Testing of the Thermo-Hydro-Mechanical-Chemical (THMC) Behavior of Lime-Treated Subgrade Marine Clays Subjected to Environmental Stresses

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Abstract

Construction of pavements requires the subgrades - which are the foundation of the structure, to be capable of supporting traffic loads that would be applied onto them. In the case that the subgrades are unable to support the structure, failure would occur. The subgrade being in-situ soil can be of poor quality if not properly constructed or improved if necessary. In Canada, the eastern region precisely Ontario and Quebec, is dominated by sensitive marine clays which when disturbed lose their strength drastically making them a geotechnical hazard. The soil's high sensitivity causes this behavior it poses. Therefore, to construct pavements in this type of soil, improvement techniques are required. One such is lime stabilization which improves the engineering properties of the soil.

Research on the stabilization of sensitive marine clay in Canada has been conducted to a certain extent showing the effectiveness of the process in improving the soil's poor engineering properties. However, during the process of stabilization, the thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes and interactions that occur influence the behavior of the stabilized clay. Environmental stresses such as moisture and temperature are also known to affect the coupled processes that occur. However, these coupled processes and their impact on the stabilized clay are not well known and understood. The goal of the research was to therefore, conduct various column experiments and monitoring to determine the evolution of the coupled THMC processes under normal curing and when daily thermal cycles were applied to the treated and untreated clay.

Various columns were prepared in the laboratory to accommodate the compacted treated and untreated sensitive marine clay for monitoring over 28 days. In addition, columns from which samples for extensive geotechnical testing were collected, were prepared. The soils' strength and hydraulic conductivity were determined through testing while the suction, electrical conductivity and temperature evolution were determined by use of sensors placed within the columns.

The developed mechanical properties of the soil were significantly improved by use of lime. This development of mechanical properties was further enhanced when the daily thermal cycles were applied to the soil due to increased curing temperature stimulated. In addition, to temperature and chemical reactions, it was observed that the hydraulic properties also contributed to the developed soil strength. The strongly coupled THMC processes were thus, observed during the treatment of the clay with lime.

The results obtained will therefore, contribute to a better understanding of the coupled THMC processes that occur when sensitive marine clay is treated with lime. It will further contribute to cost effectively designing pavements in regions with sensitive marine clays or similar.

Acknowledgement

I would like to express my profound gratitude to my research supervisor Professor Mamadou Fall for firstly providing me with an opportunity to study under his supervision and for all his guidance and support throughout the entirety of my research program. His expertise and immense knowledge helped in successfully completing this thesis. To have been a part of his research team, is of inexplicable value which I am very thankful for.

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Lastly, I cannot begin to express the gratitude I have towards my parents Able Bwalya Tunono and Lilian Mulenga Tunono for all their unwavering support, love and guidance over the years especially in my chosen career path. An extra special thank you to my father for all the help rendered during my research. And to my siblings; Bwalya, Mutale and Able, thank you for all your support.

Table of Contents

List of figures

List of tables

Chapter 1: Introduction

1.1 Problem Statement

Sensitive marine clays are clays that are distributed globally. Countries or regions such as Canada and Scandinavia are distinctively known for these soils. In Canada for instance, they are mainly found in the eastern region – Ontario and Quebec, where they are locally known as Leda clay and Champlain Sea clay. These soils which are young deposits, were formed from sedimentation of glacially ground rock flour (Taha & Fall, 2014; Torabi & Rayhani, 2017; Mayne et al., 2019). Changes in the soil properties occurred after their formation and this is attributed to leaching – where the salt concentration within the soil particles' pore water changes. According to Gillott, (1970), Quigley et al., (1983), Taha & Fall, (2014) and Mayne et al., (2019), these soils are highly sensitive therefore, they tend to drastically and destructively lose their strength when disturbed. This is because the soil structure becomes inherently unstable and tends to act like "quick clay". Upon being disturbed, they change from being a very strong brittle material, to a behaving liquid like.

Construction of highways and roads on sensitive soils presents a challenge to geotechnical engineers due to the foundation of the structure being the sensitive soil. The soils cause considerable problems and challenges in the construction of roads and highways. The challenge is mainly because pavements are light weight, they run over extensive lengths and cannot be isolated from the foundation (Maaitah, 2012). When the soil fails because of its weak properties that inhibit it from carrying loads applied onto it, the damages from within the foundation begin to propagate onto the surface of the pavements in the form of cracks or rutting. Reddy & Moorthy (2005) suggest bearing capacity failure within the subgrade soils being the cause of deformations that are observed on the pavement's surface. As a result, the structures intended engineering use would not be fully satisfied and would further cause discomfort to users. Consequently, improper construction of highways and roads on these soils without remedial methods could possibly lead to significant damages, increased design and maintenance costs.

