO</th>
<th>Stabilizer Content (%)</th>
<th>UCS (psi)</th>
<th>% Change (compared to untreated soil)</th>
<th>Secant Modulus (psi)</th>
<th>% Change (compared to untreated soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF</td>
<td>CH</td>
<td>A-7</td>
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<td>58.75</td>
<td>68</td>
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</tbody>
</table>

Figure 6: Unconfined compressive strength of 7- day lime treated samples cured at 100% humidity and 23°C (± 2°C).
3.3 Accelerated curing and moisture conditioning techniques used in this study

Studies suggest a direct relationship between temperature and the rate of the pozzolanic reaction in stabilized soil. For example, a small increase in temperature can lead to improving strengths significantly. Conversely, temperature around 40°F (4°C) slows down the pozzolanic reactions and may stop it at lower temperatures. In fact, pozzolanic reactions may remain dormant during periods of low temperatures to regain reaction potential when temperatures increase (Bell 1996 and Celaya et al. 2011). Also, pozzolanic activity commences after 1 day of curing at 72°F or 25°C and the same needed 7 days curing at a low temperature (11.5°C). These suggest that strength development from the pozzolanic activity will occur more quickly in hot semi-arid climatic zones than in cool temperature zones (Rao and Shivananda, 2005). To assess the effect of temperature on curing for the soils selected in this study one additional curing temperature was studied for two different durations. Table 5 presents a summary of the accelerated curing protocols studied in this research.

Table 5: Accelerated curing protocols studied in this research

<table>
<thead>
<tr>
<th>Accelerated Curing Protocol</th>
<th>Temperature</th>
<th>Duration</th>
<th>Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol-1 (ACP-1)</td>
<td>140°F</td>
<td>1 day</td>
<td>Not controlled</td>
</tr>
<tr>
<td>Protocol-2 (ACP-2)</td>
<td>140°F</td>
<td>2 days</td>
<td>Not Controlled</td>
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</tbody>
</table>
3.3.1 Role of moisture

The intrusion of moisture into the soil has a significant adverse effect on the performance of pavement. The leaching of additives out of the host materials due to moisture movements may result in a variation of pH and Calcium/Magnesium ratio, and this will have severe implications on the sustainability of the chemical treatment (Veisi et al. 2010). If the amount of additive does not ensure proper strength, stiffness, and durability, the stabilization would be ineffective and will result in costly rehabilitations. For this purpose, samples that were cured without moisture control were subjected to moisture conditioning via capillary saturation for several additional days and their unconfined compressive strength was measured. In this study for the samples that cured at higher temperatures (ACP-1 and ACP-2), the moisture conditioning was performed by fully submerging the samples under water for five hours. This submergence protocol was adapted from Veisi et al. (2010).

As part of the protocol, the stabilized soil sample was prepared at their optimum moister content (OMC) and maximum dry unit weight and (MDUW). The samples were dried for 48 hours (similar to the study of Veisi et al. (2010)) at 65.5°C (150°F) (Figure 8). Immediately following the oven-drying, the samples were moisture conditioned by submerging in the water as shown in Figure 9. For the moisture conditioning, the sample is kept inside a latex membrane with porous stone on both sides to avoid direct contact between soil and water and minimize surface erosion. An additional protocol with a period of 24 hours of oven-drying was also studied. After moisture conditioning, samples were tested for unconfined compressive strength (UCS) as shown in Figure 10. It can also be noted from this figure that the moisture percolation was not complete in five hours and the moisture was not uniform across the sample.

Figure 8: Oven-drying for a given amount of time.
3.3.2 Novel curing protocol

The researchers at SuRGE laboratory proposed a simplified version of accelerated curing by only increasing the temperature and keeping everything else constant (or close to static conditions). This protocol is called as humidity controlled accelerated curing (HCAC). In this protocol, the UCS sized samples was prepared at OMC and MDUW and wrapped with impermeable material as shown in Figure 2. The samples were placed inside a good quality zip-lock bag with water at the bottom of the bag. Heat resistant silicon plugs were placed inside the bag to separate the sample from the water. It was ensured that the samples rest on the silicone plug and do not touch the water. The primary intent of this setup was to avoid the submergence of the sample while maintaining 95% ± 5% humidity and the ability to put this whole setup inside a typical laboratory oven. The setup is shown in Figure 11. The whole setup is then kept inside the oven at 65.5°C (150°F) for 24 hours as shown in Figure 12. After 24 hours, the samples were tested for its strength characteristics.
Figure 11: HCAC Setup.

