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An investigation of cement treated clay subjected to cyclic wetting and drying degradation: Influence of compaction conditions

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ABSTRACT: Problematic soils, like expansive clays, are detrimental to pavement infrastructure as poor soil properties are related to pavement distresses. The swelling and shrinking properties inherent to expansive clays can cause pavement distresses like rutting due to the volumetric instability and poor stiffness of the subgrade. To mitigate this, chemical stabilization is needed to improve the engineering properties of expansive clays as it reduces plasticity and increases soil strength. Although chemical stabilization improves volumetric stability and strength, seasonal moisture variation from wetting and drying (WD) durability cycles will eventually degrade the stabilized soil. Rates of degradation from cyclic WD cycles highly depend on soil properties, one important property being the compaction condition. The relationship between water contents wetter than optimum moisture content (OMC), lower dry unit weight and varying cement content for each different compaction energies has not been directly studied and could provide better insights into the WD durability resistance of stabilized soils. Hence, the present study investigates the effect of preparing cement-stabilized clay at and above OMC conditions under modified and standard compaction conditions for 9% and 11% cement dosage. Compaction conditions of OMC, +2% OMC, and +4% OMC were prepared for WD durability tests to record mass changes and volumetric strains developed during WD cycles. Unconfined compressive strength tests were taken both before and after WD as a metric of strength to compare degradation between stabilized specimens. Results indicate that cement-stabilized clays prepared wet of OMC are more resistant to degradation by WD cycles, regardless of the compaction conditions and cement dosage. Specimens prepared for standard conditions were more volumetrically stable throughout all dosages and water contents than modified conditions. These findings suggest the role of initial moisture content is crucial to effectively stabilizing clays with cement for WD durability resistance under modified and standard compaction conditions.

KEYWORDS: expansive soils, chemical stabilization, compaction, durability

1 INTRODUCTION

Problematic soils and weak subgrades are a hazard to highway and airway pavements. Problematic soils, such as expansive clays can be detrimental to pavement performance as pavement distresses can occur from volumetric instability and low stiffness of the underlying subgrades (Nelson and Miller, 1997). Expansive soils are usually clayey soils, have prominent shrinkage and swelling characteristics due to the minerals present in the soil, such as montmorillonite. These expansive clay minerals have a strong affinity for water and positively charged ions within the pore water due to the net negative charge on the clay surface (Mitchell and Soga, 2005). Between expansive clay surfaces, a weak interlayer bond keeps the clay surfaces intact, which can be easily altered by the rush of positive ions in pore water or water molecules. With the introduction of ions and water molecules to balance out net negative charge of the clay surface, expansive clay minerals will expand in volume from the lack of stability from the bonds that keep clay surface interact. Hence, more volumetric instability as the clay particles get wet. A conventional way to attack this problematic soil directly is through chemical stabilization.

Chemical stabilization improves clay soil properties by making them less expansive and increasing soil strength (Mutaz et al., 2011). Conventional stabilizers like cement mainly improve soil properties by the cement hydration reaction in the short term and pozzolanic reaction in the long term (Prusinski and Bhattacharja, 1999; Pongsivasathit, Horpibulsuk and Piyaphipat, 2019). Cement hydration gives soil rapid strength gain in the short term by the formation of beneficial microstructural components, such as calcium-silicate hydrate and aluminum silicate hydrate. The pozzolanic reactions not only contribute to the strength gain but also a reduction of the net negative charge at the clay surface. These benefits are realized in the long term from the dissolution of calcium hydroxide (which is produced in the cement hydration reaction). The divalent calcium ions from the dissolution of calcium hydroxide lowers the net negative charge of the clay surface by replacing monovalent ions, such as sodium. Additionally, the hydroxide ions provide an alkaline environment for the 2:1 silica to alumina clay structure to become more soluble and dissolved. The products formed from the solubilization of the alumina and silica components react with the free calcium ions to generate calcium silicate hydroxide and aluminum silicate hydrate in the soil fabric. Ultimately, giving the expansive clays more strength, reduced plasticity, and better volumetric stability. However, the benefits from chemical stabilization are gradually subjected to degradation through cyclic traffic loads and stressors imposed by environmental conditions.