Therefore, to improve the engineering properties of soils such as sensitive marine clays that are considered "poor or problem" soils, soil stabilization is used as a method or technique to enhance the soil as a construction material (Firoozi et al., 2017). Resulting from this process, the soil's bearing capacity, compressibility, durability, strength and stiffness would be improved preventing the structure from failing when wheel loads are applied on to it. Effective results from the soil stabilization method will however, significantly depend on environmental stresses at the project location. Temperature and moisture infiltration are environmental stresses or conditions that affect the efficiency of the improved properties from stabilizing the soil. Global warming resulting from human activities leads to greenhouse effects that have caused significant changes in climatic conditions over the years. These conditions have been referred to as extreme in some instances, and have led to challenges of great significance in fields like geotechnical engineering. It has been agreed upon by many researchers (Jean et al., 2008; Salih, 2012; Watts, 2013; Clayton & Manning, 2018) among them, that rising temperatures around the globe have fueled; longer and hotter heat waves, frequent draughts, heavier rainfall and powerful hurricanes. With human activities continuously producing greenhouse gases, variations in environmental stresses such as temperature and moisture infiltration would be continuous for the foreseeable future. The effect of these stresses on improved subgrade soils in road/highway construction, therefore, would continue to pose challenges. It is noted that the improved soil properties become a function of what is described as the coupled Thermal-Hydro-Mechanical-Chemical (THMC) processes that occur within the soil. The coupled THMC processes are interdependent in that, each process influences the other. Resulting mechanical behavior of the soil would significantly be affected by the amount of lime used as a binder in order to achieve desired strength gain. Chemical reactions occurring when lime reacts with the soil in the presence of moisture are as well dependent on the temperature, in that, higher temperature would result in quicker reactions compared to lower temperatures. In addition, the temperature affects the soils' microstructure, affecting flow behavior of moisture in the soil particles, subsequently, affecting the mechanical behavior. As a consequence of the interdependency, the overall performance and properties of the stabilized soil depend on the coupled THMC processes.

1.2 Research objectives

The objective of the thesis is to fully understand the coupled THMC processes in lime treated sensitive marine clay subgrades, and the effect of environmental (thermal) stresses on the coupled THMC processes. This will subsequently, provide vital information which will contribute significantly, to better understanding the geotechnical engineering behavior of sensitive marine clay subgrades treated with lime under environmental stresses. The objectives will therefore, be achieved through;

- Conducting column experiments to understand the THMC behavior of lime treated sensitive marine clay.
- Column experiments subjected to daily thermal cycles, to understand the behavior of sensitive marine clay subgrades treated with lime.

1.3 Research organization

The thesis is paper based, hence, the format is that of technical papers. It contains six chapters including **Chapter 1**. Figure 1-1 shows a schematic drawing of the organization.

- **Chapter 2** provides a theoretical and technical background on: sensitive marine clays, pavement structures, and the THMC processes in soils treated with chemical binders. Additionally, chemical binders used in soil stabilization to improve the soil's engineering properties are discussed as well as soil stabilization as a soil treatment method.
- **Chapter 3** presents a background review of sensitive marine clay treated with lime and a literature review of previous studies various researchers have conducted on the coupled Thermal-Hydro-Mechanical-Chemical (THMC) processes in sensitive marine clay treated with lime.
- **Chapter 4** includes technical papers 1 and 2. The first technical paper presents the results of column experiments to study the Thermal-Hydro-Mechanical-Chemical behavior of sensitive marine clay subgrade soil treated with lime. The second paper presents the results of column experiments to study the Thermal-Hydro-Mechanical-Chemical behavior of sensitive marine clay subgrade stabilized with lime, subjected to daily thermal cycles.
- Synthesis of results obtained are provided in **Chapter 5**. The chapter further explains in detail the implications of the results on road/highway design.
- **Chapter 6** provides the main summary, conclusion and recommendations.

It should be noted that some of the results and information are repeated in the document. This is because the main results of the thesis are presented in the technical papers which were written independently without taking into consideration the document as a whole. The technical papers were written for journal submission following corresponding publication medium preparation instructions. Additionally, references are provided after each chapter.