Figure 12: Placing the HCAC samples in the oven.

3.4 Results from accelerated curing protocols

A summary of all curing protocols conducted in this research is presented in Table 6. Cement treated GF, DC, BR and NTF_LP soil samples were subjected to all four protocols. The results were compared to evaluate which the three accelerated protocols predicts UCS closest to
CCP. The protocol that best performed for cement treatments was then followed for lime treatments as well and compared with CCP data to ensure the protocol was yielding dependable results for lime treatments. The results from these analyses are presented in the following subsections.

Table 6 Summary of all curing protocols studied in this research

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Temperature</th>
<th>Duration</th>
<th>Humidity</th>
</tr>
</thead>
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<td>Conventional Curing Protocol (CCP)</td>
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<td>7 days</td>
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<tr>
<td>Accelerated Curing Protocol-1 (ACP-1)</td>
<td>150°F</td>
<td>1 day</td>
<td>Not Controlled</td>
</tr>
<tr>
<td>Accelerated Curing Protocol-2 (ACP-2)</td>
<td>150°F</td>
<td>2 days</td>
<td>Not Controlled</td>
</tr>
<tr>
<td>Humidity Controlled Accelerated Curing (HCAC)</td>
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<td>1 day</td>
<td>95%±5%</td>
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</table>

3.4.1 Cement Treated Samples

UCS values of cement treated samples from different curing and moisture conditioning protocols are summarized in Table 7 and visualized in Figure 13. The percentage of treatment was chosen as per the recommended guidelines discussed in Task 1 and Task 2, 3, & 4 reports. It can be noted in Figure 13 that HCAC curing method predicts the closest to CCP. At lower UCS values all three methods seem to predict well, however at higher UCS values ACP-1 and ACP-2 seem to under predict. To better understand this data, percentage difference in UCS values (compared to CCP strength) are tabulated in Table 8. The percentage difference between HCAC and CCP ranged from -48% to 39% while the same between ACP-1 and CCP ranged from 17% to 79%. In the case of ACP-2 the difference was between -23% and 100%. The average difference between the three new protocols and the CCP were 57%, 53%, and -8% for ACP-1, ACP-2 and HCAC, respectively. This shows that HCAC protocol is closest to predicting the CCP strengths on an average. Additionally, in contrast to ACP-1 and ACP-2 protocols, HCAC protocol has only one variable, i.e., temperature – enabling it to better represent the response of the stabilized soil and provide a better estimate of 7-day strength in most of the soil types.

Table 7: UCS test results for cement treated samples after different curing protocols

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>USCS</th>
<th>AASTHO</th>
<th>Stabilizer Content (%)</th>
<th>CCP (psi)</th>
<th>ACP -1 (psi)</th>
<th>ACP -2 (psi)</th>
<th>HCAC (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF</td>
<td>CH</td>
<td>A-7</td>
<td>3</td>
<td>27.45</td>
<td>9.14</td>
<td>0*</td>
<td>37.15</td>
</tr>
<tr>
<td>DC</td>
<td>CL</td>
<td>A-6</td>
<td>9</td>
<td>551.19</td>
<td>190.12</td>
<td>299.16</td>
<td>477.34</td>
</tr>
<tr>
<td>BR</td>
<td>CL</td>
<td>A-7-6</td>
<td>9</td>
<td>260.78</td>
<td>215.50</td>
<td>320.03</td>
<td>384.93</td>
</tr>
<tr>
<td>NTF_LP</td>
<td>ML</td>
<td>A-5</td>
<td>9</td>
<td>776.10</td>
<td>160.12</td>
<td>84.02</td>
<td>475.00</td>
</tr>
</tbody>
</table>

Note: *Sample was too delicate and test could not be completed
Figure 13: Comparing UCS data of cement treated soils for different curing methods