Focusing on environmental stressors, seasonal temperature and moisture variation are not new considerations for pavement designers, especially for subgrades. To assess the effectiveness of a stabilizer dosage design, long term health is simulated by moisture susceptibility methods (Kumar et al., 2024; Bazarbekova et al., 2025). Such methods, specifically durability cycles, are standardized by the American Society of Testing Materials (ASTM). Two such durability methods are wetting and drying method (ASTM D559) and freezing and thawing method (ASTM D560) For this study, only ASTM D559 for wetting and drying will be considered. Cyclic wetting and drying phases are applied to stabilized soil specimens to assess degradation by measuring soil-cement mass loss and volumetric deformation throughout the cycles. Many studies used ASTM D559 to study the degradation resistance to moisture variation of stabilized specimens (Chittoori, Puppala and Pedarla, 2018; Rasul, Ghataora and Burrow, 2018).

WD cycles are a complex multi-physics phenomena and degradation is heavily dependent upon soil properties. (Petry and Wohlgemuth, 1988) studied the effects of cement with the degree pulverization of the clays during sample prep. Petry and Wohlgemuth (1988) found that with finer particle sizes, specimens could stabilize better and produce more resistance to wetting and drying durability. As a part of a subsequence of tests, Kennedy et al. (1987) studied the effect of compaction effort on cement stabilized clays as well. Kennedy et al. (1987) found that the modified compaction specimens treated with cement were less durable than the standard compacted specimens. The challenge with cement stabilized expansive clays is that the optimum water content (OMC) is not always sufficient to hydrate both the expansive minerals and cement for effective chemical stabilization. This is not normally a problem for standard compaction conditions, as less energy is applied to compact the soil and therefore, more moisture is available within the pores due to the wetter OMC. With less moisture in the modified compaction energies, degradation happens at a faster rate to destruct the stabilized specimens. Furthermore, most federal and state agencies require only an unconfined compressive strength requirement as a strength metric for implementation of chemical stabilizers to the field. Even though stabilized specimens may be strong at modified compaction energies, this does not necessarily mean they are durable to resist degradation from environmental stressors. Hence, this problem needs to be addressed by evaluating the durability of cement-treated clay soils under different compaction conditions.

Thus, this study investigates the durability of cement-treated clay specimens prepared at moisture contents wetter than OMC under both standard and modified compaction energies at 9% and 11% cement dosage. This research aims to give a better understanding of the relationship between moisture content, compaction energy, and cement dosage under a lens of WD durability for treated expansive clays.

2 MATERIALS AND METHODS

2.1 *Materials and Stabilizers*

One clay soil was stabilized with ordinary Portland cement type I (OPC) for this experiment. OPC was chosen for this study as it is a well-established stabilizer known for its ability to provide rapid short term strength gain when combined with soil. The selected clay has nearly 45% fines, as shown in Figure 1 from the grain size distribution curve.

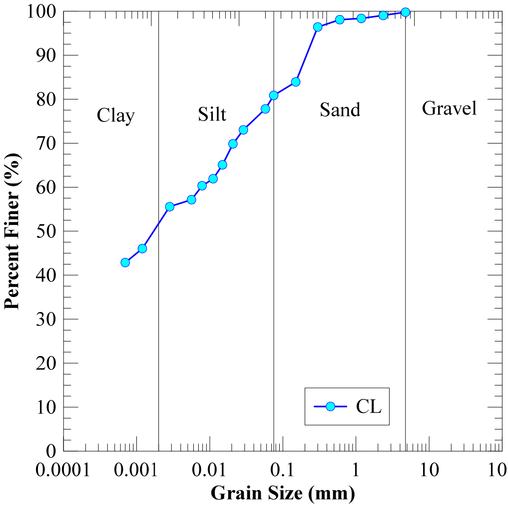


Figure 1. Gradation of clay soil

The clay has a liquid limit of 49% and a plasticity index of 30%, which is classified as a low plasticity clay (CL) by the Unified Soil Classification System. This soil is considered to be medium or marginal expansive based on recommendations from Chen (2012) and the Unified Facilities Criteria 3-250-11 (2020). The specific gravity of the soil is 2.71, measured in accordance with ASTM D854. Since the focus of this study was the durability of stabilized soils, the compaction curves of stabilized soils under two different compaction conditions, i.e., modified compaction (MC) and standard compaction (SC) energies are presented in Figure 2. The nomenclature of the labels in Figure 2 and hereon is shown as the dosage of cement used first followed by the compaction conditions. For example, "OPC9%_SC" is the compaction curve for 9% dosage with OPC treatment on the CL soil at standard compaction energy The untreated soil compaction curve is not displayed as no experimentation or analysis was performed on untreated soil.