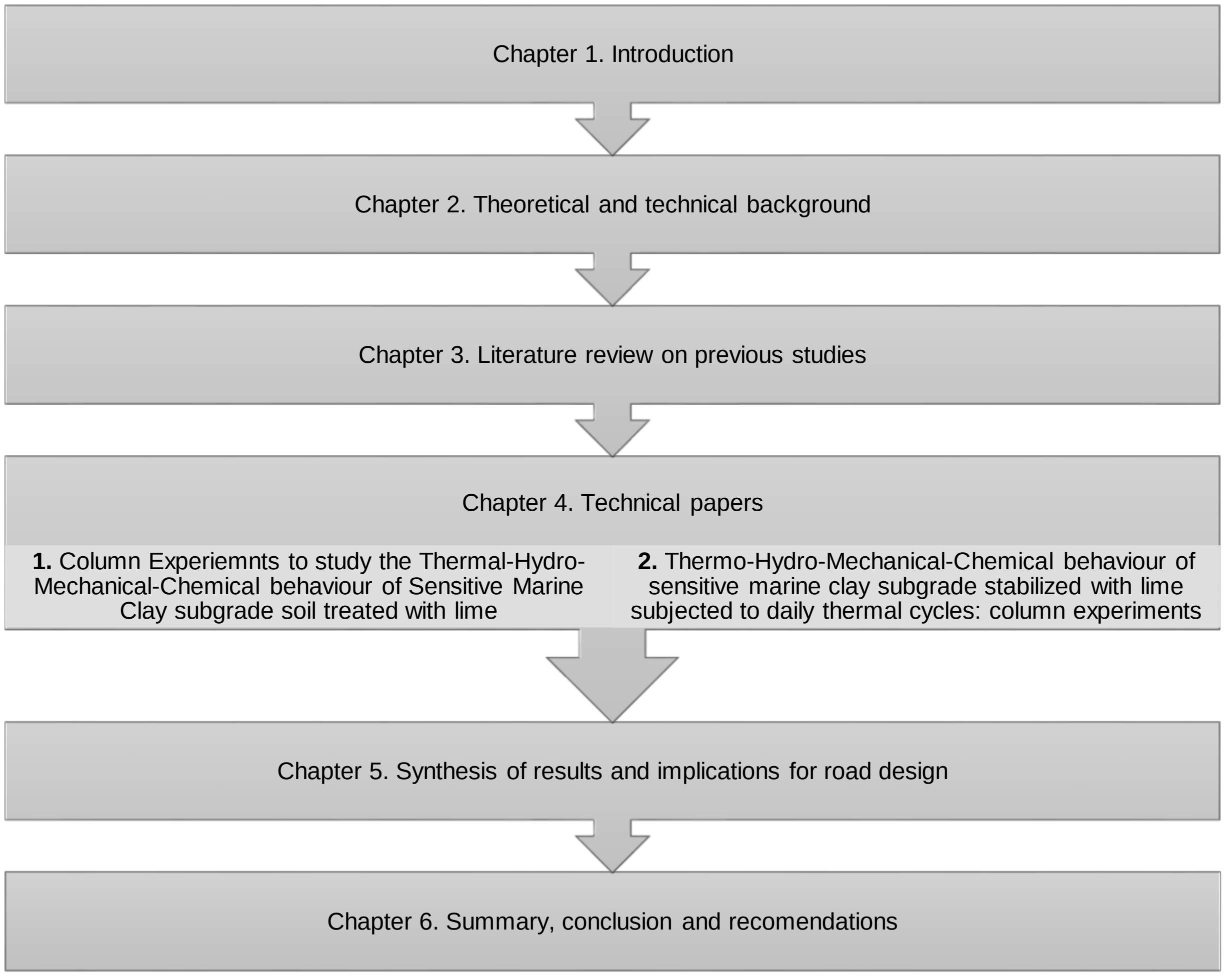

Figure 1- 1. Schematic diagram illustrating organization of the thesis

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Chapter 2: Theoretical and technical background

The objective of this chapter is to present fundamental information on the technical and theoretical background of sensitive marine clays, pavements, chemical binders, soil stabilization as a technique used to improve the engineering properties of weak soils and the THMC processes in soils treated with a binder. It is essential to gain an understanding on the use of lime in stabilizing subgrade soils, which would subsequently, lead to understanding the coupled THMC processes within the soil. Chemical reactions due to binder hydration are one of the crucial factors in these processes, therefore, should be emphasized and understood. Some of this information is briefly presented in the technical papers presented in Chapter 4, however, it is discussed in greater detail in this chapter.

2.1 Sensitive marine clays

The characteristics, properties and behavior of sensitive marine clay are an important starting point in understanding the properties that will evolve when the soil is stabilized with a binder. Sensitive Marine clays in Canada will be the main focus in this study. However, the characteristics with marine clays from other regions are similar. Sensitive marine clays other than being locally known as Leda clay and Champlain Sea clay in Canada, are also widely referred to as "Quick clays" in other regions, correlating to their sensitivity. The term "Champlain Sea clay" is derived from the Champlain Sea where the sediments originated from. On the other hand, the term Leda clay comes from the fossil 'Leda glacialis' which is in abundance in this soil (Panikom, 2020).

2.1.1 Origin and distribution of sensitive marine clays

Johnston (1917) and Brown (1962) state that Lake Frontenac was formed in the Lake Ontario – St. Lawrence Lowlands region during the retreat of the continental glacier. During this period under glaciation, the region was depressed by an ice load that led to the formation of the lake. Further retreat led to the formation of the Champlain Sea from which the fine-grained sediments that form the sensitive marine clay originated. In addition, Quigley (1980) further explains how the sedimentation in Canada occurred in proglacial and postglacial water bodies that were in existence during the retreat of the Wisconsin ice sheet 100,000 to 10,000 years ago. According to Kondo & Torrance (2005) the sensitive marine clays in Canada and Scandinavia originated from sedimentation of glacially ground rock flour. This occurred in basins that had been isostatically depressed by glacial ice sheets. The sediments were subsequently uplifted above sea level. The researchers generally agree on how the sediments that formed the sensitive marine clays originated. However, in view of Brydon & Patry (1961) the exact geological history of the sediments is uncertain and subject to disagreement. Figure 2-1 shows the landmass covered by marine and freshwater glacial and postglacial lakes. Other than the Champlain Sea, other major water bodies where sedimentation occurred existed (Figure 2-2). These bodies covered the Georgian Bay, Lake Simcoe and western Superior areas, the area extending from Lake Nipigon and Hudson Bay into the United States (Quigley, 1980; Nader, 2014; Panikom, 2020). The oldest marine sediments exist in the southern region with the youngest in the northern region.

