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Evaluation of the Rate of Secondary Swelling in Expansive Clays using Centrifuge Technology

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Evaluation of the Rate of Secondary Swelling in Expansive Clays using Centrifuge Technology

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

December 2014

To my loving parents,

Acknowledgements

I would like to express my utmost gratitude to Dr. Jorge Zornberg for his immense support and motivation throughout my time at The University of Texas at Austin. He has been a wonderful advisor and it was a privilege to work with him.

I'm extremely thankful to Dr. Chadi El Mohtar for his valuable inputs and suggestions that have greatly improved this work.

Special thanks to members of Zornberg Research Group - Michael Plaisted, Trevor Walker, Chris Armstrong, Hossein Roodi, and Federico Castro.

Finally, I would like to thank friends who made my stay in Austin memorable - Chinmoy, Harish, Rudra, Amruta, Sriram, Kumar, Pratik, Pushkar, Ritika, Neha, and Alolika.

Abstract

Evaluation of the Rate of Secondary Swelling in Expansive Clays using Centrifuge Technology

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The University of Texas at Austin, 2014

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Expansive soils are characterized as having high amount of clay minerals such as smectite, which lead to swelling during wet seasons by absorbing water and shrinking during dry seasons owing to moisture loss by evapotranspiration. The soil volumetric changes due to moisture fluctuations cause extensive damage to civil engineering structures, namely pavements, retaining walls, low rise buildings and canals founded on such soils.

The primary swelling portion of the swell curve has been studied in significant details in previous studies. However, there is a dearth of literature concerning the secondary swelling phenomenon in expansive clays, which has also been observed in experimental studies. While it may be argued that the magnitude of secondary swelling is significantly less as compared to primary swelling, the characterization of the rate of secondary swelling is relevant for fully characterizing the swell potential of the soil. The rate of secondary swelling has been used to predict the long-term swelling of expansive soils.

Conventional laboratory swell tests may take over a month for specimens to demonstrate secondary swelling behavior. A centrifuge based method has been recently developed at The University of Texas at Austin to achieve this objective in multiple specimens, and within less than a day. The effects of soil fabric, soil type, relative compaction, molding water content, gravitational gradient, and infiltrating fluid, on the rate of secondary swelling, are thoroughly investigated in this thesis. Four different expansive clays found widely in and around Texas, namely – Eagle Ford Clay, Tan Taylor Clay, Black Taylor Clay and Houston Black Clay, have been used in the study.

Based on this extensive experimental evaluation, it may be concluded that secondary swelling behavior could be explained by flow processes associated with the bimodal pore size distribution in expansive clays. The rate of secondary swelling was found to increase with increasing molding water content and increasing compaction dry unit weight. The experimental results revealed that clays with a flocculated structure (compacted dry of optimum) demonstrate rapid primary swelling but exhibit less swelling in the secondary region, as compared to clays with a dispersed structure (compacted wet of optimum). The slope of secondary swelling showed a decline with increasing gravitational gradient. The rate of secondary swelling showed evidence of upward trend with an increase in the plasticity index and clay fraction of the soil. It was observed that soils which exhibit higher primary swelling also demonstrate higher secondary swelling.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

Expansive soils undergo volumetric changes due to moisture fluctuations and cause extensive damage to pavements, walls, low rise buildings, canals and other infrastructure founded on such soils. They contain a high amount of clay minerals which lead to swelling during wet seasons by absorbing water and shrinking during dry seasons owing to moisture loss by evapotranspiration. This alternating swell-shrink behavior causes damages running into billions of dollars in the US and elsewhere (Nelson and Miller, 1992). These soils are common throughout the world and mitigation of their swell-shrink behavior has major financial impact on projects. Many methods, both empirical correlations and experimental techniques, have been developed over the years to quantify and characterize the swelling potential of soils.

Swelling in compacted clay specimens, has been reported to occur in three stages: Intervoid Swelling, Primary Swelling, and Secondary Swelling (Sivapullaiah et al., 1996). Intervoid Swelling generally corresponds to less than 10% of the total swelling. Primary Swelling constitutes about 80% of the total swelling. The slow and continued swelling with time after primary swelling has been referred to as Secondary Swelling (Sivapullaiah et al., 1996). While the primary swelling portion of the swell curve has been studied in significant detail by researchers, the secondary swelling phenomenon has been largely ignored.

Secondary swelling has been observed in the laboratory and has been treated as a phenomenon that is analogous to secondary compression (or creep) in soils. There is a dearth of literature regarding the cause and rate of secondary swelling in expansive clays. While it may be argued that the magnitude of secondary swell is significantly less as compared to primary swell, the rate of secondary swell is relevant for fully characterizing the swell potential of the soil. The rate of secondary swelling has been used to predict the long-term swelling of expansive soils (Sridharan and Gurtug, 2004).

Conventional laboratory swell tests e.g. – ASTM D4546 may take over a month to demonstrate secondary swell phenomenon. The single infiltration centrifuge set up with in-flight data acquisition, developed at The University of Texas at Austin, helps to achieve this objective in multiple specimens, and within less than a day. It also allows for greater control of test variables for monitoring the secondary swelling behavior.

1.2 Scope of this Research

The research study aims at quantifying the rate of secondary swell with time for expansive soils. The centrifuge technique was adopted for generation of experimental data. The majority of tests were performed using Tan Taylor Clay. Three other expansive clays that are abundant in and around Texas, namely – Eagle Ford Clay, Black Taylor Clay and Houston Black Clay, were also employed in the study. The specimens were compacted under different initial conditions of dry density and moisture content. Six parameters were identified, which were expected to affect the slope of the secondary swell curve. This includes molding water content, compaction dry unit weight, g-level, specimen height, head of infiltrating liquid and its concentration. The influence of each variable on secondary swelling is determined and comparisons are made by altering one parameter at a time in the swell test, while keeping the others constant.

1.3 Organization of Thesis

This thesis has been organized into seven chapters. The first chapter comprises the introductory material including motivation and scope. Chapter 2 gives an overview of expansive clays, the mechanisms that contribute to swell, a discussion on clay microstructure and the bimodal pore size distribution often observed in expansive clays. The second chapter also describes the characteristics of the swell curves and the various stages of swelling. It concludes with a discussion on literature pertaining to secondary swelling in clays. Chapter 3 presents the experimental results obtained using for Eagle Ford Clay, Tan Taylor Clay, Houston Black Clay, and Black Taylor Clay. The testing equipment, materials and procedure is described in Chapter 4. Chapter 5 outlays the testing program and presents the test results. A detailed analysis of results and the influence of each variable towards secondary swell, is shown in Chapter 6. Chapter 7 presents the conclusions of this study.

CHAPTER 2: BACKGROUND

This chapter is a review of literature concerning swelling in clays with special emphasis on the secondary swelling behavior in clays. The chapter begins with a discussion on the cause of swelling in clays focusing on the Diffuse Double Layer theory. The different types of tests for determining the swelling potential of an expansive clay have been described. The significance of bimodal pore size distribution in expansive clays toward swelling behavior has been also been discussed.

2.1 Cause of Swelling in Clays

The swelling characteristics of soils is due to the presence of clay minerals such as those of the smectite group (montmorillonite). These minerals are small particles of the order of nanometers characterized by a large specific surfaces which carry a net negative charge. The negative charge comes from isomorphous substitution and imperfections in the crystal lattice. Table 2.1 shows typical thickness, Specific Surface Area and Cation Exchange Capacity of common clay minerals.

Table 2.1: Typical Dimensions, Specific Surfaces, and Cation Exchange Capacity of Common Clay Minerals (Holtz et al. 2011, Yong and Warkentin 1975, Mitchell and Soga, 2005)

Clay Mineral	Typical Thickness (nm)	Typical Diameter (nm)	Specific Surface (km^2/kg)	Cation Exchange Capacity (meq/100 g)
Montmorillonite	3	100-1000	0.7-0.84	80-150
Illite	30	10000	0.065-0.1	10-40
Chlorite	30	10000	0.08	10-40
Kaolinite	50-2000	300-4000	0.01-0.02	2-15

Depending on their charge deficiency (Cation Exchange Capacity), the clay particles attract exchangeable cations from the solution (water). These hydrated cations attract water to the clay surface. The higher the cation exchange capacity, higher the tendency of the clay to swell due to influx of water. Water being a dipolar molecule may also be adsorbed to the clay surface by means of hydrogen bonding. The higher concentration of cations in the adsorbed water near the clay surfaces causes diffusion of these cations towards the solution. However, by virtue of being positively charged, these cations are electrically attracted to the negatively charged clay surfaces. The net result of this electrostatic attraction of cations to the clay surface, and the diffuse layer of cations gives rise to the Diffuse Double Layer shown in Figure 2.1. This explains the volume change (swelling) in expansive soils upon interaction with water. The cation concentration decreases with increasing distance away from the clay surface and equals the concentration in free water beyond this diffused thickness.

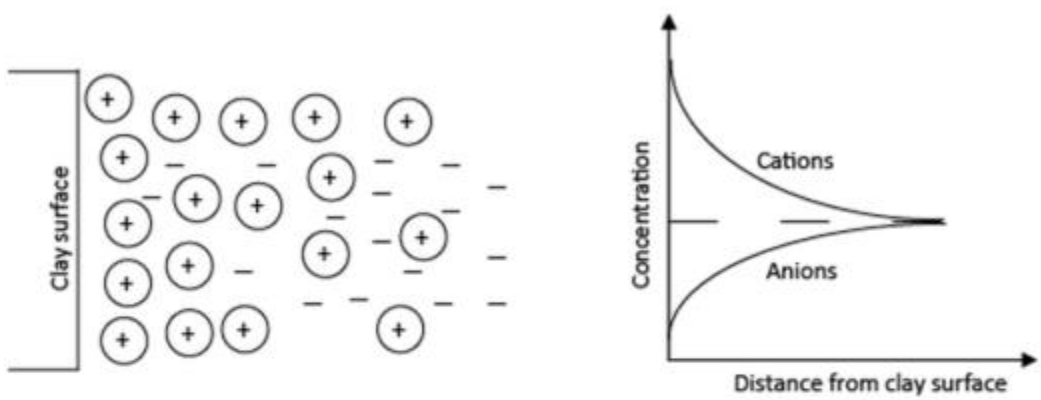


Figure 2.1: Diffuse Double Layer (after Mitchell and Soga, 2005)

2.2 Types of Swell Tests

2.2.1 FREE SWELL TEST

The standard for measuring the swelling potential of soils is given by ASTM D4546. This test is also known as the "free swell test". It is conducted in a standard consolidation cell as shown in Figure 2.2. There are different variations of the test, described by Methods A, B and C. Method A is known as the "wetting-after-loading tests on multiple specimens", where remolded or in-situ soil specimens are subjected to swelling over a minimum of four different overburden pressures, in order to establish a relationship between swell and vertical effective stress. Method B is referred to as "single point wetting-after-loading test on a single specimen" and consists of measuring the swelling of a single in-situ soil specimen tested under representative field conditions. In Method C, the soil is allowed to swell first, then a load is applied to determine the change in volume of the sample.

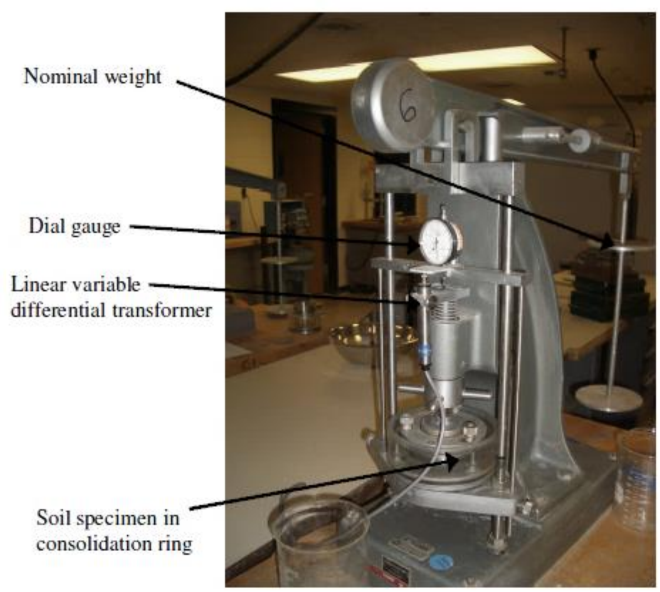


Figure 2.2: Free Swell Testing Apparatus (Kuhn, 2010)

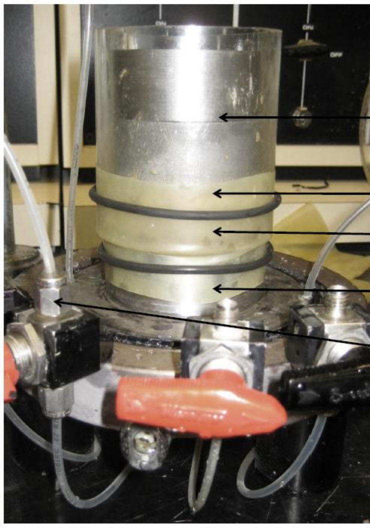
2.2.2 Swell Pressure Test

The vertical pressure that prevents the specimen from swelling, and keeps the initial height constant, is the swell pressure. It can be determined from the swell versus vertical stress curve obtained from ASTM D4546 – Method A. It can also be determined by keeping the specimen height constant by continuously increasing the overburden pressure.

2.2.3 1-G Infiltration Test

The 1-G infiltration test is similar to the free swell test, and is performed within a modified triaxial cell under constant vertical overburden and water pressure. Figure 2.3 (a) and (b) shows the setup for a 1-G infiltration test.

In free swell test, the specimen is submerged in water and wetting is governed by the matric suction within the soil. However, in a 1-G infiltration test, water flow into the specimen is driven by the hydraulic gradient between the top and bottom of the specimen. Water infiltrates into the specimen from the top and drains out from the freely draining boundary at the bottom.



(a) *(b)*

Figure 2.3: 1-G Infiltration Test (a) Specimen Setup (b) Fully Assembled Setup (Kuhn, 2010)

2.2.4 CENTRIFUGE TEST

Geotechnical centrifuges have been reported to successfully characterize expansive soils. (Frydman and Weisberg, 1991; Gadre and Chandrasekaran, 1994). Multiple specimens can be tested at a time depending on the centrifuge design. The swelling process that is initially driven by suction gradient, gets accelerated due to an imposed hydraulic gradient. The specimens are spun within the centrifuge, about a vertical axis, which subjects them to an increased gravitational field which drives water through them. Depending on the setup, water may infiltrate the soil either from the top of the specimen (Frydman et al., 1991; Plaisted, 2009; Kuhn, 2010; Walker, 2012) or from the bottom of the specimen (Gadre, et. al., 1994).

2.3 Effect of Clay Structure on Swelling

Compaction of fine-grained soils (clays) affects the soil structure and fabric, which influences swelling. Soils that are compacted dry of optimum moisture content have a flocculated structure, or more random clay plate orientation, as the diffuse double layer is not fully developed (e.g. Lambe, 1958). Clays compacted wet of optimum moisture content have a dispersed structure, or more uniform distribution of clay particle orientation, due to increased repulsion from the diffuse double layer.

The clay structure influences mechanical properties like stiffness, soil shear strength, hydraulic conductivity, and swelling and shrinking properties (e.g. Zornberg, 2012). Soils compacted dry of optimum (flocculated) tend to have a higher shear strength due to generation of negative pore pressures and an increase in the effective stresses due to initial suction. Soils compacted dry of optimum show evidence of higher hydraulic conductivity due to ‘piping’ effect of large inter-particle voids in the flocculated structure which can transmit water easily. Soils compacted dry of optimum also exhibit higher swelling upon wetting and lesser shrinking upon drying as compared to those compacted wet of optimum (e.g. Zornberg, 2012).

2.4 Bimodal Pore Size Distribution in Expansive Clays

Pusch (1982) studied the microstructure of compacted expansive clays and observed a double structure made up of clay aggregates containing highly expansive clay mineral and large macrostructural pores. The pore space inside the aggregates was constituted of microstructural voids. The behavior of the soil results from the interaction between the volume change of these clay aggregates and the rearrangement of the granular skeleton (macrostructure). Physico-chemical phenomena occurs at the microstructural level. Terzaghi's effective stress principle also holds as the microstructure remains saturated. In contrast, the macrostructure de-saturates when subjected to suction (Lloret et al., 2003). Gens and Alonso (1992) hypothesized that expansive soils undergo irreversible macrostructural rearrangements due to swelling of the microstructure which invades the macropores upon wetting the samples.

2.5 Swell Curve

Dakshanamurthy (1978) observed that the swelling-time relationship in unsaturated expansive clay specimens exposed to water, may be represented by a rectangular hyperbola. He noticed two stages of swelling in the specimens. The first stage involves hydration of dry clay particles in which water is adsorbed in successive monolayers on the surface and pushes the unit layers of montmorillonite particles (Interlayer Swelling). The second stage involves large volume changes and is due to double layer repulsion.

Sivapullaiah et al. (1996) noticed that the swelling behavior in compacted soil-bentonite mixtures follows a standard 'S' shape. They observed that swelling occurs in three stages. The first stage constitutes Intervoid Swelling and was observed to generally correspond to less than 10% of the total swelling. This is due to swelling of the clay particles within the voids of the non-swelling fraction. The second stage called Primary swelling comprises about 80% of the total swelling. It develops when the voids can no longer accommodate further clay particle swelling and occurs at a faster rate. The time required for completion of primary swelling was taken as the intersection of primary swelling and secondary swelling portion of the curve. The slow and continued swelling with time (beyond 90% of swell) after primary swelling was referred to as Secondary

Swelling and yielded a straight-line relationship with logarithmic time. The slope of this line was taken as the coefficient of secondary swelling. The coefficient of secondary swelling increases with an increase in the clay fraction of the soil.

Figure 2.4 shows the different parts of a swell curve for a compacted fine-grained soil, plotted on a semi-logarithmic scale.

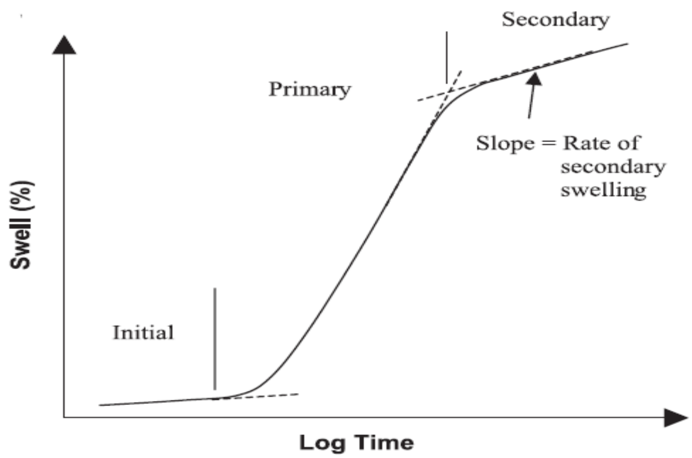


Figure 2.4: A typical Swell Curve (Sridharan and Gurtug, 2004)

2.6 Secondary Swelling in Literature

Terzaghi, Peck, and Mesri (1996) define secondary swelling as the volume increase that takes place at constant effective vertical stress. They defined the slope of e vs. log t during secondary volume increase as the secondary swelling index, $C_{s\alpha} = \Delta e/\Delta \log t$.

Mesri et. al. (1978) demonstrated during unloading of overconsolidated clay specimens, that the secondary swelling index, $C_{s\alpha} = \Delta e/\Delta \log t$, does not remain constant with time; it could increase, decrease or remain constant over a time interval. However, eventually $C_{s\alpha}$, is expected to decrease with time.

The shape of percent swell vs. log time behavior is the mirror image of the conventional log time–compression behavior (Lambe and Whitman, 1979). The ‘‘S’’ shape also indicates a diffusion process. (Feda, 1991).

The coefficient of secondary swelling increases with an increase in the percent of clay fraction. (Sivapullaiah et al., 1996). For kaolinite, the secondary swelling is very small, and the percent swell vs log t relationship is almost horizontal in the secondary region.

Kuhn (2010) compared the rate of secondary swelling versus total stress in free swell, 1-G infiltration, and centrifuge tests on compacted clay specimens. He found that the rate of secondary swelling in free swell tests decreases with increasing total stress and revealed a linear relationship for loads exceeding 1000 psf (Figure 2.5).

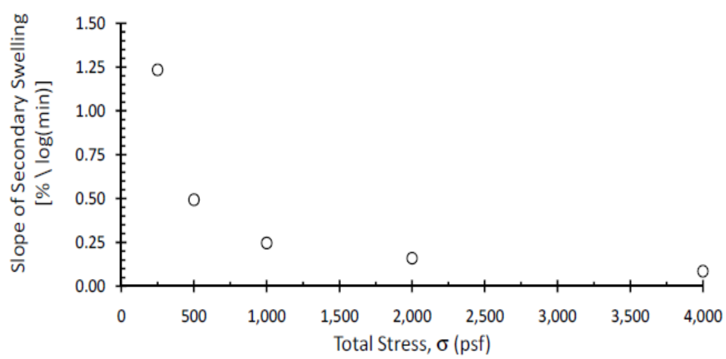


Figure 2.5: Rate of Secondary Swelling vs Stress from Free Swell Tests (Kuhn, 2010)

He also observed that the log of the slope of secondary swelling was linear with the log of the hydraulic conductivity which led him to conclude that the rate of secondary swelling may be controlled by the saturated hydraulic conductivity of the soil (Figure 2.6).

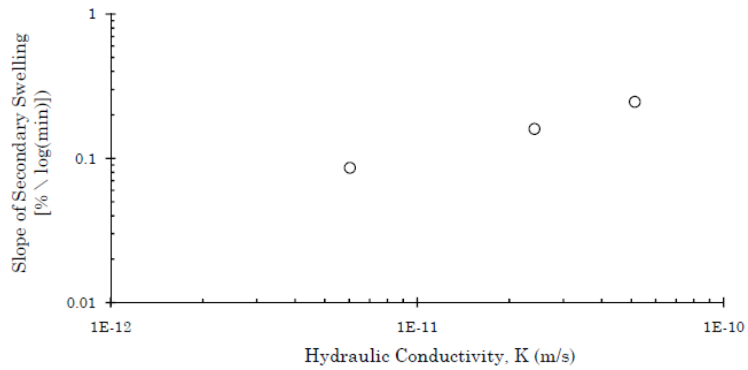


Figure 2.6: Rate of Secondary Swelling vs Saturated Hydraulic Conductivity (Kuhn, 2010)

For the centrifuge tests, the rate of secondary swelling decreased with total stress. However, the rate of secondary swelling did not vary much between G-levels (Figure 2.7)

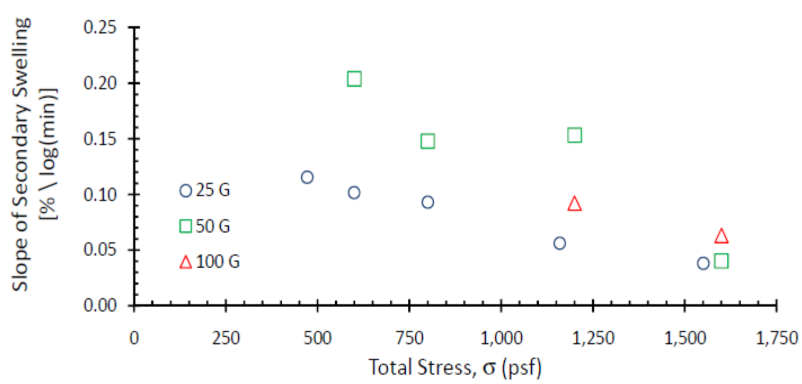


Figure 2.7: Rate of Secondary Swelling vs Stress from Centrifuge Tests (Kuhn, 2010)

2.7 Observations from Literature Review

The feasibility of centrifuge technology for characterizing the swelling potential of expansive soils was demonstrated by several researchers. The concept of bimodal pore size distribution in unsaturated expansive soils could be used to explain swelling phenomena at the microstructural and macrostructural level. The molding water content for compacted clay specimens, influences the clay structure and affects the rate and quantum of swelling. Swelling occurs in three stages: Intervoid Swelling, Primary Swelling, and Secondary Swelling. The swelling-time relationship in compacted clay specimens may be represented by a rectangular hyperbola and follows a standard ‘S’ shape. The slow and continued swelling with time, after primary swelling, is referred to as secondary swelling and yields a straight-line relationship with logarithmic time. The slope of this line is taken as the coefficient of secondary swelling.

CHAPTER 3: SOIL CHARACTERIZATION

The expansive clay used more extensively in this research to evaluate secondary swelling, is a highly plastic clay belonging to the Taylor group. By virtue of being tan in color, it was identified as Tan Taylor.

To assess the impact of soil type on secondary swelling, three other soils – Eagle Ford clay, Houston Black clay and Black Taylor clay have also been included in the study. These soils are prominent in the Austin area and expansive in nature. They have been investigated for primary swelling property at The University of Texas at Austin by Kuhn (2010), Walker (2012) and Zornberg et. al. (2013). The author makes use of characterization reports available for these soils from past studies.

The soil characterization includes index properties like – Atterberg limits, specific gravity, compaction characteristics, and grain size distribution. Results for hydraulic conductivity and mineralogical analysis on Eagle Ford are also provided (Kuhn, 2010). Tests conform to the standards laid down by ASTM.

The preparation and processing of each soil for swell testing involved air drying at room temperature until it was suitable to be crushed. The air dried soil was passed through a soil crusher twice, first with the crushing size set on the largest opening and then, with the crushing size set on the smallest opening size until passing sieve #10. After processing, the soil was stored in standard 5 gallon buckets, covered to prevent moisture interaction with the atmosphere.

3.1 Tan Taylor clay

The Tan Taylor clay belongs to the Taylor group. The soil was sourced from a stockpile of cuttings from a roadway reconstruction project near East Riverside, Austin. It was moderately to lightly weathered, characterized by a tan color. The location for the site is shown in Figure 3.1.

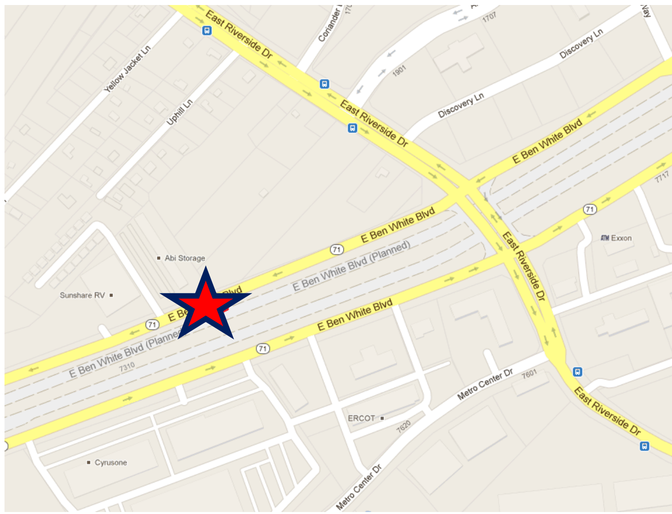


Figure 3.1: Location of Tan Taylor clay sourced for laboratory testing

3.1.1 Atterberg Limits

The Atterberg Limits for Tan Taylor were obtained in accordance with ASTM D4318. The soil has a Liquid Limit (LL) of 82 and a Plastic Limit (PL) of 40, resulting in a Plasticity Index (PI) of 42 (Table 3.1). Under the Unified Soil Classification System (USCS), the soil was classified as a clay of high plasticity (CH).

Table 3.1: Atterberg Limits and USCS Classification for Tan Taylor clay

Index Property	Value
Liquid Limit (LL)	82
Plastic Limit (PL)	40
Plasticity Index (PI)	42
Classification	CH

3.1.2 Specific Gravity

Specific gravity as per ASTM D 854-10, was found to be 2.73.

3.1.3 Compaction Characteristics

The moisture-density relationship was obtained according to ASTM D698. The processed soil was mixed at a pre-determined water content prior to the test and placed in an air-tight container for 2 days. The Standard Proctor compaction curve is shown in Figure 3.2. The maximum dry unit weight was 15.68 kN/m^3 and occurred at an optimum water content of 22.5%.

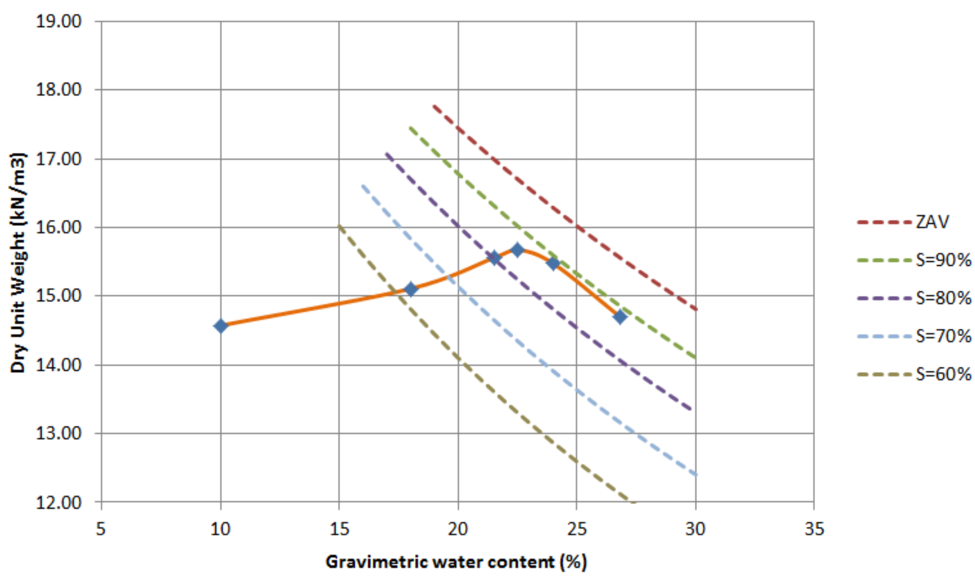


Figure 3.2: Standard Proctor curve for Tan Taylor clay

3.1.4 Grain Size Distribution

The grain size distribution for processed Tan Taylor clay was obtained using a hydrometer test conforming to ASTM D422-63. The gradation analysis indicates that approximately 86% of the soil particles are finer than Sieve #200 (Figure 3.3).

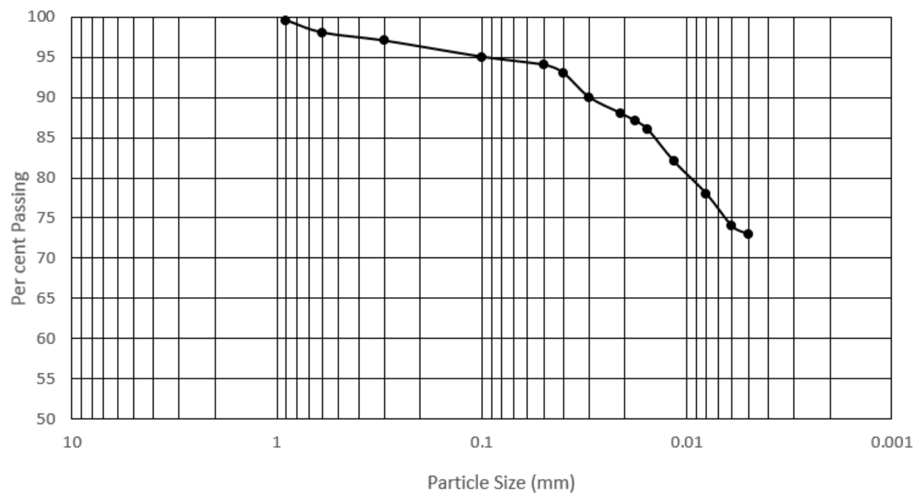


Figure 3.3: Grain Size Distribution for Tan Taylor clay

3.2 Eagle Ford clay

The Eagle Ford clay samples used in this study were collected from the Eagle Ford Formation at Hester's Crossing and Interstate Highway 35 near Round Rock (Figure 3.4). The soil was excavated from a depth of 3 meters. The soil is yellowish tan in appearance. The characterization of Eagle Ford clay was conducted by Jeffrey Kuhn (2010).

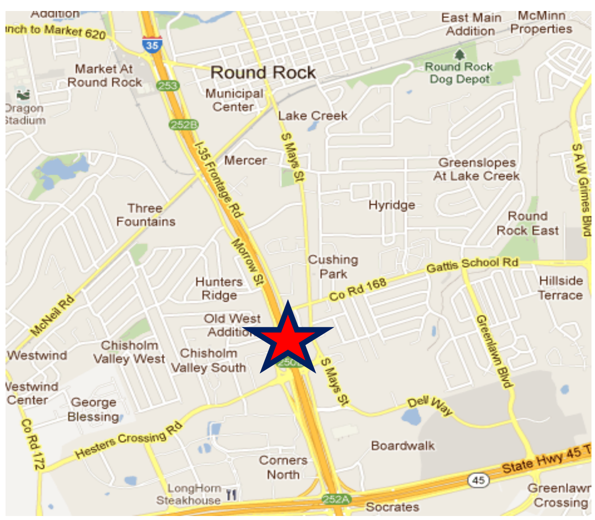


Figure 3.4: Location of Eagle Ford clay sourced for laboratory testing (Walker, 2012)

3.2.1 ATTERBERG LIMITS

The Atterberg Limits for the processed soil were determined as per procedures outlined in ASTM D4318. The Eagle Ford clay has a Liquid Limit (LL) of 88 and a Plastic Limit (PL) of 39, which gives it a Plasticity Index (PI) of 49 (Table 3.2). According to the Unified Soil Classification System (USCS), the soil was classified as a clay of high plasticity (CH).

Table 3.2: Atterberg Limits and USCS Classification for Eagle Ford clay (Kuhn, 2010)

Index Property	Value
Liquid Limit (LL)	88
Plastic Limit (PL)	39
Plasticity Index (PI)	49
Classification	CH

3.2.2 SPECIFIC GRAVITY

Specific gravity was obtained as per ASTM D854-02, giving a value of 2.74.

3.2.3 COMPACTION CHARACTERISTICS

Standard proctor test was performed in accordance with ASTM D698-00a to determine the maximum dry unit weight and the optimum moisture content. Prior to being compacted in the mold, the processed soil was brought to the target water content, and allowed to equilibrate for 48 hours in an air-tight container. The maximum dry unit weight occurred at 15.25 kN/m^3 at an optimum moisture content of 24%. Figure 3.5 displays the results of the standard proctor compaction test.