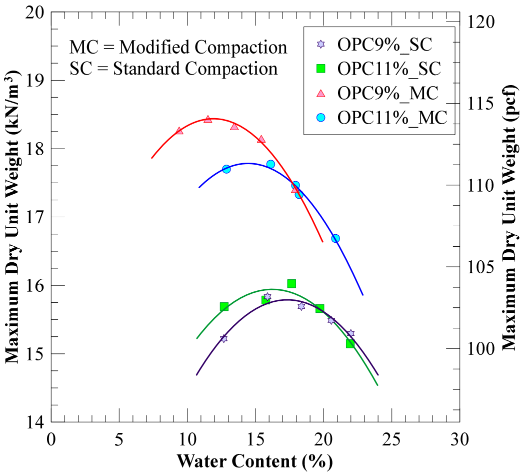


Figure 2. Compaction curves for standard and modified compaction conditions of cement stabilized clay

Two dosages of OPC at 9% and 11% were selected to stabilize the clay. Varying the cement dosages were implemented as another parameter for comparison in this study in addition to compaction energy and molding water content to further analyze the durability resistance of the stabilized clay. The OMC for the 9% and 11% OPC are 11.9% and 13.7%, respectively. Correspondingly, the maximum dry unit weights (MDUW) are 18.4 kN/m^3 and 17.8 kN/m^3 for the 9% and 11% dosages, respectively.

Clay samples were mixed by hand with cement and water before compaction to ensure uniformity and reduce heterogeneity within the samples. Samples of stabilized clay after mixing were taken for moisture content verification. Soil samples were then statically compressed into three layers with an Instron Universal Testing System. Specimens were prepared to dimension of 144 mm in height and 72 mm in diameter, which has a 2:1 height to diameter ratio. Preparing the stabilized specimens to these dimensions is outside of the requirements of ASTM D559, which require Proctor sized specimens (116.4 mm height and 101.6 mm in diameter). The dimensions were adjusted to follow guidelines for the unconfined compressive strength standard for soil-cement treated soils, ASTM D1633. Duplicates for three water contents including OMC, +2% OMC, and +4% OMC, per compaction energy, per dosage of OPC, and both before and after the WD cycle were prepared. Varying the moisture content during the sample preparation and curing process will give some insights into the effect of initial molding moisture content on durability resistance. The MDUW for each moisture content considered in this study was prepared by following the respective compaction curve for the dosage and compaction condition desired. In essence, specimens prepared wet of OMC were compacted to lower dry unit weights based on the respective compaction curves. All specimens prepared were above 97% relative compaction, which was deemed sufficient for testing purposes. A total of 48 stabilized clays were prepared in this study. Stabilized specimens were cured in a humid room at 100% relative humidity and 23 ºC for seven days.

2.2 *Wetting-Drying Durability*

The WD durability test was performed in accordance with ASTM D559. Each wetting phase consisted of 5 hours of complete submergence in water. Each drying phase was comprised of 42 hours of drying at 70 ºC. After the completion of each environmental phase, mass and dimensions of the stabilized specimens were measured to track mass changes and volumetric strain developed throughout the durability cycles, which give an indication of the deformation induced by the environmental conditions. These measurements provide insights as to how the soil fabric evolves with more durability cycles. The completion of a sequential wetting and drying phase is referred to as a cycle. Stabilized clay specimens were subjected to 12 cycles of WD durability. The standard requires wire brushing for mass-loss measurements. However, this procedure was omitted in the study, instead, the residual unconfined compressive strength after durability cycles was measured as it is a better indicator of the strength of the specimens.