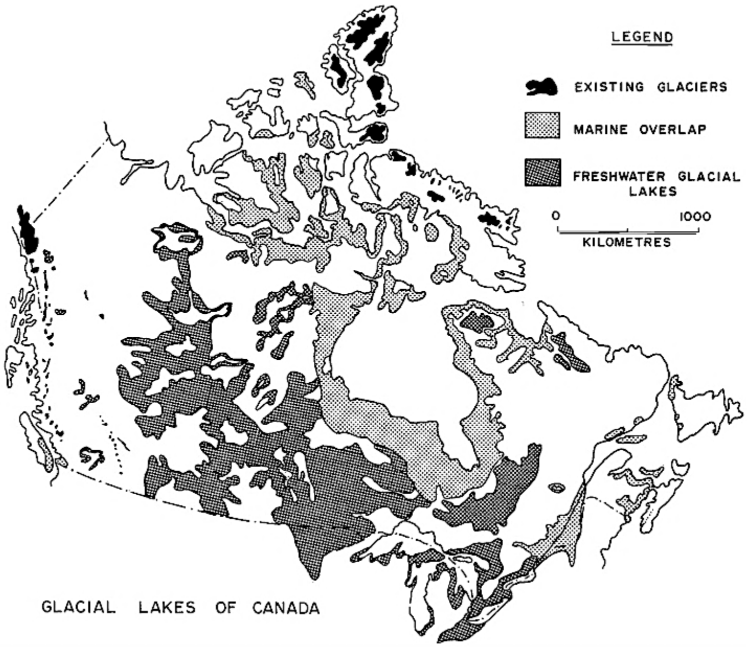


Figure 2- 1. Distribution of marine and freshwater glacial and postglacial lakes of Canada. (Quigley, 1980)

In landlocked freshwater lakes, varved clays were deposited while flocculated marine clays were deposited in the coastal regions after saline water infiltrated. In the Ottawa region, Crawford (1968) suggests a major redeposition of marine clays into freshwater. It was opined that the water salinity changed because of fresh water influx from the great lakes region. According to literature (Brown, 1962; Andrews, 1973; Quigley, 1980; Belrose, 2015; Nader, 2014) ice fronts occurred in subsequent periods where early deposition of sediments happened in 13000 BP in the freshwater lake in southern Ontario (Nader, 2014).

Figure 2- 2. Major glacial lakes of Canada (Quigley, 1980; Panikom, 2020)

The ice sheets thinned out and subsequently retreated northward while the earth's crust rebounded isostatically. Ice sheets thinning out was attributed to climatic changes which according to Quigley (1980) significantly controlled the rate of the Wisconsin withdrawal, glacio-isostatic rebound and eustatic rise in sea level. Andrews (1973) further shows postglacial rebound of major areas in eastern Canada (Figure 2-3). The contour lines show the Hudson Bay region rebounded more than 250m compared to the Ottawa region which was nearly 200m. The significance of the heights to which the regions rebounded is to indicate and predict the elevations at which the marine sediments may be found.

It has been noted that the deposits resulted from sedimentation during the glacial period. In addition to the origin and process of formation of the deposits, Liebling & Kerr, (1965) and Barnes, (2016) state that the soils can further be separated into two categories; soils deposited directly by ice and soils deposited by melt-waters. The soils deposited by ice are referred to as till - finer matrix and are embedded with gravel, cobble and boulder-size lumps of rock. The soils deposited by melt-waters which are referred to as outwash deposits include finer particles of clays and silts that were deposited during the glacial melt and retreat. Laminated and varved clays were subsequently produced from this.

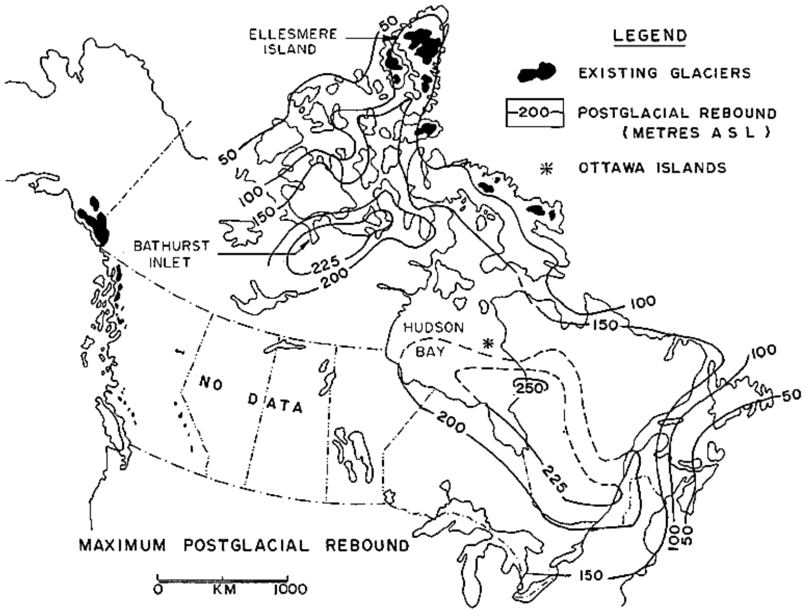


Figure 2- 3. Postglacial rebounds of eastern Canada (Quigley, 1980; Andrews, 1973)

Majority of the sensitive marine clays occurred in the valleys of the Ottawa and St. Lawrence rivers (Crawford, 1968; Dreimanis, 1977; McEniry, 1978; Quigley, 1980) where they were bound by the inland sea limit of the Champlain sea. Figure 2-4 illustrates the approximative extents to which the deposits run in the USA and Canada. Major cities in Canada such as Ottawa, Montreal and Quebec City are situated in this region. However, Al-Umar et al., (2020) states that the soils are found particularly in the Ottawa region.