Table 8 Percentage difference in UCS values of the accelerated protocols compared to CCP

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>Stabilizer Content (%)</th>
<th>CCP (psi)</th>
<th>Percentage Difference compared to CCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF</td>
<td>3</td>
<td>27.45</td>
<td>67</td>
</tr>
<tr>
<td>DC</td>
<td>9</td>
<td>551.19</td>
<td>66</td>
</tr>
<tr>
<td>BR</td>
<td>9</td>
<td>260.78</td>
<td>17</td>
</tr>
<tr>
<td>NTF_LP</td>
<td>9</td>
<td>776.1</td>
<td>79</td>
</tr>
<tr>
<td><strong>Average Percentage Difference</strong></td>
<td></td>
<td><strong>57</strong></td>
<td><strong>53</strong></td>
</tr>
</tbody>
</table>

In addition to the UCS, the water contents for various curing conditions were recorded for all protocols and the data is summarized in Table 9 and visualized in Figure 14. The water content of the tested samples was consistently lower than OMC which is expected due to loss of moisture during hydration and pozzolanic compound formation. ACP-1 and ACP-2 had non-uniform moisture contents over the length of the sample. In addition to that, samples that were cured with ACP-1 and ACP-2 protocols have a non-uniform distribution of moisture along the sample as seen in Figure 9. Therefore, the strength results of these tests might not be representative of the actual strength.
Table 9: Water content at the time of testing for different curing conditions for cement stabilized soils

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>USCS</th>
<th>AASTHO</th>
<th>Cement Content (%)</th>
<th>CCP</th>
<th>W/C after Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ACP-1</td>
</tr>
<tr>
<td>GF</td>
<td>CH</td>
<td>A-7</td>
<td>11</td>
<td>40.00</td>
<td>36.38</td>
</tr>
<tr>
<td>DC</td>
<td>CL</td>
<td>A-6</td>
<td>9</td>
<td>17.00</td>
<td>15.47</td>
</tr>
<tr>
<td>BR</td>
<td>CL</td>
<td>A-7-6</td>
<td>9</td>
<td>21.00</td>
<td>19.42</td>
</tr>
<tr>
<td>NTF_LP</td>
<td>ML</td>
<td>A-5</td>
<td>9</td>
<td>27.00</td>
<td>17.64</td>
</tr>
<tr>
<td>NTF_HP</td>
<td>CH</td>
<td>A-7-6</td>
<td>11</td>
<td>24.00</td>
<td>22.27</td>
</tr>
</tbody>
</table>

Further, the Student’s t-test was performed to determine if there were statistically significant differences between the protocols. Student’s t-test (Montgomery and Runger, 2014) is a commonly used statistical significance test when comparing two different protocols. The t-test is generally performed on samples of smaller sizes, and hence this test was best for this study as the sample size was five under each curing method (de Winter, 2013). The t-test was conducted at different confidence levels (CL) indicating how likely are any two protocols to be the same or different. The test results are presented in Table 7. These results show that the p-value for all three methods is above the significance level of 0.05 with the highest value of 0.832 for HCAC protocol. This indicates that HCAC is most likely to have UCS predictions similar to conventional protocol (CCP).
Table 10: Statistical t-test results for the three accelerated curing protocols

<table>
<thead>
<tr>
<th>Curing Protocol</th>
<th>P-Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACP-1</td>
<td>0.077</td>
<td>The protocols are significantly different at 90% confidence level (CL) but not significantly different at 95% or 99% CLs</td>
</tr>
<tr>
<td>ACP-2</td>
<td>0.215</td>
<td>The protocols are not significantly different at 90%, 95% or 99% CLs</td>
</tr>
<tr>
<td>HCAC</td>
<td>0.832</td>
<td>The protocols are not significantly different at 90%, 95% or 99% CLs</td>
</tr>
</tbody>
</table>

3.4.2 Lime Treated Samples

UCS values for lime treated samples after different curing and moisture conditioning protocols are summarized in Table 11 and visualized in Figure 15. As seen in case of cement treated soils (Figure 13), ACP-1 and ACP-2 almost always underestimated the 7-day UCS strength and caused samples to fail in some case before strength measuring test could be performed. Therefore, HCAC was only used for the lime treated samples. The HCAC strength lies in between 50% and 171% of the 7-day strength. The lower percentage (underestimation) was seen in case of GF treated with lower lime content (i.e., 2%) whereas the high percentage (overestimation) was seen in case of DC treated with 4% lime. Strength after HCAC on 4% GF and 2% DC was closer to 7-day strength. The p-value after the t-test on lime treated samples was 0.909 which is significantly higher than the accepted significance level of 0.05 (95%).