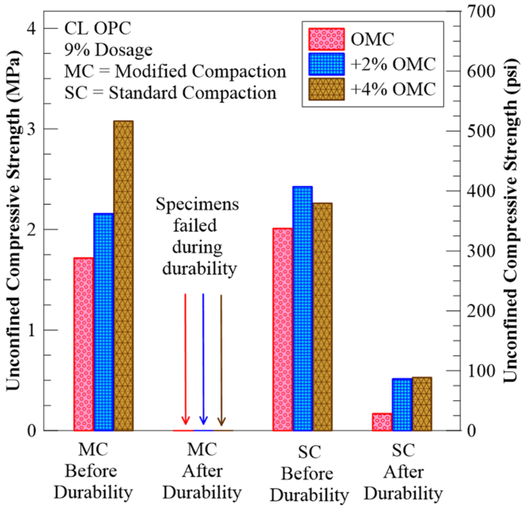
2.3 *Unconfined Compression Test*

Unconfined compression strength (UCS) test was conducted, in accordance with ASTM D1633, on specimens before and after durability cycles. The UCS before durability acted as control values to assess the degree of degradation of the specimens after WD cycles. Stabilized specimens were submerged in water for four hours before UCS testing commenced. After UCS, specimens were placed in an oven at 105 ºC for moisture content determination.

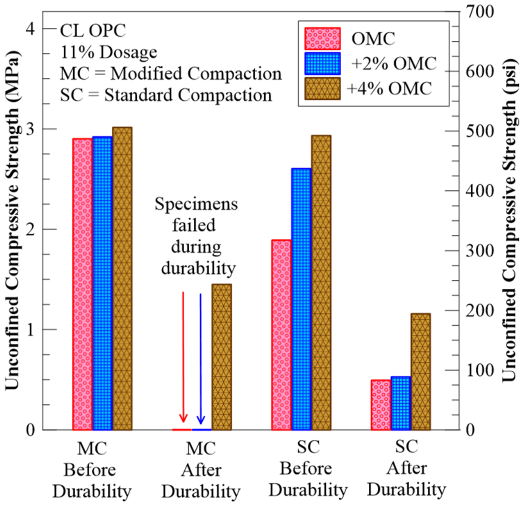
3 RESULTS

3.1 *Unconfined Compressive Strength*

To interpret the overall interaction of cement dosage, initial water content, and compaction condition, the UCS values before and after durability cycles are presented in Figure 3a and Figure 3b.



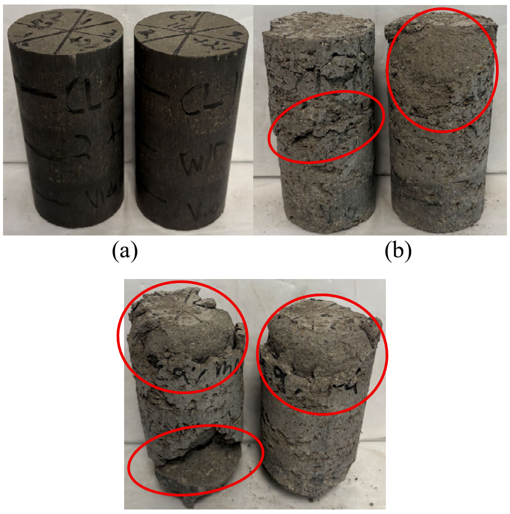
(a)



(b)

Figure 3. UCS of stabilized clay before and after cycles for a) 9% dosage and b) 11% dosage.

Figure 3a displays the UCS values for the 9% dosage of cement for both standard and modified compactions, with Figure 3b following the same convention for 11% cement dosage. In Figure 3a, none of the MC specimens survived 12 durability cycles, regardless of the initial moisture content level at compaction. Specimens significantly deteriorated and crumbled apart before the end of the 12 WD cycles. In contrast, all SC specimens treated with 9% cement survived the WD cycles and all showed reductions in UCS. The highest UCS strength retained was in the +4% OMC specimen at a value of 23%. Moving on to Figure 3b, the MC specimens prepared at OMC and +2% OMC did not survive durability cycles to perform a UCS test. However, the specimens prepared at +4% OMC under MC conditions did survive, with UCS values of specimens reduced from 3.49 MPa (before durability) to 1.68 MPa (after 12 WD cycles) for a value of 48% UCS strength retained. In contrast, under SC conditions, nearly all specimens survived the WD cycles. Specifically, the +4% OMC at SC in Figure 3b had the highest residual strength, which was around 39% of the original strength. Pictures of the failed OMC +2% at 11% and 9% of dosages are shown in Figure 4.