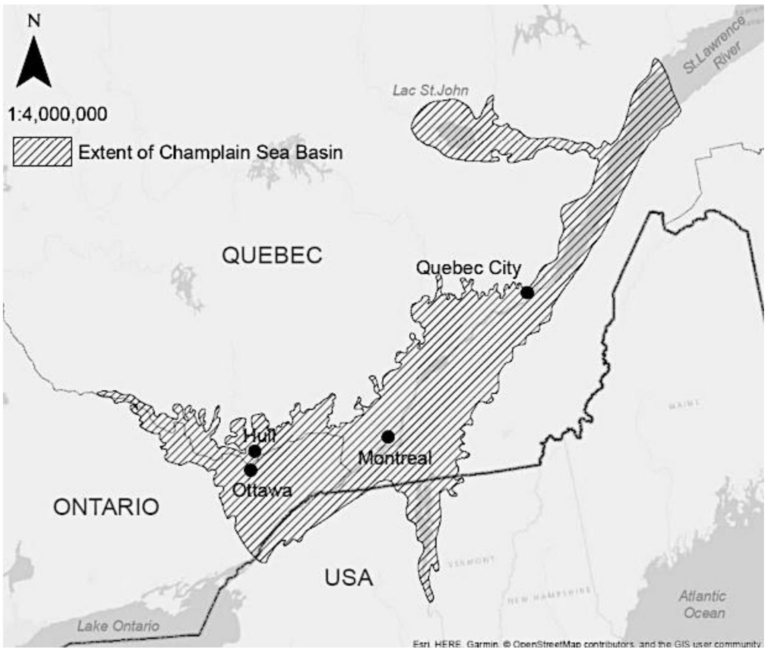


Figure 2- 4. Extent of Sensitive marine clays limit in Ottawa valley and Quebec areas (McEniry, 1978; Panikom, 2020)

2.1.2 Structural characteristics of sensitive marine clays

Structure or fabric of a soil refers to the manner in which the individual soil particles are arranged and held together. According to Sorensen (2006) it is a relative measure which is generally used in soil mechanics context as a measure to describe components of the micro and macro structure of intact or artificially cemented soil that are removed upon reconstitution. The individual soil particles are held together by different kind of bonds that are either flexible or rigid (Crawford, 1968) and differ in strength. In Addition, Barnes (2016) suggests that the type of bonds in between the soil particles is dependent on the type of clay minerals within the soil. The soil structures can range from a random or card-house to parallel orientation (Figure 2-5) and will vary depending on size, shape and geometric arrangement of the particles. To better understand the engineering behavior of the soil such as sensitivity, the nature of the microstructure has to firstly be understood. In addition to the microstructure which is less than 1mm, the macrostructure needs to be understood too. This structure is more than 1mm in size, and can be seen by the naked eye (Panikom, 2020) unlike the microstructure.

Surfaces of weakness such as voids, fissures and skins of different composition materials separate soil particles in a cluster (Edil, 1988). This occurs in peds which have been used to define macroscopic units. Due to the aforementioned surface weaknesses, macrostructure units can be seen with the unaided eye. On the contrary, microstructure units range from single particles acting independently to a group of particles acting as a unit. Hence can only be seen under an electron microscope.

Sensitive marine clay structures consist of silts and clay size rock fragments with clay minerals that are randomly oriented. They are said to have card-house structures with flocculated particles (Quigley, 1980; Taha, 2010; Monsif et al., 2020) which when disturbed, will easily enable the soil to drastically change from being a brittle material to flowing like a liquid. Gillott (1970) instead referred to the structure of Leda clay as 'loose' or having an 'open' arrangement. It was explained that when a disturbance occurs, the open structure breaks down causing the particles to become closely packed. With the particles being closely packed and the water content staying the same, these particles become fully saturated causing the liquid – like behavior. The soil particles in the card-house structure have pore fluid containing salt. This salt content is as a result of the soil's environment during deposition. Leaching of salt from the pore fluid equally has a profound impact on the stability of the sensitive marine clay soil structure. This is because it causes an imbalance in the forces between the soil particles (Monsif et al., 2020) by removing the dissolved salt ions from part of the soil profile. Essentially, when moisture infiltrates into sensitive marine clay the salt content changes leading to the distortion of the structure, therefore, significantly damages structures laid on this soil. The mechanism of how quick clays are formed according to Rankka et al., (2004) follows the general theory of clay size particles containing non-swelling clay minerals sedimenting in a flocculated condition. Sedimentation occurs due to low electrokinetic potential because of the water being salt or because of adsorption of bounded counter ions such as Fe^{3+}. As a result of leaching, reduction of trivalent to bivalent iron, the electrokinetic potential increases after deposition and moderate consolidation. A subsequent mechanical remolding of the clay causes a unidirection of the particles and because of the strong repulsive forces between the particles, re-flocculation is not possible thereafter (Rankka et al., (2004).