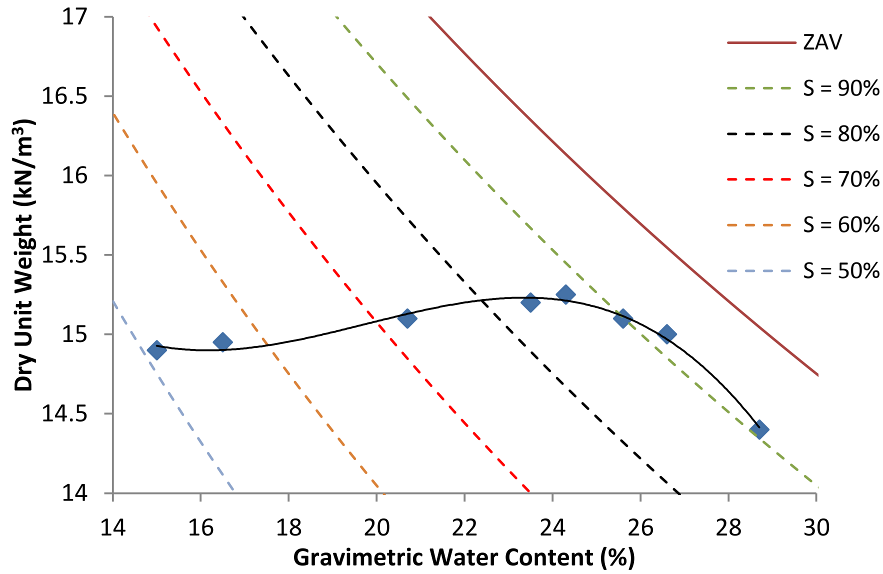


Figure 3.5: Standard Proctor curve for Eagle Ford clay (Zornberg et. al., 2013)

3.2.4 Grain Size Distribution

The grain size distribution for processed Eagle Ford clay was obtained using a hydrometer test conforming to ASTM D422-63. As per the gradation analysis, 89.5% of the soil particles passed through Sieve #200 and 74% was finer than 0.002 mm, which resulted in a clay content of 74%. The results from the hydrometer test are shown in Figure 3.6.

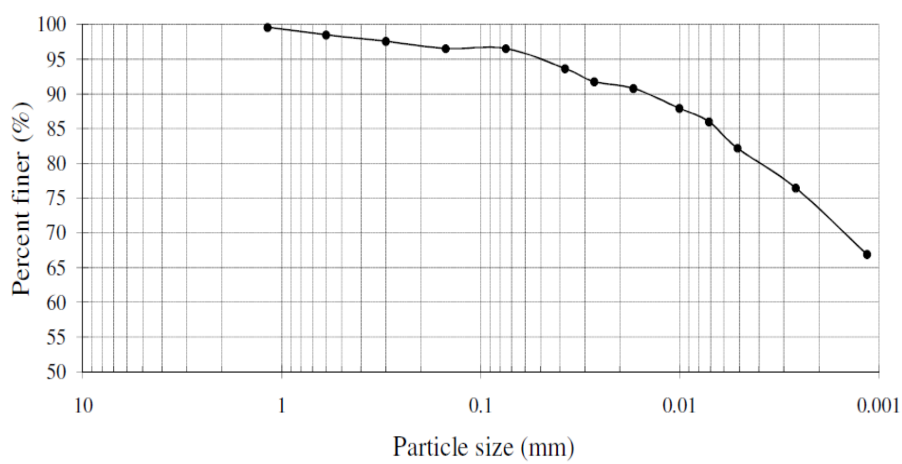


Figure 3.6: Grain Size Distribution for Eagle Ford clay (Kuhn, 2010)

3.2.5 MINERALOGICAL COMPOSITION

The mineralogical analysis of Eagle Ford clay was performed using X-ray diffraction, procedure for which is described by Kuhn (2010). The results from the X-ray diffraction test are shown in Table 3.3 and Figure 3.7.

Compounds that have a high probability of occurrence include Quartz, Kaolinite, and Jarosite. Other important compounds are Halloysite, Muscovite, and Montmorillonite.

Table 3.3: Probable compounds in Eagle Ford clay determined from X-Ray Diffraction (Kuhn, 2010)

Compound Name	Chemical Formula	Reference Code*
Quartz	SiO_2	01-078-1252
Kaolinite	$Al_2Si_2O_5\left(OH\right)_4$	00-006-0221
Jarosite	$KFe_3\left(SO_4\right)_2\left(OH\right)_6$	01-071-1777

*International Center for Diffraction Data Reference Code

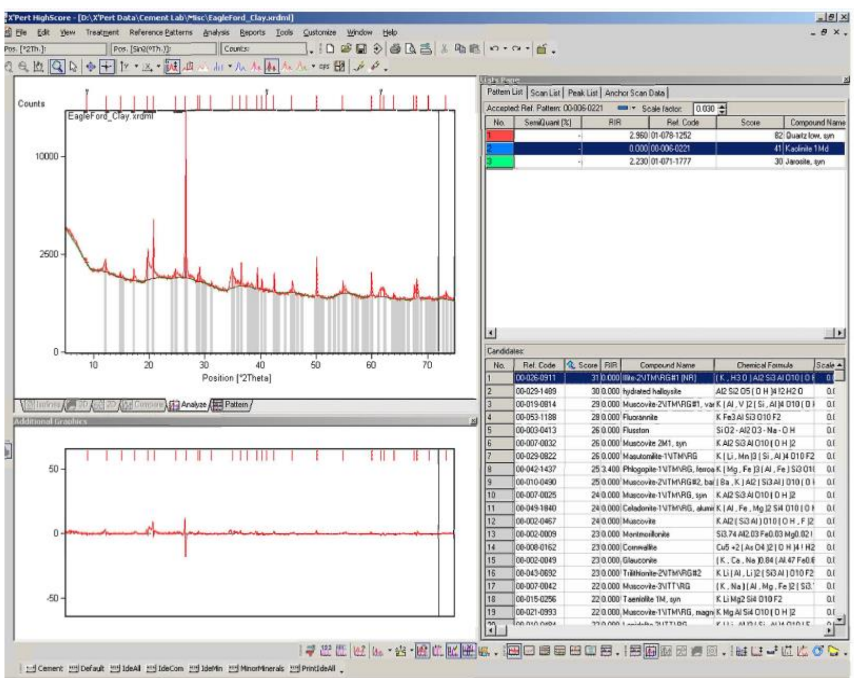


Figure 3.7: Screenshot of Mineralogical Composition of Eagle Ford clay (Kuhn, 2010)

3.2.6 SATURATED HYDRAULIC CONDUCTIVITY

The saturated hydraulic conductivity was measured in a flexible wall permeameter cell. The specimen was compacted at a dry unit weight of 98.7 pcf at optimum moisture content. The sample was tested at effective stresses of 1,000, 2,000, and 4,000 psf (Kuhn, 2010). B-value of 0.95 ensured proper saturation. A hydraulic gradient of 30 was applied across the test specimen, and the flow rate was monitored until the ratio of outflow to inflow reached 0.99. The saturated hydraulic conductivity at different effective stresses is shown in Figure 3.8.

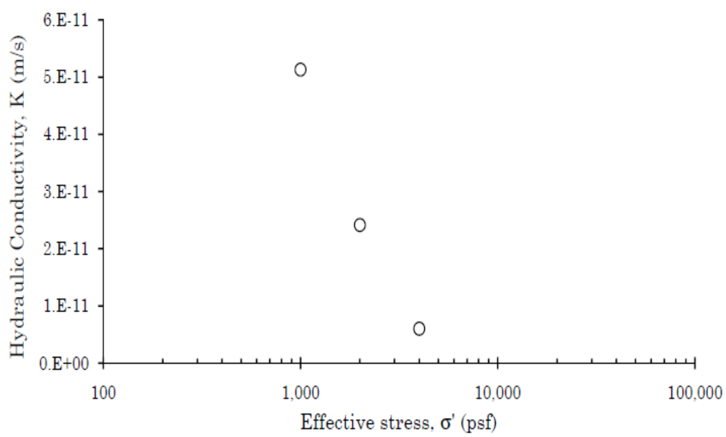


Figure 3.8: Hydraulic Conductivity vs. Effective Stress for compacted Eagle Ford clay specimens (Kuhn, 2010)

3.3 Houston Black clay

The Houston Black clay was obtained jointly with the Texas Department of Transportation (TxDOT). It was sourced from a stockpile generated by a project on Highway 79. The soil is dark gray to black in color. It was obtained the intersection of Highway 79 and Tollway 130, West of Hutto, Texas. (Figure 3.9)

Figure 3.9: Location of Houston Black clay sourced for laboratory testing (Walker, 2012)

3.3.1 ATTERBERG LIMITS

The Atterberg Limits for the soil were obtained as per procedures outlined in ASTM D4318. The Houston Black clay has a Liquid Limit (LL) of 62 and a Plastic Limit (PL) of 27, which gives it a Plasticity Index (PI) of 35 (Table 3.4). Under the Unified Soil Classification System (USCS), the soil was classified as a clay of high plasticity (CH).

Table 3.4: Atterberg Limits and USCS Classification for Houston Black clay (Walker, 2012)

Index Property	Value
Liquid Limit (LL)	62
Plastic Limit (PL)	27
Plasticity Index (PI)	35
Classification	CH

3.3.2 SPECIFIC GRAVITY

Specific gravity was determined according to ASTM D854-02, yielding a value of 2.70.

3.3.3 COMPACTION CHARACTERISTICS

Standard Proctor test was conducted to obtain the relationship between dry density and moisture content. The procedure adhered to guidelines laid down by ASTM D698-00a. Before compaction, the processed soil passing Sieve #4, was brought to the target water content and cured for 48 hours. The maximum dry unit weight was 14.72 kN/m^3 occurring at an optimum moisture content of 25.5% (Figure 3.10).

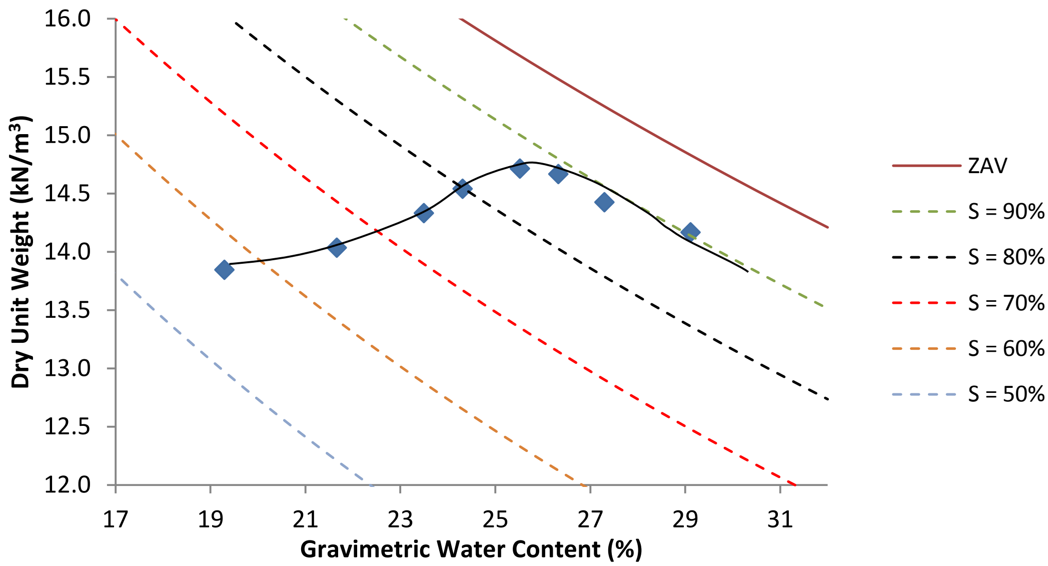


Figure 3.10: Standard Proctor curve for Houston Black clay (Zornberg et. al., 2013)

3.3.4 GRAIN SIZE DISTRIBUTION

The grain size distribution for processed Houston Black clay was obtained in accordance with ASTM D422-63. The gradation suggested that 52% of the soil particles were finer than Sieve #200. The gradation analysis is shown in Figure 3.11.

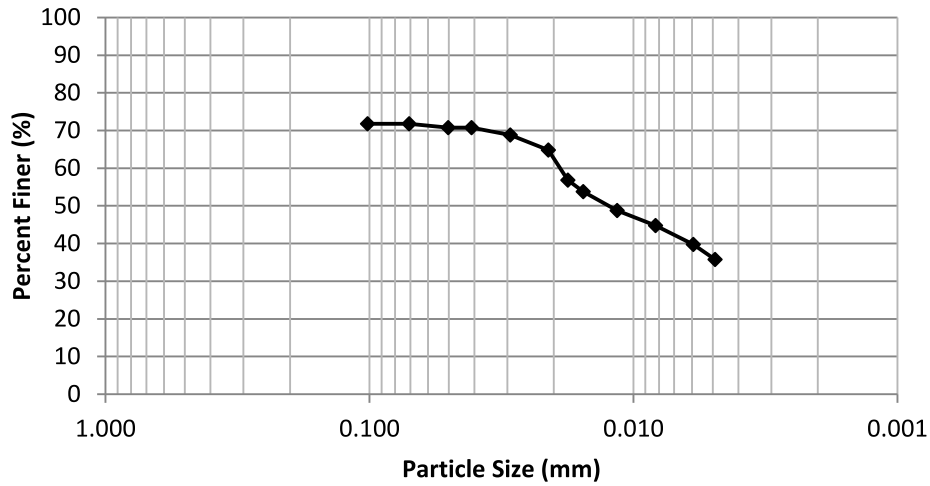


Figure 3.11: Grain Size Distribution for Houston Black clay (Walker, 2012)

3.4 Black Taylor clay

The Black Taylor clay belongs to the Taylor group. It was obtained from an excavation for a drilled shaft retaining wall located east of Manor, Texas (Figure 3.12). The soil was weathered and characterized by a dark gray color.

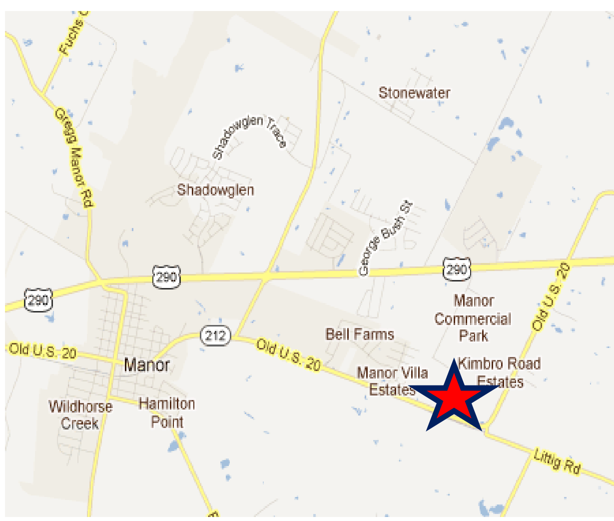


Figure 3.12: Location of Black Taylor clay sourced for laboratory testing (Walker, 2012)

3.4.1 ATTERBERG LIMITS

The Atterberg Limits for the processed clay were determined as per procedures outlined in ASTM D4318. The Black Taylor clay has a Liquid Limit (LL) of 55 and a Plastic Limit (PL) of 28, which gives it a Plasticity Index (PI) of 27 (Table 3.5). According to the Unified Soil Classification System (USCS), the soil was classified as a clay of high plasticity (CH).

Table 3.5: Atterberg Limits and USCS Classification for Black Taylor clay (Walker, 2012)

Index Property	Value
Liquid Limit (LL)	55
Plastic Limit (PL)	28
Plasticity Index (PI)	27
Classification	CH

3.4.2 SPECIFIC GRAVITY

Specific gravity as per ASTM D 854-02, was found to be 2.71.

3.4.3 COMPACTION CHARACTERISTICS

The moisture-density relationship was obtained according to ASTM D698-00a. The processed soil was passed through sieve #4, mixed with desired water quantity and placed in an air-tight container for 2 days. The Standard Proctor compaction curve is presented in Figure 3.13. The maximum dry unit weight was 15.34 kN/m^3 and occurred at an optimum water content of 23.3%.

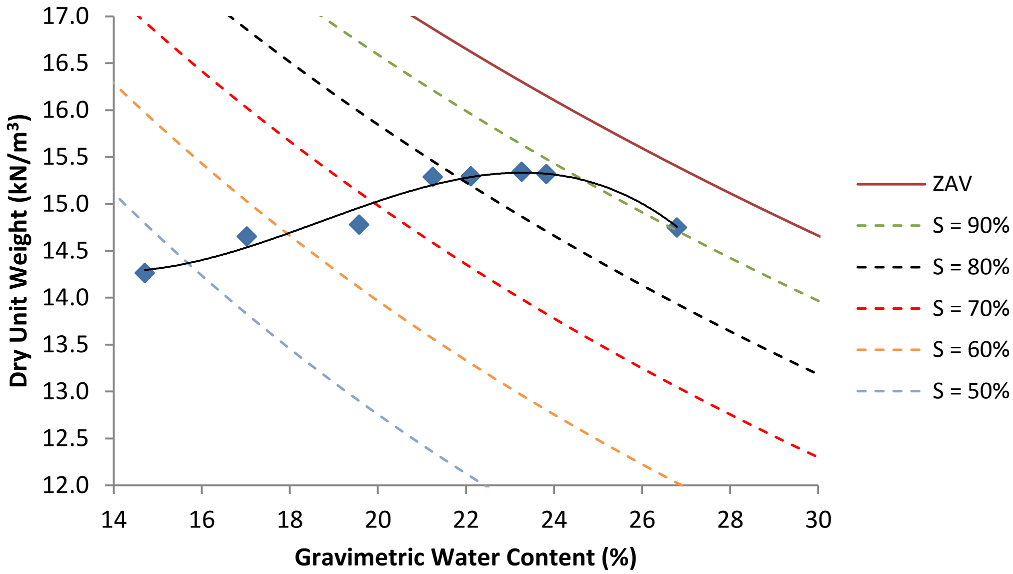


Figure 3.13: Standard Proctor curve for Black Taylor clay (Zornberg et. al., 2013)

3.4.4 GRAIN SIZE DISTRIBUTION

The grain size distribution for processed Black Taylor clay was obtained using a hydrometer test conforming to ASTM D422-63. The gradation analysis indicates that approximately 67% of the soil particles are finer than Sieve #200. (Figure 3.14)

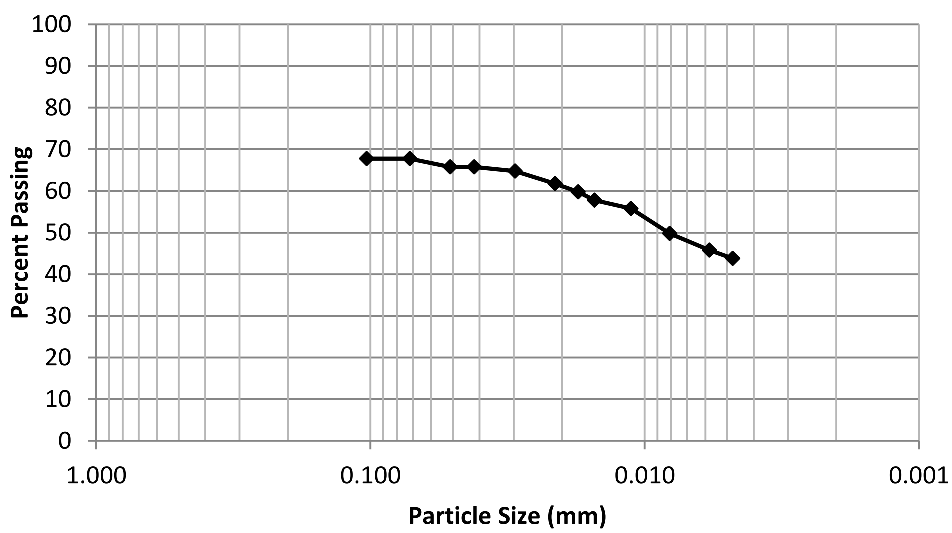


Figure 3.14: Grain Size Distribution for Black Taylor clay (Walker, 2012)

3.5 Summary of Soil Characterization

The following table displays the index properties of Tan Taylor clay, Eagle Ford clay, Houston Black clay, and Black Taylor clay.

Table 3.6: Summary of Soil Characterization of Tan Taylor clay, Eagle Ford clay, Houston Black clay, and Black Taylor clay

Summary of Soil Characterization					
Soil	**Plasticity Index**	**Per cent passing sieve #200**	**Max. Dry Unit Wt. (kN/m^3)**	**Optimum Water Content (%)**	**Specific Gravity**
Tan Taylor clay	42	86	15.68	22.5	2.73
Eagle Ford clay	49	89.5	15.25	24	2.74
Houston Black clay	35	52	14.72	25.5	2.70
Black Taylor clay	27	67	15.34	23.3	2.71

CHAPTER 4: EQUIPMENT AND TESTING PROCEDURE

The characterization of secondary swelling using centrifuge technology has numerous advantages. The testing time is significantly reduced and multiple specimens can be tested at the same time. This chapter gives a description of the centrifuge equipment and testing procedure.

4.1 Centrifuge Testing Setup

4.1.1 CENTRIFUGES

Two centrifuges were used over the course of this research. The majority of the tests were performed using the Damon IEC CRU-5000 (Figure 4.1), and a small number of 200g tests were completed using the Fisher IEC EXD Thermo Explosion Resistant centrifuge (Figure 4.2).

The Damon IEC CRU-5000 consists of a Model 259 rotor having six metal centrifuge buckets to accommodate six centrifuge cups. Two of the buckets housed the Data Acquisition System (DAQ) which meant four specimens could be tested per spin of the centrifuge. The control panel has knobs for RPM, temperature control, timer, an on/off power switch, start button, stop button, and a brake switch.

The Fisher IEC EXD has a Model 249 rotor having a capacity of four centrifuge cups. Similar to the previous centrifuge, it also contained the Data Acquisition System (DAQ) in two of the cups, effectively allowing two specimens to be tested per run of the centrifuge.

Figure 4.1: Damon IEC CRU-5000 Centrifuge and Control Panel (Walker, 2012)

Figure 4.2: Fisher IEC EXD Thermo Explosion Resistant Centrifuge (Walker, 2012)

4.1.2 Centrifuge Components

The centrifuge cup has two components, the metal bucket and the permeameter cup. The metal buckets (Figure 4.3) contain the permeameter cups and latch on to the arms of the rotor. The distance from the center of rotation to the bottom of the soil specimen within the cup was 20.8 centimeters.

Figure 4.3: Metal Centrifuge Buckets (Walker, 2012)

The permeameter cup comprises four major components: the top cup, the cup base, two porous disks, and two filter papers (Figure 4.4). The cup base acts as the outflow chamber and collects water that is not absorbed by the soil specimen.

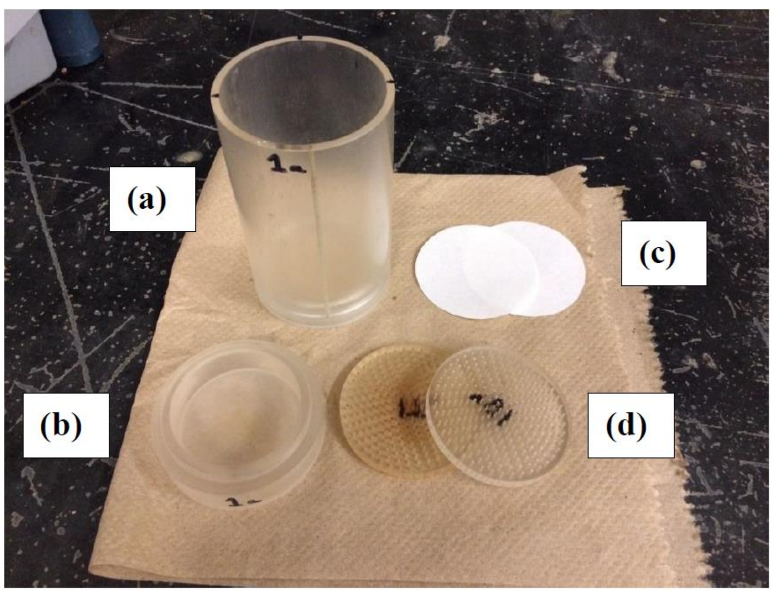


Figure 4.1: Parts of Permeameter Cup: a) Top Cup, b) Cup Base, c) Filter paper, d) Porous disks (Armstrong, 2014)

A few small washers impart the required overburden stress to the soil specimen during centrifugation. Another set of washers simulating the weight of 2 cm head of water ponded over the soil specimen is used during the compression/decompression cycle, where the seating height is to be determined. The mass of these washers, along with the mass of 2 cm water head and the linear position sensor (LPS), provide the overburden stress during the centrifugation of the soil sample.

4.1.3 DATA ACQUISITION SYSTEM (DAQ)

The Data Acquisition System (DAQ) consists of Linear Position Sensors (LPS) to monitor the heights of the soil specimens, an internal JeeNode Arduino with A/D Convertor (Analog to Digital Convertor) to digitize the signal, and an external JeeNode Arduino to communicate readings from the internal JeeNode to the computer. A LabVIEW program is used to record the raw voltage data from the LPS and accelerometer to text files. Figure 4.5 shows a Linear Position Sensor (LPS) from the testing program.

Figure 4.5: Linear Position Sensor (Walker, 2012)

4.2 Testing Procedure

The testing procedure was derived from the small centrifuge testing method developed by Plaisted (2009), and a centrifuge testing procedure incorporating an in-flight data acquisition system by Walker (2012).

4.2.1 TESTING PRINCIPLE

The specimen was compacted unsaturated under different conditions of dry density and water contents. Water ponded over the specimen was allowed to infiltrate through it under an imposed gravitational gradient. The sample absorbed water and underwent swelling. The water which was not absorbed by the specimen was collected in the cup base (outflow chamber). The test schematic is shown in Figure 4.6.

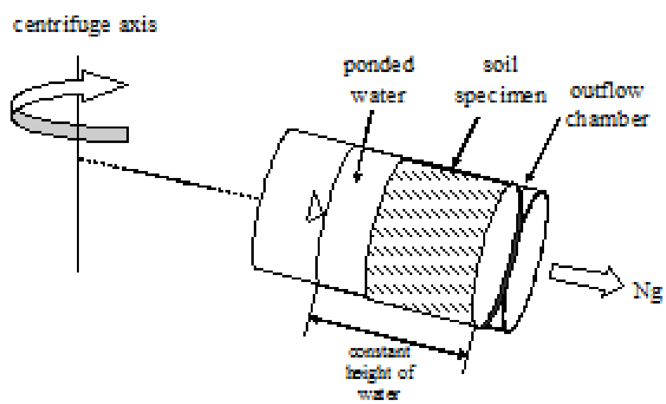


Figure 4.6: Centrifuge Test Schematic (Plaisted, 2009)

4.2.2 SOIL PREPARATION

The processed soil was passed through Sieve No. 10 to remove larger clods. The soil was mixed with distilled water from a spray bottle in multiple mixing cycles. The target water content during mixing was 0.5% higher than the initial molding water content to compensate for moisture loss during mixing and compaction. The initial gravimetric water content of the stock soil was also taken into account. The soil was mixed in small batches to overcome the problem of moisture loss during storage over a long period. The soil and water mix was stored in airtight Ziploc bags, and allowed to equilibrate to a uniform water content throughout, for 48 hours prior to the test. The acceptable range of molding water content for the testing program was specified at +/- 0.5% of the target molding water content.

4.2.3 PERMEAMETER CUP PREPARATION

- The porous disks, top cup and bottom cup were thoroughly cleaned and air dried. Special care was taken to clean the finer perforations of the porous disks to remove any soil particles from previous testing.
- The mass of the top cup and cup base was recorded. The base was then screwed to the top cup.
- A filter paper was cut according to the dimensions of the porous disk. The filter paper rested on the porous disk placed on the bottom ledge of the top cup.
- A thin layer of vacuum grease was applied on the inner surface of the top cup to reduce friction between the specimen and cup walls during testing.
- The combined mass of the cup, base, porous disk, filter paper, and vacuum grease, was recorded.
- The height of the combined set up was measured to the nearest 1/1000" using a vertical mounted caliper.

4.2.4 SOIL SPECIMEN COMPACTION

- A predetermined mass of the cured soil from Ziploc bag was poured in the cup using a funnel. The cup was tapped and shaken to evenly distribute the soil particles. An additional 0.2-0.4 grams of soil was added to account for mass loss during compaction.

- Water content of the cured soil was measured to determine the initial molding water content.
- The soil was compacted using the large diameter kneading compactor and rubber mallet shown in Figure 4.7. The small diameter kneading compactor was also used to maintain a constant height and even surface across the specimen. The height of the specimen was constantly monitored during the compaction process.

Figure 4.7: Compaction equipment used during specimen preparation (Walker, 2012)

- When the specimen height was within 0.02 inch of the target height, the rubber mallet was gently tapped on top of the large diameter compactor, rotating the cup 45 degrees per four blows of the mallet. (Figure 4.8)

Figure 4.8: Compaction using rubber mallet and large diameter compactor (Walker, 2012)

- For compacting local uneven areas on the surface of the specimen, the small diameter kneading compactor was used. (Figure 4.9)

Figure 4.9: Compaction using small diameter kneading compactor (Walker, 2012)

- The final sample height (~ 1 cm for baseline condition) was recorded at the middle, top, right, bottom, and left of the specimen.
- A filter paper and porous disk were then lowered into the cup to sit on top of the specimen.
- The total mass of the permeameter set up was recorded.

4.2.5 ASSEMBLY

- Washers were used to impose overburden stress on top of the specimen during centrifugation. The mass of the overburden washer/washers was recorded.
- A set of washers weighing 51.3 grams were stacked on the top porous disk. This set of washers simulated the effect of 2 cm head of infiltrating (ponded) liquid during the compression/decompression cycle.
- The mass of the final assembly was taken and the set up was lowered into the metal buckets hanging from the arms of the rotor inside the centrifuge.
- The Linear Position Sensors (LPS) were inserted into the center holes of the washers until they touch the center of the top porous disk.
- Electrical tapes were used to secure the metal bucket and top cap in order to stabilize the Linear Position Sensors during testing.
- The battery source was connected to the Data Acquisition System (DAQ) to complete the circuit. The complete assembly is shown in Figure 4.10.
- The centrifuge was started and the RPM level adjusted using the knobs on the console.

Figure 4.10: Final assembly within the centrifuge (Walker, 2012)

4.2.6 DATA ACQUISITION

The LabVIEW program is activated using the RUN button, when the circuit is complete. Figure 4.11 presents a screenshot of the program functions and controls. The RUN and STOP buttons start and terminate data recording by the program. The ADC reference voltage acts as a scaling factor for the ADC reading and is set at 1.0. The ADC codes and voltage readings for LPS displacement and accelerometer are closely monitored during the compression/decompression stage and initial testing stage of the centrifuge. The amplitude monitor shows the LPS output data which indicates the direction (upward or downward) of displacement of the sensors. A downward displacement corresponds to compression and upward displacement indicates swelling of the specimen. Data is recorded at an interval of approximately 1 minute. The raw data collected as a text file is processed using a Python Script whose output is shown in Figure 4.12.