Table 11 Results of CCP and HCAC – Lime

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>USCS</th>
<th>AASTHO</th>
<th>Stabilizer Content (%)</th>
<th>CCP (psi)</th>
<th>HCAC (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF</td>
<td>CH</td>
<td>A-7</td>
<td>2</td>
<td>58.70</td>
<td>31.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>79.74</td>
<td>67.57</td>
</tr>
<tr>
<td>DC</td>
<td>CL</td>
<td>A-6</td>
<td>2</td>
<td>99.27</td>
<td>154.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>231.38</td>
<td>287.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>92.48</td>
<td>100.02</td>
</tr>
<tr>
<td>NTF_LP</td>
<td>ML</td>
<td>A-5</td>
<td>2</td>
<td>102.27</td>
<td>97.25</td>
</tr>
</tbody>
</table>
Summary and conclusions
This report presented the results from Task 5 – Curing and Moisture Conditioning protocols whose goal was to establish curing and moisture conditioning protocols based on Montana soils. For this purpose, four different curing protocols were studied including, CCP, ACP-1, ACP-2, and HCAC were studied using the various types of soil from Montana. All the soils, GF, BR, DC, NTF_LP, NTF_HP, and CNK, were treated with cement, whereas all except CNK were treated with lime. Percentage of stabilizers used here were based on established stabilization guidelines. Unconfined compressive strength was used to measure the strength characteristics for most of the soils except for CNK soil. CNK soil was predominantly sand, and conducting UCS on sand is not feasible; hence, CBR was used to determine the strength of CNK soil. GF and DC only qualified for lime treatment. Although, BR, NTF_LP, and NTF_HP were also studied with lime stabilization for the sake of completeness.

The following observations were made:

1. It was noted that only 2% of lime was sufficient to increase strength above 50 psi for all soils tested in this research. However, some of these samples have sulfates present in them which may cause issues for durability. This aspect is currently being studied as a part of task 6.
2. Optimum percentage of lime for GF and DC was 4%. Further increasing the amount of lime decreased the strength.
3. DC has the highest increase in strength compared to untreated strength followed by GF.
4. GF required 7% cement to increase the strength above 50 psi whereas 2% lime was enough. This observation is consistent with high plastic soils behavior that is better stabilized with lime than cement.

5. CNK with 2% cement increases the CBR of the soil specimens above 100%.

6. All three accelerated curing techniques (ACP-1, ACP-2, HCAC) were determined to be producing similar results as CCP. However, HCAC is the most practical and highest reliable of the three.

7. For cement treated soils, the UCS value of the HCAC samples ranged from 61% to 209% of the CCP.

8. ACP-1 and ACP-2 procedures were problematic with GF soil due to surface cracking; this soil is a highly plastic soil.

9. HCAC cured lime treated soil samples had UCS values between 50% and 171% of the 7-day strength.

Curing and moisture conditioning methods for stabilized soil that accelerated the laboratory mix design while maintaining similar strength characteristics are preferred. Also, protocols that can be implemented comfortably in a typical geotechnical laboratory are preferred. Based on these requirements we recommend that HCAC protocol is used when time is of the essence. This method is simple, can estimate treated soil strength consistently, and is easier to conduct in the laboratory. CCP is recommended for all other cases.