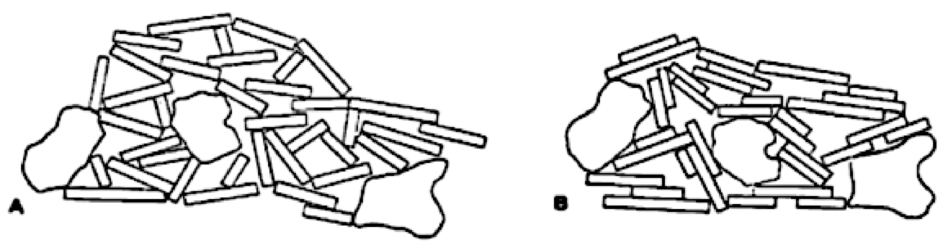


Figure 2- 5. Undisturbed "card-house" - A, structure constructed with a parallel structure - B. (Gillott, 1987)

In view of Penner (1965), Leda clay consists of surfaces that are negatively charged in excess. He further explains that the excess negative surface charges which are balanced out by positive ions from surrounding liquid are accounted for by the lattice imperfections in the crystal. When bonding occurs between the negatively charged soil surface and the water molecules, the soil begins to swell up. This is attributed to the repulsive forces being more than the attractive forces existing. Figure 2-6 shows a double layer from which Penner, explains electrokinetic potential using the clay surface negative charges and ions from water. Nader (2014) explains electrokinetic potential as the potential difference between the clay particles and the surrounding liquid which Penner further describes as a semiquantitative guide to the degree of repulsion between the ions from the surrounding liquid and the soil surface charges. The positively charged diffuse layer would be attracted to the negative electrode dragging with it water when an external potential is applied to the surface of the soil particles. The soil particles with adsorbed water molecules, called immobile layer, would be attracted to the positive electrode. This process explains the behavior of sensitive marine clay when in contact with water and how swelling occurs in these soils. However, as water adsorption occurs continuously, repulsive forces between charged particles reduce with an increase in clay-water systems.

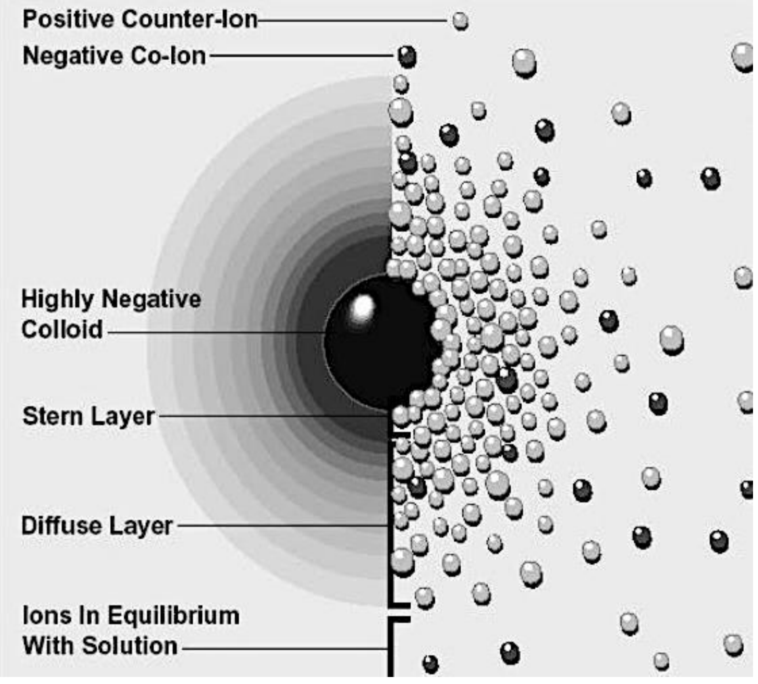


Figure 2- 6. Double layer concept (Nader, 2014)

Among factors significantly influencing the clay fabric are the state of flocculation at the time of sedimentation and the amounts of carbonates present in the soil (Gillott, 1970). The former was thought to have the most importance in affecting the clay fabric and essentially, the properties of the soil.

Soil properties at any time including possible changes they may go through, can therefore, be assessed by having a good understanding of the soil fabric as well as principles that govern it such as the interparticle forces.

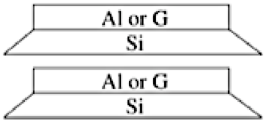
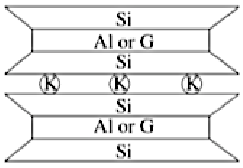
2.1.3 Chemical and mineralogical characteristics of sensitive marine clays

The geotechnical behavior of sensitive marine clays is greatly influenced by their chemical and mineralogical characteristics due to these aspects controlling the soil's sensitivity. According to Quigley (1980) sensitivity is a complex mineralogical and geochemical phenomenon. Sensitivity is described as a ratio of the natural shear strength of the soil to its remolded strength (Penner, 1965). It is of significance to understand the soil's chemical and mineralogical characteristics because they aid further understanding of the soil's geotechnical behavior which are vital in subgrade construction.