(a) (b)

(c)

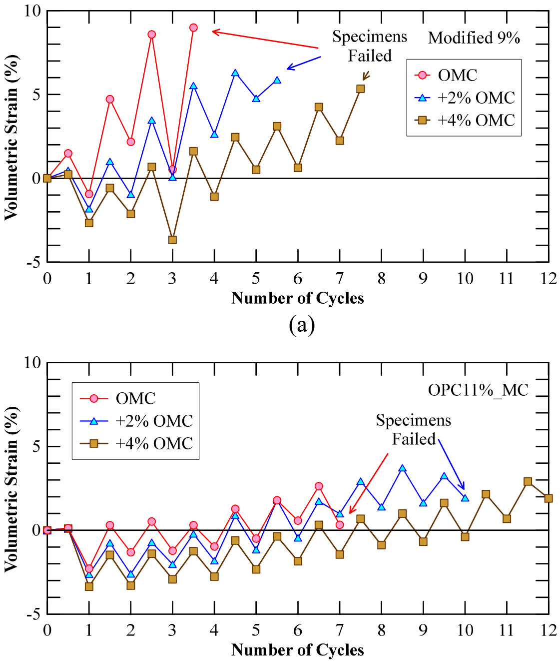
Figure 4. Stabilized specimens at modified compaction (a) 11% OPC with +2% OMC, before durability, b) 11% OPC with +2% OMC, near failure; and c) 9% OPC with +2% OMC at failure.

In Figure 4b and 4c, major crack development and degradation of the surface of the stabilized specimens in the bottom and top layers are observed. Specimens were too fragile to measure strength, as most samples fell apart during the handling process for mass and volume measurements.

Between both Figures 3a and 3b, regarding the effect of compaction, results showed that SC specimens were more durable than MC specimens. It is well known that with higher compaction energies the soil specimens are stronger due to the more packed particle arrangements that provide more frictional resistance to the applied loads. However, in the context of durability resistance, this study showed the opposite. Specifically, specimens compacted under lower energies have a higher durability resistance, at least with OPC as a stabilizer from the presented UCS results.

3.2 *Volumetric Strain*

Volumetric strain developed throughout durability phases can indirectly indicate internal soil fabric changes due to the WD cycles. Only the MC specimens at 9% and 11% cement dosage are presented in Figures 5a and 5b, respectively. SC specimens are not shown as a more insights can be drawn due to the failures from some of the MC specimens.



(a)

(b)

Figure 5. Volumetric strain developed during WD cycles for all compaction conditions at a) 9% dosage at modified conditions and b) 11% dosage at modified conditions.

As can be seen from Figure 5a, the OMC, +2% OMC, and +4% OMC specimens failed by the 4th, 6th, and 8th cycle, respectively. At 9% cement dosage, the OMC is relatively dry at a value of 11.9%. It is possible there wasn't an adequate amount of moisture available to form cementitious products to properly stabilize the specimen. However, due to the higher energy and the relatively dryer OMC, the increase in water content improved the durability, as shown throughout the volumetric strain measurements. This trend agrees with the residual UCS results, that is, increasing molding moisture content is making the specimens more durable. A similar trend can be seen from Figure 5b with the 11% dosage; a higher initial water content showed better durability resistance throughout the cycles.

As a simple way to describe the relationship of molding water content during sample preparation and volumetric strain developed during durability cycles, Figure 6 plots the maximum volumetric strain produced throughout all the cycles with regard to the initial water content under all the cement dosages and compaction conditions examined in the study. The maximum volumetric strains values are displayed regardless of how long the specimens survived. For example, since the OPC9%_MC sample survived only through 3 cycles, the maximum volumetric strain before failure is presented, i.e., after 3 cycles. The general trend is that with an increase in initial molding water content, the maximum volumetric strain accumulated during WD cycles decreases. The only outlier within the data is the OPC11%_MC specimen at 13% initial moisture content, as it has a lower volumetric strain developed than the +2% OMC and +4% OMC counterparts.