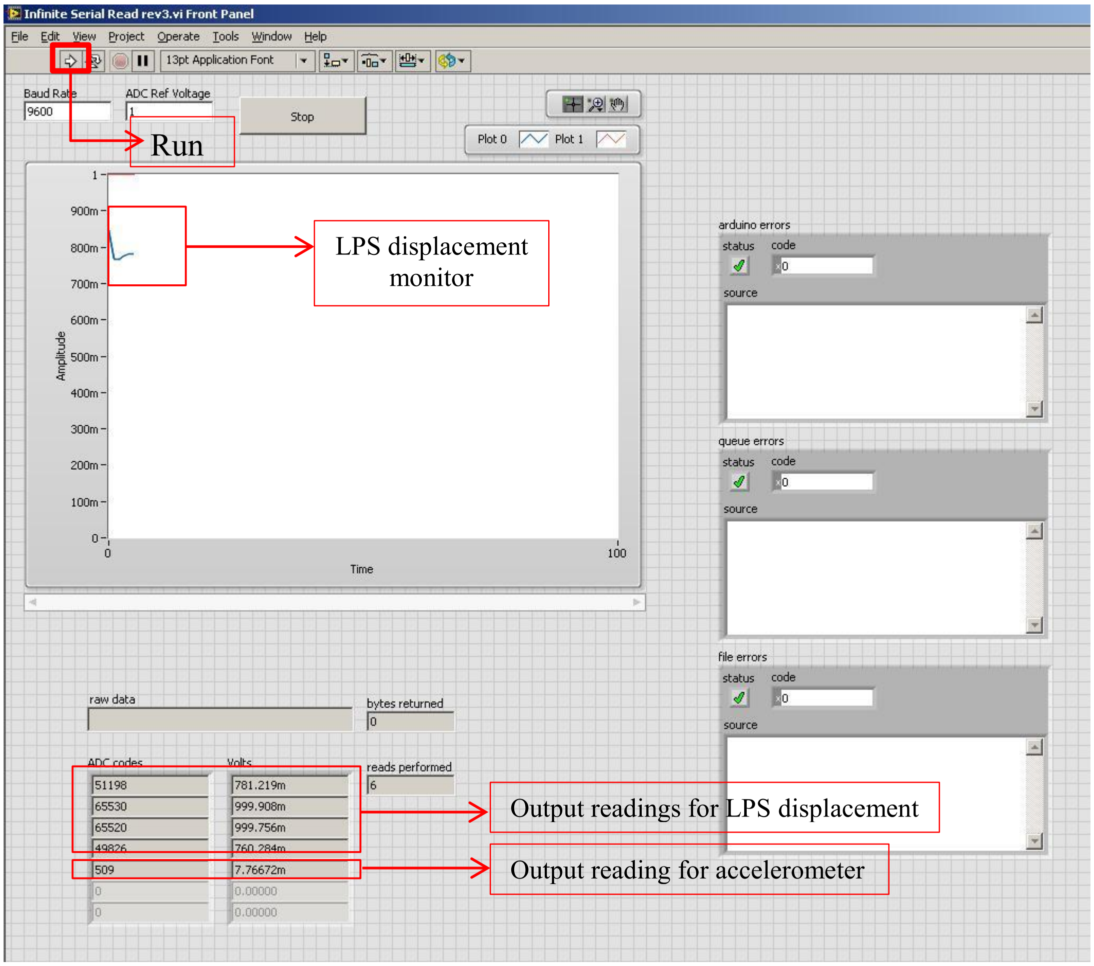


Figure 4.11: Screenshot of LabVIEW program showing various functions and controls (Walker, 2012)

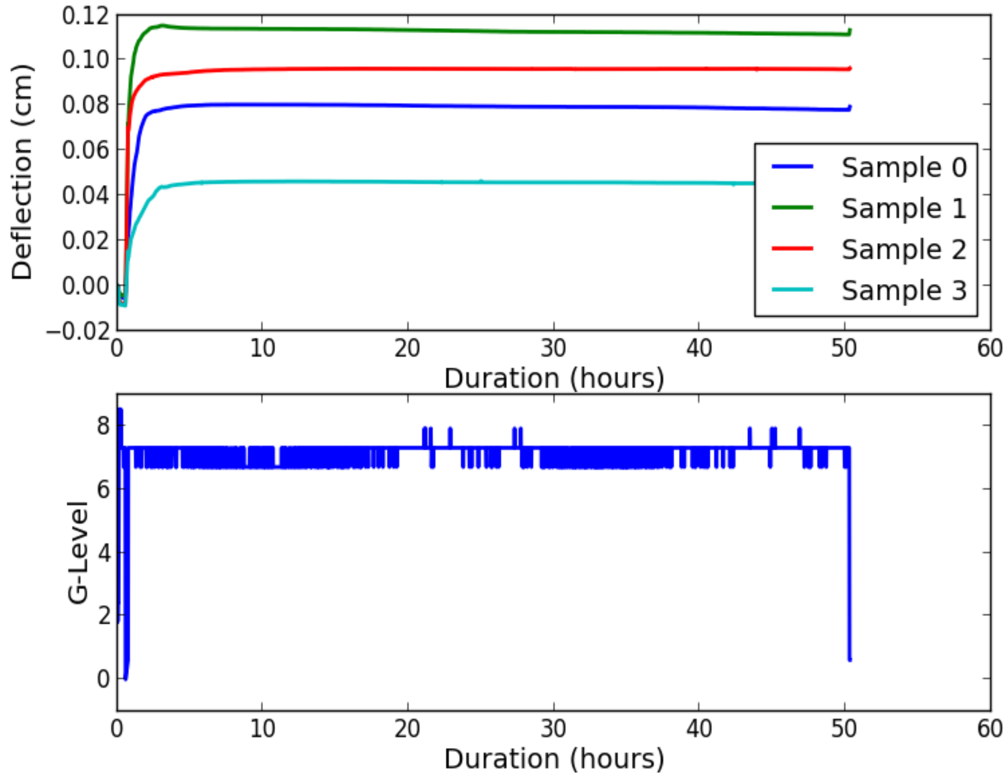


Figure 4.12: Screenshot of Python program used for processing the raw data generated by LabVIEW

4.2.7 COMPRESSION/DECOMPRESSION STAGE

The specimen was subjected to a compression/decompression stage to determine the seating height and initial height of sample after compaction. For the seating height, the centrifuge was spun to a very low g-level (~ 2-3g) for 5 minutes. The speed (or RPM) was then increased gradually till the centrifuge attained the target g-level, and maintained for about 20 minutes. The sample height at the end of this stage gives the initial height of specimen. A compression/decompression stage depicting the seating height and initial height of specimen is shown in Figure 4.13.

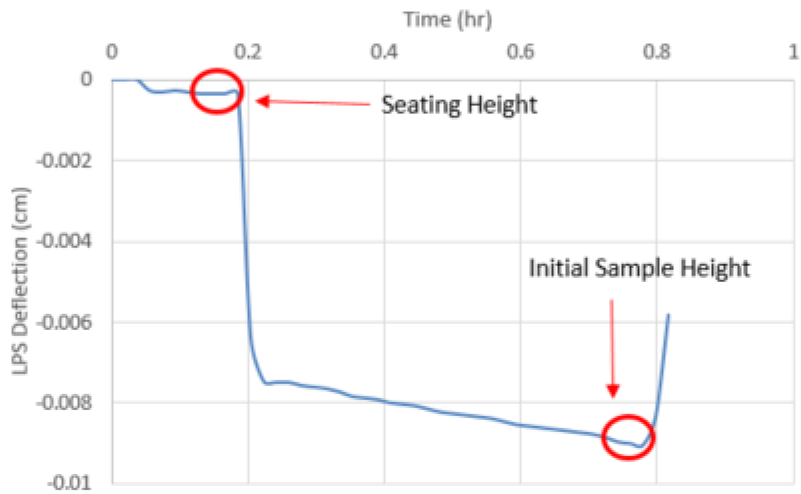


Figure 4.13: Compression/Decompression stage in a specimen of Tan Taylor clay tested at baseline conditions

4.2.8 FINAL PERMEAMETER CUP PREPARATION

- The permeameter cup was removed from the centrifuge at the end of the compression/decompression stage.
- The set of washers simulating ponded water, was removed and 51.3 grams of water corresponding to 2 cm of water (baseline condition) was added.
- The height of the set up and the total mass were recorded.
- The permeameter assembly was quickly transferred to the centrifuge to continue testing.

4.2.9 TEST DURATION AND TERMINATION

The samples were spun inside the centrifuge for a duration of 24-48 hours. Primary swelling was observed to be complete within 10-15 hours of testing after which the specimens undergo secondary swelling. The slope of secondary swelling was calculated in the log cycle of 10 to 100. The STOP button on the centrifuge console terminates the test. The samples were removed and measurements were taken for the specimen height, mass of water absorbed by the specimen and mass of water collected in the outflow chamber.

The significance of centrifuge testing for evaluating secondary swelling in expansive soils lies in the fact that soils can be tested over a range of stresses. Specimens in Free Swell test may take over a month to exhibit secondary swelling behavior. Centrifuge testing helps to achieve this objective within 1-2 days. The in-flight Data Acquisition System (DAQ) is a valuable addition which enables collection of data in real time.

CHAPTER 5: TESTING PROGRAM AND RESULTS

The testing program conducted as part of this research aims at quantifying the rate of secondary swelling for expansive soils conducted as part of this research. This chapter presents the trends observed in the slope of secondary swelling in Tan Taylor clay specimens, plotted against parameters including molding water content, compaction dry unit weight, g-level, specimen height, head of infiltrating liquid and its concentration.

5.1 Scope of the Testing Program

The majority of tests were performed using Tan Taylor clay. Reconstituted specimens were used in the experimental component of this research. The methodology adopted involved specimens compacted under different initial conditions of dry density and moisture content. Six parameters were identified, which were expected to affect the slope of the secondary swell curve. This includes molding water content, compaction dry unit weight, g-level, specimen height, head of infiltrating liquid and its concentration. The influence of each variable on secondary swelling is determined and comparisons are made by altering one parameter at a time in the swell test, while keeping the others constant. Finally, efforts were made to explain the mechanism leading to the secondary swelling phenomenon in soils.

In addition to Tan Taylor clay, three other expansive soils namely, Eagle Ford clay, Houston Black clay, and Black Taylor clay were used in the study to assess the effect of soil type on the rate of secondary swelling in soils.

Results from the single infiltration (infiltration at the top) centrifuge set up, developed at The University of Texas at Austin, have been reported to correlate well with those from ASTM D4546 tests as demonstrated by Plaisted (2009), Kuhn (2010) and

Walker (2012). This set up was adopted over the conventional 1g method as it greatly reduced the time taken for completion of primary swelling and commencement of secondary swelling. It also allowed multiple specimens (up to 4) to be tested in a single spin. The centrifuge method also offered better flexibility and control over test variables in comparison to conventional methods.

5.2 Nomenclature

This section presents the terminology adopted over the course of this thesis.

5.2.1 MOLDING WATER CONTENT

Compaction (Molding) water content refers to the moisture content at which the soil was molded. It is the initial water content, prior to testing. Soils in the testing program were compacted at moisture content values corresponding to: dry of optimum (DOPT or w_{opt} - 3%), optimum (OPT or w_{opt}), and wet of optimum (WOPT or w_{opt} + 3%).

5.2.2 RELATIVE COMPACTION

Relative Compaction (RC) relates the compaction dry unit weight of soil to the maximum dry unit weight achieved at optimum moisture content in a Standard Proctor test. The program involved compacting specimens to achieve 94%, 97% or 100% relative compaction according to Standard Proctor compaction energy.

5.2.3 G-LEVEL

The centrifuge was accelerated to impose 5g, 25g, or 200g, providing a range of stress for the testing program. G-levels of 5, 25, and 200g correspond to effective stresses of 30 psf, 80 psf, and 600 psf respectively. Tests conducted at a higher g-level (200g) yielded a very low value of secondary swelling, probably owing to the high stresses. A g-level of 5 was found to be the condition that led to the higher values of secondary swelling, facilitating investigation of relevant variables.

5.2.4 SPECIMEN HEIGHT

The height of specimen was set at 1 cm in most cases. It was suspected that specimens less than 1 cm might yield erroneous values of swell due to side wall interference and uneven compaction. This is also the standard height as per ASTM D4546. Effect of specimen height on secondary swell was evaluated using 1.5 cm and 1.8 cm high specimens.

5.2.5 HEAD OF INFILTRATING LIQUID

The infiltrating liquid was usually deaired, distilled water infiltrating through the specimen from the top (pore pressure is zero at the bottom). The infiltrating water was imposed at a hydraulic gradient corresponding to the gravitational gradient. It also contributed to stress atop the specimen. 51.3 g of water corresponding to 2 cm head of water was used in most cases. However, infiltrating water heads of 1.5 cm and 2.5 cm were also employed in the study to demonstrate the influence of a higher hydraulic gradient toward secondary swell. It may be noted that at high g-levels, the water finds alternate flow channels through the sides and surface of the specimen, resulting in a lower swell value.

5.2.6 CONCENTRATION OF INFILTRATING LIQUID

The pore fluid (or infiltrating solution) during the course of the tests was deaired, distilled water. Tap water and 1M NaCl solution were substituted in some cases, to gauge the effect of pore fluid composition and osmotic gradient on secondary swell. The cationic concentration of tap water is in between that of deaired, distilled water and 1M NaCl solution.

5.2.7 Baseline Condition

The baseline testing condition used as reference for the testing program in this study involves Tan Taylor clay specimens prepared at a relative compaction of 97% and optimum water content, with a specimen height of 1cm and 2cm head of ponded water for infiltrating through the specimen.

5.3 Testing Conditions

Figure 5.1, Figure 5.2, Figure 5.3, and Figure 5.4 depict the Standard Proctor curves for the four soils used within this investigation, with the compaction conditions marked by black crosses and the baseline condition marked red. Proctor curve for Eagle Ford clay was reported by Kuhn (2010). Compaction curves for Houston Black clay and Black Taylor clay were generated by Walker (2012).

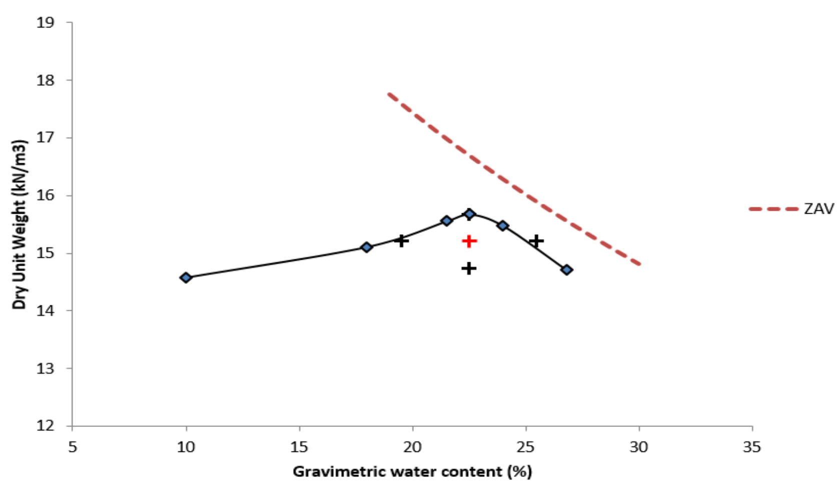


Figure 5.1: Compaction Conditions for Tan Taylor clay

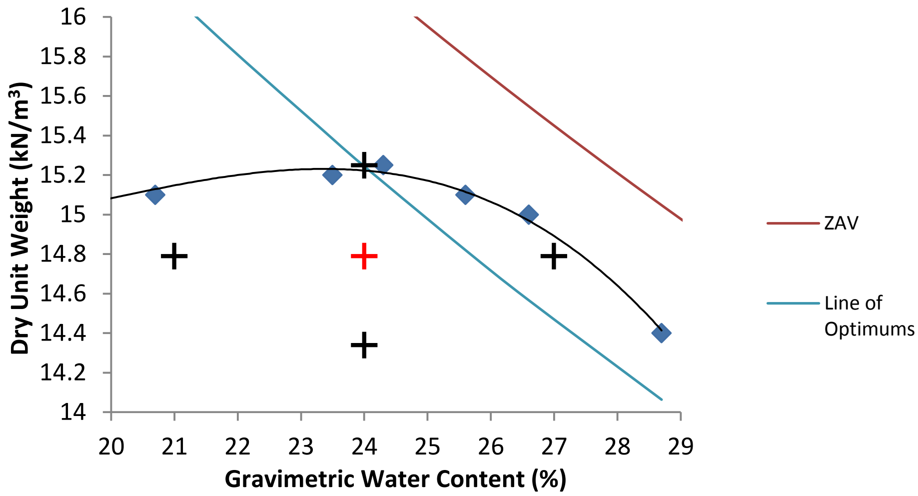


Figure 5.2: Compaction Conditions for Eagle Ford clay (Kuhn, 2010)

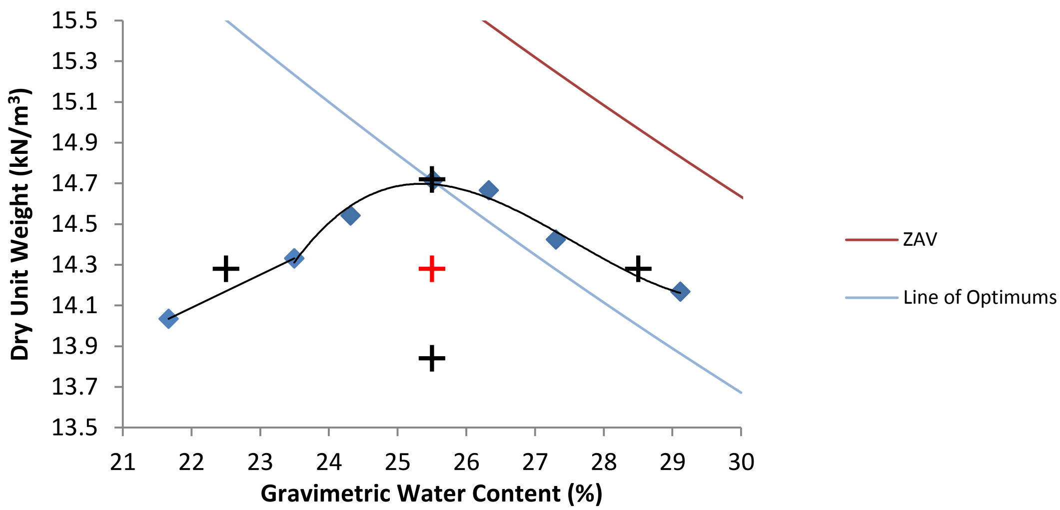


Figure 5.3: Compaction Conditions for Houston Black clay (Walker, 2012)

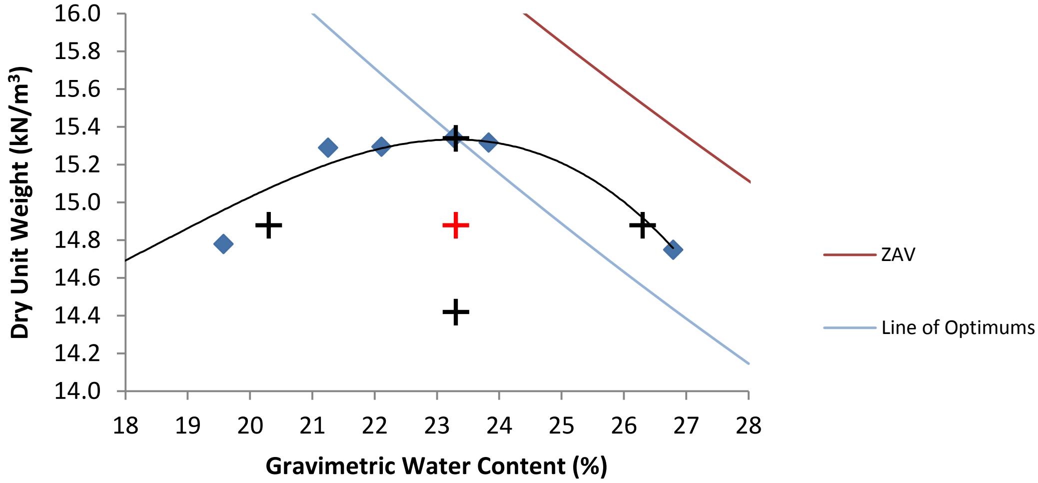


Figure 5.4: Compaction Conditions for Black Taylor clay (Walker, 2012)

Table 5.1, Table 5.2, Table 5.3, and Table 5.4 present the scope of the testing program for Tan Taylor clay, Eagle Ford clay, Houston Black clay, and Black Taylor clay respectively. Tests on Eagle Ford clay, Houston Black clay, and Black Taylor clay were reported by Walker (2012).

Table 5.1: Testing Program for Tan Taylor clay

Soil	G-Level	Ponded Solution	Initial Level of Ponded Solution	Target Specimen Height (cm)	Molding Water Content (%)	Relative Compaction (%)	Slope of Secondary Swell (%/log cycle)
TT	5.54	Distilled water	2	1	22.4	93.6	1.05
TT	5.54	Distilled water	2	1	22.4	94	0.56
TT	6.84	Distilled water	2	1	22.5	94.1	1.11
TT	6.84	Distilled water	2	1	22.5	94.3	0.75
TT	7.02	Distilled water	2	1	22.1	96.7	1.51
TT	7.02	Distilled water	2	1	22.5	97.1	1.71
TT	8.53	Distilled water	2	1	22.7	97.2	1.38
TT	8.53	Distilled water	2	1	22.9	97.4	1.81
TT	6.24	Distilled water	2	1	22.6	99.8	2.41
TT	6.24	Distilled water	2	1	22.6	99.9	3.27
TT	5.22	Distilled water	2	1	22.5	100	2.71
TT	5.22	Distilled water	2	1	22.5	100	1.94
TT	7.02	Distilled water	2	1	19.1	97.2	0.99
TT	7.02	Distilled water	2	1	19.2	97.4	1.14
TT	7.59	Distilled water	2	1	19.6	96.7	0.90
TT	7.59	Distilled water	2	1	20	96.5	0.70
TT	6.24	Distilled water	2	1	25.2	97	1.92
TT	6.24	Distilled water	2	1	25.5	97.1	2.26
TT	5.22	Distilled water	2	1	25.7	97	2.60
TT	5.22	Distilled water	2	1	26	97.2	2.19
TT	25.44	Distilled water	2	1	22.5	93.7	0.71
TT	26.09	Distilled water	2	1	22.5	94.1	0.86
TT	26.2	Distilled water	2	1	22.5	94.2	1.08
TT	26.59	Distilled water	2	1	22.5	94.4	1.19
TT	26.59	Distilled water	2	1	22	96.6	1.24
TT	26.09	Distilled water	2	1	22.4	97	1.39
TT	25.44	Distilled water	2	1	22.5	97.1	1.65
TT	26.8	Distilled water	2	1	22.8	97.3	1.15
TT	25.71	Distilled water	2	1	22.5	99.6	2.32
TT	25.71	Distilled water	2	1	22.2	99.9	2.59
TT	26.8	Distilled water	2	1	22.2	99.9	1.96
TT	26.2	Distilled water	2	1	22.5	100	1.71
TT	5.54	Distilled water	2	1.5	22.7	96.6	1.27
TT	5.54	Distilled water	2	1.5	22.7	97	1.38
TT	5.54	Distilled water	2	1.8	22.7	97.2	1.47
TT	5.54	Distilled water	2	1.8	22.5	97	1.20
TT	7.25	Distilled water	1.5	1	22.7	97.2	1.80
TT	7.25	Distilled water	1.5	1	22.7	97.4	1.75
TT	7.25	Distilled water	2.5	1	22.6	97	2.32
TT	7.25	Distilled water	2.5	1	22.6	97.2	2.28
TT	6.61	Tap Water	2	1	22.7	97	2.08
TT	6.61	Tap Water	2	1	22.7	97	1.96
TT	6.84	1M NaCl	2	1	22.2	97.2	1.14
TT	6.84	1M NaCl	2	1	22.2	97.2	1.36
TT	201.9	Distilled water	2	1	22.2	97.8	0.30
TT	201.9	Distilled water	2	1	22.1	97	0.11

Table 5.2: Testing Program for Eagle Ford clay (Walker, 2012)

Soil	G-Level	Ponded Solution	Initial Level of Ponded Solution	Target Specimen Height (cm)	Molding Water Content (%)	Relative Compaction (%)	Slope of Secondary Swell (%/log cycle)
EF	6.84	Distilled water	2	1	23.9	100	5.57
EF	6.84	Distilled water	2	1	23.9	100	4.65
EF	7.46	Distilled water	2	1	24.1	94.2	7.07
EF	7.46	Distilled water	2	1	24.1	94.6	5.87
EF	5.53	Distilled water	2	1	23	96.8	6.85
EF	5.53	Distilled water	2	1	23	94.8	4.38
EF	7.71	Distilled water	2	1	24	97.1	3.24
EF	7.71	Distilled water	2	1	24	97	4.78
EF	25.5	Distilled water	2	1	25.4	99.6	3.57
EF	25.5	Distilled water	2	1	25.4	100	3.63
EF	25.5	Distilled water	2	1	21.9	96.5	5.89
EF	25.5	Distilled water	2	1	23.9	95	3.35
EF	26.5	Distilled water	2	1	23.9	98.2	3.05
EF	26.5	Distilled water	2	1	23.9	98.2	3.37
EF	27.33	Distilled water	2	1	27.4	97.6	2.22
EF	27.33	Distilled water	2	1	27.4	97.3	3.18

Table 5.3: Testing Program for Houston Black clay (Walker, 2012)

Soil	G-Level	Ponded Solution	Initial Level of Ponded Solution	Target Specimen Height (cm)	Molding Water Content (%)	Relative Compaction (%)	Slope of Secondary Swell (%/log cycle)
HB	6.96	Distilled water	2	1	25.1	98.2	0.67
HB	6.96	Distilled water	2	1	25.1	98.2	0.33
HB	8.51	Distilled water	2	1	25.6	100	1.48
HB	8.51	Distilled water	2	1	25.6	100	2.86
HB	7.53	Distilled water	2	1	25.7	97.5	0.88
HB	7.53	Distilled water	2	1	25.7	97.2	0.90
HB	7.49	Distilled water	2	1	25.6	100	1.55
HB	7.49	Distilled water	2	1	26.8	96.4	0.87
HB	25.61	Distilled water	2	1	25.3	98.1	1.66
HB	25.61	Distilled water	2	1	25.1	96.7	1.49
HB	26.84	Distilled water	2	1	25.8	100	0.76

Table 5.4: Testing Program for Black Taylor clay (Walker, 2012)

Soil	G-Level	Ponded Solution	Initial Level of Ponded Solution	Target Specimen Height (cm)	Molding Water Content (%)	Relative Compaction (%)	Slope of Secondary Swell (%/log cycle)
BT	6.84	Distilled water	2	1	23.3	98	1.12
BT	25.89	Distilled water	2	1	20.8	98.2	1.03
BT	26.87	Distilled water	2	1	23.2	95	1.18
BT	24.07	Distilled water	2	1	23.7	100	0.39

5.4 Test Results

The phenomenon of secondary swelling in Tan Taylor clay was investigated in significant detail. The rate of secondary swell is relevant to completely characterize the swell potential of an expansive soil. This chapter depicts the different trends observed in the slope of secondary swell curve when testing Tan Taylor clay specimens using different variables. Chapter 6 will analyze the trends observed, ascribing the possible reasons for the observed responses.

5.4.1 Molding Water Content

The rate of secondary swelling was found to increase with increasing compaction water content. The trend was found to be consistent for the different g-levels. Figure 5.5 shows the swelling vs. time curves for specimens of Tan Taylor clay compacted under different initial water contents at 5g-level and relative compaction of 97% RC.

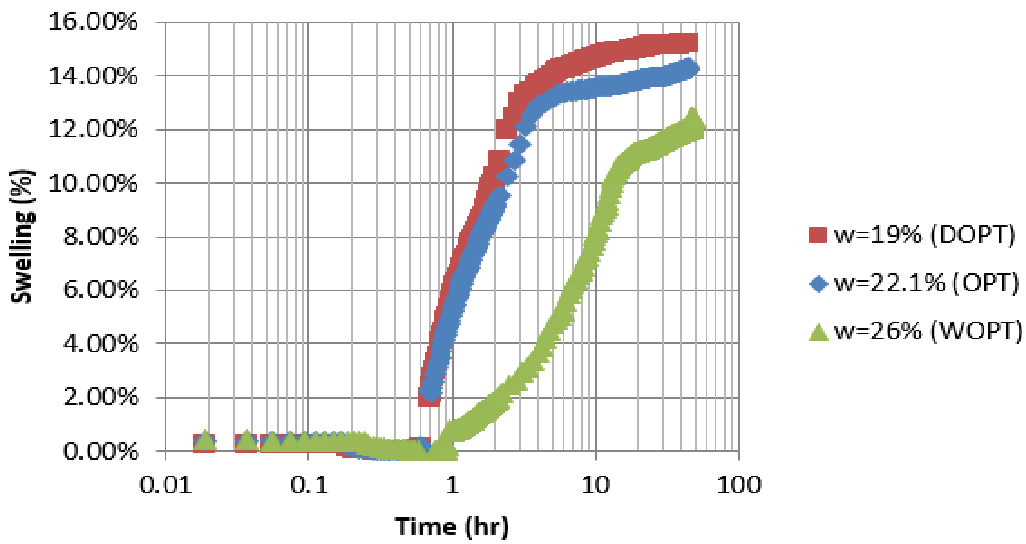


Figure 5.5: Swelling vs. Time for different initial water contents (Tan Taylor, 5g, 97% RC)

Figure 5.6 and Figure 5.7 present the slope of secondary swelling in Tan Taylor clay for a relative compaction of 97%, as a function of molding water content at 5g and 25g.

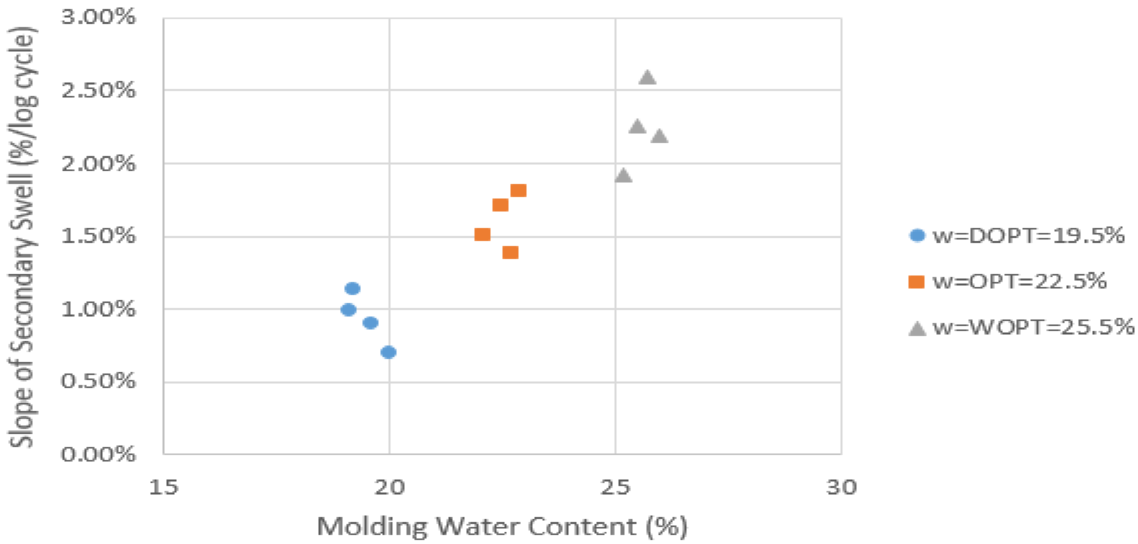


Figure 5.6: Secondary Swelling vs Compaction Water Content at 5g and 97% RC for Tan Taylor clay

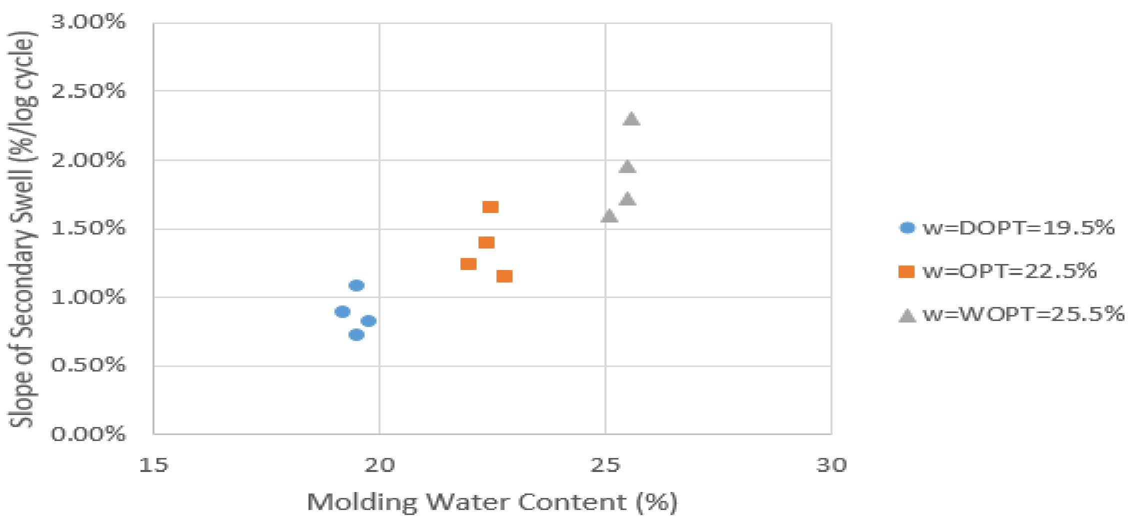


Figure 5.7: Secondary Swelling vs Compaction Water Content at 25g and 97% RC for Tan Taylor clay

5.4.2 RELATIVE COMPACTION

At a given water content, secondary swelling was found to increase with increasing relative compaction. Figure 5.8 depicts the swelling vs. time curves for specimens of Tan Taylor clay compacted under different dry densities at 5g-level and optimum water content.

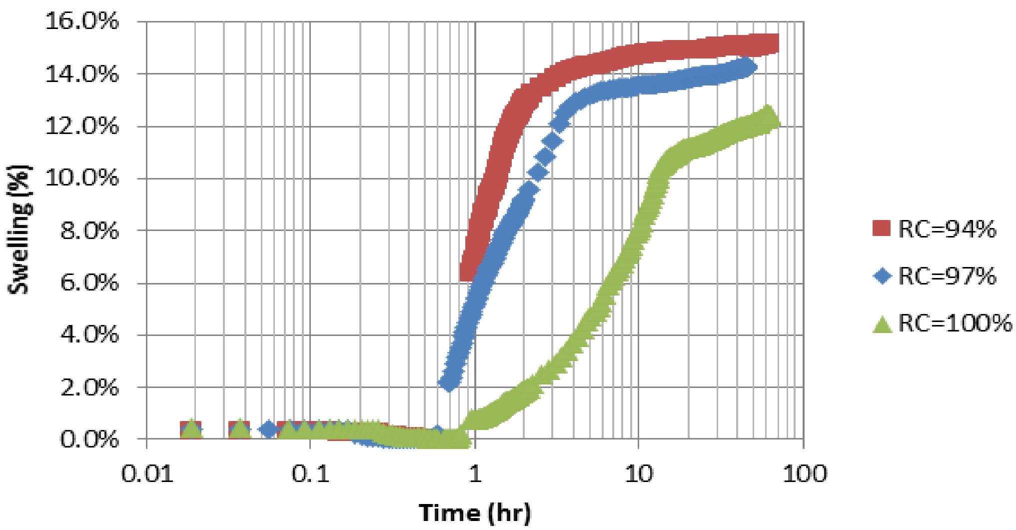


Figure 5.8: Swelling vs. Time for different initial dry densities (Tan Taylor, 5g, OPT)

Figure 5.9 and Figure 5.10 show the slope of secondary swelling in Tan Taylor clay at optimum water content, as a function of relative compaction at 5g and 25g.