According to Nader (2014) oxides provide a coating around the clay particles and contribute to bonding mechanisms as well as cementation. In a study by Locat et al., (1984) in which the interrelationship among the mineralogical, chemical and physical properties of some marine clays from eastern Canada was conducted, it was stated that aluminum, iron and silica are amorphous oxides. Quigley (1980) made reference to an amorphous material whose main constituents were the oxides suggested by Locat et al., and Nader. He was of the opinion that if the amorphous oxides are not too abundant, the resulting soils' sensitivity will be very high. It was further suggested that the amorphous material which is chemically active behaves like a clay mineral thickener when in large amounts and equally coats clay particles which Nader (2014) agreed with. In this instance, the soils' remolded shear strength would increase significantly, hence, effectively reducing the sensitivity. In sensitive marine clays from eastern Canada, Aluminum oxide (Al_2O_3) and Trioxidosilicate (SiO_3) are abundant with the former being dominant (Locat et al.,1984). In smaller amounts, Calcium oxide (CaO), Potassium oxide (K_2O), Iron oxide (FeO), Sodium oxide (Na_2O), Magnesium oxide (MgO) and H_2O_T are found in these soils too.

Clay minerals according to Barnes, (2016) are small crystalline substances with sheet like structures that are distinctive and produce plate-shaped particles. Table 2-1 shows an illustration of two common mineral types including the type of bond between the layers of the structure and the base exchange capacity.

Table 2- 1. Clay mineral structures (Barnes, 2016)

Mineral	Layer structure	Stack structure	Bonding between layers	Base exchange capacity (me/100g)
Kaolinite	1:1		Hydrogen bonds (strong)	3-15
Illite	2:1		Potassium ion (weaker than hydrogen bonds)	10-15

The layer structure describes how the units in each structure are layered. These units in the structure are held together by bonds that vary in strength. Base exchange which is also referred to as the cation exchange capacity is the ability for the clay minerals to exchange cations within its structure for other cations. All the components described in Table 2-1 differ for all minerals.

In a study performed on soil samples from the St. Lawrence valley, the mineral analysis revealed chlorite, illite, amphibole, quartz and feldspar as the main minerals comprised in these soils (Crawford, 1968). Another study performed by Brydon & Patry (1961) on soil samples from the Ottawa area revealed no difference in the minerology. The soils contained chlorites, micas, amphibole, quartz and feldspar. Quigley (1980), Locat et al., (1984), Kondo & Torrance (2005), Taha (2010) and Nader (2014) agree with the sensitive marine clays containing the aforementioned minerals although suggest plagioclase, microcline, hornblende, dolomite, calcite, smectite and montmorillonite as also being present. Montmorillonite and smectite were said to be in trace amounts compared to the other minerals. Further to the authors agreeing on the mineral composition in sensitive marine clay, it was also agreed on that the amounts of each mineral would vary depending on the location and depth from which the soil samples were sourced.

2.1.4 Pore water chemistry

A soils' porewater chemistry is important to determine and understand because it contains dissolved minerals that affect and influence the geotechnical properties such as soil sensitivity and flocculation of soil particles. Torrance (1979) adds chemical conditions in depositional environment and post depositional changes as contributing factors to porewater influence on the soil behavior. It was suggested to firstly have an understanding of the initial chemical conditions of sea deposits from the Champlain sea before presenting and reporting present day deposit conditions.

Porewater of sediments from the Champlain Sea were said to be highly saline. Although this was the case for the marine portion, 2 - 8m of varved sediments that lay at the base of the deposits had porewater with low salinity (Torrance, 1979). It was suggested that the salinity in the varved sediments' porewater was low due to the presence of freshwater and occurrence of leaching. In studies conducted by Torrance (1976) to determine the effect of sample storage and porewater chemistry, and Quigley (1980), it was concluded that salinity has a relationship with the soil's sensitivity in that the higher the salinity, the lower the sensitivity and vice versa. Moreover, salinity within the porewater also influences the soil particles' flocculation of which a minimum of 2 - 3% concentration is said to induce it (Nader, 2014). Therefore, according to the origin of sensitive marine clays, porewater in the sediments at the time of deposition were of high salinity. Weathering and erosion resulted into varved sediments containing porewater with low salinity of which the presence of fresh water and leaching contributed largely.

It has been determined by researchers (Penner, 1965; Torrance, 1976 and 1979, and Quigley, 1980) that the porewater of Leda clay has different cations. The studies show that sodium ions (Na^{+}), magnesium ions (Mg^{2+}), calcium ions (Ca^{2+}) and potassium ions (Ka^{2+}) are present with Na^{+} being in significant amounts. Sangrey & Paul (1971) state that the younger deposits would have higher concentrations of Ca^{2+} due to freshwater environment compared to the older deposits of marine environment in which higher concentration of Na^{+} were reported within the porewater. Concentrations of these ions in the porewater of the soil were seen to increase with depth at different locations suggesting an increase in salinity. This was attributed to weathering which occurred and flow of freshwater at the surfaces therefore, causing the salt to leach out of the soil particles. Diffusion of minerals from high to low concentration areas, is another way through which leaching may occur until uniformity is reached (Panikom, 2020). At the base of the deposits near the bedrock, the level of salinity would reflect that near the surface due to groundwater flow which would cause leaching of salts. So leaching of salts from the porewater reduces salinity concentrations and subsequently, increases sensitivity. This would suggest sensitivity varying along the depths of soil based on the relationship with salinity discussed earlier.

