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Laboratory Testing of Cement-Treated Wet Subgrade and Design Recommendations

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Abstract: Portland cement has widely been used to improve weak and wet subgrade soils in highway construction. Its effectiveness on enhancing subgrade soils, however, depends on multiple factors. This paper aims at building a reliable cement-treated subgrade layer by checking its Unconfined Compression Strength (UCS) and developing a guideline for selecting appropriate cement content based on the field moisture content of subgrade soils. A series of laboratory tests were conducted on two typical low-plasticity subgrade soils encountered in Louisiana, which examine the possible correlation among UCS, molding moisture content, dry unit weight, and water-cement ratio. Based on these laboratory testing results, a tentative procedure to construct a reliable cement-treated subgrade layer is proposed.

***Key words**: Cement-mixed soil; Cement-treated soil; Subgrade; Unconfined compression strength; Water-cement ratio.*

Introduction

Many Louisiana pavements are built on areas of wet soil with low shear strength and minimum bearing capacities that exhibit detrimental pumping action under traffic. These wet subgrades cause both construction and performance problems. The Louisiana Department of Transportation and Development (LADOTD) typically provides a lime treatment item to be used at the discretion of project engineers when pumping conditions are en- countered [1]. A previous study indicates that using cement to treat wet, low plastic soils (Plastic Index (PI) less than 25) will provide better results with a strong working table for pavement structure [2]. The reason of using cement rather than lime for these Louisiana subgrade soils lies in the fact that the effectiveness of lime stabilization largely depends on the amount and type of clay present in the subgrgade while cement stabilization is less affected by the factor. Fig. 1 shows the benefit of such an approach, which compares the field determined structure numbers (SN) of two pavement sections from a roadway with a very weak subgrade. The SN is an abstract number expressing the structural strength of a pavement required to support total traffic for given combinations of soil and environment conditions. Compared with the designed SN of 5.0, the section with cement treated subgrade had a field SN close to the designed value, but the SN of the same pavement structure directly on a raw subgrade were only half of the designed SN on average. The other half of the pavement structure had been used to compensate the weak subgrade in the latter case.

Most state highway agencies require that cement treated subgrade layers be compacted at the optimum moisture content with a variation of ±2 percent to achieve at least 95 percent of the maximum dry unit weight determined by a laboratory Proctor test. Sometimes this requirement cannot be met due to high field moisture contents. Very often, a tight construction schedule requires that a subgrade layer be compacted at the field moisture content to avoid a construction delay. Therefore, designing and building a reliable subgrade layer on weak or wet subgrade becomes an issue that needs to be addressed to guide engineering practice.

Historically, Portland cement has been successfully used to stabilize weak or wet soils in various engineering environments to gain enough strength to support structures. The strength can directly be used as a parameter to guide design and construction if the contributions of cement treatment to the strength development of wet subgrade soils are properly understood and quantified in subgrade treatment. For instance, it is believed that the parameter governing the strength and deformation characteristics of clay-cement mixtures is the clay-water/cement ratio, C_w/A_w [3, 4]. Here, C_w is the molding moisture content of clay-cement mixtures determined from the dry weight of soil only; A_w is the cement content defined as the percentage ratio of the cement weight to the soil dry weight. The latest development on this topic is that soil after-curing void ratio, e_{ot}, and A_w together can better predict the unconfined compression strength (UCS) of clay-cement mixture [5].

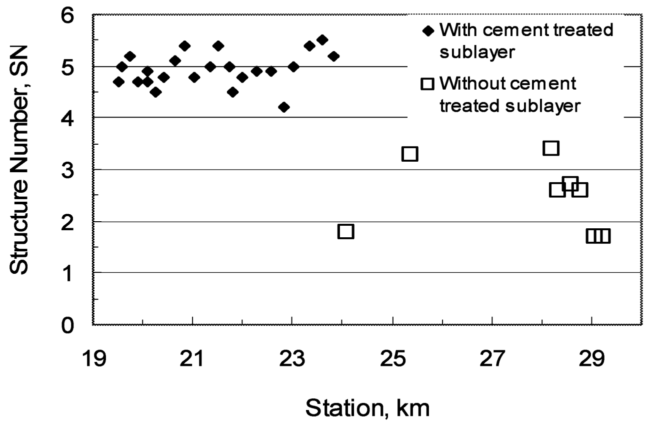

Fig.1. Comparison of Pavement Structures with and without Stabilized Subgrade.

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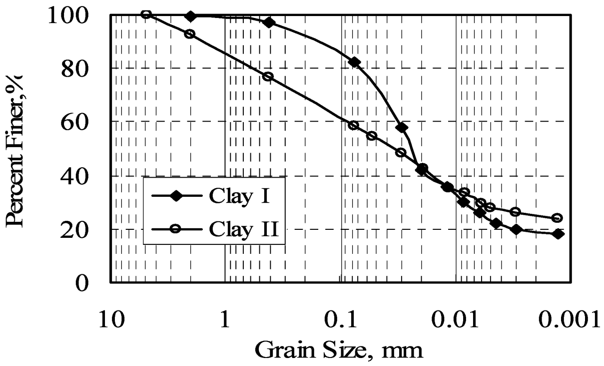


Fig. 2. Grain Size Distribution Curves of Soils I and II.