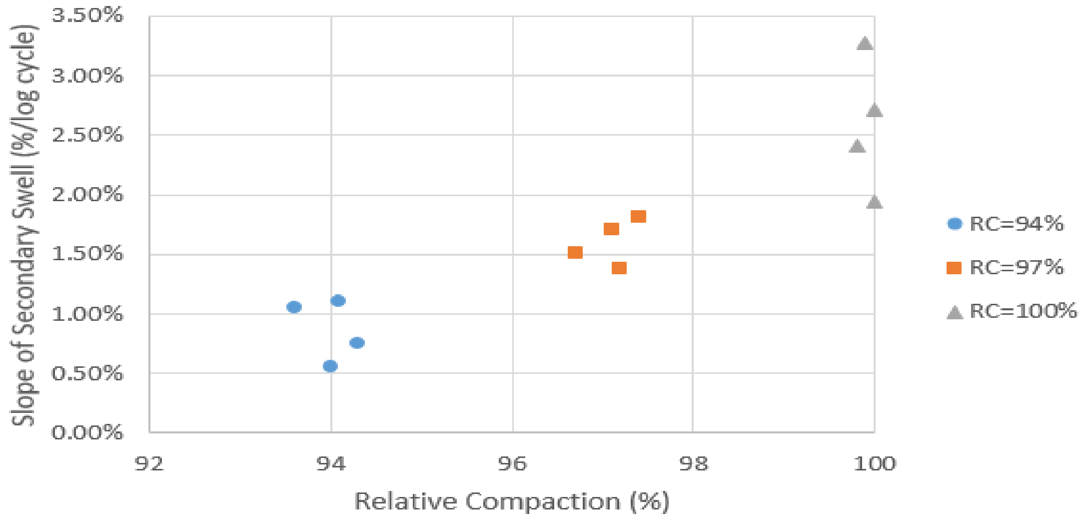


Figure 5.9: Secondary Swelling vs Relative Compaction at 5g and OPT for Tan Taylor clay

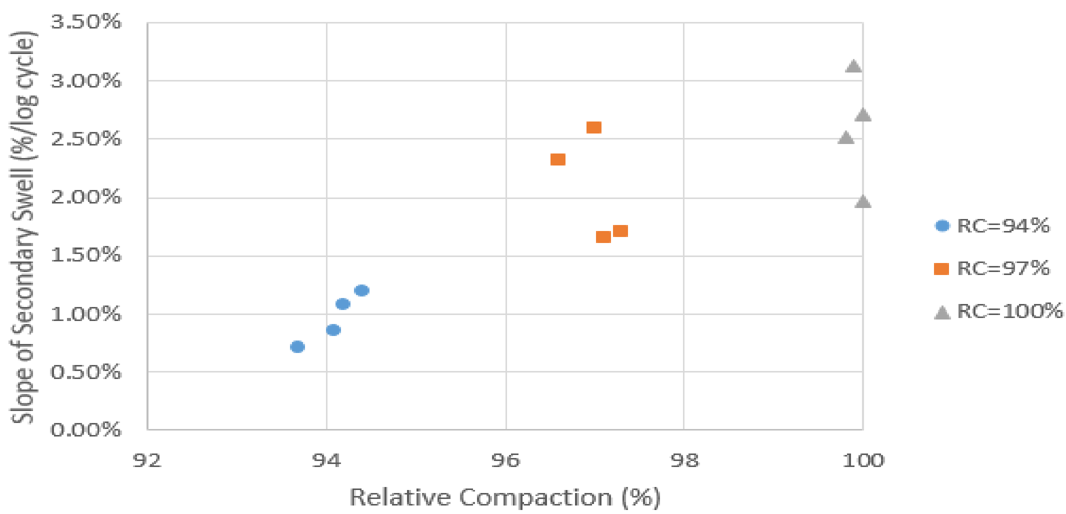


Figure 5.10: Secondary Swelling vs Relative Compaction at 25g and OPT for Tan Taylor clay

5.4.3 G-Level

A decrease in the rate of secondary swelling was seen upon increasing the g-level. The quantum of primary swelling was also found to decrease with increasing g-level. Figure 5.11 depicts the effect for baseline condition of increasing g-level for Tan Taylor specimens.

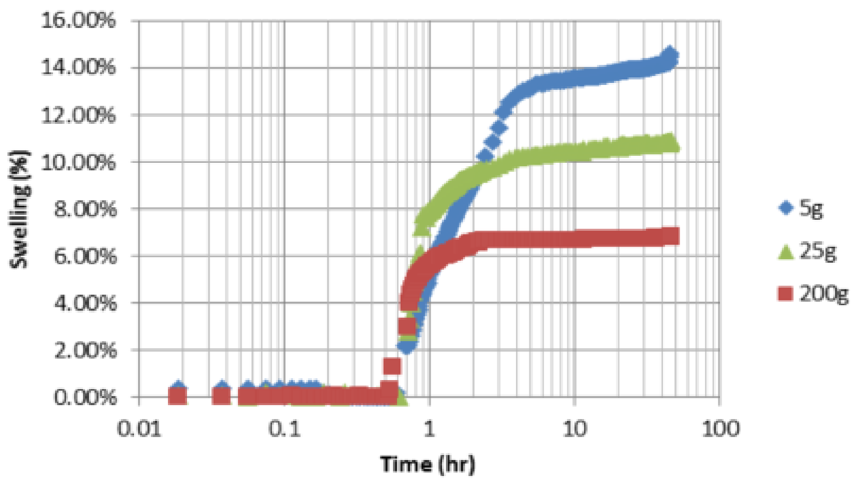


Figure 5.11: Swelling vs. Time for different g-levels (Tan Taylor, 97% RC, OPT)

5.4.4 SPECIMEN HEIGHT

Change in specimen height introduced additional stress and affected the overall quantum of swelling. However it had a comparatively minor effect on the slope of the secondary swelling portion. Figure 5.12 shows the swelling vs. time curves for specimens of Tan Taylor clay compacted to different initial heights at 5g-level, 97% RC and OPT.

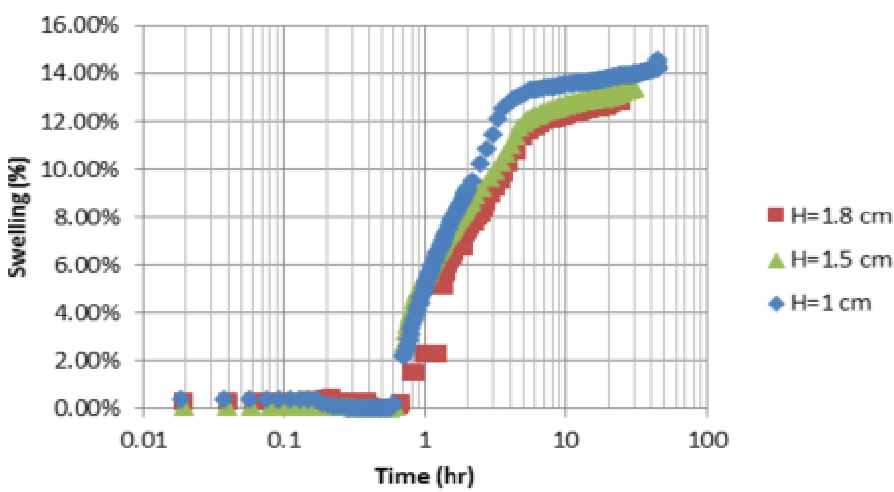


Figure 5.12: Swelling vs. Time for different specimen heights (Tan Taylor, 5g, 97% RC, OPT)

5.4.5 HEAD OF INFILTRATING LIQUID

Altering the level of infiltrating liquid was found not to affect the rate of secondary swelling appreciably. However, a slight increase in the secondary swelling rate was observed with higher imposed hydraulic gradient. Figure 5.13 presents the swelling vs. time curves for specimens of Tan Taylor clay subjected to different heads of infiltrating liquid at 5g-level, 97% RC and OPT.

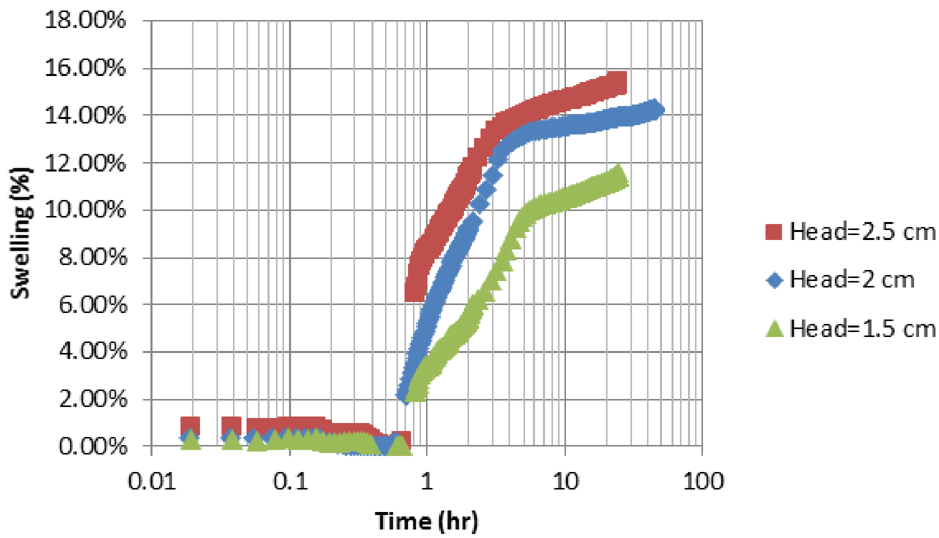


Figure 5.13: Swelling vs. Time for different liquid heads (Tan Taylor, 5g, 97% RC, OPT)

5.4.6 CONCENTRATION OF INFILTRATING LIQUID

The rate of secondary swelling did not seem to change significantly with the concentration of the infiltrating liquid. The quantum and rate of primary swelling was found to vary considerably with concentration of different solutions. Results from tests at baseline conditions and 5g for deaired, distilled water, tap water and 1M NaCl solution point toward this conclusion. Figure 5.14 depicts the trend at 97% RC at OPT in Tan Taylor clay specimens.

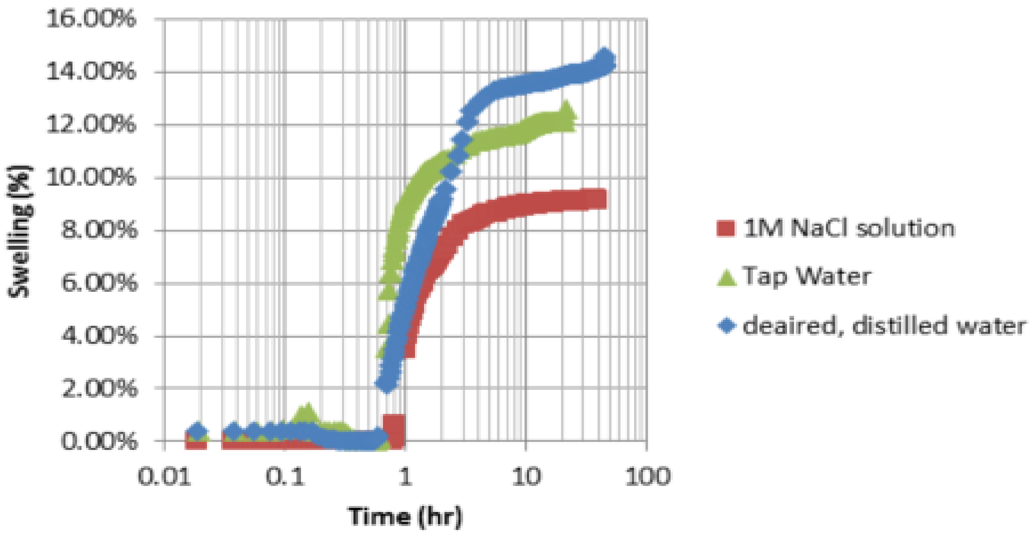


Figure 5.14: Swelling vs. Time for different concentration of infiltrating liquids (Tan Taylor, 5g, 97% RC, OPT)

5.4.7 Comparison of Different Soils

The dependence of the rate of secondary swelling on molding water content and relative compaction was compared at 5g and 25g levels for the other expansive soils - Eagle Ford clay, Houston Black clay, and Black Taylor clay. The testing program for these soils was completed by Walker (2012). Figure 5.15 and Figure 5.16 depict the effect of molding water content on secondary swelling for the soils at 5g and 25g respectively. Figure 5.17 and Figure 5.18 present the trend for relative compaction plotted against the slope of secondary swelling for the soils at 5g and 25g respectively.

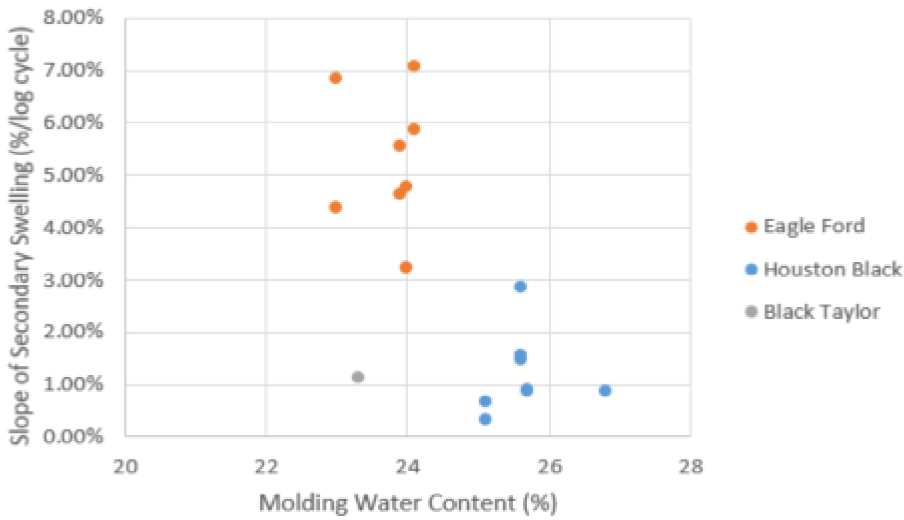


Figure 5.15: Secondary Swelling vs Molding Water Content for Eagle Ford clay, Houston Black clay, and Black Taylor clay at 5g-level and 97% RC (after Walker, 2012)

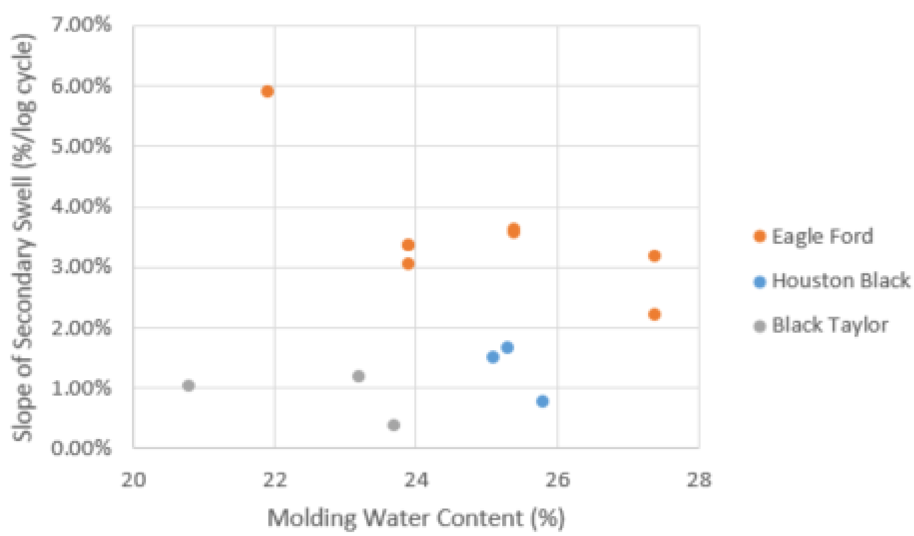


Figure 5.16: Secondary Swelling vs Molding Water Content for Eagle Ford clay, Houston Black clay, and Black Taylor clay at 25g-level and 97% RC (after Walker, 2012)

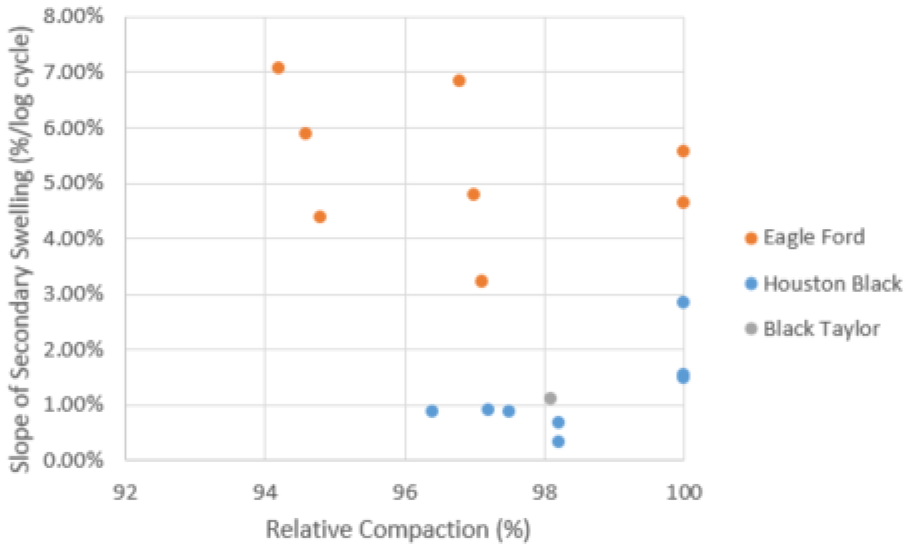


Figure 5.17: Secondary Swelling vs Relative Compaction for Eagle Ford clay, Houston Black clay, and Black Taylor clay at 5g-level and OPT (after Walker, 2012)

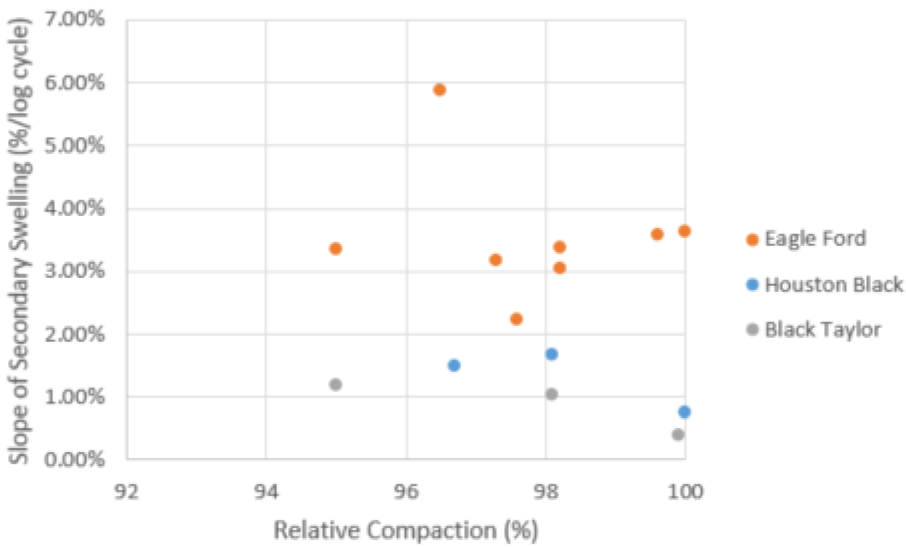


Figure 5.18: Secondary Swelling vs Relative Compaction for Eagle Ford clay, Houston Black clay, and Black Taylor clay at 25g-level and OPT (after Walker, 2012)

5.5 Summary of Test Results

The rate of secondary swelling in Tan Taylor specimens was found to increase with increasing molding water content and increasing relative compaction. The slope of secondary swelling showed a decline with increasing g-level. Changing the height of specimen had a similar effect as that of altering the g-level. The head of infiltrating liquid and its concentration, did not affect the rate of secondary swelling appreciably.

CHAPTER 6: ANALYSIS OF TEST RESULTS

The trends observed in the rate of secondary swelling for Tan Taylor clay, plotted against parameters including molding water content, compaction dry unit weight, g-level, specimen height, head of infiltrating liquid and its concentration, were carefully evaluated. The secondary swelling test results for Eagle Ford clay, Houston Black clay, and Black Taylor clay were also analyzed and compared with those obtained for Tan Taylor clay. A detailed analysis of the results is presented in this chapter.

6.1 Effect of Molding Water Content

The rate of secondary swelling was found to increase with increasing molding water content. The trend was found to be consistent across different g-levels. The effect was conspicuous in going from a dry of optimum moisture content towards wet of optimum. Figure 6.1 presents secondary swelling for a relative compaction of 97%, as a function of molding water content at 5g and 25g.

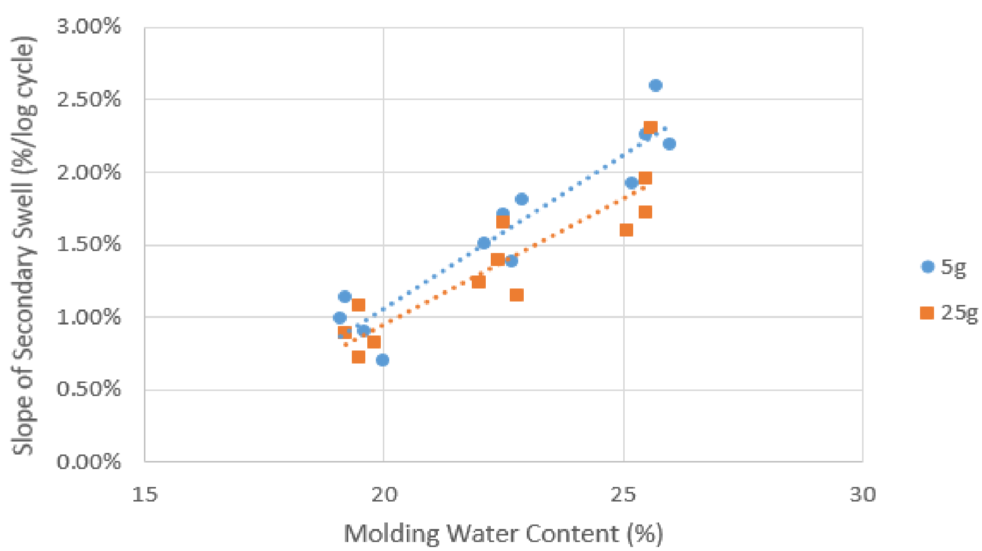


Figure 6.1: Secondary Swelling vs Compaction Water Content at 97% RC for Tan Taylor clay

The concept of flow processes associated with bimodal pore size distribution in an unsaturated expansive clay may be invoked to explain this trend. Soils compacted dry of optimum have a flocculated structure with a higher hydraulic conductivity due to 'piping' effect. Water can easily access the micropores causing rapid primary swelling. The high suction gradient drives the swelling mechanism. This is reflected as a steep slope in the primary swelling region. At the end of primary swelling, the macrostructure is invaded by swollen micropores and irreversible structural rearrangement takes place diminishing the capacity of the clay to swell in the secondary region.

On the other hand, soils compacted wet of optimum have a dispersed structure with lower hydraulic conductivity. Water takes time to reach the micropores, hence they possess a higher capacity for swell in the secondary region.

The swell vs. time curves depicted in Figure 6.2, for specimens compacted dry of optimum and wet of optimum water contents, supports the trend observed in Figure 6.1.

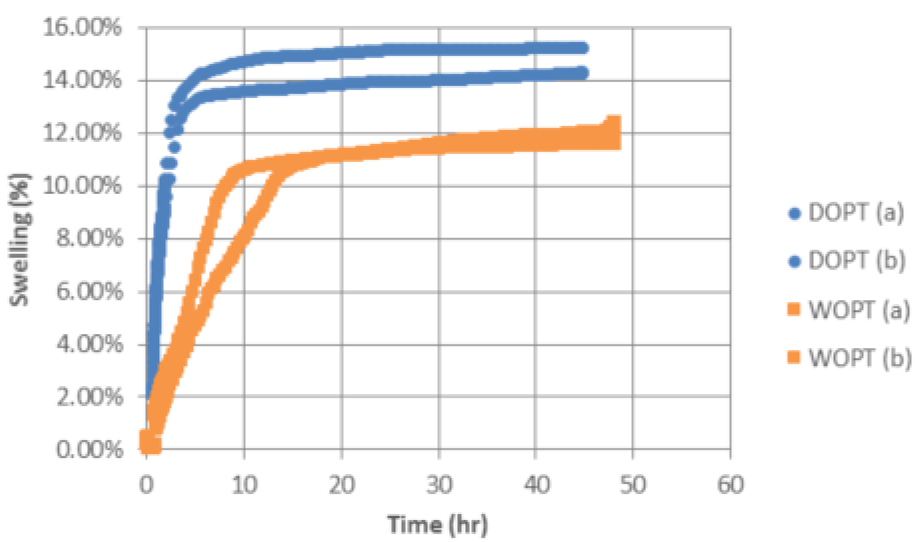


Figure 6.2: Swelling vs Time curves for Tan Taylor specimens compacted at different initial water contents at 5g-level and 97% RC

Based on the above discussion, it may be inferred that higher secondary swelling in an expansive clay (Tan Taylor) is associated with lower primary swelling. The discrepancy in swelling in the secondary region (Figure 6.2) is due to variation in the initial molding water content which leads to difference in clay structure during compaction.

6.2 Effect of Relative Compaction

At a given water content, secondary swelling was found to increase with increasing relative compaction. This effect is displayed in Figure 6.3.

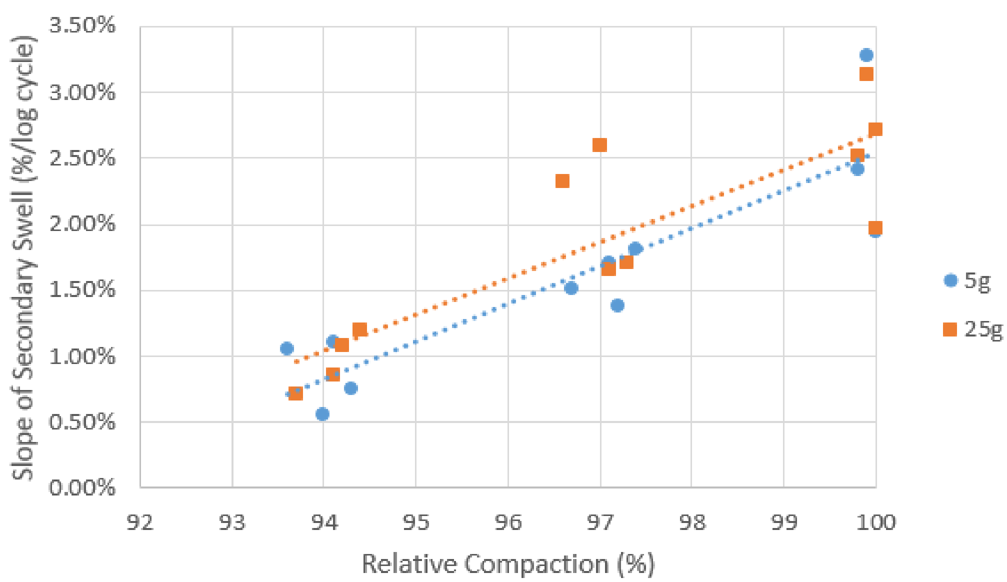


Figure 6.3: Secondary Swelling vs Relative Compaction at baseline conditions for Tan Taylor clay

The trend may be explained using Figure 6.4, which depicts the effect of compaction on soil structure. The orange arrow indicates the direction of increased dispersion.

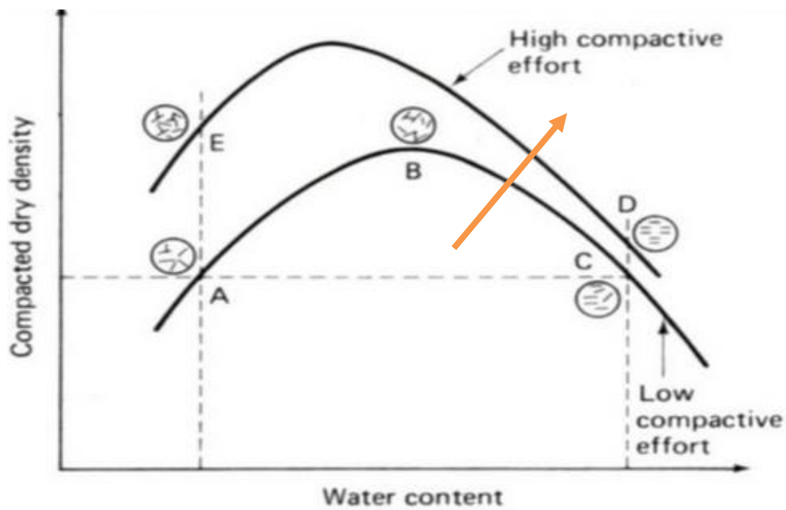


Figure 6.4: Effect of compaction on soil structure (after Lambe 1958)

The above figure (after Lambe 1958) shows that the degree of dispersion increases with relative compaction. Soils compacted to a lower dry density tend to have a less dispersed structure. The infiltrating liquid can easily reach the pores causing higher primary swelling. However, the capacity for secondary swelling is reduced in these specimens.

On the other hand, soils at a higher relative compaction have a more dispersed structure and higher capacity for swelling in the secondary region.

The swell vs. time curves presented in Figure 6.5, for specimens compacted at different relative compaction, concurs with the trend noticed in Figure 6.3. The initial molding water content is same (= OPT) in both cases leading to a similarity in the clay structure. This effect is reflected in the identical secondary swelling values observed for the soils compacted at different dry densities.

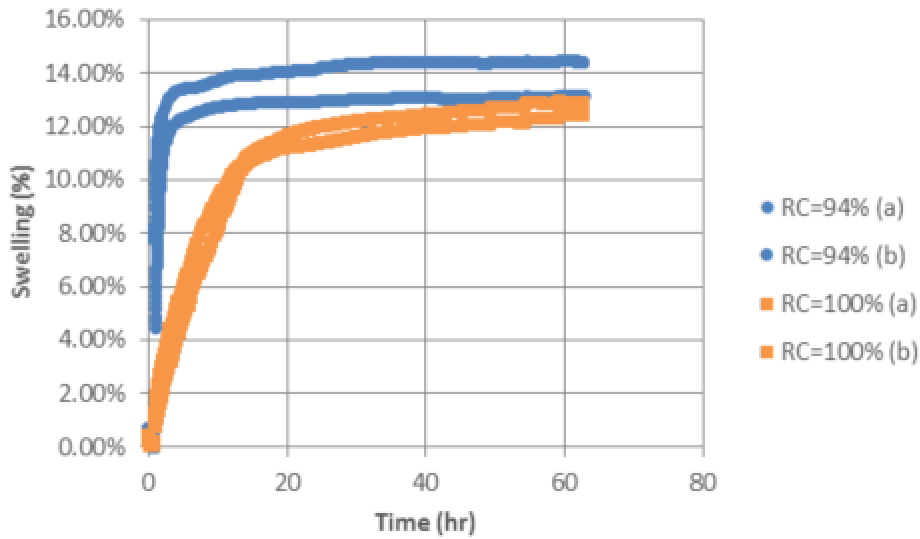


Figure 6.5: Swelling vs Time curves for Tan Taylor specimens at different relative compaction for 5g-level at OPT

6.3 Effect of G-level

A decrease in the rate of secondary swelling was seen upon increasing the g-level. This could be due to higher imposed stresses at increasing g-levels. The effect was found to be particularly noticeable at higher g-levels namely, 200g. Figure 6.6 depicts the effect for Tan Taylor clay at baseline condition.

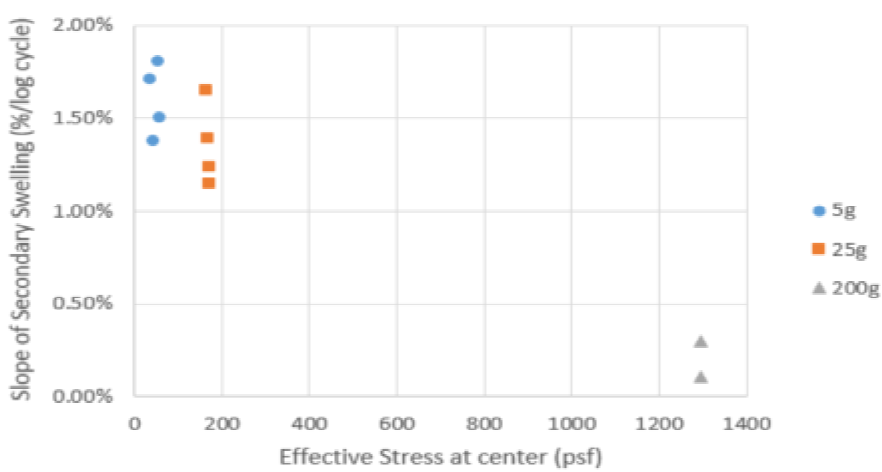


Figure 6.6: Secondary Swelling vs Effective Stress at center of specimen for different g-levels (Tan Taylor clay at baseline conditions)

Tests conducted at a higher g-level (200g) yielded a very low value of secondary swell owing to excessive stress and preferential flow channels through the specimen. A g-level of 5 was found to be the condition that led to the higher values of secondary swelling, facilitating investigation of relevant variables.

6.4 Effect of Specimen Height

Change in specimen height introduced additional stress and affected the overall quantum of swelling. It was observed that the slope of secondary swelling exhibits a gentle negative slope with increasing specimen heights. The effect is similar to that of altering the g-level. However, unlike the imposed g-level, it had a comparatively minor effect on the slope of the secondary swelling portion as the stresses were significantly low. Figure 6.7 shows the swell vs stress curve for Tan Taylor clay specimens compacted to different heights prior to testing.

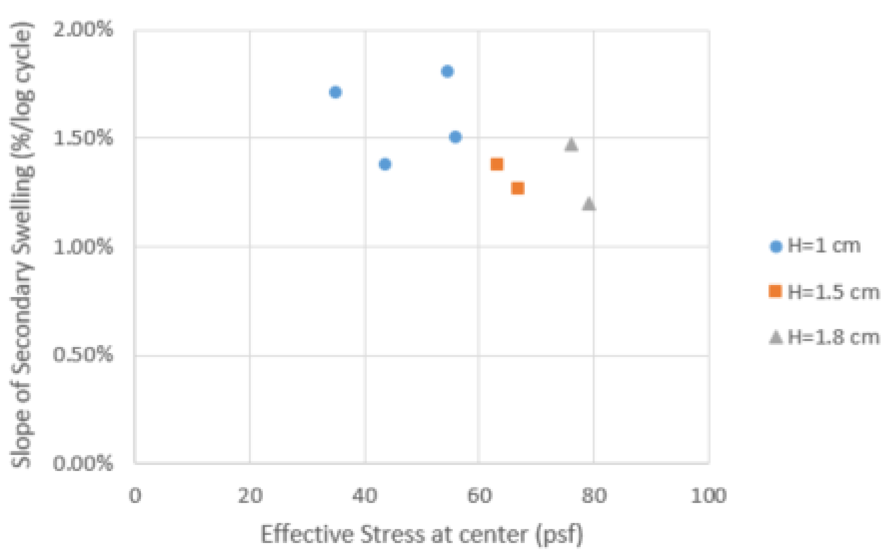


Figure 6.7: Secondary Swelling vs Effective Stress at center of specimen for different specimen heights (Tan Taylor clay at 5g-level, OPT, 97% RC)

6.5 Effect of Head of Infiltrating Liquid

Altering the level of infiltrating liquid was found not to affect the rate of secondary swelling appreciably. The slope of the secondary swelling curve was expected to remain fairly unchanged with infiltrating liquid (water) head provided water was available during the secondary swelling phase and did not get completely expended during any stage of the test. Figure 6.8 presents the effect of head of the infiltrating liquid in Tan Taylor clay samples at baseline condition and 5g-level.