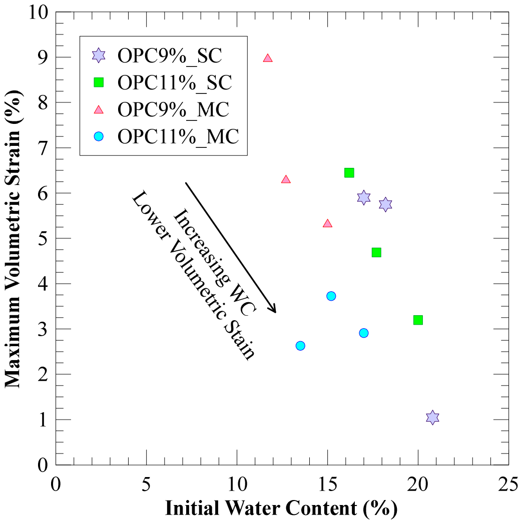


Figure 6. Initial water content versus maximum volumetric strain for all compaction conditions and OPC dosages.

4 DISCUSSION

First a brief discussion of WD degradation mechanisms is presented to set the basis for interpreting the variation in soil properties on durability resistance. Afterwards the effects of water content, compaction effort and cement dosage will be presented.

4.1 *WD Degradation of Stabilized Specimens*

Degradation of stabilized specimens via cyclic WD durability is inevitable and is not a new area of study. During wetting, specimens are submerged in water. Upon submersion, a hydraulic gradient is induced between the internal moisture distribution within the stabilized specimens and the environment. The hydraulic gradient will induce water flow, and the low hydraulic conductivity of the stabilized specimen will generate pore pressure buildup by moisture ingress Citation here). In addition, matric suction within the specimens starts to decrease as pore water fills the voids, allowing the specimens to expand. In the process, the buildup of internal pore pressures is unavoidable due to the high hydraulic gradient, low hydraulic conductivity and decrease in matric suction of the soil-cement system. The buildup of local pore pressures across the specimen will cause irreversible internal damage (Estabragh et al., 2013). During the drying phase, the moisture accumulated with the specimen after wetting will start evaporating with the change in temperature. As temperature increases, pore water in the stabilized soil system evaporates and induces tensile stresses in the soil fabric. The cementitious products restrict strain from accumulating within the specimen, allowing internal tensile stress derived from capillary pressures to develop within the soil structure. Microcracks within the soil fabric form when the internal tensile stresses exceed the tensile strength of the soil. (Peron et al., 2009). Development of microcracks is a result of varying temperature gradient in the specimens, evaporating water at different rates, non-uniform pore size distribution, and uneven suctions applied locally across the specimen. After the first drying phase and onwards, the dry specimens will be submerged in water again. Since the specimens are now at a lower moisture content, capillary pressures are increased relative to the first cycle of wetting. The intense matric suction increases the capillary forces within the specimen by causing more irreversible deformation to the stabilized specimens. Then the drying process begins, and this sequence continues so on and so forth until the specimens collapse or durability cycles end.

4.2 *Effect of Water Content*

The effect of initial moisture content seems to be the most crucial factor in determining WD durability resistance. Throughout all compaction conditions and dosages, durability resistance increased with higher moisture contents. Indications were interpreted through specimen survival in the volumetric strain measurements and the evaluation of UCS values before and after WD durability. This is highlighted in the +4% OMC test in relation to the +2% OMC and OMC conditions, irrelevant of the cement dosage. In MC specimens at 11%. +4% OMC specimens survived all 12 cycles and stayed intact for a UCS test, while other moisture contents could not. For MC specimens at 9% dosage, the +4% OMC conditions survived the longest, at 7 cycles, as shown in the volumetric strain measurements in Figure 4a. At 11% SC and 9% SC conditions, both +4% OMC specimens showed higher strength UCS strength after durability compared to the +2% OMC and OMC values.