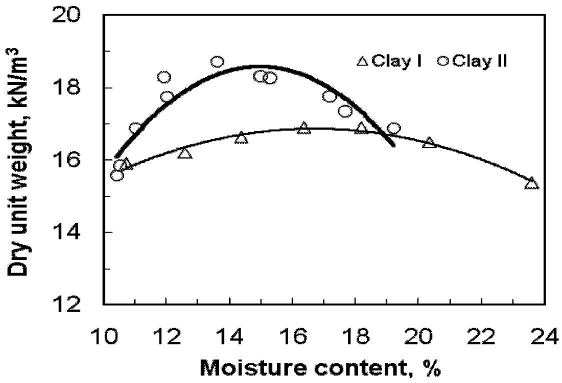


Fig. 3. Compaction Curves of Soils Tested.

The work covered in this paper is mainly focused on the laboratory evaluation of two soil types encountered in Louisiana to demonstrate influence factors on the strength development of cement-treated wet subgrade soils. The main objective of this study is to explore a methodology to predict such strength and develop guidelines for selecting appropriate cement content for construction according to field moisture content.

Test Materials

The two types of soils used in this study were from Baton Rouge, Louisiana. They cover the range of embankment soils allowed by the LADOTD specifications. Table 1 shows the general physical properties of the soils with a specific gravity of 2.65 (Clay I) and 2.72 (Clay II) respectively. Their Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO) classifications are: CL/A-6, Group Index (GI) 11 and CL/A-7, GI 10, respectively. Fig. 2 shows their grain size distribution curves, and Fig. 3 shows their compaction curves. Their maximum dry unit weights were 17.0kN/m^3 (108pcf) and 18.7kN/m^3 (119pcf) at the corresponding optimum moisture contents of 17.5 and 13.5 percent, respectively. The UCS values at the optimum moisture and maximum dry unit weight (standard proctor) were 0.262MPa (38psi) for Clay I and 0.345MPa (50psi) for Clay II with a CBR value of 12 for both soils. The CBR of 12 was obtained at the optimum moisture content and maximum dry unit weight.

Test Procedure and Data Reduction

A series of UCS tests was conducted on cement-mixed soil specimens molded at different moistures and cement contents and cured over different durations. The test procedure was complied with ASTM D1633, and Table 2 shows the factorial test plan for the cement-mixed soils.

Molding Procedure

The specimens were molded as follows: Weigh 2,000g of the soil with hygroscopic moisture content (w_{hy}) and thoroughly mix it with the amount of Portland cement determined by multiplying the nominal cement content, A_n, given in Table 2 with the 2,000g weight. Here, w_{hy} was based on the weight of the dry soil, and A_n was based on the weight of soil with the w_{hy}.

Next, the cement and soil mixture was thoroughly mixed with the amount of water determined by multiplying the nominal moisture content (w_n), also shown in Table 2. Consequently, w_n is based on the total weight of cement-soil mixture with w_{hy}. Specimens were immediately molded using the Standard Proctor procedure (ASTM 968) with molding moisture content (w_m) taken. Here, w_m is based on the weight of dry cement-soil mixture.

Raw soil specimens (0 percent cement) were wrapped in plastic bags and cured in laboratory room temperature for one day while cement-mixed soil specimens were wrapped in plastic bags and cured in a 100 percent humidity room with a temperature of 23°C (73°F) for 7, 14, or 28 days. Cured specimens were submerged in water for four hours with weights taken before and after. Then, they were loaded to failure according to ASTM 1633 with the moisture content at failure (w_b) taken at the end of the tests. Here, w_b is based on the weight of the dry hydrated cement-soil mixture.

Analysis Formulas

Table 1. Physical Indices of Soils Tested.

Soil No.	Percent of Silt, %	Percent of Clay, %	LL, %	PI, %	Optimum Moisture Content, %	Group Index, GI	Soil Classification USCS/AASHTO
Clay I	64.5	27.5	34	12	17.5	11	CL/A-6
Clay II	30.6	27.9	37	22	13.5	10	CL/A-7

Table 2. Test Factorial.

Soil Type	Nominal Cement Content, A_n, %	Nominal Moisture Content, w_n, %	Curing Time (day)
Clay I	0, 4, 8, 12	8.5 – too wet to mold	7, 14, 28
Clay II	0, 4, 6, 8, 12	7.5 – too wet to mold	7, 14, 28

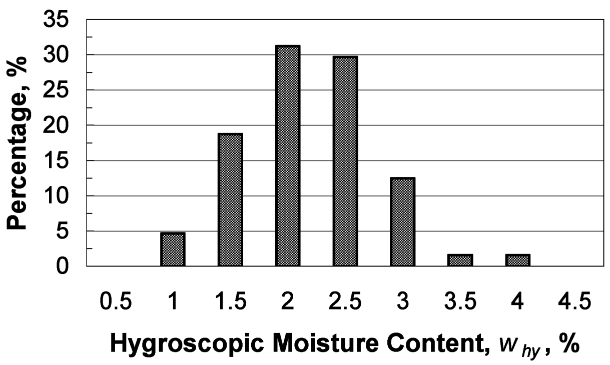


Fig. 4. Histogram of Hygroscopic Moisture Content of Soil Tested.