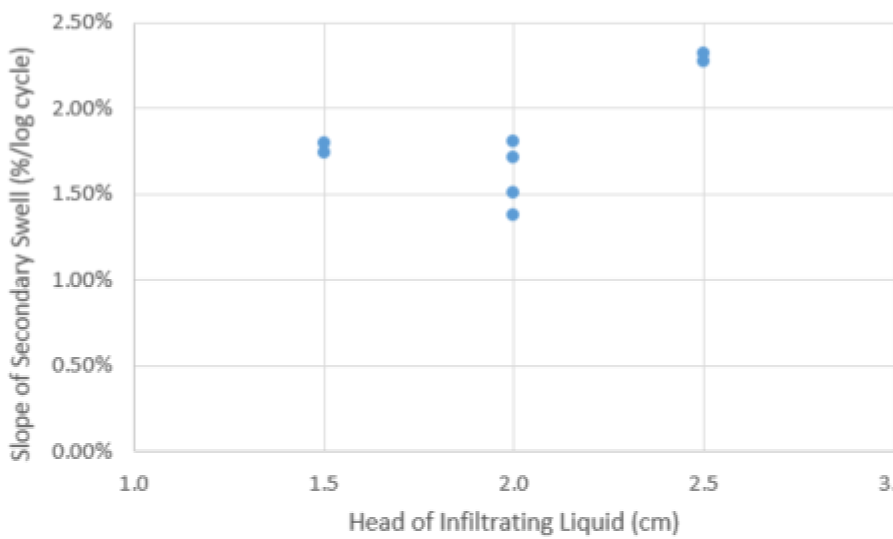


Figure 6.8: Secondary Swelling vs Infiltrating Liquid Head in Tan Taylor (5g, OPT, 97% RC)

However, a slight increase in the secondary swelling rate was observed for 2.5 cm head of water. It has been observed that a higher imposed hydraulic gradient creates preferential flow channels through the sides of the sample in contact with the walls of the cup. It could be reasoned that the flow causes uneven swelling of the specimen which probably led to erroneous LPS (Linear Position Sensor) readings.

6.6 Effect of Concentration of Infiltrating Liquid

The rate of secondary swelling did not seem to change significantly with the concentration of the infiltrating liquid. Results from tests at baseline conditions and 5g for deaired, distilled water, tap water and 1M NaCl solution point toward this conclusion. Figure 6.9 depicts the trend.

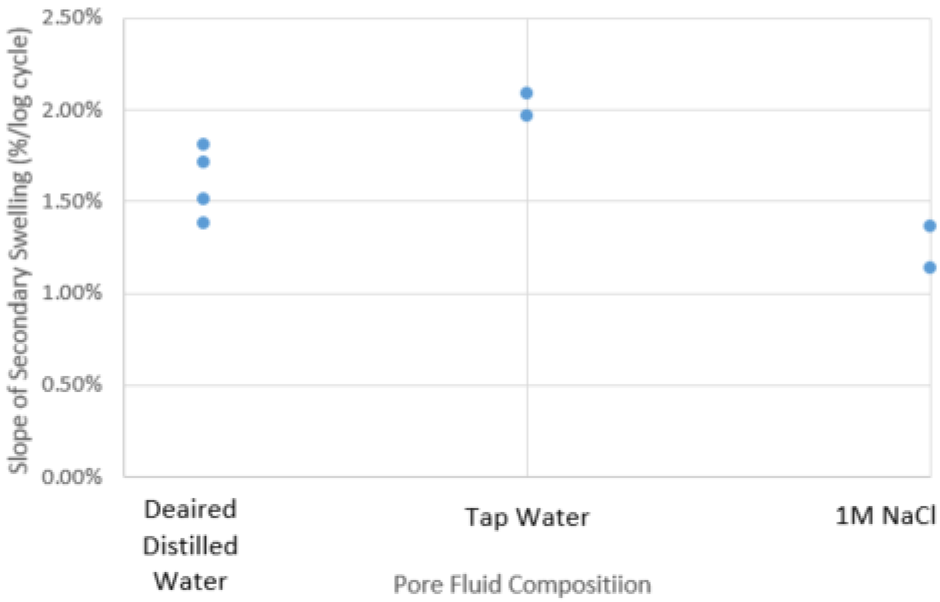


Figure 6.9: Secondary Swelling as a function of the Concentration of Infiltrating Liquid for Tan Taylor specimens (5g, OPT, 97% RC)

However, the overall swell decreased with an increase in concentration of the ponded solution. This finding is consistent with the Diffuse Double Layer theory for mechanism of swelling in clays. If the concentration of cations in the solution is more, the diffuse double layer cations would have less tendency to migrate (diffuse) and the double layer shrinks leading to less swell. After the primary swelling is complete, the diffuse double layer thickness remains same and cationic exchange (diffusion) attains a dynamic equilibrium. Hence, there is no noticeable effect on secondary swelling.

6.7 Effect of Soil Type

The dependence of the rate of secondary swelling on molding water content and relative compaction was compared at 5g and 25g levels for Tan Taylor clay, Eagle Ford clay, Houston Black clay, and Black Taylor clay. Figure 6.10 and Figure 6.11 present the effect of molding water content on secondary swelling for the soils at 5g and 25g respectively. Figure 6.12 and Figure 6.13 depict the trend for relative compaction plotted against the slope of secondary swelling for the soils at 5g and 25g respectively.

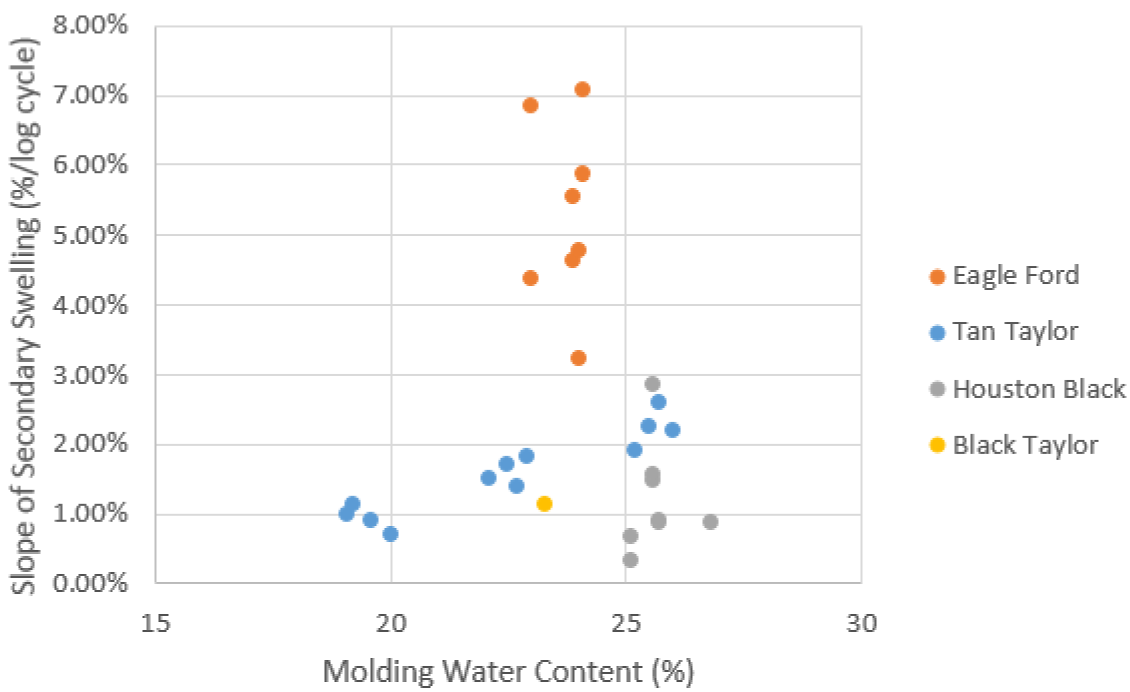


Figure 6.10: Comparison of Secondary Swelling vs Molding Water Content for all soils at 5g-level and 97% RC

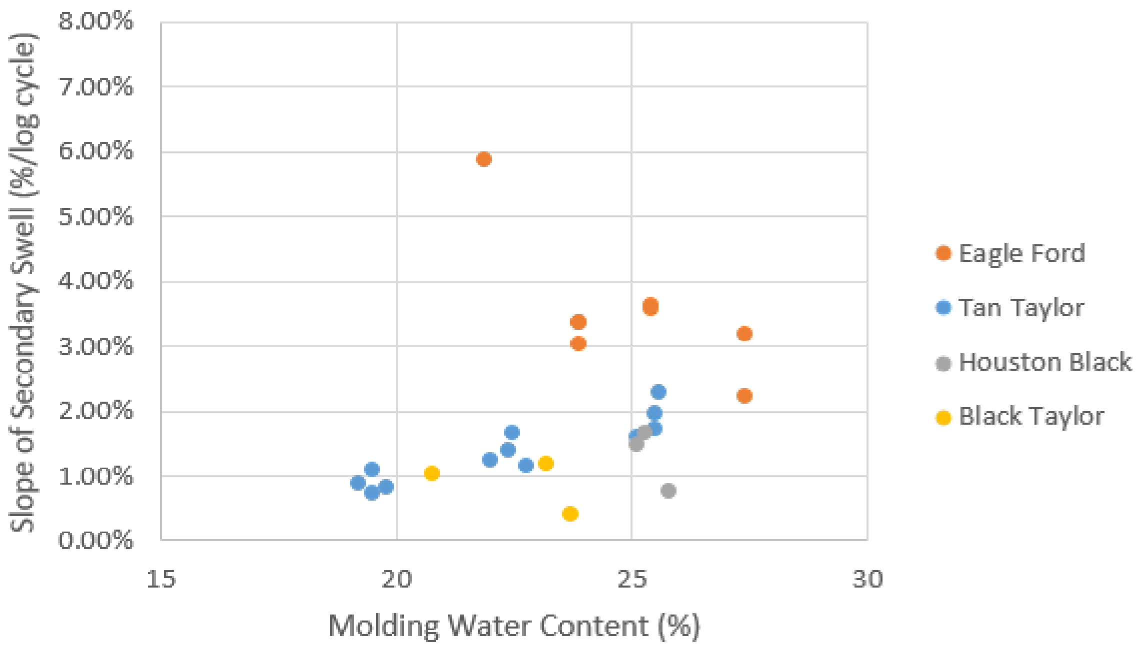


Figure 6.11: Comparison of Secondary Swelling vs Molding Water Content for all soils at 25g level and 97% RC

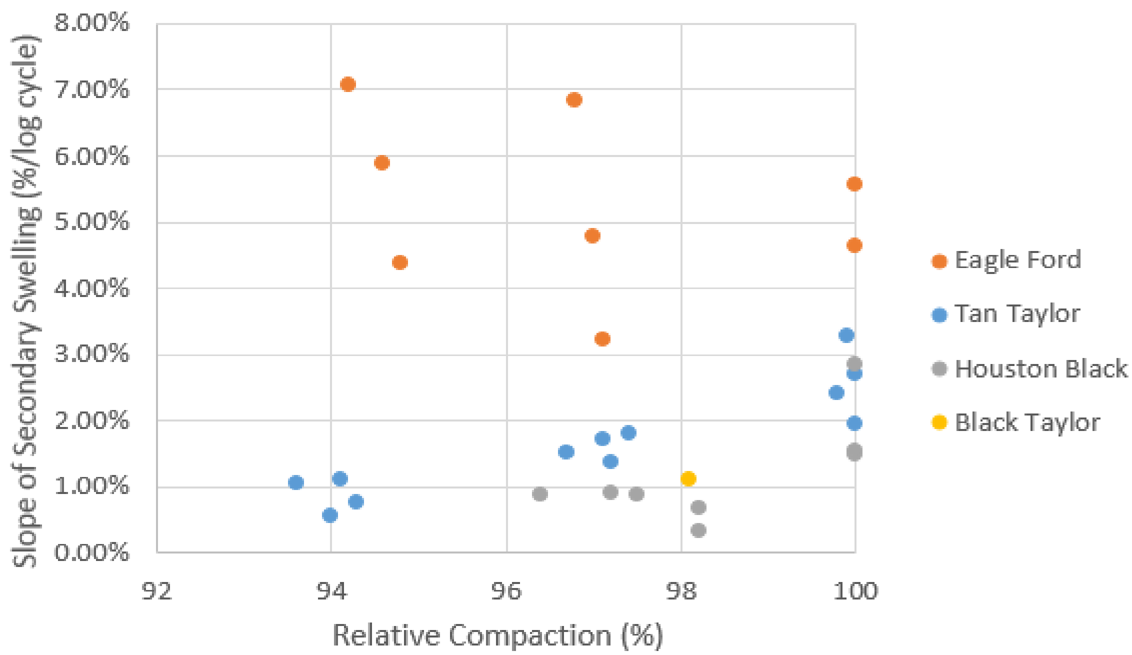


Figure 6.12: Comparison of Secondary Swelling vs Relative Compaction for all soils at 5g level and OPT

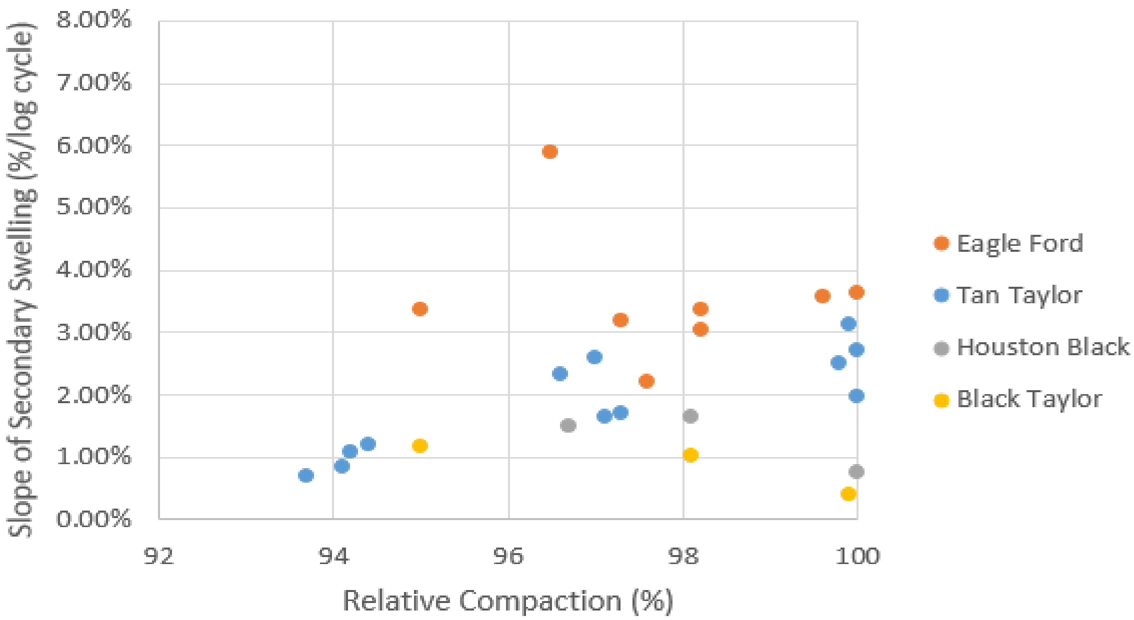


Figure 6.13: Comparison of Secondary Swelling vs Relative Compaction for all soils at 25g-level and OPT

The trend shows soils having comparable clay fractions (activity) show similar secondary swelling. The rate of secondary swelling was found to increase with an increase in the clay fraction of the soil. The scatter in the above plot indicates that swell phenomena depends on the mineralogical composition of the soils. Secondary swelling may be interpreted to result from the interaction between volume change of expansive clay minerals at the microstructural level and the macrostructural pores.

The slope of secondary swelling when plotted against the Plasticity Index and Liquid Limit also shows an upward trend as shown in Figure 6.14 and Figure 6.15.

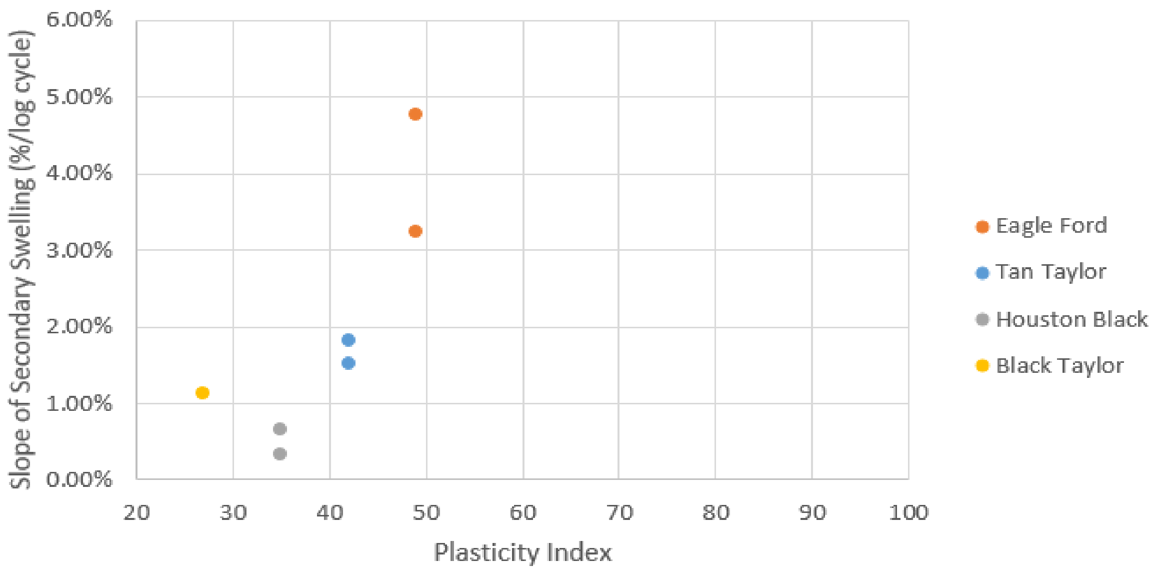


Figure 6.14: Secondary Swelling vs Plasticity Index for all soils at 5g and baseline conditions

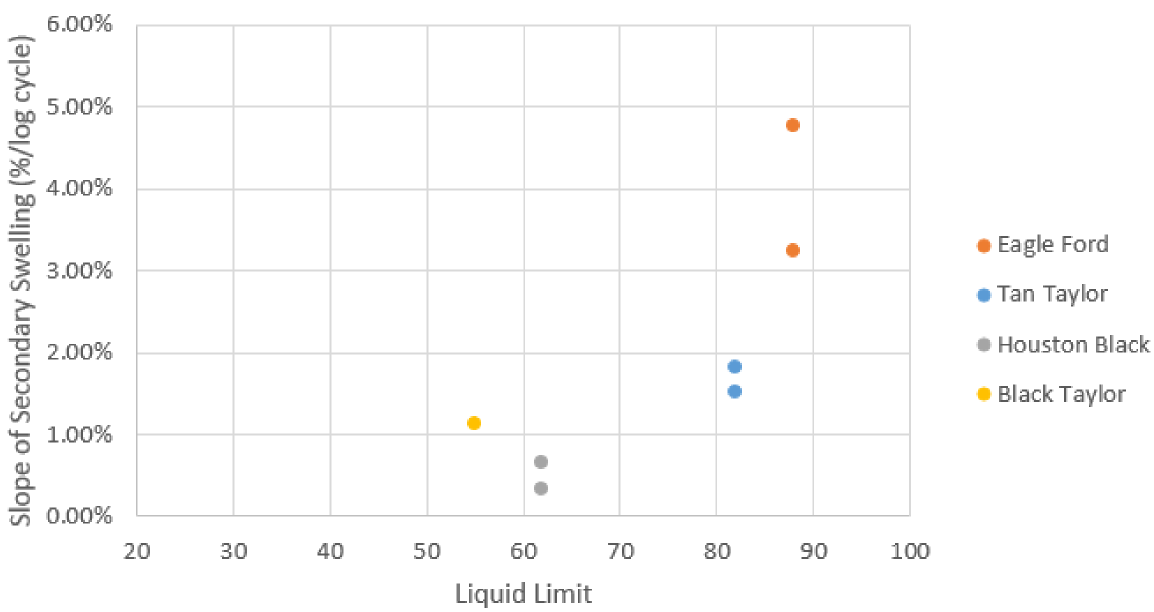


Figure 6.15: Secondary Swelling vs Liquid Limit for all soils at 5g and baseline conditions

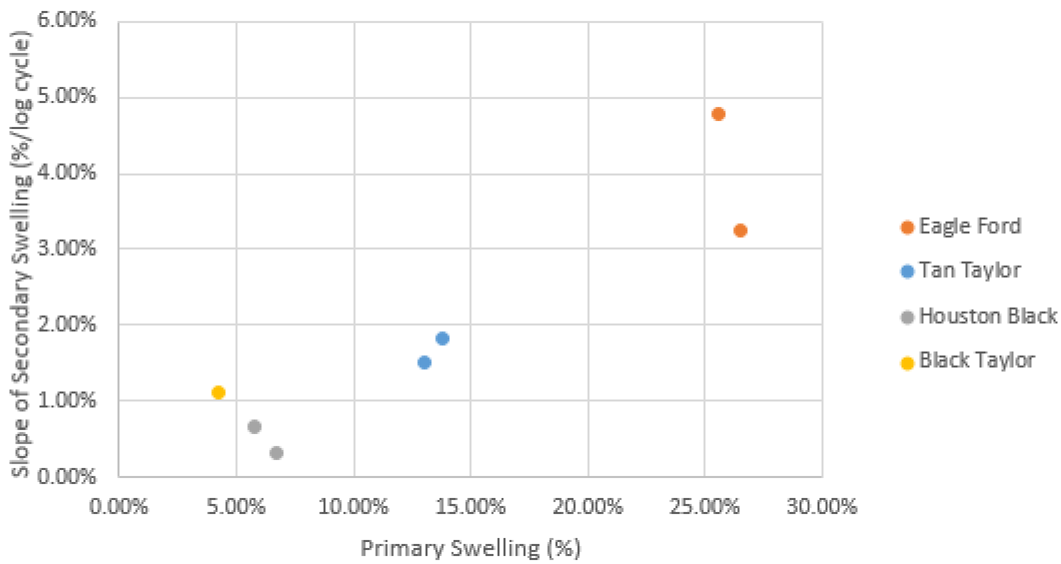


Figure 6.16: Comparison of Slope of Secondary Swelling vs Primary Swelling for all soils at baseline conditions and 5g-level

The slope of secondary swelling for different soils when plotted against the magnitude of primary swelling, showed an upward trend with increasing primary swelling. The comparison is presented in Figure 6.16.

6.8 Concluding Remarks

The effect of testing parameters including molding water content, compaction dry unit weight, g-level, specimen height, head of infiltrating liquid and its concentration, on the rate of secondary swelling in Tan Taylor clay specimens, were thoroughly analyzed. Analysis of results from testing program conducted by Walker (2012) on Eagle Ford clay, Houston Black clay, and Black Taylor clay were also included in this chapter, specifically the influence of molding water content, relative compaction, and soil mineralogy and index properties. This concludes the analysis of test results for this study.

CHAPTER 7: CONCLUSIONS

The phenomenon of secondary swelling in expansive clays was examined in this investigation. Specifically, the secondary swelling behavior of Tan Taylor clay was evaluated in detail using a centrifuge based method. The centrifuge set up was preferred to the traditional ASTM D4546 method as it significantly reduces the time taken to exhibit secondary swelling in clays. Swell curves for other high PI clays namely – Eagle Ford, Black Taylor and Houston Black, were also studied to determine reasons for this additional swell beyond primary swelling.

Based on the results from the testing program, the following conclusions may be drawn:

- The rate of secondary swelling was found to increase with increasing molding water content of reconstituted clay samples.
- Samples compacted under dry initial conditions which leads to a flocculated structure exhibit rapid primary swelling. However, they were found to exhibit less secondary swelling as compared to samples prepared under wet initial conditions which lead to a dispersed structure.
- The slope of secondary swell curve was found to increase with increasing compaction dry unit weight (relative compaction).
- The rate of secondary swelling showed a decline with increasing gravitational gradient (g-level).
- Altering the height of specimen did not affect the slope of secondary swelling significantly.
- No appreciable change in the rate of secondary swelling was observed with changes in the head of the infiltrating liquid or its concentration.

- The rate of secondary swelling showed evidence of upward trend with an increase in the plasticity index and clay fraction of the soil.
- The slope of secondary swelling among expansive soils was found to increase with increasing magnitude of primary swelling implying soils which exhibit higher primary swelling also undergo higher secondary swelling.
- Secondary swelling may be explained by flow processes associated with the bimodal pore size distribution in expansive clays.

While the magnitude of secondary swelling is comparatively smaller than primary swelling, the rate of secondary swelling is relevant to completely characterize the swell behavior of expansive soils.

APPENDIX A: CENTRIFUGE SWELL TESTS ON TAN TAYLOR CLAY

The detailed results of centrifuge swell tests on Tan Taylor clay, in a standardized format, are reported in this appendix.

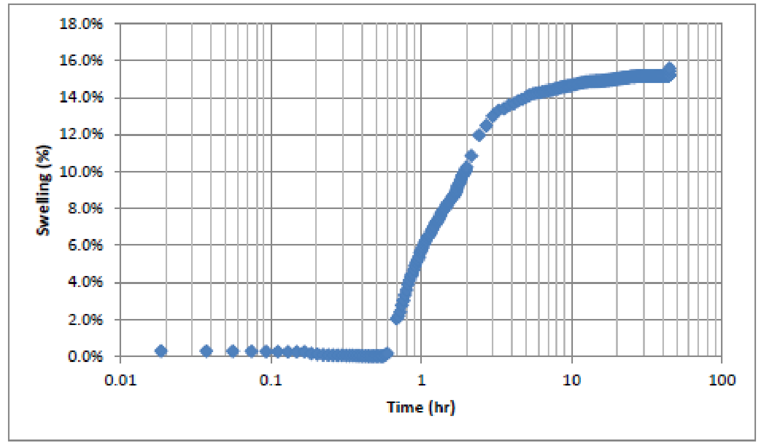
CENTRIFUGE TEST

Date test conducted	2/8/2013
Centrifuge used	Small
Cup Number	1
Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	8.53	gravity
	Initial ω	22.5%	22.1%	%
	Mass Soil added	49.17	49.22	g
	Dry Unit Weight	15.21	15.35	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	0.998	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.998	cm
	Testing Height	0.995	1.133	cm
	Void Ratio, e	0.745	0.986	-
	ω	22.1%	36.4%	%
	Saturation	81.0%	100.0%	%
	Change in ω	-	14.3%	%
	Overburden Mass	-	16.09	g
	Height of water	-	2.00	cm
	Swell	-	13.8%	%



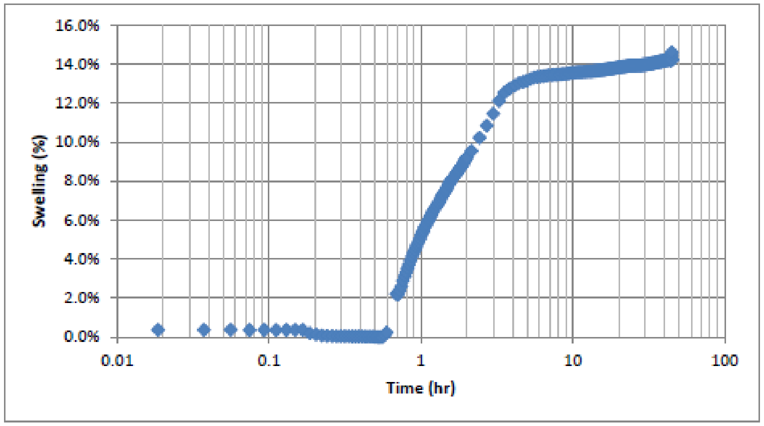
Slope of Secondary Swelling	1.512	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/8/2013
	Centrifuge used	Small
	Cup Number	2
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	8.53	gravity
	Initial ω	22.5%	22.9%	%
	Mass Soil added	49.17	49.20	g
	Dry Unit Weight	15.21	15.32	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.001	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.998	cm
	Testing Height	0.995	1.133	cm
	Void Ratio, e	0.745	0.986	-
	ω	22.9%	36.4%	%
	Saturation	80.6%	99.9%	%
	Change in ω	-	13.5%	%
	Overburden Mass	-	16.06	g
	Height of water	-	2.00	cm
	Swell	-	13.0%	%



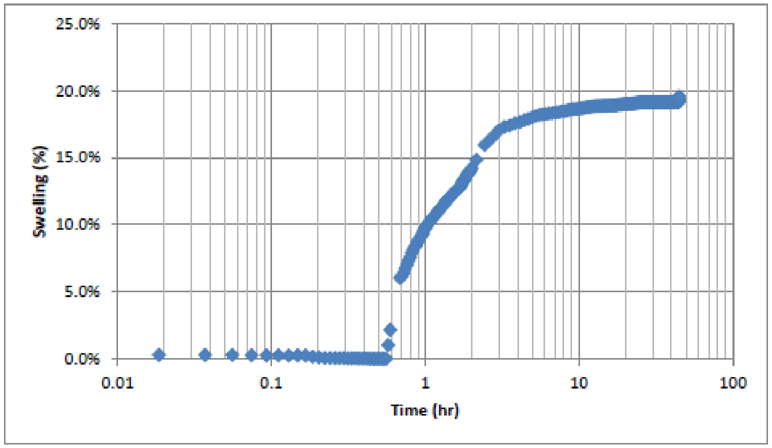
Slope of Secondary Swelling	1.814	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/4/2013
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	20%
	Water Content	DOPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	8.53	gravity
	Initial ω	19.5%	19.1%	%
	Mass Soil added	49.17	49.20	g
	Dry Unit Weight	15.21	15.32	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.002	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	1.002	cm
	Testing Height	0.997	1.127	cm
	Void Ratio, e	0.745	0.986	-
	ω	19.1%	34.2%	%
	Saturation	81.4%	98.2%	%
	Change in ω	-	15.1%	%
	Overburden Mass	-	16.06	g
	Height of water	-	2.00	cm
	Swell	-	19.5%	%



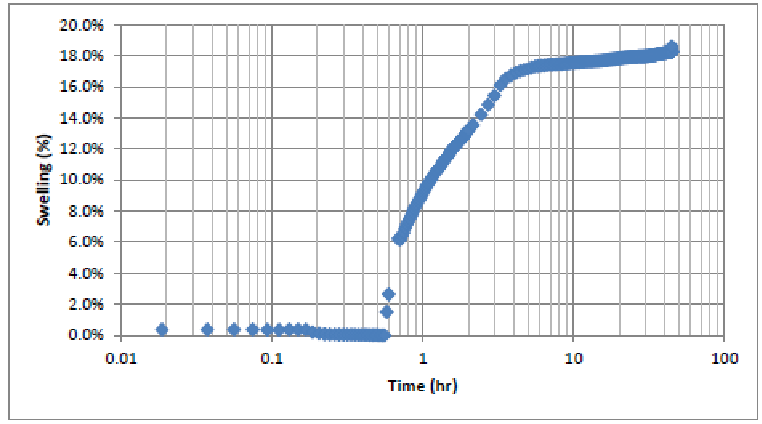
Slope of Secondary Swelling	1.142	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/4/2013
	Centrifuge used	Small
	Cup Number	2
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	20%
	Water Content	DOPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	8.53	gravity
	Initial ω	19.5%	19.2%	%
	Mass Soil added	49.17	49.20	g
	Dry Unit Weight	15.21	15.32	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.001	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	1.001	cm
	Testing Height	0.997	1.127	cm
	Void Ratio, e	0.748	0.985	-
	ω	19.2%	34.2%	%
	Saturation	80.6%	99.9%	%
	Change in ω	-	15.0%	%
	Overburden Mass	-	16.06	g
	Height of water	-	2.00	cm
	Swell	-	18.0%	%



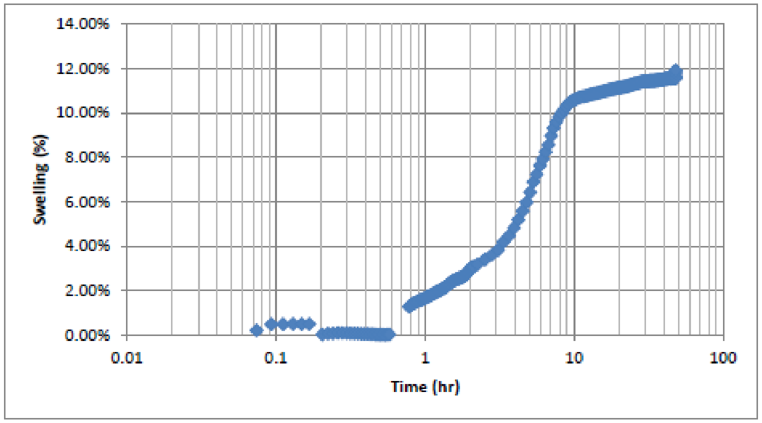
Slope of Secondary Swelling	0.903	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/4/2013
	Centrifuge used	Small
	Cup Number	3
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	WOPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	7.62	gravity
	Initial ω	25.5%	24.1%	%
	Mass Soil added	50.38	50.32	g
	Dry Unit Weight	15.22	15.14	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.001	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	1.035	cm
	Testing Height	1.030	1.139	cm
	Void Ratio, e	0.797	0.987	-
	ω	24.1%	34.0%	%
	Saturation	82.5%	94.0%	%
	Change in ω	-	9.9%	%
	Overburden Mass	-	15.46	g
	Height of water	-	2.00	cm
	Swell	-	10.5%	%