With the +4% OMC prepared specimens, the moisture differential between the water during submersion and the specimen is lower compared to the OMC and +2% OMC in the wetting phase. Since there is more water, the capillary pressures causing damage to the species aren't as strong, resulting in less destruction to the soil fabric. During drying, the specimens do have more moisture to lose, and this can be seen from the volumetric strain measurements as the +4% OMC specimens shrink the most in the first drying phase of the WD cycles. However, expansion is the more important volumetric change when compared with the degree of shrinking. The preparation of slightly lower dry unit weight during sample prep in the +4% OMC specimens did shrink more than the other specimens prepared with lower moisture contents. But higher moisture content and lower dry unit weight allows for a relatively more open pore network for water to flow more easily within the specimen upon rewetting. Additionally, it's possible for more microstructural components to have formed within the +4% OMC specimens during the curing phase due to more water available for the cement hydration reaction. Consequentially, nearly all +4% OMC specimens have higher UCS values before durability than their lower moisture content counterparts. The higher cementitious products provide more microstructural stability, hence, making them more resistant to deformation and degradation from cyclic moisture ingress.

4.3 *Effect of Compaction Effort*

The effect of compaction effort on durability encompasses two main soil properties that are critical to durability resistance. The first is the change in moisture content and the second is the change in dry density. As compaction efforts go up, less water is needed to lubricate and densify the specimens because of the increased energy applied to the specimens. Even though the modified energies give greater strength to the specimens, it does not mean MC specimens are more durable, which is supported by Figure 6, especially for the 9% cement-treated specimens. The OPC9%_SC specimens consistently have lower volumetric strains developed compared to the OPC9%_MC counterparts. The lower volumetric strain developed is due to the relative more open pore structure and the volume of water in the voids in the SC specimens. The lower moisture differential upon rewetting allows to water to flow less destructively through the specimen, causing less damage per cycle, largely due to the compaction energy when compared to the MC specimens. Additionally, since the capillary pressures developed in the specimen upon rewetting after drying are dependent upon pore size and degree of saturation, the magnitude of capillary forces is less because of the more open pore network as capillary pressures depend on pore diameter. Lower dry unit weight inherently means less particles are in contact with each other, allowing for bigger pore sizes to be formed. Hence, the SC specimens in general are more durable than the MC specimens.

4.4 *Effect of Cement Dosage*

Cement dosage of the specimens was more crucial for the MC specimens as compared to the SC specimens. The UCS results in Figures 3a and 3b for the +4% OMC tests showed this clearly. Specimens survived durability at this moisture state at 11% cement dosage and did not survive at 9% dosage. This observation is also supported by the volumetric measurements since samples collapsed during the 8th cycle with 9% cement treatment, while all specimens survived 12 cycles with 11% cement under +4% OMC conditions. Based on the UCS and volumetric strain results, the effect of cement dosage on durability resistance is dependent upon the initial moisture content. This will vary between compaction efforts, as generally, water contents are higher in SC than in MC. The major consideration is that cement needs an adequate amount of water during sample preparation to hydrate and stabilize the soil effectually. Stabilizer amount is higher in MC than SC specimens; hence, more water may be needed to fully hydrate the cement for the microstructural benefits. The tradeoff between OMC, MDUW, and proper hydration of cement is an inherent challenge with the MC specimens as OMC is generally lower in these compaction conditions. Increased moisture contents above OMC may be needed to better hydrate the cement and realize the durability resistance benefits.

5 CONCLUSION

This research investigated the effect of increasing water contents, different compaction energy levels, and cement dosages on durability resistance of OPC-treated clay to moisture ingress from cyclic WD durability test. The major takeaways from this study are as follows:

- Moisture content was the most important soil property when considering compaction conditions and cement dosages for durability resistance of cement-stabilized soil.
- Between modified and standard compaction conditions, specimens prepared under standard compaction conditions are more durable than those prepared under modified compaction conditions.
- Increasing moisture content of stabilized specimens beyond OMC enhances volumetric stability at all

compaction levels. Increasing moisture in MC specimens may be required for successful stabilization of the geomaterials.

This study was limited to one soil type and one stabilizer. Further studies should explore different types of stabilizers including other calcium-based stabilizers (such as Portland Limestone cement) and non-calcium-based stabilizers (such as polymers). Other durability methods, such as freezing and thawing, should be studied for the effect of compaction state, as the mechanisms of degradation are different compared to WD durability. Further understanding of the durability of the stabilized soils for environmental stressors will allow for safer and more resilient geotechnical infrastructure designs.

6 ACKNOWLEDGMENTS

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