Several calculation formulas were derived to analyze the testing results as follows.

Hygroscopic Moisture Content, w_{hy}, of Soil Tested

Soil will absorb a certain amount of moisture from the air during its process and storage in the laboratory, which can be described by w_{hy}. This moisture is needed to determine the water-cement ratio of cement-mixed soil and can be calculated as follows:

$$w_{hy} = \frac{(w_m w_n)(100 + A_n)}{10000 + 100w_n + A_n(w_n w_m)} \tag{1}$$

where (w_{hy}, w_m, w_n, and A_n) are all defined before and in percentage (see Appendix for details). Fig. 4 shows the histogram of w_{hy} for a group of specimens tested. It closely follows a normal distribution with a mean of 1.92 percent and standard deviation of 0.59 percent in this particular group of specimens.

Because of the w_{hy}, the actual cement content (A_w) used in the laboratory test has a relationship with the A_n as follows (see Appendix for details):

$$A_w = A_n\left(1 + \frac{w_{hy}}{100}\right) \tag{2}$$

Moisture-Cement Ratio

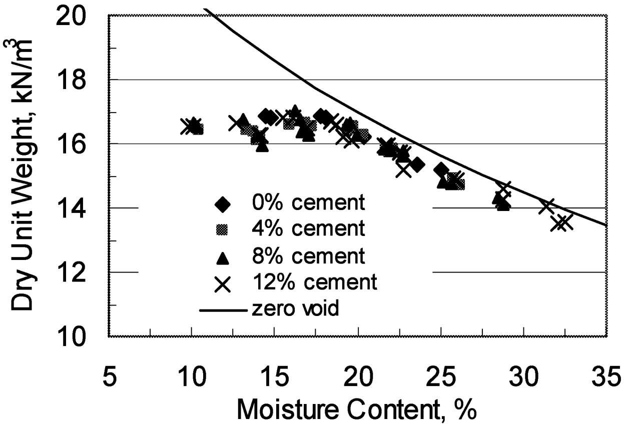
The moisture-cement ratio of cement-mixed soil at molding (C_{wm}/A_w) is defined based on the weight of dry soil, where C_{wm} is defined as moisture content at molding. Eq. (3) can determine the ratio of cement-mixed soil as follows.

$$\frac{C_{wm}}{A_w} = \left(1 + \frac{A_n}{100} + \frac{100 \cdot w_{ky}}{w_n \cdot (100 + w_{ky})}\right) \cdot \frac{w_n}{A_n} \tag{3}$$

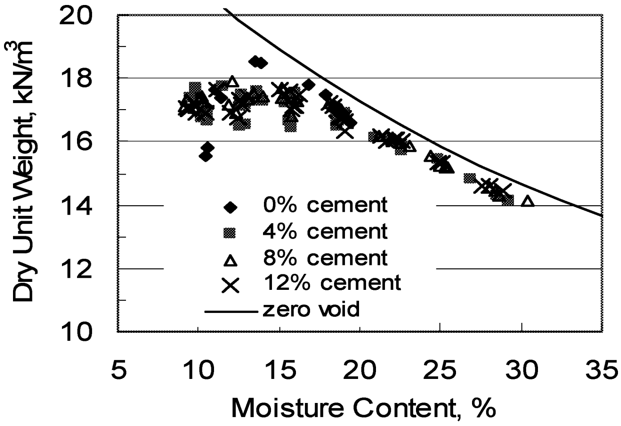
where (w_{hy}, w_n, and A_n) are all in percentage as before (see Appendix for details).

Discussion of Results

Specimen Compaction



Clay I



Clay II

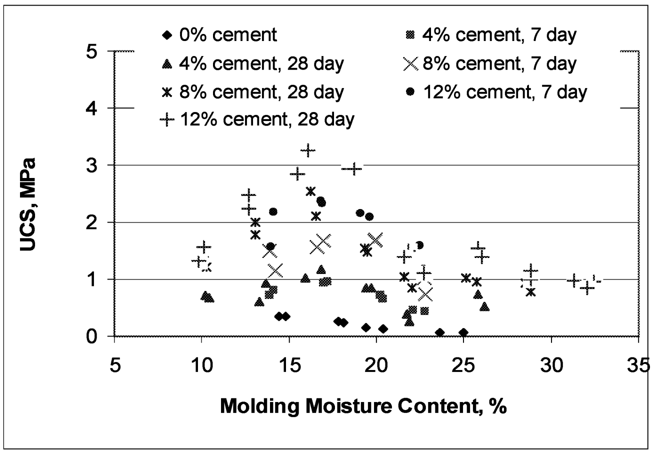
Fig. 5. Correlation of Dry Unit Weight and Moisture Content.