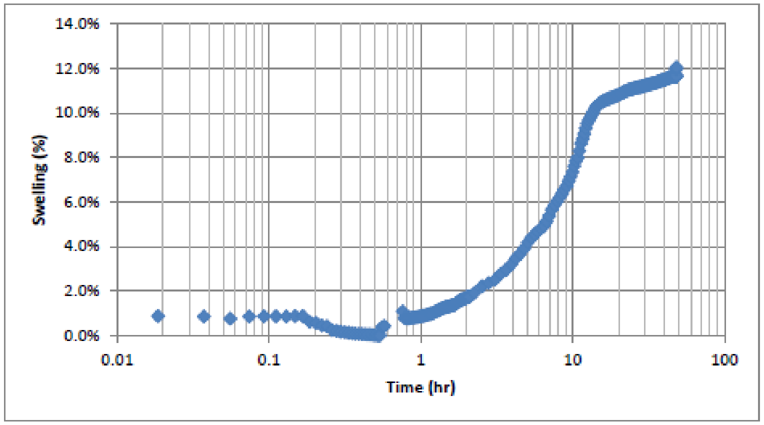
Slope of Secondary Swelling	1.923	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/4/2013
	Centrifuge used	Small
	Cup Number	4
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	WOPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.62	gravity
	Initial ω	25.5%	25.7%	%
	Mass Soil added	50.38	50.37	g
	Dry Unit Weight	15.22	15.53	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.000	cm
	Testing Height	0.991	1.094	cm
	Void Ratio, e	0.725	0.904	-
	ω	25.7%	34.3%	%
	Saturation	90.8%	100.0%	%
	Change in ω	-	8.6%	%
	Overburden Mass	-	15.35	g
	Height of water	-	2.00	cm
	Swell	-	10.4%	%



Slope of Secondary Swelling	2.607	%/log cycle

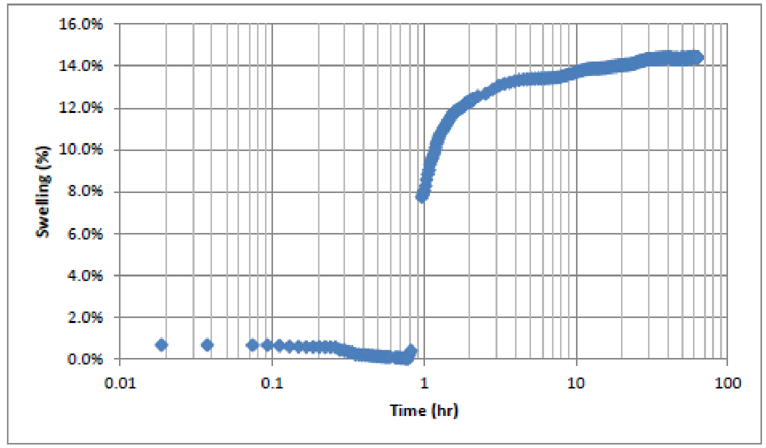
CENTRIFUGE TEST

Date test conducted	4/1/2013
Centrifuge used	Small
Cup Number	1
Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	94%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.45	gravity
	Initial ω	22.5%	22.4%	%
	Mass Soil added	47.65	47.90	g
	Dry Unit Weight	14.74	14.96	kN/m^3
	Relative Compaction	94%	94%	%
	Height of Sample	1.000	0.998	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.997	cm
	Testing Height	0.992	1.120	cm
	Void Ratio, e	0.790	1.022	-
	ω	22.4%	35.7%	%
	Saturation	77.4%	99.2%	%
	Change in ω	-	13.3%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	12.5%	%



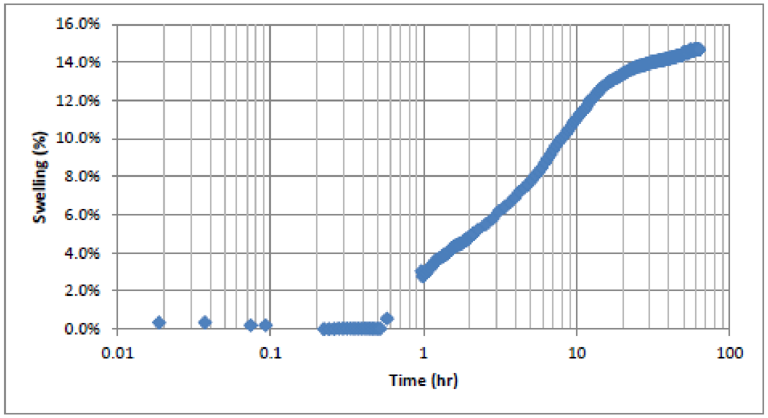
Slope of Secondary Swelling	1.051	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	4/1/2013
	Centrifuge used	Small
	Cup Number	3
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	100%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	7.45	gravity
	Initial ω	22.5%	22.2%	%
	Mass Soil added	50.70	50.81	g
	Dry Unit Weight	15.69	15.85	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	0.998	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.995	cm
	Testing Height	0.994	1.102	cm
	Void Ratio, e	0.690	0.873	-
	ω	22.2%	32.1%	%
	Saturation	87.9%	100.0%	%
	Change in ω	-	9.9%	%
	Overburden Mass	-	21.67	g
	Height of water	-	2.00	cm
	Swell	-	14.7%	%



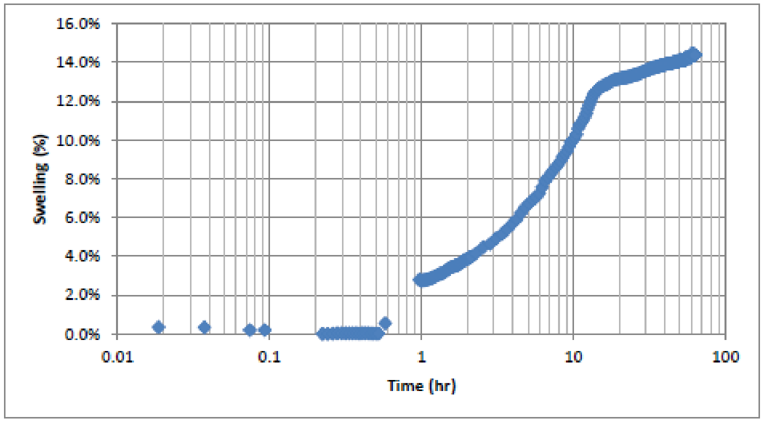
Slope of Secondary Swelling	3.274	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	4/1/2013
	Centrifuge used	Small
	Cup Number	4
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	100%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	7.45	gravity
	Initial ω	22.5%	22.2%	%
	Mass Soil added	50.70	50.68	g
	Dry Unit Weight	15.69	15.75	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	1.001	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	1.001	cm
	Testing Height	0.998	1.103	cm
	Void Ratio, e	0.700	0.879	-
	ω	22.2%	33.1%	%
	Saturation	86.6%	100.0%	%
	Change in ω	-	10.9%	%
	Overburden Mass	-	21.55	g
	Height of water	-	2.00	cm
	Swell	-	14.4%	%



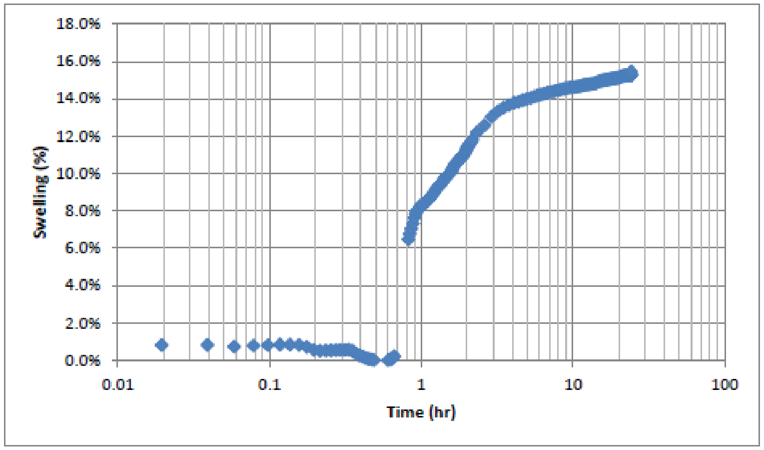
Slope of Secondary Swelling	2.412	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/26/2014
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.25	gravity
	Initial ω	22.5%	22.7%	%
	Mass Soil added	49.17	49.25	g
	Dry Unit Weight	15.21	15.34	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.996	cm
	Testing Height	0.992	1.143	cm
	Void Ratio, e	0.746	1.013	-
	ω	22.7%	36.0%	%
	Saturation	83.1%	98.9%	%
	Change in ω	-	13.3%	%
	Overburden Mass	-	22.31	g
	Height of water	-	1.50	cm
	Swell	-	15.3%	%



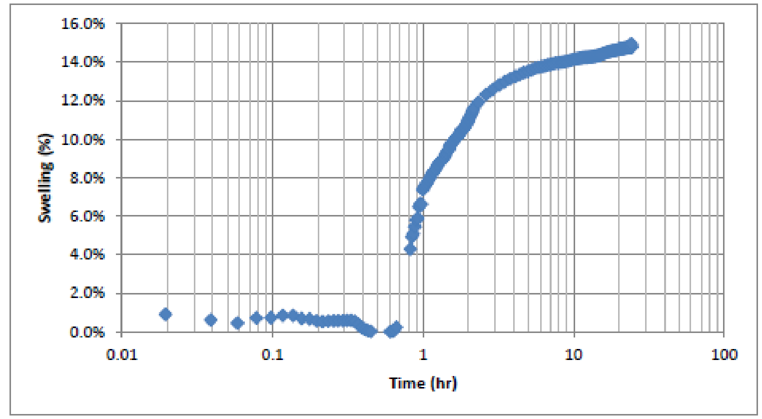
Slope of Secondary Swelling	1.796	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/26/2014
	Centrifuge used	Small
	Cup Number	3
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.25	gravity
	Initial ω	22.5%	22.7%	%
	Mass Soil added	49.17	49.15	g
	Dry Unit Weight	15.21	15.35	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.992	cm
	Testing Height	0.989	1.135	cm
	Void Ratio, e	0.744	1.002	-
	ω	22.7%	36.1%	%
	Saturation	83.3%	98.3%	%
	Change in ω	-	13.4%	%
	Overburden Mass	-	21.60	g
	Height of water	-	1.50	cm
	Swell	-	14.8%	%



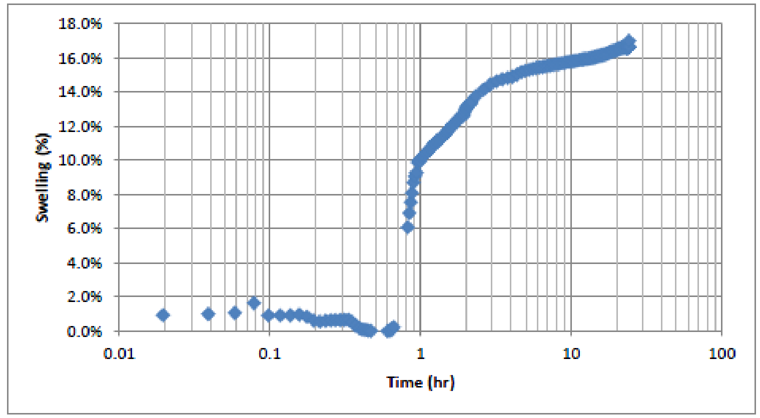
Slope of Secondary Swelling	1.745	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/26/2014
	Centrifuge used	Small
	Cup Number	2
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.25	gravity
	Initial ω	22.5%	22.7%	%
	Mass Soil added	49.17	49.19	g
	Dry Unit Weight	15.21	15.38	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.992	cm
	Testing Height	0.988	1.153	cm
	Void Ratio, e	0.742	1.032	-
	ω	22.7%	34.7%	%
	Saturation	83.6%	99.1%	%
	Change in ω	-	12.0%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.50	cm
	Swell	-	16.6%	%



Slope of Secondary Swelling	2.32	%/log cycle

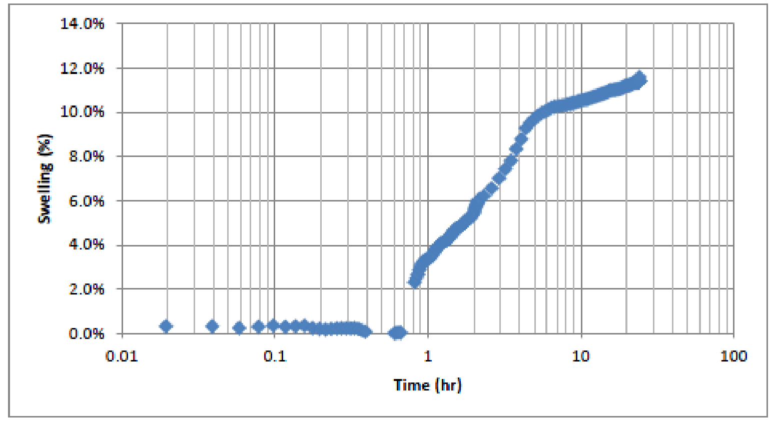
CENTRIFUGE TEST

Date test conducted	2/26/2014
Centrifuge used	Small
Cup Number	4
Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.25	gravity
	Initial ω	22.5%	22.7%	%
	Mass Soil added	49.17	49.17	g
	Dry Unit Weight	15.21	15.28	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.996	cm
	Testing Height	0.994	1.108	cm
	Void Ratio, e	0.753	0.953	-
	ω	22.7%	34.4%	%
	Saturation	82.3%	99.7%	%
	Change in ω	-	11.7%	%
	Overburden Mass	-	21.46	g
	Height of water	-	2.50	cm
	Swell	-	11.4%	%



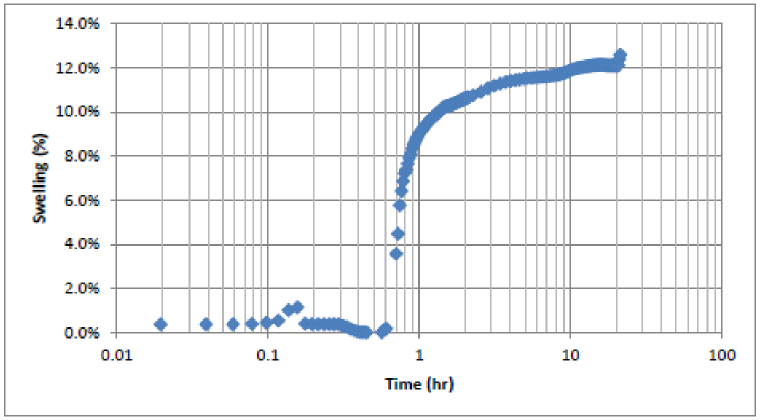
Slope of Secondary Swelling	2.275	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/2/2014
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23% (tap water)
	Water Content	OPT (tap water)
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	6.61	gravity
	Initial ω	22.5%	22.7%	%
	Mass Soil added	49.17	49.19	g
	Dry Unit Weight	15.21	15.25	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.000	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.999	cm
	Testing Height	0.996	1.117	cm
	Void Ratio, e	0.756	0.968	-
	ω	22.7%	35.5%	%
	Saturation	82.0%	100.0%	%
	Change in ω	-	12.8%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	12.1%	%



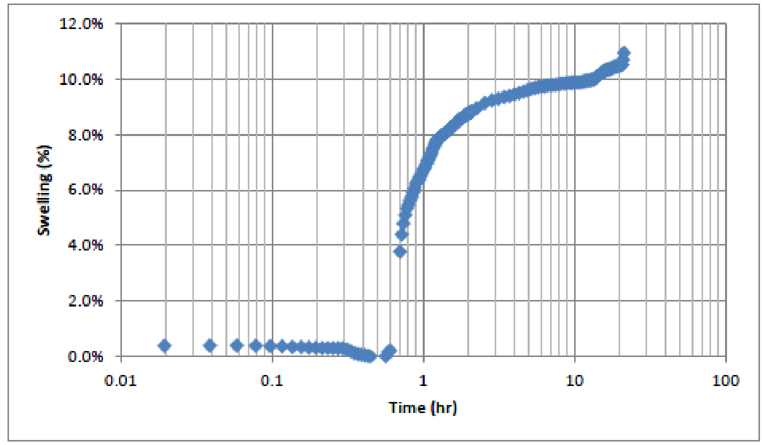
Slope of Secondary Swelling	1.964	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/2/2014
	Centrifuge used	Small
	Cup Number	2
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23% (tap water)
	Water Content	OPT (tap water)
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	6.61	gravity
	Initial ω	22.5%	22.7%	%
	Mass Soil added	49.17	49.19	g
	Dry Unit Weight	15.21	15.25	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.999	cm
	Testing Height	0.996	1.101	cm
	Void Ratio, e	0.757	0.942	-
	ω	22.7%	34.5%	%
	Saturation	81.9%	100.0%	%
	Change in ω	-	11.8%	%
	Overburden Mass	-	22.31	g
	Height of water	-	2.00	cm
	Swell	-	10.5%	%



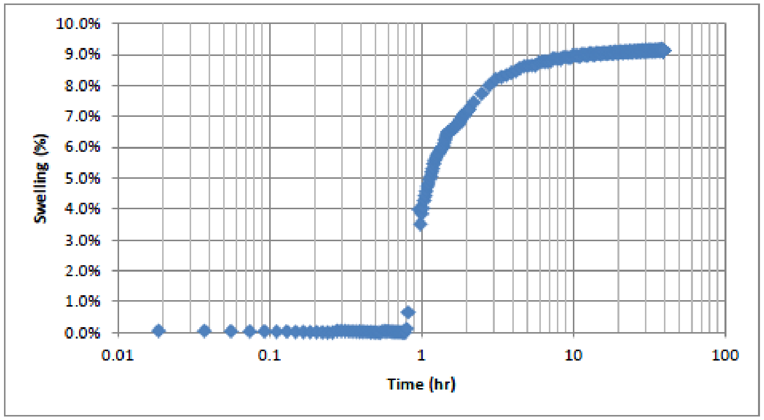
Slope of Secondary Swelling	2.084	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/16/2014
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23% (1M NaCl soln.)
	Water Content	OPT (1M NaCl soln.)
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	6.84	gravity
	Initial ω	22.5%	22.2%	%
	Mass Soil added	49.17	49.25	g
	Dry Unit Weight	15.21	15.42	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.000	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	1.000	cm
	Testing Height	0.991	1.081	cm
	Void Ratio, e	0.737	0.896	-
	ω	22.2%	30.7%	%
	Saturation	82.2%	99.2%	%
	Change in ω	-	8.5%	%
	Overburden Mass	-	21.21	g
	Height of water	-	2.00	cm
	Swell	-	8.5%	%



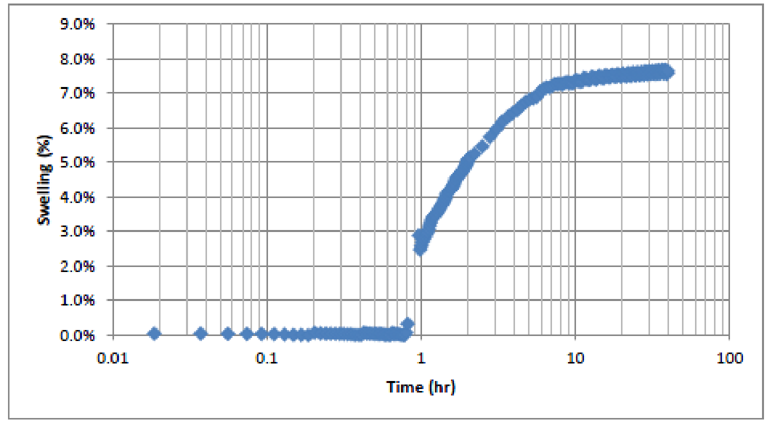
Slope of Secondary Swelling	1.14	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/16/2014
	Centrifuge used	Small
	Cup Number	2
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23% (1M NaCl soln.)
	Water Content	OPT (1M NaCl soln.)
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	6.84	gravity
	Initial ω	22.5%	22.2%	%
	Mass Soil added	49.17	49.16	g
	Dry Unit Weight	15.21	15.43	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	0.997	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.997	cm
	Testing Height	0.988	1.064	cm
	Void Ratio, e	0.736	0.868	-
	ω	22.2%	30.6%	%
	Saturation	82.3%	99.8%	%
	Change in ω	-	8.4%	%
	Overburden Mass	-	20.89	g
	Height of water	-	2.00	cm
	Swell	-	7.6%	%



Slope of Secondary Swelling	1.362	%/log cycle

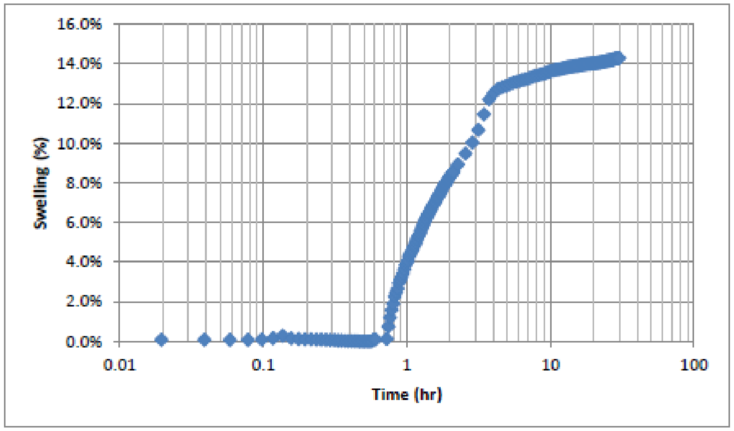
CENTRIFUGE TEST

Date test conducted	2/27/2014
Centrifuge used	Small
Cup Number	2
Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	5.54	gravity
	Initial ω	22.5%	22.7%	%
	Mass Soil added	73.76	73.66	g
	Dry Unit Weight	15.35	15.27	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.497	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	1.498	cm
	Testing Height	1.496	1.737	cm
	Void Ratio, e	0.761	1.044	-
	ω	22.7%	36.0%	%
	Saturation	81.4%	99.1%	%
	Change in ω	-	13.3%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	13.1%	%



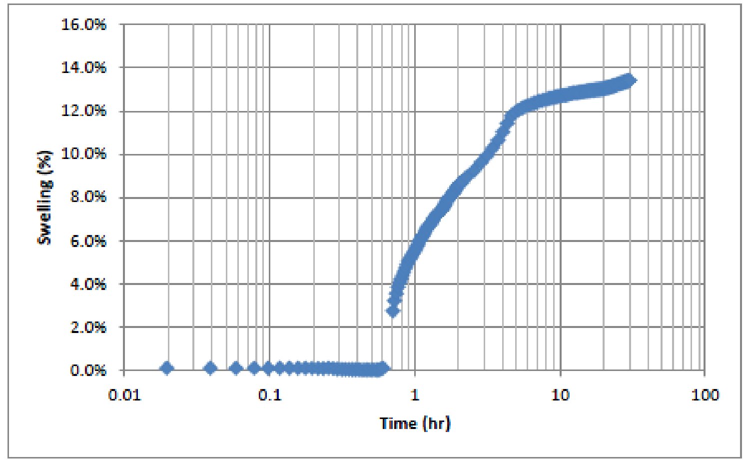
Slope of Secondary Swelling	1.272	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/27/2014
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	5.54	gravity
	Initial ω	22.5%	22.7%	%
	Mass Soil added	98.32	98.34	g
	Dry Unit Weight	15.35	15.42	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.800	1.805	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.805	cm
	Testing Height	1.800	2.011	cm
	Void Ratio, e	0.762	1.027	-
	ω	22.7%	36.0%	%
	Saturation	81.3%	96.2%	%
	Change in ω	-	13.3%	%
	Overburden Mass	-	22.31	g
	Height of water	-	2.00	cm
	Swell	-	12.8%	%



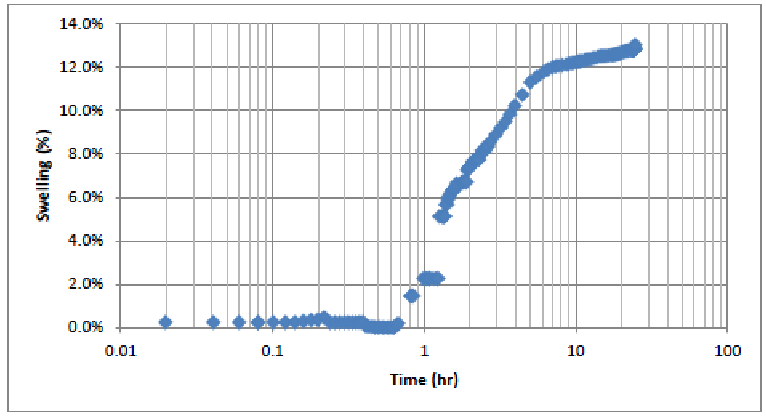
Slope of Secondary Swelling	1.473	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/14/2014
	Centrifuge used	Small
	Cup Number	2
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	5.22	gravity
	Initial ω	22.5%	22.0%	%
	Mass Soil added	73.76	73.79	g
	Dry Unit Weight	15.35	15.35	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.500	1.497	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.496	cm
	Testing Height	1.494	1.685	cm
	Void Ratio, e	0.745	0.969	-
	ω	22.0%	33.2%	%
	Saturation	80.6%	97.9%	%
	Change in ω	-	11.2%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	13.0%	%



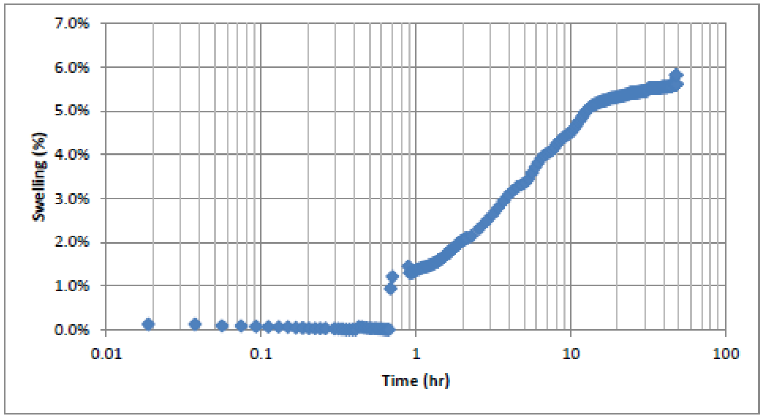
Slope of Secondary Swelling	1.377	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/3/2013
	Centrifuge used	Small
	Cup Number	3
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	WOPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	27.09	gravity
	Initial ω	25.5%	25.6%	%
	Mass Soil added	50.38	50.22	g
	Dry Unit Weight	15.22	15.49	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	0.999	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.993	cm
	Testing Height	0.979	1.028	cm
	Void Ratio, e	0.729	0.817	-
	ω	25.6%	30.0%	%
	Saturation	95.8%	100.0%	%
	Change in ω	-	4.4%	%
	Overburden Mass	-	21.83	g
	Height of water	-	2.00	cm
	Swell	-	6.0%	%



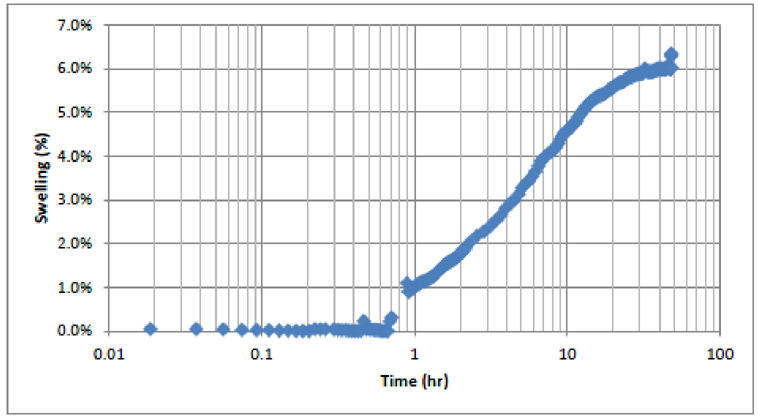
Slope of Secondary Swelling	1.602	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/3/2013
	Centrifuge used	Small
	Cup Number	4
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	WOPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	27.09	gravity
	Initial ω	25.5%	25.6%	%
	Mass Soil added	50.38	50.47	g
	Dry Unit Weight	15.22	15.41	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	0.999	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.001	cm
	Testing Height	0.988	1.041	cm
	Void Ratio, e	0.738	0.830	-
	ω	25.6%	30.7%	%
	Saturation	94.8%	100.0%	%
	Change in ω	-	5.1%	%
	Overburden Mass	-	21.49	g
	Height of water	-	2.00	cm
	Swell	-	6.2%	%



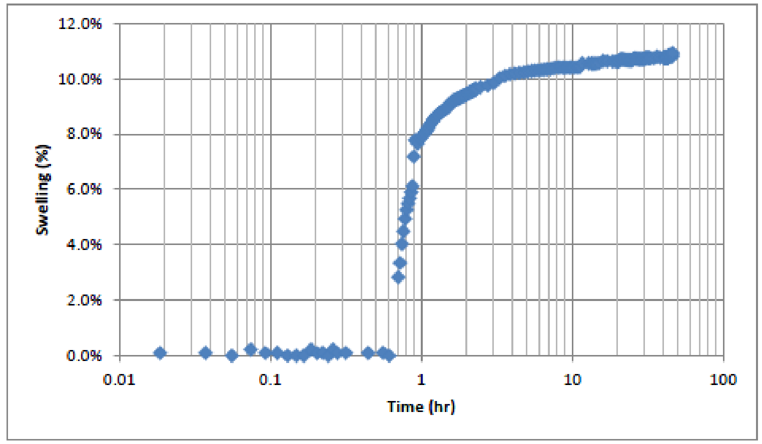
Slope of Secondary Swelling	1.724	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/6/2013
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	25.00	26.09	gravity
	Initial ω	22.5%	22.1%	%
	Mass Soil added	49.17	49.20	g
	Dry Unit Weight	15.21	15.46	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	0.998	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.998	cm
	Testing Height	0.988	1.088	cm
	Void Ratio, e	0.732	0.908	-
	ω	22.1%	32.2%	%
	Saturation	82.4%	98.3%	%
	Change in ω	-	10.1%	%
	Overburden Mass	-	16.09	g
	Height of water	-	2.00	cm
	Swell	-	10.2%	%



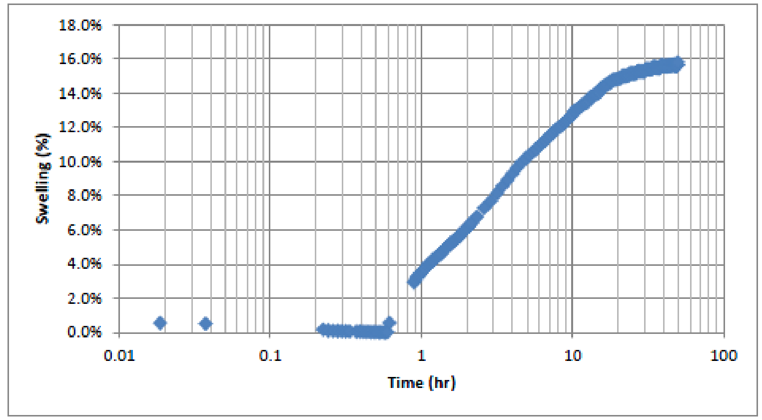
Slope of Secondary Swelling	1.244	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	4/17/2013
	Centrifuge used	Small
	Cup Number	3
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	20%
	Water Content	DOPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	24.21	gravity
	Initial ω	19.5%	19.8%	%
	Mass Soil added	49.17	49.22	g
	Dry Unit Weight	15.21	15.25	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.954	cm
	Testing Height	0.993	1.149	cm
	Void Ratio, e	0.711	0.978	-
	ω	19.8%	32.0%	%
	Saturation	76.8%	98.6%	%
	Change in ω	-	12.2%	%
	Overburden Mass	-	21.67	g
	Height of water	-	2.00	cm
	Swell	-	15.7%	%



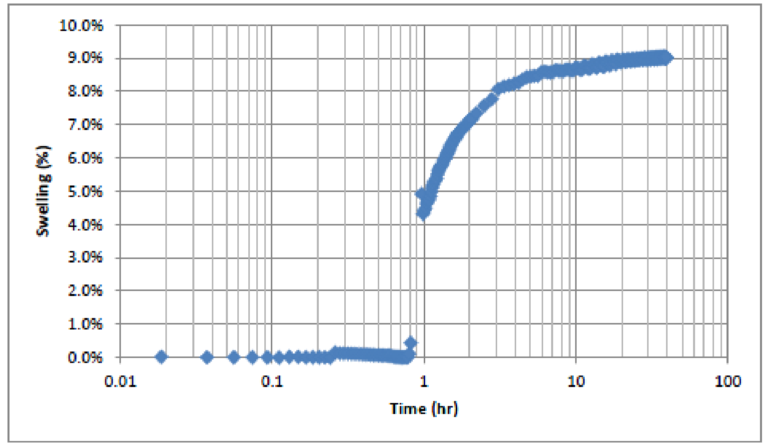
Slope of Secondary Swelling	0.825	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	9/20/2013
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	26.80	gravity
	Initial ω	22.5%	22.8%	%
	Mass Soil added	49.17	49.14	g
	Dry Unit Weight	15.21	15.34	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.003	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.002	cm
	Testing Height	0.994	1.083	cm
	Void Ratio, e	0.746	0.904	-
	ω	22.8%	31.3%	%
	Saturation	81.2%	98.2%	%
	Change in ω	-	8.5%	%
	Overburden Mass	-	22.00	g
	Height of water	-	2.00	cm
	Swell	-	9.0%	%



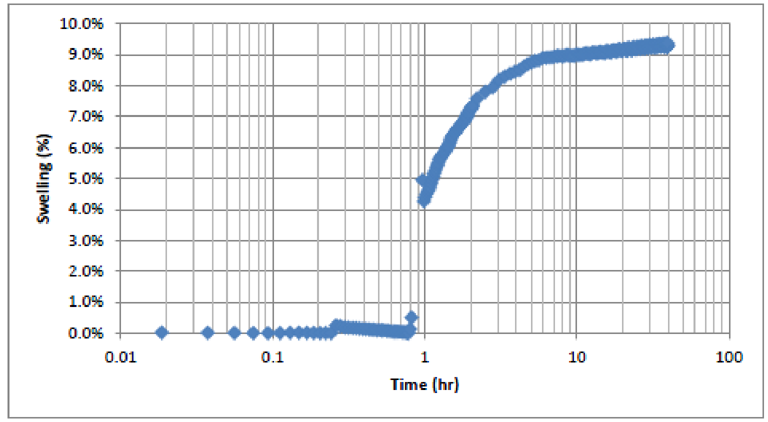
Slope of Secondary Swelling	1.15	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	9/20/2013
	Centrifuge used	Small
	Cup Number	2
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	25.00	26.80	gravity
	Initial ω	22.5%	22.4%	%
	Mass Soil added	49.17	49.15	g
	Dry Unit Weight	15.21	15.46	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.000	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.999	cm
	Testing Height	0.986	1.078	cm
	Void Ratio, e	0.732	0.893	-
	ω	22.4%	31.8%	%
	Saturation	82.8%	98.6%	%
	Change in ω	-	9.4%	%
	Overburden Mass	-	21.76	g
	Height of water	-	2.00	cm
	Swell	-	9.3%	%