Testing is currently underway to determine which of these samples (lime and cement treated) will last for 12 durability cycles as per the guidelines outlined by the Federal Highway Administration (FHWA) (FHWA, 1992). The results from this testing will be submitted as a separate report summarizing task 6 activities.
5 References
Appendix A: Unconfined Compressive Strength Test Data for Cement Treated Soils
**Figure A-1: UCS test on treated BR 3% Cement HCAC Sample 1**

Stress-strain curve from UCS test BR 3% Cement HCAC Sample 1

**Figure A-2: UCS test on treated BR 3% Cement HCAC Sample 2**

Stress-strain curve from UCS test BR 3% Cement HCAC Sample 2

Unconfined Compressive Strength = 1280.67 kPa
Unconfined Compressive Strength = 185.70 psi
Figure A-3: UCS test on treated BR 7% Cement HCAC Sample 1

Figure A-4: UCS test on treated BR 9% Cement HCAC Sample 1
Figure A-5: UCS test on treated DC 9% Cement HCAC Sample 1

Figure A-6: UCS test on treated DC 9% Cement HCAC Sample 2
Figure A-7: UCS test on treated GF 3% Cement HCAC Sample 1

Stress-strain curve from UCS test GF 3% Cement HCAC Sample 1

Unconfined Compressive Strength = 241.35 kPa

Figure A-8: UCS test on treated GF 3% Cement HCAC Sample 2

Stress-strain curve from UCS test GF 3% Cement HCAC Sample 2

Unconfined Compressive Strength = 282.62 kPa
Figure A-9: UCS test on treated GF 6% Cement HCAC Sample 1

Figure A-10: UCS test on treated GF 6% Cement HCAC Sample 2
Figure A-11: UCS test on treated GF 11% Cement HCAC Sample 1

Unconfined Compressive Strength = 638.33 kPa

Figure A-12: UCS test on treated GF 11% Cement HCAC Sample 2

Unconfined Compressive Strength = 905.43 kPa
Figure A-13: UCS test on treated NTF_LP 3% Cement HCAC Sample 1

Figure A-14: UCS test on treated NTF_LP 3% Cement HCAC Sample 2
Figure A-15: UCS test on treated NTF_LP 9% Cement HCAC Sample 1

Unconfined Compressive Strength = 2304.71 kPa

Figure A-16: UCS test on treated NTF_LP 9% Cement HCAC Sample 2

Unconfined Compressive Strength = 3211.29 kPa
Figure A-17: UCS test on treated NTF_LP 9% Cement HCAC Sample 3

Figure A-18: UCS test on treated NTF_LP 9% Cement HCAC Sample 4
Figure A- 19: UCS test on treated NTF_LP 9% Cement HCAC Sample 5

Unconfined Compressive Strength = 2309.71 kPa

Figure A- 20: UCS test on treated NTF_HP 11% Cement HCAC Sample 1

Unconfined Compressive Strength = 4075.54 kPa
Figure A-21: UCS test on treated NTF_HP 11% Cement HCAC Sample 2

Stress-strain curve from UCS test NTF_HP 11% Cement HCAC Sample 2

Unconfined Compressive Strength = 3537.97 kPa

Figure A-22: UCS test on treated BR 9% Cement Accelerated Sample 1

Stress-strain curve from UCS test BR 9% Cement 48 Hour 60C 5 Hour Submergence Sample 1

Unconfined Compressive Strength = 2045.65 kPa
Figure A-23: UCS test on treated BR 9% Cement Accelerated Sample 2

Stress-strain curve from UCS test BR 9% Cement 48 Hour 60C 5 Hour Submergence Sample 2

Unconfined Compressive Strength = 2380.56 kPa

Figure A-24: UCS test on treated DC 9% Cement Accelerated Sample 1

Stress-strain curve from UCS test DC 9% Cement 48 Hour 60C 5 Hour Submergence Sample 1

Unconfined Compressive Strength = 2134.08 kPa

Unconfined Compressive Strength = 309.44 psi
Figure A-25: UCS test on treated DC 9% Cement Accelerated Sample 2

Figure A-26: UCS test on treated NTF_LP 9% Cement Accelerated Sample 1
Figure A-27: UCS test on treated NTF_LP 9% Cement Accelerated Sample 2

Figure A-28: UCS test on treated NTF_HP 11% Cement 24 Hour Accelerated Sample 1
Figure A-29: UCS test on treated NTF_HP 11% Cement 24 Hour No Submergence Sample 2