The quality of specimens prepared in this study was evaluated through the relationships between their moisture content and dry unit weight, as shown in Fig. 5. This figure indicates that before any cement hydration occurs, the impact of cement on soil compaction for low plasticity soils is mainly limited to the dry side of the compaction curve. On the wet side of compaction curve, the variation of dry unit weight at the same moisture content is very limited for different cement contents. This is the range of moisture content encountered in the field with wet subgrade situations.

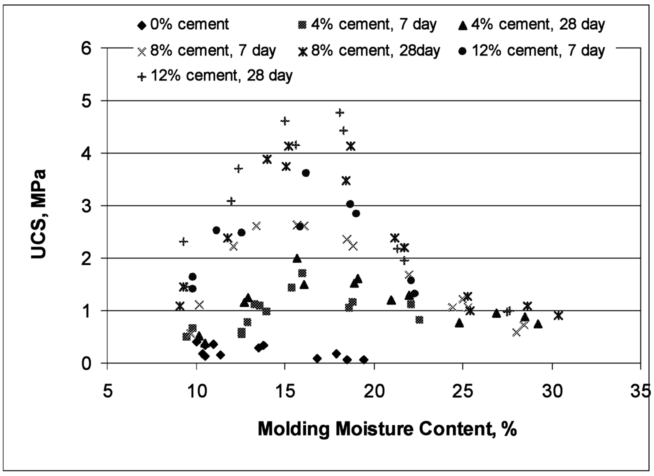
Unconfined Compressive Strength

Fig. 6 shows the UCS of the two soils mixed with 4, 8, and 12 percent cement and cured for 7 and 28 days. As expected, cement content, molding moisture content, dry unit weight, and curing period control the UCS of cement-mixed soils. Higher cement content and longer curing time result in higher strength. A higher molding dry unit weight also brings in higher strength. For the moisture content, on the dry side of compaction curve, increase in molding moisture content will increase the strength of cement-mixed soils; while on the wet side of the compaction curve, increase in the molding moisture content will decrease the strength of the mixtures.

Molding Moisture Content



Clay I



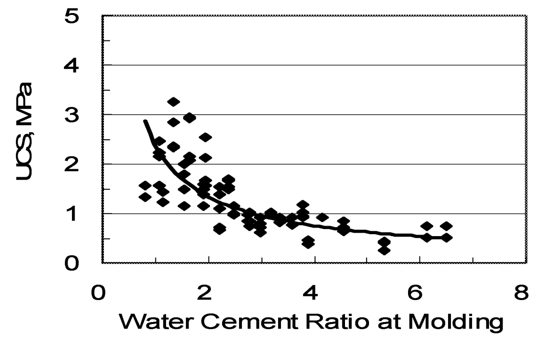
Clay II

Fig. 6. UCS and Moisture Content at Molding of Various Conditions.

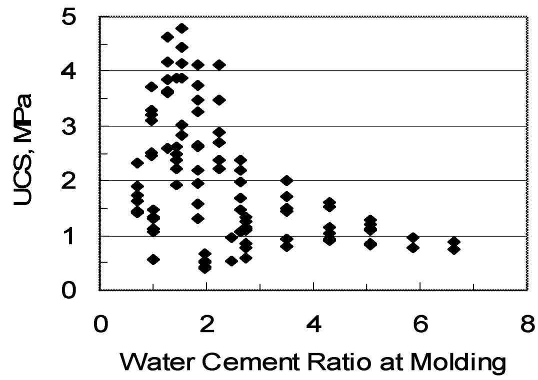
The relationship between the moisture content at molding and the specimen's UCS is quite complicated because the moisture content not only determines the availability of free water in the soil for cement hydration, but also affects the dry unit weight of the specimen molded. Therefore, UCS does not always decrease with the increase of moisture content under the same cement content and curing duration. Instead, the correlation between the UCS and moisture content at molding for the cement-mixed soils follows a pattern similar to that of the correlation between the dry unit weight and moisture content of the material. The highest strength is not at the lowest moisture content (lowest water-cement ratio at molding), but around the optimum moisture content of the soils with the highest density. Therefore, the correlations of specimens' UCS with their water-cement ratio at molding, as shown in Fig. 7, are widely scattered for the specimens molded along a compaction curve, especially for the range of the low water-cement ratios at molding.

Different Trends along Compaction Curve

Cement-mixed soils perform quite differently on the dry and wet sides of a compaction curve, as indicated in Fig. 8. It indicates that different patterns exist between the strength and water-cement ratio on the dry and wet sides of compaction curves.