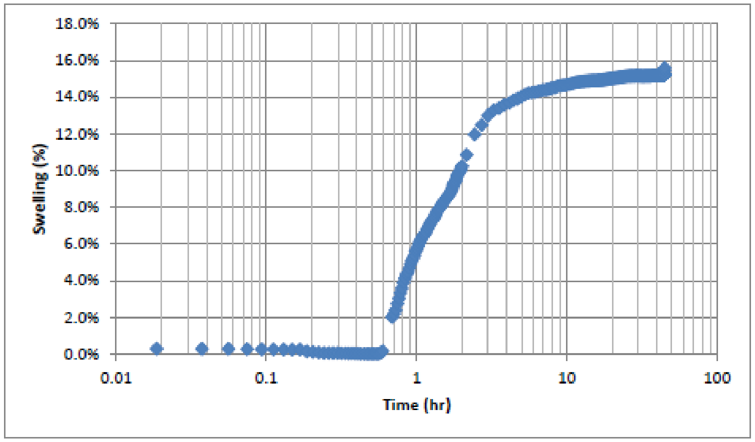
Slope of Secondary Swelling	1.393	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/16/2013
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	100%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	24.22	gravity
	Initial ω	22.5%	22.1%	%
	Mass Soil added	50.70	50.81	g
	Dry Unit Weight	15.69	15.85	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	0.998	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.999	cm
	Testing Height	0.998	1.103	cm
	Void Ratio, e	0.700	0.879	-
	ω	22.1%	33.1%	%
	Saturation	86.6%	100.0%	%
	Change in ω	-	11.0%	%
	Overburden Mass	-	21.55	g
	Height of water	-	2.00	cm
	Swell	-	13.2%	%



Slope of Secondary Swelling	1.712	%/log cycle

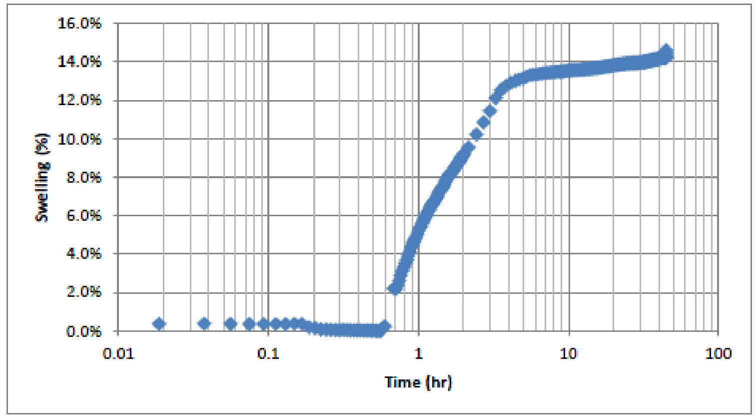
CENTRIFUGE TEST

Date test conducted	2/16/2013
Centrifuge used	Small
Cup Number	2
Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	100%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	24.22	gravity
	Initial ω	22.5%	22.1%	%
	Mass Soil added	50.70	50.68	g
	Dry Unit Weight	15.69	15.75	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	1.001	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.997	cm
	Testing Height	0.994	1.102	cm
	Void Ratio, e	0.690	0.873	-
	ω	22.1%	32.1%	%
	Saturation	87.9%	100.0%	%
	Change in ω	-	10.0%	%
	Overburden Mass	-	21.67	g
	Height of water	-	2.00	cm
	Swell	-	13.4%	%



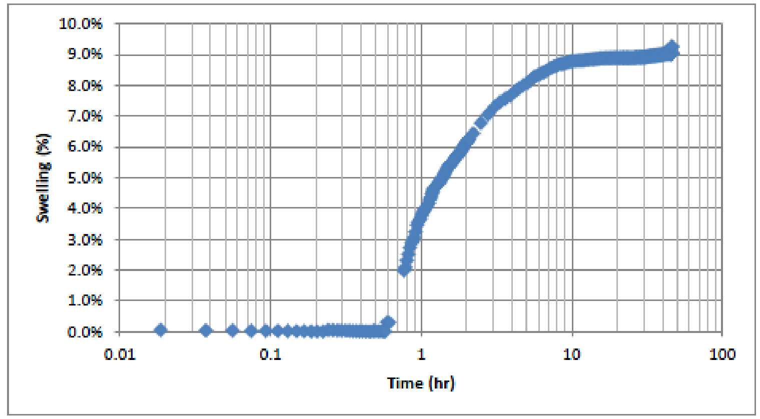
Slope of Secondary Swelling	2.324	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/7/2013
	Centrifuge used	Small
	Cup Number	3
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	94%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	25.00	26.33	gravity
	Initial ω	22.5%	22.4%	%
	Mass Soil added	47.65	47.90	g
	Dry Unit Weight	14.74	14.96	kN/m^3
	Relative Compaction	94%	94%	%
	Height of Sample	1.000	1.000	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	1.000	cm
	Testing Height	0.990	1.071	cm
	Void Ratio, e	0.691	0.829	-
	ω	22.4%	30.5%	%
	Saturation	88.9%	100.0%	%
	Change in ω	-	8.1%	%
	Overburden Mass	-	15.46	g
	Height of water	-	2.00	cm
	Swell	-	8.2%	%



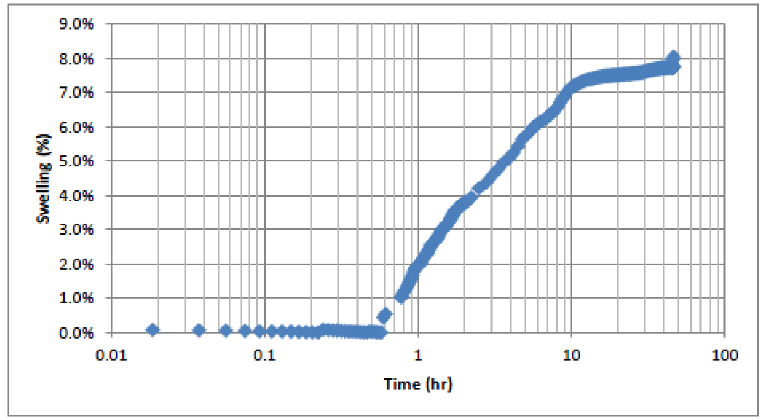
Slope of Secondary Swelling	0.714	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/7/2013
	Centrifuge used	Small
	Cup Number	4
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	94%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	26.33	gravity
	Initial ω	22.5%	22.2%	%
	Mass Soil added	47.65	47.65	g
	Dry Unit Weight	14.74	14.89	kN/m^3
	Relative Compaction	94%	94%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.000	cm
	Testing Height	0.986	1.053	cm
	Void Ratio, e	0.683	0.798	-
	ω	22.2%	30.1%	%
	Saturation	90.0%	100.0%	%
	Change in ω	-	7.9%	%
	Overburden Mass	-	15.35	g
	Height of water	-	2.00	cm
	Swell	-	6.8%	%



Slope of Secondary Swelling	0.864	%/log cycle

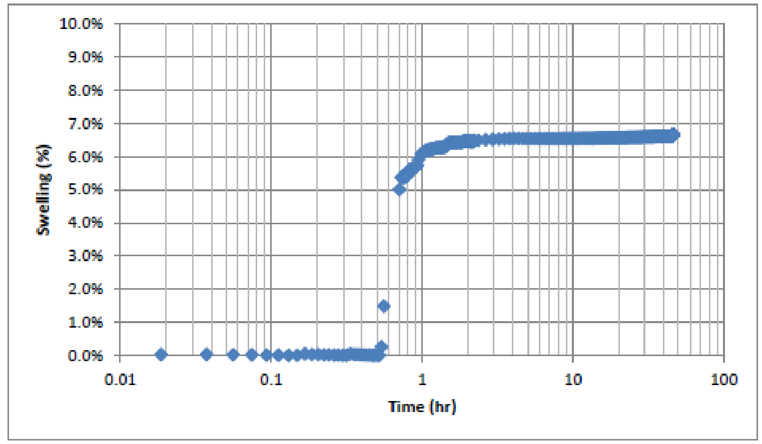
CENTRIFUGE TEST

Date test conducted	5/22/2013
Centrifuge used	Small
Cup Number	1
Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	200.00	201.86	gravity
	Initial ω	22.5%	22.2%	%
	Mass Soil added	49.17	49.14	g
	Dry Unit Weight	15.21	15.34	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.003	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.999	cm
	Testing Height	0.974	1.037	cm
	Void Ratio, e	0.765	0.880	-
	ω	22.2%	30.6%	%
	Saturation	71.6%	96.4%	%
	Change in ω	-	8.4%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	6.5%	%



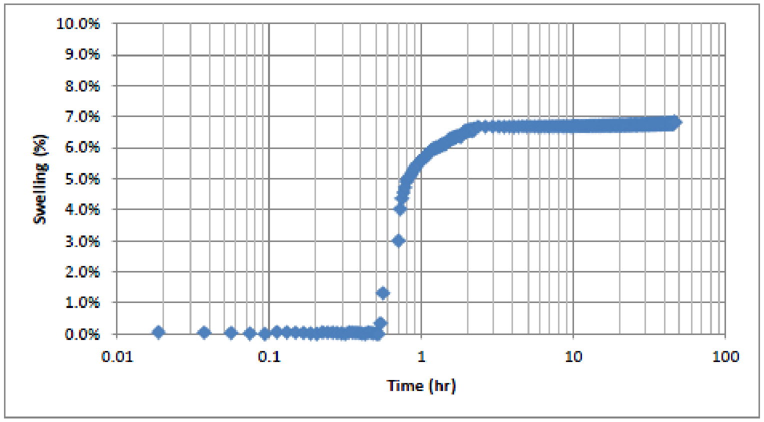
Slope of Secondary Swelling	0.105	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	5/22/2013
	Centrifuge used	Small
	Cup Number	3
	Conducted by	Das

SOIL Information	Soil	TT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.73

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	200.00	201.86	gravity
	Initial ω	22.5%	22.1%	%
	Mass Soil added	49.17	49.20	g
	Dry Unit Weight	15.21	15.39	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	0.998	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.996	cm
	Testing Height	0.980	1.040	cm
	Void Ratio, e	0.711	0.827	-
	ω	22.1%	28.4%	%
	Saturation	74.8%	96.8%	%
	Change in ω	-	6.3%	%
	Overburden Mass	-	21.67	g
	Height of water	-	2.00	cm
	Swell	-	6.8%	%



Slope of Secondary Swelling	0.322	%/log cycle

APPENDIX B: CENTRIFUGE SWELL TESTS ON EAGLE FORD CLAY

The detailed results of centrifuge swell tests on Eagle Ford clay, in a standardized format, are reported in this appendix. The tests were conducted by Walker (2012).

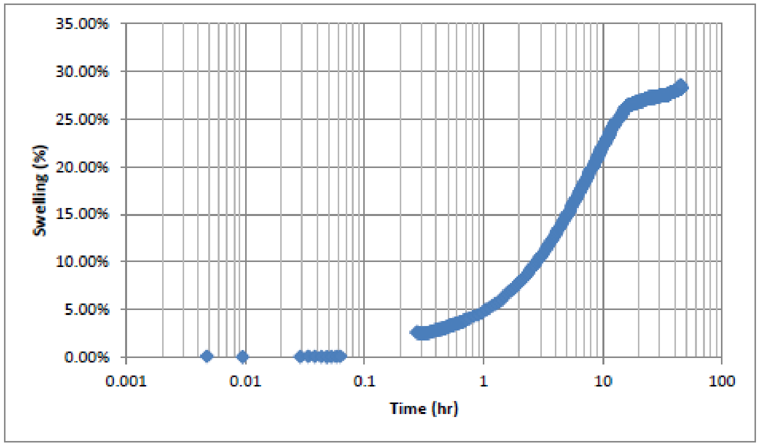
CENTRIFUGE TEST

Date test conducted	9/28/2012
Centrifuge used	Damon
Cup Number	1
Conducted by	Chris

SOIL Information	Soil	EF
	Relative Compaction	97%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.71	gravity
	Initial ω	24.0%	24.0%	%
	Mass Soil added	48.40	48.40	g
	Dry Unit Weight	14.80	14.83	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.999	cm
	Testing Height	0.998	1.262	cm
	Void Ratio, e	0.813	1.293	-
	ω	24.0%	49.5%	%
	Saturation	80.9%	100.0%	%
	Change in ω	-	25.5%	%
	Overburden Mass	-	22.32	g
	Height of water	-	2.00	cm
	Swell	-	26.5%	%



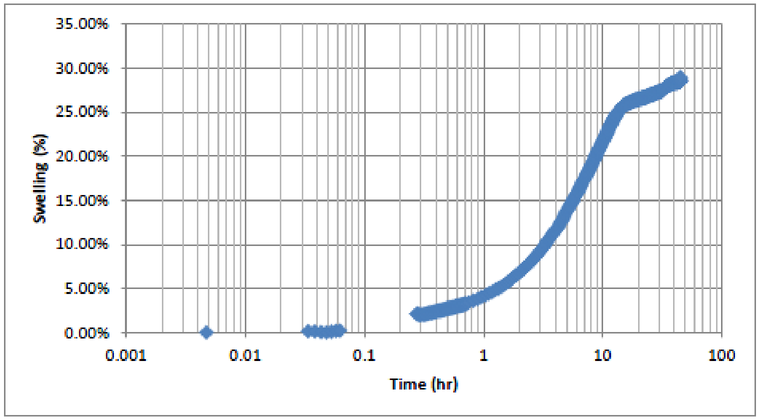
Slope of Secondary Swelling	3.237	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	9/28/2012
	Centrifuge used	Damon
	Cup Number	2
	Conducted by	Chris

SOIL Information	Soil	EF
	Relative Compaction	97%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.71	gravity
	Initial ω	24.0%	24.0%	%
	Mass Soil added	48.40	48.40	g
	Dry Unit Weight	14.80	14.83	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.999	cm
	Testing Height	0.997	1.259	cm
	Void Ratio, e	0.812	1.286	-
	ω	24.0%	50.5%	%
	Saturation	81.0%	100.0%	%
	Change in ω	-	26.5%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	26.2%	%



Slope of Secondary Swelling	4.777	%/log cycle

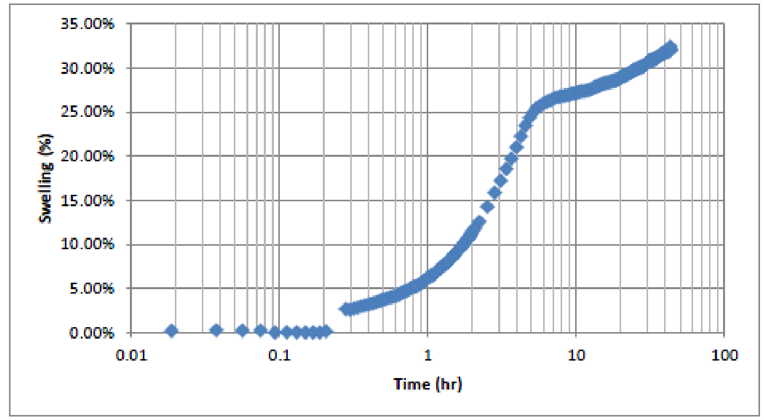
CENTRIFUGE TEST

Date test conducted	2/20/2013
Centrifuge used	Damon
Cup Number	2
Conducted by	Chris

SOIL Information	Soil	EF
	Relative Compaction	94%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.46	gravity
	Initial ω	24.0%	24.1%	%
	Mass Soil added	46.91	46.79	g
	Dry Unit Weight	14.34	14.39	kN/m^3
	Relative Compaction	94%	94%	%
	Height of Sample	1.000	0.998	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.995	cm
	Testing Height	0.993	1.264	cm
	Void Ratio, e	0.868	1.377	-
	ω	24.1%	55.1%	%
	Saturation	76.1%	100.0%	%
	Change in ω	-	31.0%	%
	Overburden Mass	-	22.21	g
	Height of water	-	2.00	cm
	Swell	-	27.2%	%



Slope of Secondary Swelling	7.065	%/log cycle

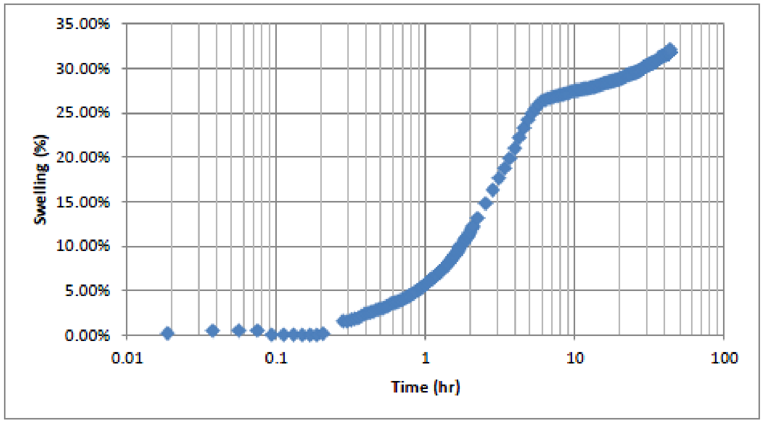
CENTRIFUGE TEST

Date test conducted	2/20/2013
Centrifuge used	Damon
Cup Number	3
Conducted by	Chris

SOIL Information	Soil	EF
	Relative Compaction	94%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	7.46	gravity
	Initial ω	24.0%	24.1%	%
	Mass Soil added	46.91	47.00	g
	Dry Unit Weight	14.34	14.34	kN/m^3
	Relative Compaction	94%	94%	%
	Height of Sample	1.000	1.006	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	1.006	cm
	Testing Height	1.001	1.276	cm
	Void Ratio, e	0.874	1.389	-
	ω	24.1%	54.6%	%
	Saturation	75.6%	100.0%	%
	Change in ω	-	30.5%	%
	Overburden Mass	-	21.65	g
	Height of water	-	2.00	cm
	Swell	-	27.5%	%



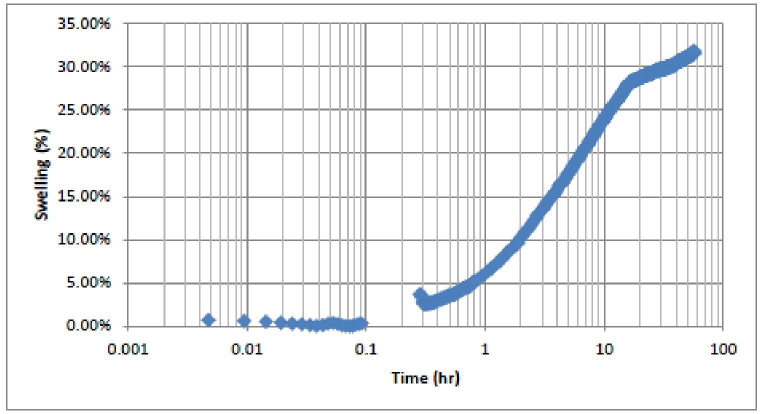
Slope of Secondary Swelling	5.87	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/17/2012
	Centrifuge used	Damon
	Cup Number	3
	Conducted by	Trevor

SOIL Information	Soil	EF
	Relative Compaction	100%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	6.84	gravity
	Initial ω	24.0%	23.9%	%
	Mass Soil added	49.91	49.86	g
	Dry Unit Weight	15.26	15.40	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.991	cm
	Testing Height	0.990	1.272	cm
	Void Ratio, e	0.745	1.242	-
	ω	23.9%	47.3%	%
	Saturation	87.9%	100.0%	%
	Change in ω	-	23.3%	%
	Overburden Mass	-	21.52	g
	Height of water	-	2.00	cm
	Swell	-	28.5%	%



Slope of Secondary Swelling	5.567	%/log cycle

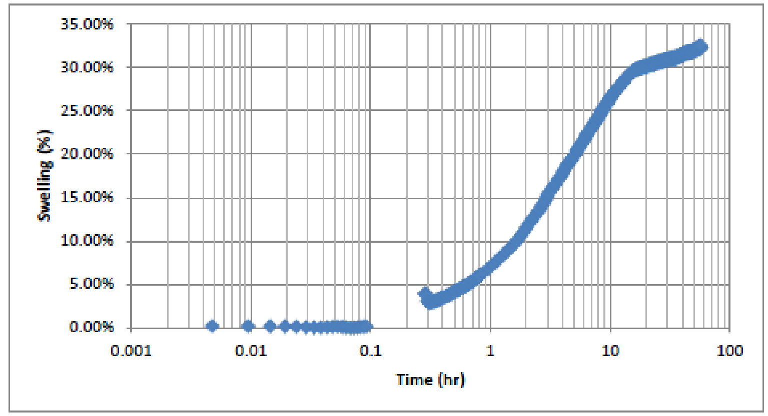
CENTRIFUGE TEST

Date test conducted	2/17/2012
Centrifuge used	Damon
Cup Number	4
Conducted by	Trevor

SOIL Information	Soil	EF
	Relative Compaction	100%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	6.84	gravity
	Initial ω	24.0%	23.9%	%
	Mass Soil added	49.91	49.98	g
	Dry Unit Weight	15.26	15.28	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	1.003	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.001	cm
	Testing Height	1.001	1.295	cm
	Void Ratio, e	0.759	1.276	-
	ω	23.9%	48.3%	%
	Saturation	86.3%	100.0%	%
	Change in ω	-	24.4%	%
	Overburden Mass	-	21.42	g
	Height of water	-	2.00	cm
	Swell	-	29.4%	%



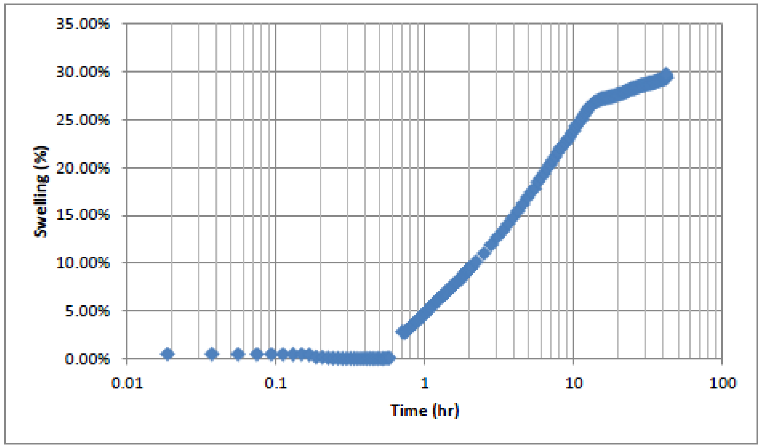
Slope of Secondary Swelling	4.645	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/27/2013
	Centrifuge used	Small
	Cup Number	1
	Conducted by	Das

SOIL Information	Soil	EF
	Relative Compaction	94%
	Target Water Content	24%
	Water Content	DOPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	6.85	gravity
	Initial ω	24.0%	23.0%	%
	Mass Soil added	46.91	46.96	g
	Dry Unit Weight	14.34	14.64	kN/m^3
	Relative Compaction	94%	96%	%
	Height of Sample	1.000	0.993	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.993	cm
	Testing Height	0.988	1.252	cm
	Void Ratio, e	0.836	1.325	-
	ω	23.0%	51.7%	%
	Saturation	75.4%	100.0%	%
	Change in ω	-	28.7%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	26.7%	%



Slope of Secondary Swelling	5.533	%/log cycle

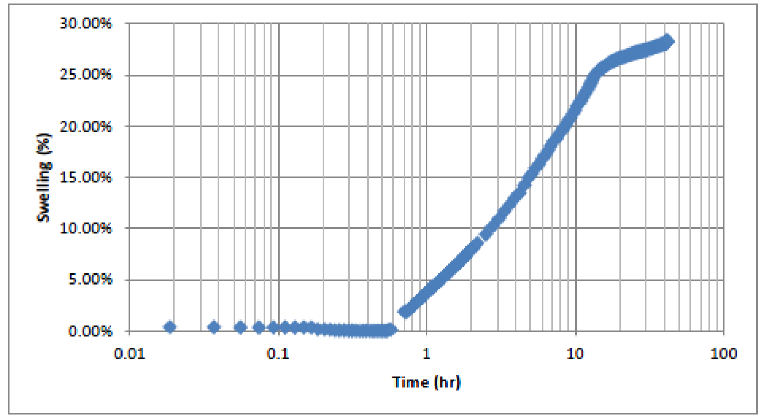
CENTRIFUGE TEST

Date test conducted	3/27/2013
Centrifuge used	Small
Cup Number	2
Conducted by	Das

SOIL Information	Soil	EF
	Relative Compaction	94%
	Target Water Content	24%
	Water Content	DOPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	6.85	gravity
	Initial ω	24.0%	23.0%	%
	Mass Soil added	46.91	46.87	g
	Dry Unit Weight	14.34	14.51	kN/m^3
	Relative Compaction	94%	95%	%
	Height of Sample	1.000	0.998	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.999	cm
	Testing Height	0.995	1.254	cm
	Void Ratio, e	0.852	1.334	-
	ω	23.0%	51.1%	%
	Saturation	73.9%	100.0%	%
	Change in ω	-	28.1%	%
	Overburden Mass	-	22.21	g
	Height of water	-	2.00	cm
	Swell	-	26.0%	%



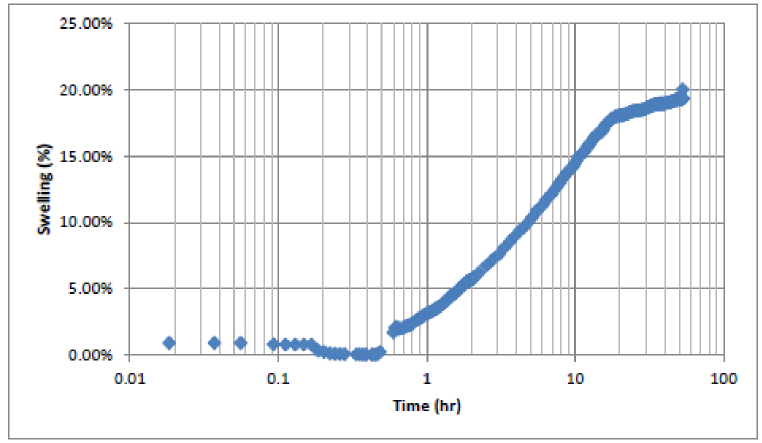
Slope of Secondary Swelling	4.383	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/15/2013
	Centrifuge used	Damon
	Cup Number	1
	Conducted by	Chris

SOIL Information		
	Soil	EF
	Relative Compaction	97%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	25.00	26.50	gravity
	Initial ω	24.0%	23.9%	%
	Mass Soil added	48.40	48.37	g
	Dry Unit Weight	14.80	14.93	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.000	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.999	cm
	Testing Height	0.991	1.170	cm
	Void Ratio, e	0.800	1.125	-
	ω	23.9%	44.0%	%
	Saturation	81.8%	100.0%	%
	Change in ω	-	20.1%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	18.0%	%



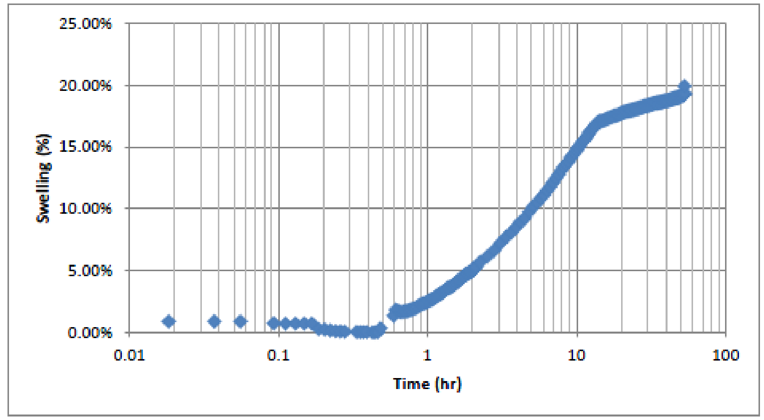
Slope of Secondary Swelling	3.047	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/15/2013
	Centrifuge used	Damon
	Cup Number	2
	Conducted by	Chris

SOIL Information	Soil	EF
	Relative Compaction	97%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	26.50	gravity
	Initial ω	24.0%	23.9%	%
	Mass Soil added	48.40	48.46	g
	Dry Unit Weight	14.80	15.00	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.996	cm
	Testing Height	0.989	1.166	cm
	Void Ratio, e	0.792	1.113	-
	ω	23.9%	45.2%	%
	Saturation	82.6%	100.0%	%
	Change in ω	-	21.3%	%
	Overburden Mass	-	22.22	g
	Height of water	-	2.00	cm
	Swell	-	17.9%	%



Slope of Secondary Swelling	3.367	%/log cycle

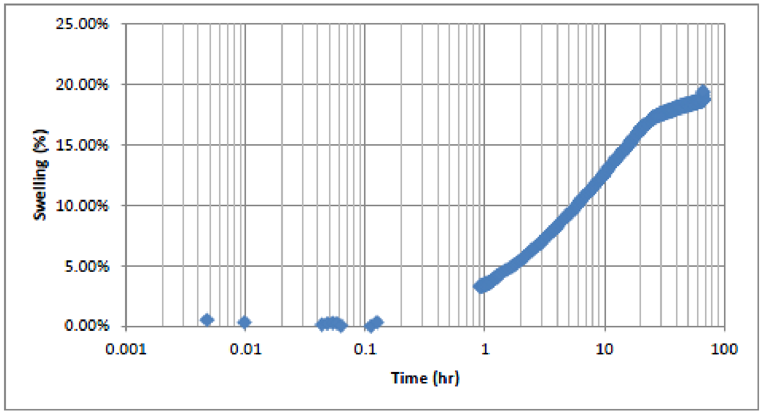
CENTRIFUGE TEST

Date test conducted	1/6/2012
Centrifuge used	Damon
Cup Number	2
Conducted by	Trevor

SOIL Information	Soil	EF
	Relative Compaction	97%
	Target Water Content	21%
	Water Content	DOPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	25.50	gravity
	Initial ω	21.0%	21.9%	%
	Mass Soil added	47.23	46.91	g
	Dry Unit Weight	14.80	14.67	kN/m^3
	Relative Compaction	97%	96%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.993	cm
	Testing Height	0.995	1.165	cm
	Void Ratio, e	0.833	1.148	-
	ω	21.9%	43.5%	%
	Saturation	72.1%	100.0%	%
	Change in ω	-	21.6%	%
	Overburden Mass	-	22.27	g
	Height of water	-	2.00	cm
	Swell	-	17.2%	%



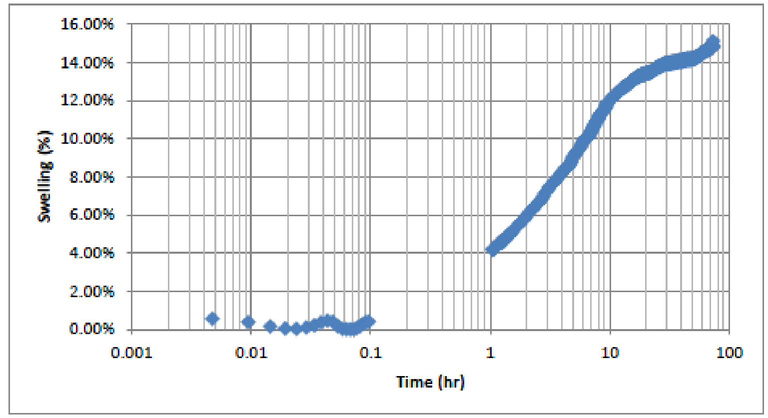
Slope of Secondary Swelling	5.886	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	12/20/2011
	Centrifuge used	Damon
	Cup Number	3
	Conducted by	Trevor

SOIL Information	Soil	EF
	Relative Compaction	97%
	Target Water Content	27%
	Water Content	WOPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	27.33	gravity
	Initial ω	27.0%	27.4%	%
	Mass Soil added	49.57	49.64	g
	Dry Unit Weight	14.79	14.86	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.995	cm
	Testing Height	0.994	1.131	cm
	Void Ratio, e	0.809	1.059	-
	ω	27.4%	43.6%	%
	Saturation	92.6%	100.0%	%
	Change in ω	-	16.2%	%
	Overburden Mass	-	21.54	g
	Height of water	-	2.00	cm
	Swell	-	13.8%	%



Slope of Secondary Swelling	2.218	%/log cycle

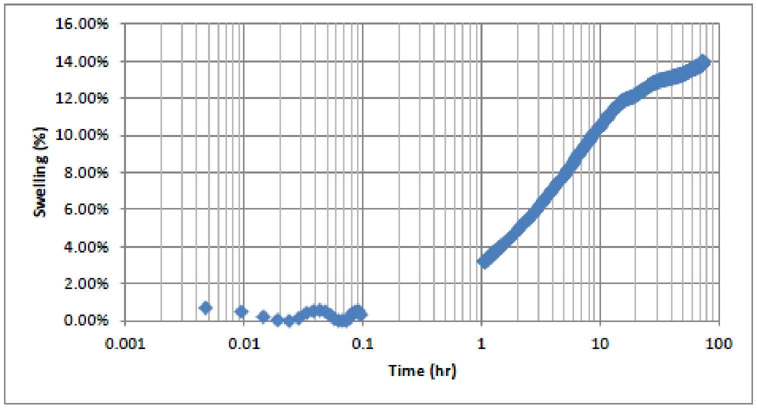
CENTRIFUGE TEST

Date test conducted	12/20/2011
Centrifuge used	Damon
Cup Number	4
Conducted by	Trevor

SOIL Information	Soil	EF
	Relative Compaction	97%
	Target Water Content	27%
	Water Content	WOPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	27.33	gravity
	Initial ω	27.0%	27.4%	%
	Mass Soil added	49.57	49.50	g
	Dry Unit Weight	14.79	14.86	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.991	cm
	Testing Height	0.991	1.116	cm
	Void Ratio, e	0.809	1.036	-
	ω	27.4%	43.0%	%
	Saturation	92.7%	100.0%	%
	Change in ω	-	15.6%	%
	Overburden Mass	-	21.42	g
	Height of water	-	2.00	cm
	Swell	-	12.6%	%