Figure A-30: UCS test on treated NTF_HP 11% Cement 48 Hour 60C 5 Hour Submergence Sample 1
Figure A-31: UCS test on treated NTF_HP 11% Cement 48 Hour Accelerated Sample 2

Figure A-32: UCS test on treated BR 3% Cement 7-Day Cure Sample 1
Figure A-33: UCS test on treated BR 3% Cement 7-Day Cure Sample 2

Stress-strain curve from UCS test BR 3% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 710.83 kPa

Figure A-34: UCS test on treated BR 7% Cement 7-Day Cure Sample 1

Stress-strain curve from UCS test BR 7% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 1457.56 kPa
Figure A-35: UCS test on treated BR 7% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 1767.31 kPa

Figure A-36: UCS test on treated BR 9% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 1831.82 kPa
Figure A-37: UCS test on treated BR 9% Cement 7-Day Cure Sample 2

Stress-strain curve from UCS test BR 9% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 1797.06 kPa

Figure A-38: UCS test on treated BR 11% Cement 7-Day Cure Sample 1

Stress-strain curve from UCS test BR 11% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 1914.76 kPa
Figure A-39: UCS test on treated BR 11% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 1564.54 kPa
Unconfined Compressive Strength = 226.86 psi

Figure A-40: UCS test on treated DC 2% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 574.85 kPa
Figure A-41: UCS test on treated DC 2% Cement 7-Day Cure Sample 2

Stress-strain curve from UCS test DC 2% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 701.20 kPa

Figure A-42: UCS test on treated DC 4% Cement 7-Day Cure Sample 1

Stress-strain curve from UCS test DC 4% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 1353.48 kPa
Figure A-43: UCS test on treated DC 4% Cement 7-Day Cure Sample 2

Figure A-44: UCS test on treated DC 4% Cement 7-Day Cure Sample 3

Stress-strain curve from UCS test DC 4% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 1344.19 kPa

Stress-strain curve from UCS test DC 4% Cement 7-Day Cure Sample 3

Unconfined Compressive Strength = 1353.48 kPa
Figure A-45: UCS test on treated DC 6% Cement 7-Day Cure Sample 1

Stress-strain curve from UCS test DC 6% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 2085.68 kPa

Figure A-46: UCS test on treated DC 6% Cement 7-Day Cure Sample 2

Stress-strain curve from UCS test DC 6% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 1999.62 kPa
Stress-strain curve from UCS test DC 7% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 1574.12 kPa

Figure A-47: UCS test on treated DC 7% Cement 7-Day Cure Sample 1

Stress-strain curve from UCS test DC 7% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 1666.29 kPa

Figure A-48: UCS test on treated DC 7% Cement 7-Day Cure Sample 2
Figure A-49: UCS test on treated DC 7% Cement 7-Day Cure Sample 3

Stress-strain curve from UCS test DC 7% Cement 7-Day Cure Sample 3

Unconfined Compressive Strength = 2484.98 kPa

Figure A-50: UCS test on treated DC 7% Cement 7-Day Cure Sample 4

Stress-strain curve from UCS test DC 7% Cement 7-Day Cure Sample 4

Unconfined Compressive Strength = 1749.56 kPa
Figure A- 51: UCS test on treated DC 9% Cement 7-Day Cure Sample 1

Figure A- 52: UCS test on treated DC 9% Cement 7-Day Cure Sample 2
Figure A-53: UCS test on treated DC 11% Cement 7-Day Cure Sample 1

Figure A-54: UCS test on treated DC 11% Cement 7-Day Cure Sample 2
Figure A-55: UCS test on treated GF 3% Cement 7-Day Cure Sample 1

Stress-strain curve from UCS test GF 3% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 250.49 kPa

Figure A-56: UCS test on treated GF 3% Cement 7-Day Cure Sample 2

Stress-strain curve from UCS test GF 3% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 140.69 kPa
Figure A-57: UCS test on treated GF 6% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 178.48 kPa

Figure A-58: UCS test on treated GF 6% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 181.14 kPa
Figure A- 59: UCS test on treated GF 7% Cement 7-Day Cure Sample 1