Clay I



Clay II

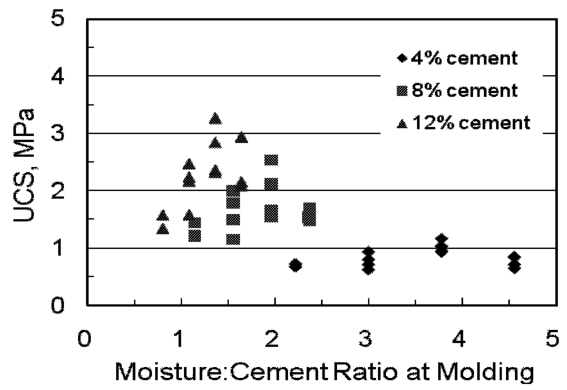
Fig. 7. UCS and Water-Cement Ratio at Molding.

Table 3 explains the phenomenon shown in Fig. 8. If the cement content increases, the strength will increase, and the water-cement ratio will decrease. For the molding moisture content on the dry side of a compaction curve, as moisture content increases, both dry unit weight and strength will increase, so will water- cement ratio; on the wet side of the compaction curve, the increase of molding moisture will reduce both dry unit weight and strength but increase the water-cement ratio. The conclusion is that on the wet side of the compaction curve, the water-cement ratio is a good indicator for the strength of cement-mixed soils. The strength will increase with the decrease of water-cement ratio. The strong correlation of water-cement ratio with UCS values on the wet side of compaction curves provides a quick means of approximating strength. For example, on the wet side of the compaction curves UCS values of 1.03MPa (150psi) and 0.69MPa (100psi) can at least be expected at water-cement ratios of 2.0 and 3.0, respectively. A minimum seven-day

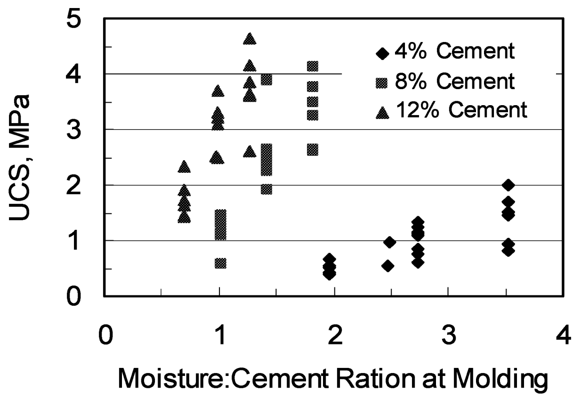
Table 3. Correlation among Different Factors.

Independent Factors	Dependent Factors			
Cement Content (↑)	Dry side of compaction curve		Wet side of compaction curve	
	Water-cement ratio (↓) Strength (↑)		Water-cement ratio (↓) Strength (↑)	
Molding Moisture Content (↑)	Dry side of compaction curve		Wet side of compaction curve	
	Water-cement ratio(↑) Dry unit weight (↑)	Strength (↑)	Water-cement ratio (↑) Dry unit weight(↓)	Strength (↓)

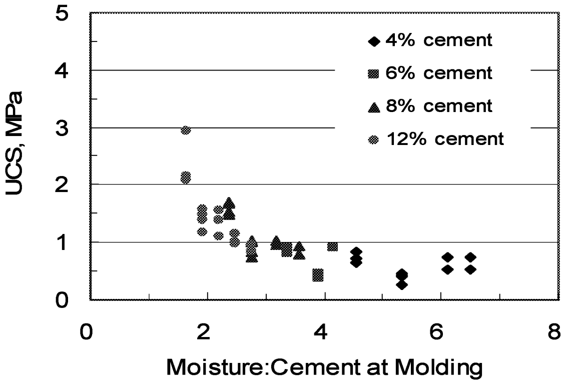
Note: ↑ = increase; and ↓ = decrease.



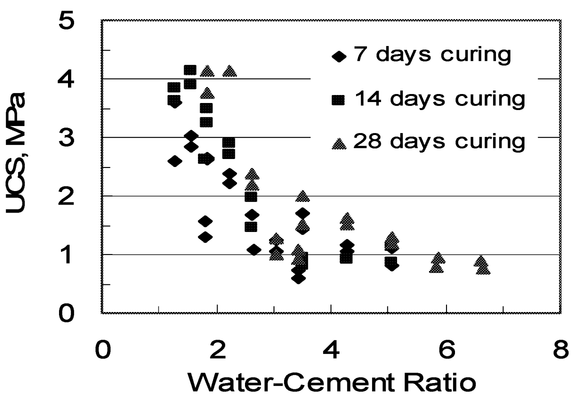
Clay I, Dry Side



Clay II, Dry Side



Clay II, Wet Side



Clay II, Wet Side

Fig. 8. Different Performance on Dry and Wet Sides of Compaction Curves.

UCS value of 1.03MPa (150psi) is currently used by some state highway agencies in USA to ensure durability of cement-stabilized subgrade, although the viability of such practice remains to be verified [6, 7]. This correlation of water-cement ratio with UCS on the wet side of compaction curve, as shown in Fig. 8, also illustrates the limitation of using cement in stabilizing wet subgrade clays–a minimum 12 percent of cement is required to get a water-cement ratio of 2.0 and thus ensure a UCS of 1.03MPa when a subgrade clay has in-situ moisture content of 24 percent. At such a high percentage of cement, cement stabilization becomes uneconomical, and other stabilization alternative should be considered (such as the use of lime to dry subgrade soil first and then apply cement).