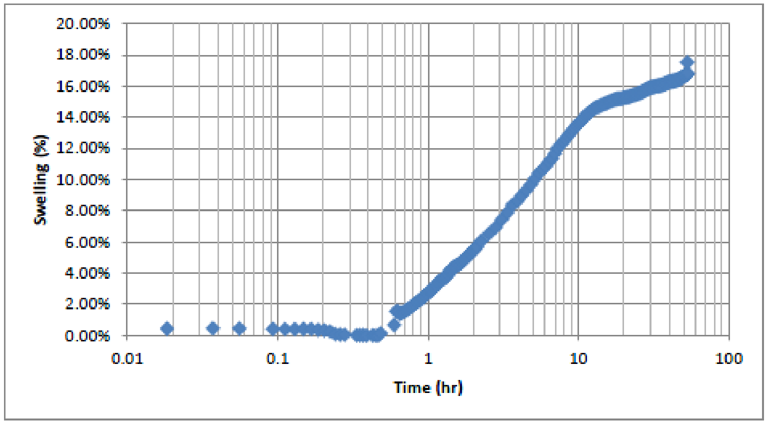
Slope of Secondary Swelling	3.184	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/15/2013
	Centrifuge used	Damon
	Cup Number	4
	Conducted by	Chris

SOIL Information	Soil	EF
	Relative Compaction	94%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	26.50	gravity
	Initial ω	24.0%	23.9%	%
	Mass Soil added	46.91	46.97	g
	Dry Unit Weight	14.34	14.47	kN/m^3
	Relative Compaction	94%	95%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.997	cm
	Testing Height	0.993	1.144	cm
	Void Ratio, e	0.857	1.139	-
	ω	23.9%	46.1%	%
	Saturation	76.3%	100.0%	%
	Change in ω	-	22.2%	%
	Overburden Mass	-	21.55	g
	Height of water	-	2.00	cm
	Swell	-	15.1%	%



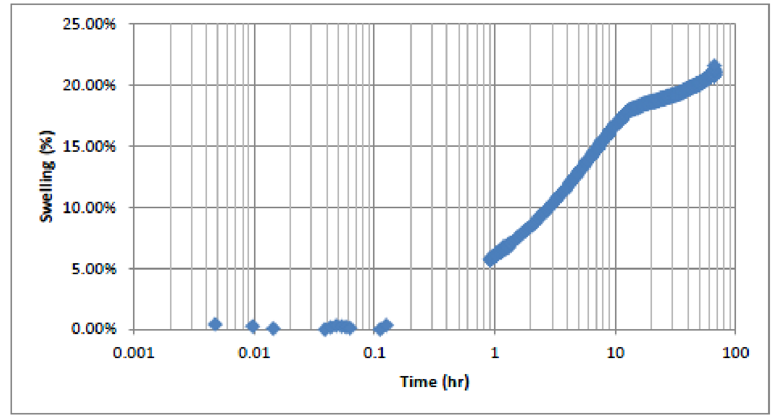
Slope of Secondary Swelling	3.353	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	1/6/2012
	Centrifuge used	Damon
	Cup Number	3
	Conducted by	Trevor

SOIL Information	Soil	EF
	Relative Compaction	100%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	25.50	gravity
	Initial ω	24.0%	25.4%	%
	Mass Soil added	49.91	49.90	g
	Dry Unit Weight	15.26	15.15	kN/m^3
	Relative Compaction	100%	99%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.996	cm
	Testing Height	0.996	1.183	cm
	Void Ratio, e	0.775	1.108	-
	ω	25.4%	41.2%	%
	Saturation	89.8%	100.0%	%
	Change in ω	-	15.8%	%
	Overburden Mass	-	21.54	g
	Height of water	-	2.00	cm
	Swell	-	18.8%	%



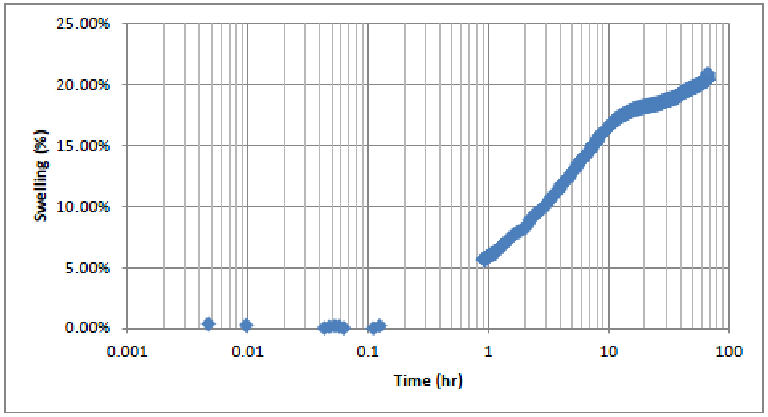
Slope of Secondary Swelling	3.573	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	1/6/2012
	Centrifuge used	Damon
	Cup Number	4
	Conducted by	Trevor

SOIL Information	Soil	EF
	Relative Compaction	100%
	Target Water Content	24%
	Water Content	OPT
	Specific Gravity	2.74

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	25.50	gravity
	Initial ω	24.0%	25.4%	%
	Mass Soil added	49.91	49.93	g
	Dry Unit Weight	15.26	15.19	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.992	cm
	Testing Height	0.994	1.175	cm
	Void Ratio, e	0.770	1.093	-
	ω	25.4%	41.9%	%
	Saturation	90.4%	100.0%	%
	Change in ω	-	16.5%	%
	Overburden Mass	-	21.42	g
	Height of water	-	2.00	cm
	Swell	-	18.2%	%



Slope of Secondary Swelling	3.626	%/log cycle

APPENDIX C: CENTRIFUGE SWELL TESTS ON HOUSTON BLACK CLAY

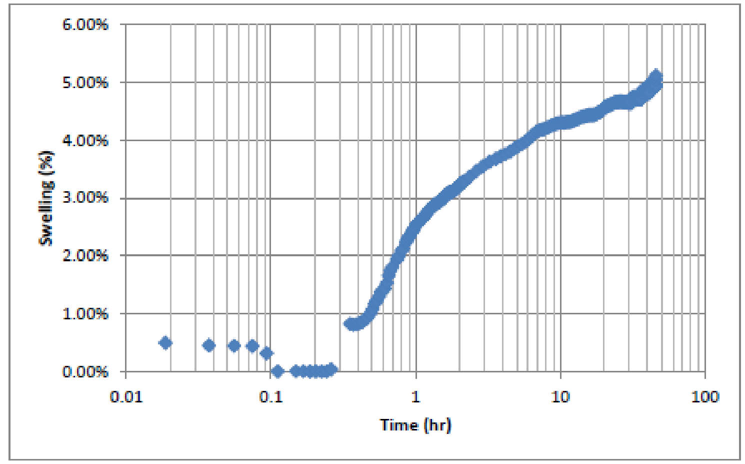
The detailed results of centrifuge swell tests on Houston Black clay, in a standardized format, are reported in this appendix. The tests were conducted by Walker (2012).

CENTRIFUGE TEST		
	Date test conducted	4/9/2013
	Centrifuge used	Damon
	Cup Number	1
	Conducted by	Chris

SOIL Information	Soil	HB
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.53	gravity
	Initial ω	25.5%	25.7%	%
	Mass Soil added	47.30	47.31	g
	Dry Unit Weight	14.29	14.30	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.003	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.003	cm
	Testing Height	0.998	1.041	cm
	Void Ratio, e	0.853	0.933	-
	ω	25.7%	35.2%	%
	Saturation	81.3%	100.0%	%
	Change in ω	-	9.6%	%
	Overburden Mass	-	22.26	g
	Height of water	-	2.00	cm
	Swell	-	4.3%	%



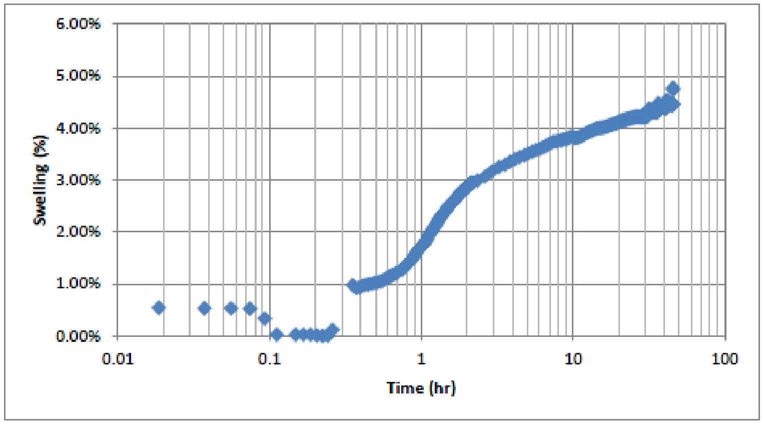
Slope of Secondary Swelling	0.879	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	4/9/2013
	Centrifuge used	Damon
	Cup Number	2
	Conducted by	Chris

SOIL Information	Soil	HB
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.53	gravity
	Initial ω	25.5%	25.7%	%
	Mass Soil added	47.30	47.39	g
	Dry Unit Weight	14.29	14.34	kN/m^3
	Relative Compaction	97%	97%	%
	Height of Sample	1.000	1.003	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.002	cm
	Testing Height	0.997	1.037	cm
	Void Ratio, e	0.847	0.921	-
	ω	25.7%	35.1%	%
	Saturation	81.8%	100.0%	%
	Change in ω	-	9.4%	%
	Overburden Mass	-	22.22	g
	Height of water	-	2.00	cm
	Swell	-	4.0%	%



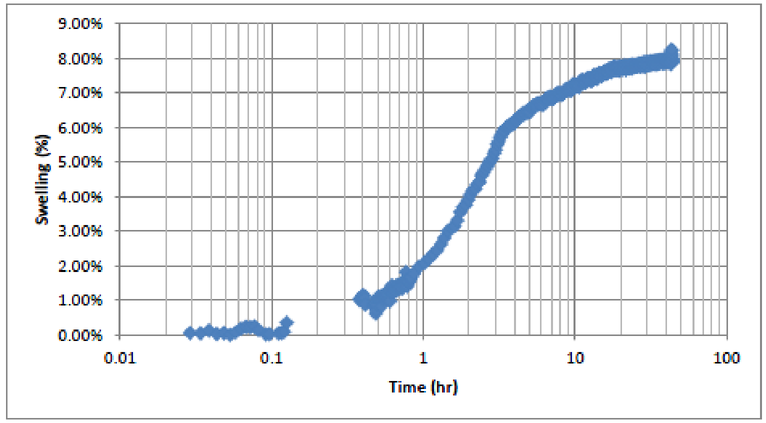
Slope of Secondary Swelling	0.898	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/13/2012
	Centrifuge used	Damon
	Cup Number	3
	Conducted by	Trevor

SOIL Information	Soil	HB
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	6.96	gravity
	Initial ω	25.5%	25.1%	%
	Mass Soil added	47.30	47.33	g
	Dry Unit Weight	14.29	14.41	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.994	cm
	Testing Height	0.995	1.068	cm
	Void Ratio, e	0.838	0.974	-
	ω	25.1%	33.4%	%
	Saturation	80.9%	92.8%	%
	Change in ω	-	8.3%	%
	Overburden Mass	-	21.53	g
	Height of water	-	2.00	cm
	Swell	-	7.4%	%



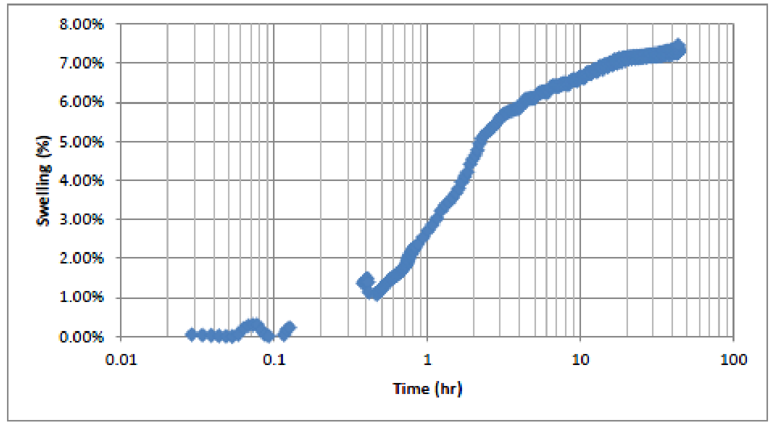
Slope of Secondary Swelling	0.666	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/13/2012
	Centrifuge used	Damon
	Cup Number	4
	Conducted by	Trevor

SOIL Information	Soil	HB
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	6.96	gravity
	Initial ω	25.5%	25.1%	%
	Mass Soil added	47.30	47.30	g
	Dry Unit Weight	14.29	14.39	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.003	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.998	cm
	Testing Height	0.996	1.067	cm
	Void Ratio, e	0.841	0.972	-
	ω	25.1%	34.1%	%
	Saturation	80.6%	94.8%	%
	Change in ω	-	9.0%	%
	Overburden Mass	-	21.42	g
	Height of water	-	2.00	cm
	Swell	-	7.1%	%



Slope of Secondary Swelling	0.333	%/log cycle

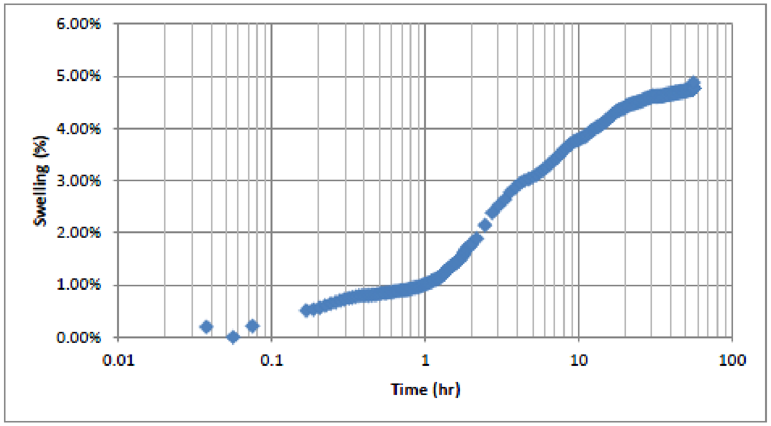
CENTRIFUGE TEST

Date test conducted	10/30/2012
Centrifuge used	Damon
Cup Number	3
Conducted by	Chris

SOIL Information	Soil	HB
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.25	gravity
	Initial ω	25.5%	26.8%	%
	Mass Soil added	47.30	47.26	g
	Dry Unit Weight	14.29	14.19	kN/m^3
	Relative Compaction	97%	96%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.993	cm
	Testing Height	0.996	1.036	cm
	Void Ratio, e	0.867	0.942	-
	ω	26.8%	44.4%	%
	Saturation	83.4%	100.0%	%
	Change in ω	-	17.6%	%
	Overburden Mass	-	21.58	g
	Height of water	-	2.00	cm
	Swell	-	4.0%	%



Slope of Secondary Swelling	0.869	%/log cycle

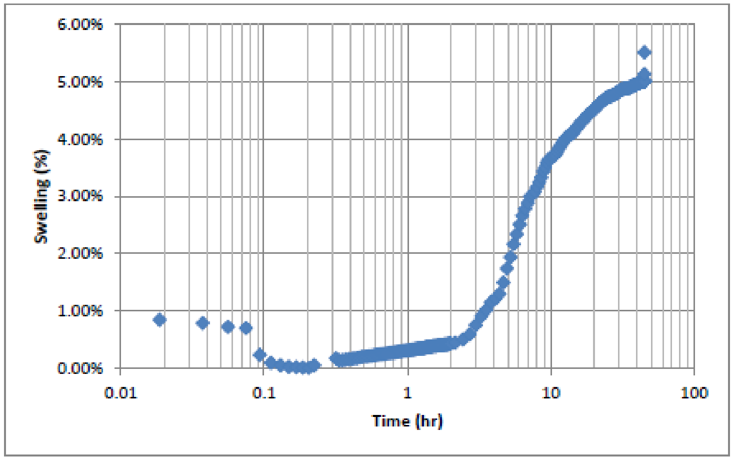
CENTRIFUGE TEST

Date test conducted	3/14/2013
Centrifuge used	Damon
Cup Number	1
Conducted by	Chris

SOIL Information		
	Soil	HB
	Relative Compaction	100%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	5.00	8.51	gravity
	Initial ω	25.5%	25.6%	%
	Mass Soil added	48.75	48.75	g
	Dry Unit Weight	14.72	15.19	kN/m^3
	Relative Compaction	100%	103%	%
	Height of Sample	1.000	0.977	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.975	cm
	Testing Height	0.968	1.013	cm
	Void Ratio, e	0.743	0.823	-
	ω	25.6%	32.4%	%
	Saturation	93.1%	100.0%	%
	Change in ω	-	6.8%	%
	Overburden Mass	-	22.25	g
	Height of water	-	2.00	cm
	Swell	-	4.6%	%



Slope of Secondary Swelling	1.479	%/log cycle

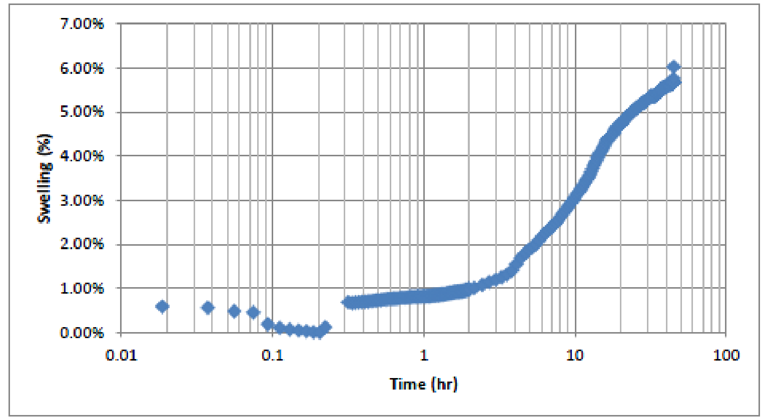
CENTRIFUGE TEST

Date test conducted	3/14/2013
Centrifuge used	Damon
Cup Number	2
Conducted by	Chris

SOIL Information	Soil	HB
	Relative Compaction	100%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	8.51	gravity
	Initial ω	25.5%	25.6%	%
	Mass Soil added	48.75	48.80	g
	Dry Unit Weight	14.72	14.88	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	0.996	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.994	cm
	Testing Height	0.989	1.035	cm
	Void Ratio, e	0.780	0.862	-
	ω	25.6%	33.7%	%
	Saturation	88.8%	100.0%	%
	Change in ω	-	8.1%	%
	Overburden Mass	-	22.21	g
	Height of water	-	2.00	cm
	Swell	-	4.7%	%



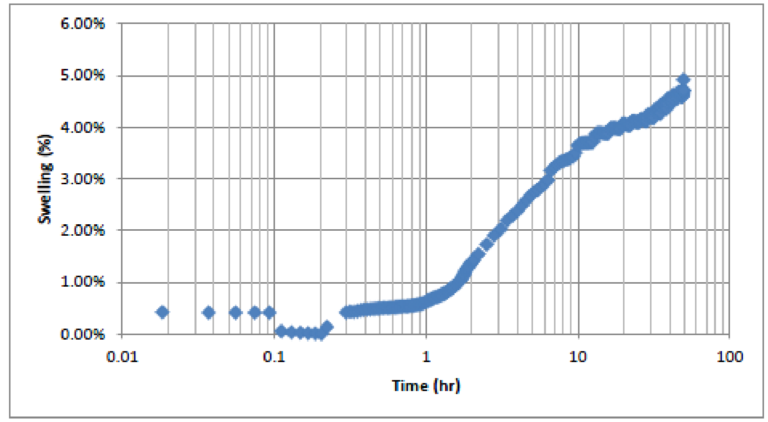
Slope of Secondary Swelling	2.86	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	5/11/2013
	Centrifuge used	Damon
	Cup Number	4
	Conducted by	Chris

SOIL Information	Soil	HB
	Relative Compaction	100%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	7.49	gravity
	Initial ω	25.5%	25.6%	%
	Mass Soil added	48.75	48.80	g
	Dry Unit Weight	14.72	14.78	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	1.001	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	1.000	cm
	Testing Height	0.996	1.038	cm
	Void Ratio, e	0.792	0.866	-
	ω	25.6%	34.7%	%
	Saturation	87.3%	100.0%	%
	Change in ω	-	9.1%	%
	Overburden Mass	-	21.56	g
	Height of water	-	2.00	cm
	Swell	-	4.2%	%



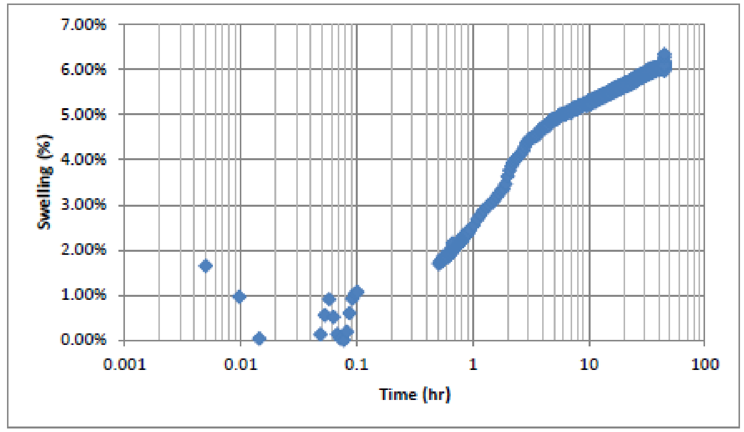
Slope of Secondary Swelling	1.554	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	1/11/2012
	Centrifuge used	Damon
	Cup Number	2
	Conducted by	Trevor

SOIL Information	Soil	HB
	Relative Compaction	97%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	25.61	gravity
	Initial ω	25.5%	25.3%	%
	Mass Soil added	47.39	46.93	g
	Dry Unit Weight	14.31	14.41	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.984	cm
	Testing Height	0.985	1.033	cm
	Void Ratio, e	0.838	0.928	-
	ω	25.3%	32.0%	%
	Saturation	81.6%	93.2%	%
	Change in ω	-	6.7%	%
	Overburden Mass	-	22.13	g
	Height of water	-	2.00	cm
	Swell	-	4.9%	%



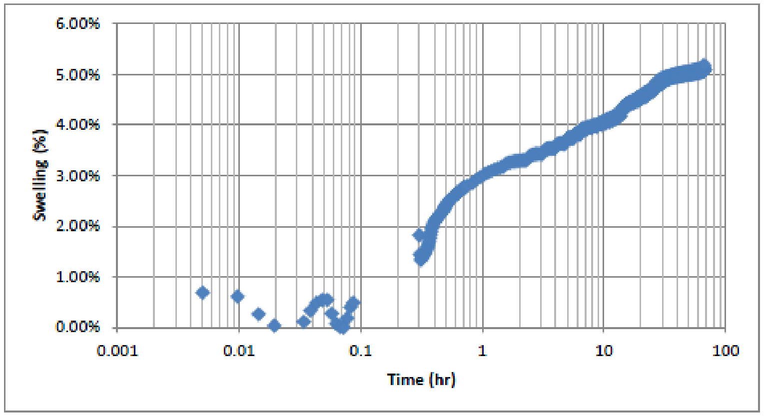
Slope of Secondary Swelling	1.658	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	1/20/2012
	Centrifuge used	Damon
	Cup Number	4
	Conducted by	Trevor

SOIL Information	Soil	HB
	Relative Compaction	94%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	25.00	26.70	gravity
	Initial ω	25.5%	25.1%	%
	Mass Soil added	45.84	45.86	g
	Dry Unit Weight	13.85	14.06	kN/m^3
	Relative Compaction	94%	96%	%
	Height of Sample	1.000	0.995	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.988	cm
	Testing Height	0.988	1.037	cm
	Void Ratio, e	0.884	0.977	-
	ω	25.1%	34.3%	%
	Saturation	76.7%	94.8%	%
	Change in ω	-	9.2%	%
	Overburden Mass	-	21.55	g
	Height of water	-	2.00	cm
	Swell	-	5.0%	%



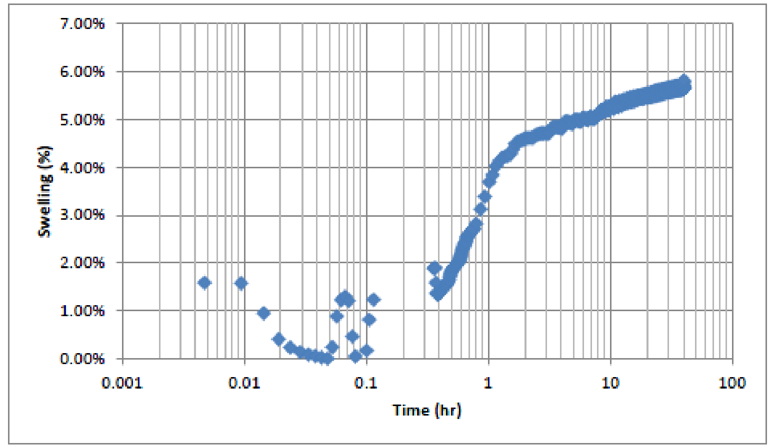
Slope of Secondary Swelling	1.491	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/15/2012
	Centrifuge used	Damon
	Cup Number	1
	Conducted by	Trevor

SOIL Information	Soil	HB
	Relative Compaction	100%
	Target Water Content	26%
	Water Content	OPT
	Specific Gravity	2.7

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	26.84	gravity
	Initial ω	25.5%	25.8%	%
	Mass Soil added	48.75	48.79	g
	Dry Unit Weight	14.72	14.97	kN/m^3
	Relative Compaction	100%	100%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.991	cm
	Testing Height	0.982	1.033	cm
	Void Ratio, e	0.770	0.862	-
	ω	25.8%	28.3%	%
	Saturation	90.6%	88.8%	%
	Change in ω	-	2.5%	%
	Overburden Mass	-	22.32	g
	Height of water	-	2.00	cm
	Swell	-	5.2%	%



Slope of Secondary Swelling	0.762	%/log cycle

APPENDIX D: CENTRIFUGE SWELL TESTS ON BLACK TAYLOR CLAY

The detailed results of centrifuge swell tests on Black Taylor clay, in a standardized format, are reported in this appendix. The tests were conducted by Walker (2012).

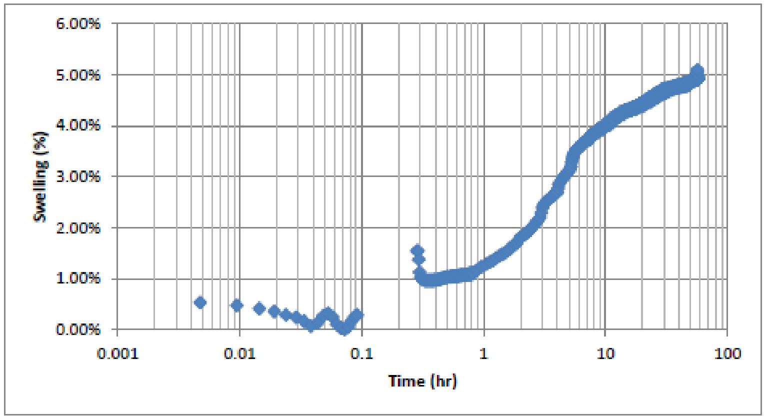
CENTRIFUGE TEST

Date test conducted	2/17/2012
Centrifuge used	Damon
Cup Number	2
Conducted by	Trevor

SOIL Information	Soil	BT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.71

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	5.00	6.84	gravity
	Initial ω	23.3%	23.3%	%
	Mass Soil added	48.42	48.41	g
	Dry Unit Weight	14.89	14.96	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	1.000	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.995	cm
	Testing Height	0.995	1.037	cm
	Void Ratio, e	0.777	0.851	-
	ω	23.3%	30.8%	%
	Saturation	81.2%	98.0%	%
	Change in ω	-	7.5%	%
	Overburden Mass	-	22.25	g
	Height of water	-	2.00	cm
	Swell	-	4.2%	%



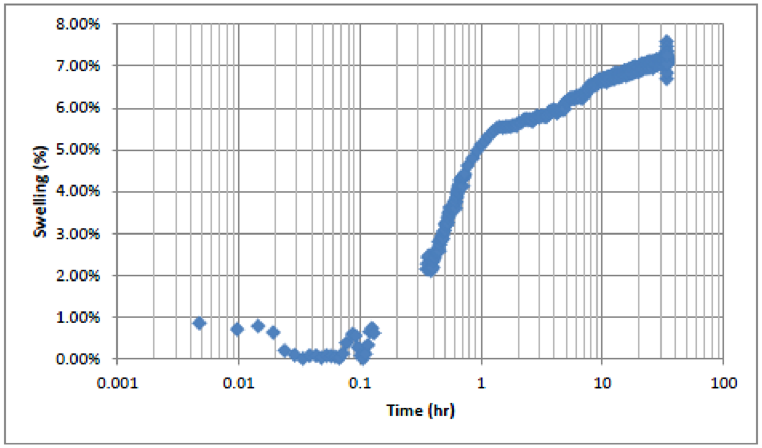
Slope of Secondary Swelling	1.122	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	2/10/2012
	Centrifuge used	Damon
	Cup Number	1
	Conducted by	Trevor

SOIL Information	Soil	BT
	Relative Compaction	97%
	Target Water Content	20%
	Water Content	DOPT
	Specific Gravity	2.71

TESTING SETUP information	Property	Target	Actual	Unit
	G-Level	25.00	25.89	gravity
	Initial ω	20.3%	20.8%	%
	Mass Soil added	47.24	47.27	g
	Dry Unit Weight	14.88	14.98	kN/m^3
	Relative Compaction	97%	98%	%
	Height of Sample	1.000	0.997	cm

TEST RESULTS Information	Property	Initial	Final	Unit
	Seating Height	-	0.991	cm
	Testing Height	0.990	1.056	cm
	Void Ratio, e	0.775	0.893	-
	ω	20.8%	30.9%	%
	Saturation	72.7%	93.9%	%
	Change in ω	-	10.1%	%
	Overburden Mass	-	22.32	g
	Height of water	-	2.00	cm
	Swell	-	6.6%	%



Slope of Secondary Swelling	1.033	%/log cycle

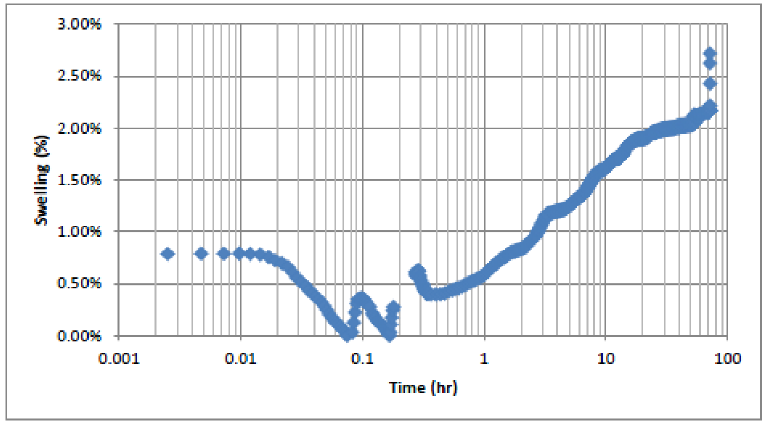
CENTRIFUGE TEST

Date test conducted	10/22/2011
Centrifuge used	Damon
Cup Number	2
Conducted by	Trevor

SOIL Information	Soil	BT
	Relative Compaction	97%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.71

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	24.07	gravity
	Initial ω	23.3%	23.7%	%
	Mass Soil added	49.93	49.98	g
	Dry Unit Weight	15.35	15.48	kN/m^3
	Relative Compaction	97%	100%	%
	Height of Sample	1.000	0.997	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.989	cm
	Testing Height	0.990	1.006	cm
	Void Ratio, e	0.717	0.746	-
	ω	23.7%	27.4%	%
	Saturation	89.4%	99.3%	%
	Change in ω	-	3.7%	%
	Overburden Mass	-	22.27	g
	Height of water	-	2.00	cm
	Swell	-	1.7%	%



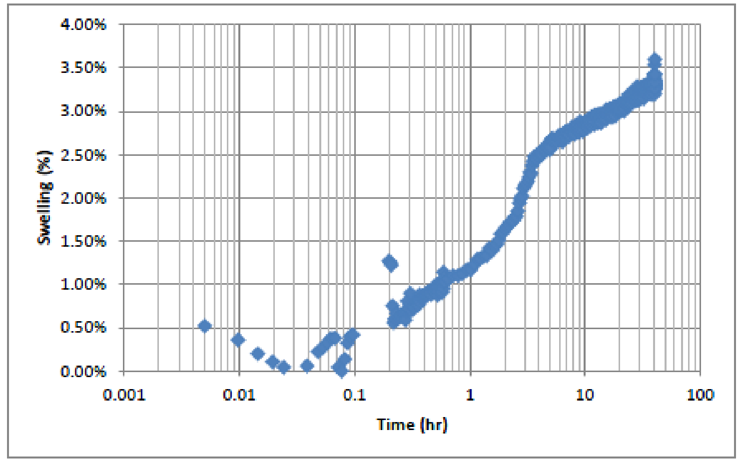
Slope of Secondary Swelling	0.391	%/log cycle

CENTRIFUGE TEST		
	Date test conducted	3/28/2012
	Centrifuge used	Damon
	Cup Number	1
	Conducted by	Trevor

SOIL Information	Soil	BT
	Relative Compaction	94%
	Target Water Content	23%
	Water Content	OPT
	Specific Gravity	2.71

	Property	Target	Actual	Unit
TESTING SETUP information	G-Level	25.00	26.87	gravity
	Initial ω	23.3%	23.2%	%
	Mass Soil added	46.92	46.92	g
	Dry Unit Weight	14.42	14.60	kN/m^3
	Relative Compaction	94%	95%	%
	Height of Sample	1.000	0.995	cm

	Property	Initial	Final	Unit
TEST RESULTS Information	Seating Height	-	0.989	cm
	Testing Height	0.989	1.017	cm
	Void Ratio, e	0.821	0.872	-
	ω	23.2%	29.8%	%
	Saturation	76.5%	92.5%	%
	Change in ω	-	6.6%	%
	Overburden Mass	-	22.24	g
	Height of water	-	2.00	cm
	Swell	-	2.9%	%



Slope of Secondary Swelling	1.18	%/log cycle

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