Figure A- 60: UCS test on treated GF 7% Cement 7-Day Cure Sample 2
Figure A-61: UCS test on treated GF 9% Cement 7-Day Cure Sample 1

Stress-strain curve from UCS test GF 9% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 414.03 kPa

Figure A-62: UCS test on treated GF 9% Cement 7-Day Cure Sample 2

Stress-strain curve from UCS test GF 9% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 414.03 kPa
Figure A-63: UCS test on treated GF 9% Cement 7-Day Cure Sample 3

Unconfined Compressive Strength = 789.82 kPa

Figure A-64: UCS test on treated GF 11% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 276.64 kPa
Figure A- 65: UCS test on treated GF 11% Cement 7-Day Cure Sample 2

Figure A- 66: UCS test on treated GF 11% Cement 7-Day Cure Sample 3
Figure A-67: UCS test on treated GF 11% Cement 7-Day Cure Sample 4

Figure A-68: UCS test on treated GF 13% Cement 7-Day Cure Sample 1
Figure A- 69: UCS test on treated GF 13% Cement 7-Day Cure Sample 2

Figure A- 70: UCS test on treated GF 13% Cement 7-Day Cure Sample 3
Figure A- 71: UCS test on treated NTF_LP 3% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 631.74 kPa

Figure A- 72: UCS test on treated NTF_LP 3% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 513.77 kPa
Figure A- 73: UCS test on treated NTF_LP 7% Cement 7-Day Cure Sample 1

Figure A- 74: UCS test on treated NTF_LP 7% Cement 7-Day Cure Sample 2
Figure A- 75: UCS test on treated NTF_LP 7% Cement 7-Day Cure Sample 3

Figure A- 76: UCS test on treated NTF_HP 3% Cement 7-Day Cure Sample 1
Figure A- 77: UCS test on treated NTF_HP 3% Cement 7-Day Cure Sample 2

Figure A- 78: UCS test on treated NTF_HP 9% Cement 7-Day Cure Sample 1
Figure A- 79: UCS test on treated NTF_HP 9% Cement 7-Day Cure Sample 2

Figure A- 80: UCS test on treated NTF_HP 11% Cement 7-Day Cure Sample 1
Figure A-81: UCS test on treated NTF_HP 11% Cement 7-Day Cure Sample 2

Figure A-82: UCS test on treated NTF_HP 13% Cement 7-Day Cure Sample 1
Figure A-83: UCS test on treated NTF_HP 13% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 3260.18 kPa

Figure A-84: UCS test on treated NTF_LP 9% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 5263.48 kPa
Figure A-85: UCS test on treated NTF_LP 9% Cement 7-Day Cure Sample 2

Unconfined Compressive Strength = 5446.57 kPa

Figure A-86: UCS test on treated NTF_LP 11% Cement 7-Day Cure Sample 1

Unconfined Compressive Strength = 6005.48 kPa
Figure A- 87: UCS test on treated NTF_LP 11% Cement 7-Day Cure Sample 2

Stress-strain curve from UCS test NTF_LP 11% Cement 7-Day Cure Sample 2

Unconfined Compressive Stress = 6061.61 kPa
Appendix B: Unconfined Compressive Strength Test Data for Lime Treated Soil
Figure B-1: UCS test on treated DC 2% Lime HCAC Sample 1

Stress-strain curve from UCS test DC 2% Lime HCAC Sample 1

Unconfined Compressive Strength = 1118.23 kPa

Figure B-2: UCS test on treated DC 2% Lime HCAC Sample 2

Stress-strain curve from UCS test DC 2% Lime HCAC Sample 2

Unconfined Compressive Strength = 395.02 kPa
Figure B-3: UCS test on treated DC 2% Lime HCAC Sample 2

Stress-strain curve from UCS test DC 2% Lime HCAC Sample 3

Unconfined Compressive Strength = 1007.21 kPa

Axial Stress, kPa
Axial strain (%)

Figure B-4: UCS test on treated DC 4% Lime HCAC Sample 1

Stress-strain curve from UCS test DC 4% Lime HCAC Sample 1

Unconfined Compressive Strength = 1891.30 kPa

Axial Stress, psi
Axial strain (%)