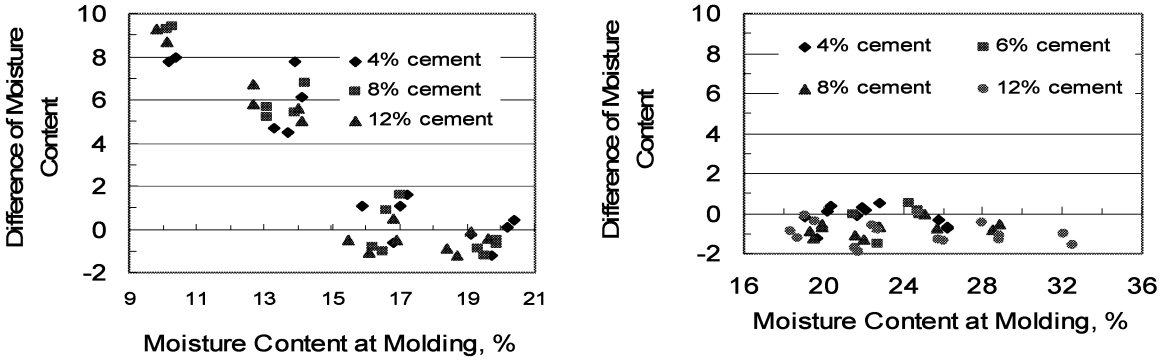
The testing data in Figs. 9 and 10 may also shed some light on the different performances shown in Fig 8. They show the correlations between the moisture content of specimens at molding and the change of moisture content during specimen curing, where the difference was calculated as the subtraction of the moisture content at molding from the one at failure by loading. Therefore, the positive difference indicates that specimens absorb moisture during the curing process. The data indicate that a strong interaction occurs between specimens and free water for specimens molded on the dry side of the compaction curve, and specimens with ability to absorb more free water during curing will have lower strength.

The interaction among soil, cement, and water during curing time and its impact on the strength development of cement-mixed soils also depended on the plasticity (defined by PI) of raw soils. Soils with a higher PI tend to be affected more by the moisture absorption than the ones with a lower PI, as indicated by comparing Figs. 9 and 10, when cement is mixed with the soils on the dry side of compaction curves.

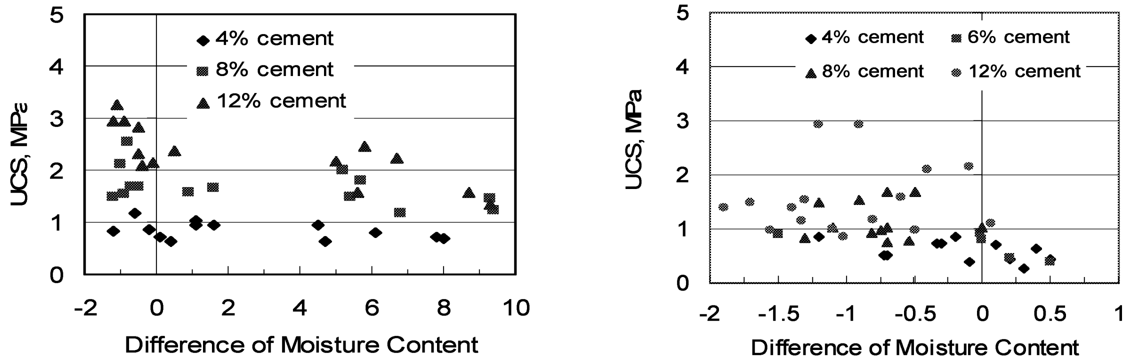
Conclusions

The following conclusions, which are only relevant to fine-grained soils with AASHTO soil classification of A-6 and A-7 with PI less than 25, are drawn from the research work conducted in this study.

- The water-cement ratio of cement-soil mixtures at molding has a good correlation with UCS only for samples compacted on the wet side of compaction curves.
- On the wet side of the compaction curve, cement-soil mixtures with a water-cement ratio of 2 at molding will have a minimum UCS of 1.03MPa (150psi), while cement-soil mixtures with a water-cement ratio of 3 at molding will have a minimum UCS of 0.69MPa (100psi).
- Cement-soil mixtures compacted on the dry side of compaction curves will experience complex physical-chemical changes during curing period, which could result in a lower strength. Currently, this phenomenon is not fully understood, and therefore, its impact on mixtures' strength cannot be predicted accurately.
- The addition of cement to soils with PI less than 25 has a very limited impact on the compaction curves of cement-soil mixtures when compared to the original soil compaction curve if the compaction is conducted before any hydration occurs.
- Using cement to treat wet subgrade has its own limitation with respect to moisture content. This limit is material



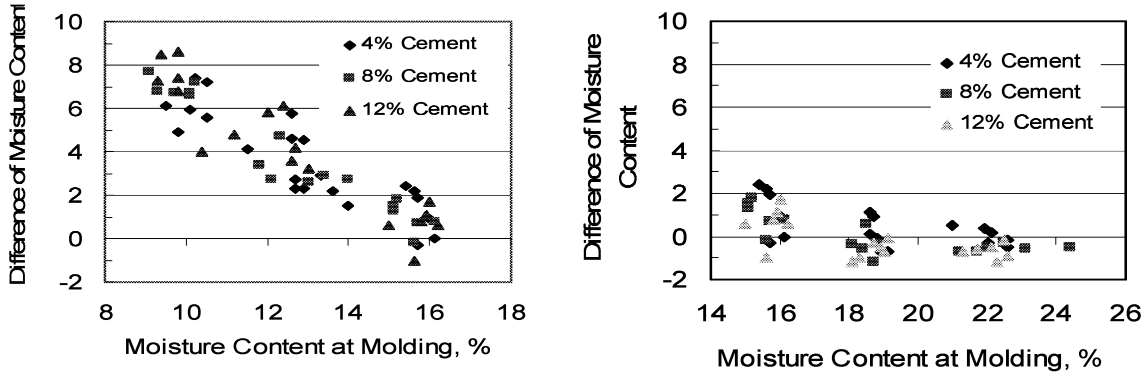
Changes of Moisture Content during Curing



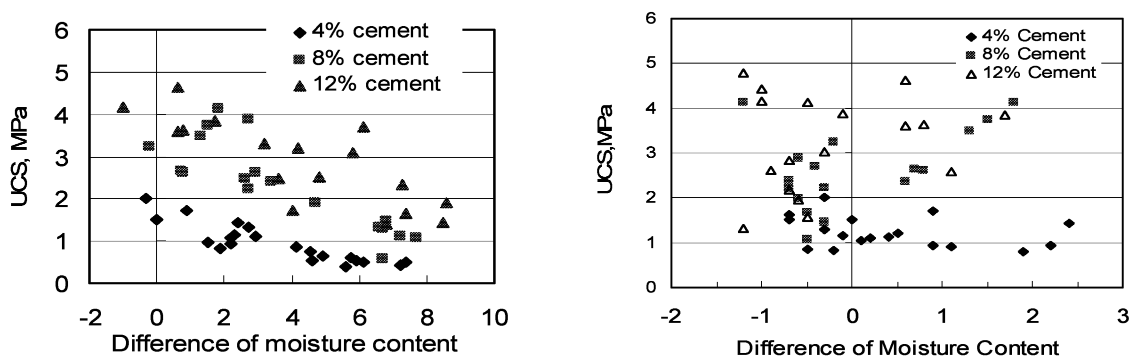
Impact of Moisture Changes on Strength

Dry Side Wet Side

Fig. 9. Variation of Moisture and Strength of Cement-Mixed Clay I.



Changes of Moisture Content during Curing



Impact of Moisture Changes on Strength

Dry Side Wet Side

Fig. 10. Variation of Moisture and Strength of Cement-Mixed Clay II.

dependent, and beyond this limit, such as cement content larger than 12 percent, this approach will become uneconomical.

Recommendation

The following recommendations are made with respect to using cement-soil mixtures in the highway construction.

- ✧ Prohibit compacting cement-soil mixtures on the dry side of compaction curves due to the unreliable and unpredictable strength development during mixtures' curing period. For example, the moisture content for the field compaction should be at the optimum moisture content with ±1% variation.
- ✧ For cases where cement is used to treat wet or weak subgrade (moisture content higher than the optimum) with at least 7 days for curing, the following relationship (derived from the data shown in Fig. 8) can be used as guideline for design and construction:

Target value of UCS	Water-Cement Ratio, R_{wc}
0.34MPa (50psi)	5.0
0.69MPa (100psi)	3.0
1.03MPa (150psi)	2.0
1.38MPa (200psi)	1.75

  More laboratory tests can be conducted to verify this.
- ✧ Field compaction on wet cement-mixed subgrade should reach 100 percent of the dry unit weight at the corresponding field moisture content determined in the laboratory by the standard proctor compaction test.
- ✧ If cement content (A_n) is determined at the optimum moisture content (w_o), extra cement (ΔA_{wf}) should be added to wet subgrade for cases where field moisture content (w_f) is higher than the optimum, as calculated as follows.

$$\Delta A_{wf} = \frac{w_f - w_o}{R_{wc}}$$

  Note: if $w_f < w_o$, water is required to be added in the field.
- ✧ In cases where the field soil is different from the one tested in the laboratory and no extra time available for laboratory testing, the cement content can be estimated as follows.

$$A_{wf} = \frac{w_f}{R_{wc}}$$

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Appendix

Assume: w_{hy} is the weight of hygroscopic moisture of soil;
w_{soil} is the weight of dry soil;
w_{cement} is the weight of cement added to soil;
w_{water} is the weight of water added to soil.