Figure B-5: UCS test on treated DC 4% Lime HCAC Sample 2

Stress-strain curve from UCS test DC 4% Lime HCAC Sample 2

Unconfined Compressive Strength = 2072.62 kPa

Figure B-6: UCS test on treated DC 6% Lime HCAC Sample 1

Stress-strain curve from UCS test DC 6% Lime HCAC Sample 1

Unconfined Compressive Strength = 731.93 kPa
Figure B-7: UCS test on treated DC 6% Lime HCAC Sample 2

Stress-strain curve from UCS test DC 6% Lime HCAC Sample 2

Unconfined Compressive Strength = 647.69 kPa

Figure B-8: UCS test on treated DC 8% Lime HCAC Sample 1

Stress-strain curve from UCS test DC 8% Lime HCAC Sample 1

Unconfined Compressive Strength = 555.89 kPa
Figure B-9: UCS test on treated DC 8% Lime HCAC Sample 2

Figure B-10: UCS test on treated GF 2% Lime HCAC Sample 1
Figure B-11: UCS test on treated GF 2% Lime HCAC Sample 2

Stress-strain curve from UCS test GF 2% Lime HCAC
Sample 2

Unconfined Compressive Strength = 230.39 kPa

Figure B-12: UCS test on treated GF 2% Lime HCAC Sample 3

Stress-strain curve from UCS test GF 2% Lime HCAC
Sample 3

Unconfined Compressive Strength = 262.64 kPa
Figure B-13: UCS test on treated GF 4% Lime HCAC Sample 1

Figure B-14: UCS test on treated DC 4% Lime 7-Day Cure Sample 3
Figure B-15: UCS test on treated DC 4% Lime 7-Day Cure Sample 4

Figure B-16: UCS test on treated GF 2% Lime 7-Day Cure Sample 1
Figure B-17: UCS test on treated GF 2% Lime 7-Day Cure Sample 2

Stress-strain curve from UCS test GF 2% Lime 7-Day Cure Sample 2

Unconfined Compressive Strength = 455.18 kPa

Figure B-18: UCS test on treated GF 4% Lime 7-Day Cure Sample 1

Stress-strain curve from UCS test GF 4% Lime 7-Day Cure Sample 1

Unconfined Compressive Strength = 598.74 kPa
Figure B-19: UCS test on treated GF 4% Lime 7-Day Cure Sample 2

Stress-strain curve from UCS test GF 4% Lime 7-Day Cure Sample 2

Unconfined Compressive Strength = 513.62 kPa

Unconfined Compressive Strength = 394.35 kPa

Figure B-20: UCS test on treated GF 6% Lime 7-Day Cure Sample 1
Figure B-21: UCS test on treated GF 6% Lime 7-Day Cure Sample 2

Figure B-22: UCS test on treated GF 6% Lime 7-Day Cure Sample 3
Figure B-23: UCS test on treated GF 6% Lime 7-Day Cure Sample 4

Figure B-24: UCS test on treated GF 8% Lime 7-Day Cure Sample 2
Figure B-25: UCS test on treated GF 8% Lime 7-Day Cure Sample 3

Figure B-26: UCS test on treated GF 8% Lime 7-Day Cure Sample 4

Stress-strain curve from UCS test GF 8% Lime 7-Day Cure Sample 3

Unconfined Compressive Strength = 433.55 kPa

Stress-strain curve from UCS test GF 8% Lime 7-Day Cure Sample 4

Unconfined Compressive Strength = 430.05 kPa
Figure B-27: UCS test on treated BR 2% Lime 7-Day Cure Sample 1

Stress-strain curve from UCS test BR 2% Lime 7-Day Cure Sample 1

Unconfined Compressive Strength = 460.23 kPa

Figure B-28: UCS test on treated BR 2% Lime 7-Day Cure Sample 2

Stress-strain curve from UCS test BR 2% Lime 7-Day Cure Sample 2

Unconfined Compressive Strength = 484.90 kPa
Figure B-29: UCS test on treated NTF_HP 2% Lime 7-Day Cure Sample 1

Figure B-30: UCS test on treated NTF_HP 2% Lime 7-Day Cure Sample 2