By definition:

$$\omega_{hy} = \frac{W_{hy}}{W_{soil}} \quad (1)$$

$$A_n = \frac{W_{cement}}{W_{soil} + W_{hy}} = \frac{W_{cememt}}{W_{soil} \cdot (1 + \omega_{hy})} \quad \text{(using Eq. (1))} \quad (2)$$

$$\omega_n = \frac{W_{water}}{W_{cement} + W_{soil} + W_{hy}}$$

$$= \frac{W_{watyer}}{A_n \cdot W_{soil} \cdot (1 + \omega_{hy}) + W_{soil} + \omega_{hy} \cdot W_{soil}} \quad \text{(using Eqs. (1) and (2))}$$

$$= \frac{W_{water}}{W_{soil} \cdot [A_n \cdot (1 + \omega_{hy}) + 1 + \omega_{hy}]}$$

$$= \frac{W_{water}}{W_{soil} \cdot (1 + A_n) \cdot (1 + \omega_{hy})} \quad (3)$$

$$\omega_m = \frac{W_{water} + W_{hy}}{W_{soil} + W_{cement}}$$

$$= \frac{W_{watyer} + \omega_{hy} \cdot W_{soil}}{W_{soil} + A_n \cdot W_{soil} \cdot (1 + \omega_{hy})} \quad \text{(using Eqs. (1) and (2))}$$

$$= \frac{W_{water} + \omega_{hy} \cdot W_{soil}}{W_{soil} \cdot [1 + A_n \cdot (1 + \omega_{hy})]}$$

$$= \frac{\omega_n \cdot W_{soil} \cdot (1 + \omega_{hy}) \cdot (1 + A_n) + \omega_{hy} \cdot W_{soil}}{W_{soil} \cdot [1 + A_n \cdot (1 + \omega_{hy})]} \quad \text{(using Eq. (3))}$$

$$= \frac{\omega_n \cdot (1 + \omega_{hy}) \cdot (1 + A_n) + \omega_{hy}}{1 + A_n \cdot (1 + \omega_{hy})} \quad (4)$$

Resolve Eq. (4) for ω_{hy}:

$$\omega_{hy} = \frac{(\omega_m - \omega_n) \cdot (1 + A_n)}{1 + \omega_n + \cdot A_n \cdot (\omega_n - \omega_m)]} \quad (5)$$

If all parameters in Eq. (5) are in percent, Eq. (5) will be:

$$\omega_{hy} = \frac{(\omega_m - \omega_n) \cdot (100 + A_n)}{10000 + 100 \cdot \omega_n + \cdot A_n \cdot (\omega_n - \omega_m)]} \quad (6)$$

By definition:

$$A_w = \frac{W_{cement}}{W_{soil}} = \frac{A_n \cdot W_{soil} \cdot (1+\omega_{hy})}{W_{soil}} = A_n \cdot (1+\omega_{hy}) \quad (7)$$

By definition:

$$C_{wm} = \frac{W_{water} + W_{hy}}{W_{soil}} = \frac{\omega_n \cdot (W_{cememt} + W_{soil} + W_{hy}) + W_{hy}}{W_{soil}}$$

$$= \frac{\omega_n \cdot (W_{cememt} + W_{soil}) + W_{hy} \cdot (1+\omega_n)}{W_{soil}}$$

$$= \frac{\omega_n \cdot [A_n \cdot W_{soil} \cdot (1+\omega_{hy}) + W_{soil}] + \omega_{hy} \cdot W_{soil} \cdot (1+\omega_n)}{W_{soil}}$$

$$= \omega_n \cdot [A_n \cdot (1+\omega_{hy}) + 1] + \omega_{hy} \cdot (1+\omega_n) \quad (8)$$

So

$$\frac{C_{wm}}{A_w} = \frac{\omega_n \cdot [A_n \cdot (1+\omega_{hy}) + 1] + \omega_{hy} \cdot (1+\omega_n)}{A_n \cdot (1+\omega_{hy})} \quad \text{(using Eq. (3))}$$

$$= \frac{A_n \cdot (1+\omega_{hy}) + 1 + \omega_{hy} \cdot (\frac{1}{\omega_n} + 1)}{1+\omega_{hy}} \cdot \frac{\omega_n}{A_n}$$

$$= [A_n + 1 + \frac{\omega_{hy}}{\omega_n \cdot (1+\omega_{hy})}] \cdot \frac{\omega_n}{A_n}$$

$$= [1 + A_n + \frac{\omega_{hy}}{\omega_n \cdot (1+\omega_{hy})}] \cdot \frac{\omega_n}{A_n} \quad (9)$$

Or

$$\frac{C_{wm}}{A_w} = [1 + \frac{A_n}{100} + \frac{100\omega_{hy}}{\omega_n \cdot (100+\omega_{hy})}] \cdot \frac{\omega_n}{A_n} \quad (10)$$

if all parameters in Eq. (10) are in percent.