2.1.5 Geotechnical properties of sensitive marine clays

This section discusses geotechnical properties of sensitive marine clay that are important in designing and constructing safe and durable structures such as pavements in these problem soils. Due to their high sensitivity, challenges are faced by engineers when working with them. Therefore, there is need for better understanding of the geotechnical properties in order to achieve safe and cost-effective construction.

2.1.5.1 Compression and consolidation

It has been determined that sensitive marine clay has a structure or fabric described as being "card-house". The structure contributes significantly to the soils compressibility and consolidation behavior. Consolidation is the process in which pore water is dissipated from the pores of soil over time as a result of constant compressive pressure exerted by an overburden load. In addition to factors such as overburden and remolding, Kondo & Torrance (2005) indicated that self-weight of the soil could result into consolidation. As a result of dissipated pore water during consolidation, the pore sizes of the soil reduce leading to decreased void ratios and porosity. Soil compressibility on the other hand is the ease with which soil volume decreases due to loads they are subjected to.

Preconsolidation pressure according to Panikom (2020) is the maximum effective past pressure. It is the critical limit reached when pressure exerted onto the soil fabric from the overburden continuously increases. Other than the overburden, changes in temperature, salt concentration, cementing agents, and ion exchange can lead to preconsolidation. As depth increases, preconsolidation pressure is generally believed to increase (Nader, 2014). This can be attributed to the increased self-weight of the soil. At the point of preconsolidation, the bonds between the soil particles breakdown resulting in collapse of the soil structure. Consequently, particle parallelism is induced (Quigley & Thompson, 1966) which can be seen in Figure 2-7. The structure of sensitive marine clays prevents the soil from experiencing significant settlement before reaching preconsolidation pressure due to its ability to bear the loads before the limit is reached.

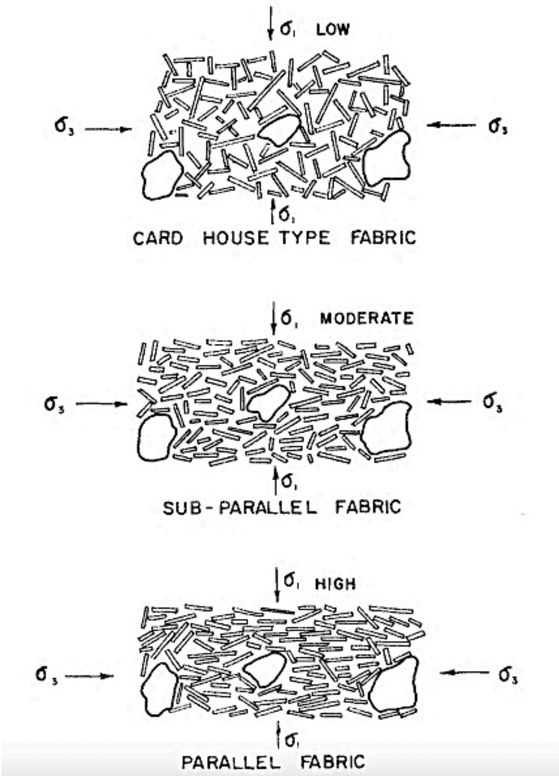


Figure 2- 7. Structure of sensitive marine clay at different stages of consolidation (Quigley & Thompson, 1966)

With increasing exerted loads applied onto the soil, it can be seen from Figure 2-7 that the particle orientation increasingly becomes parallel. The process can be seen as progressive. It can thus, be concluded that there is a direct relationship between void ratio and the induced particle parallelism in which parallelism increases as the void ratio decreases. This conclusion was arrived at by Quigley & Thompson (1966) after carrying out research on the relationship between the structure of sensitive marine clay from the Ottawa region and consolidation. Delage & Lefebvre (1984) agreed with this relationship, however, he further expressed that the largest existing pores are the only ones to collapse under a given effective stress. The smaller pores would only be compressed under larger pressures and in addition only when all macro pores have collapsed. Therefore, during consolidation, compression could also be related to dissipated pore water and the soil structure collapse which results from bonds breaking. Leda clay deposits that are highly plastic are very compressible according to Crawford (1968) who further indicated a significant amount of compression could be observed at pressures well below the preconsolidation pressure.

Consolidation occurs in two states including normal consolidation and overconsolidation. Normally consolidated soils are soils that have present overburden pressure equal to the maximum overburden pressure experienced in the past. Whereas overconsolidated soils are soils with present overburden pressure less than experienced in the past (Panikom, 2020). The rate at which consolidation occurs in soils is known as the coefficient of consolidation (C_v). It is essential to determine the coefficient of consolidation because it aids prediction of the time it will take for an area of soil to settle.

2.1.5.2 Thermal conductivity

Effects of temperature on the behavior of fine-grained soils are of great significance. The temperature gradients due to environmental temperatures and upward flow of heat from the earth's interior, alter the soils' composition particularly with regard to the amount and condition of water. Understanding a soils' thermal conductivity becomes important in order to determine heat flow within the soil. This is particularly important in sensitive marine clays due to the typically high moisture content.

Thermal conductivity, a thermal parameter, is the amount of heat passing in a unit cross sectional area of soil under a unit temperature gradient applied in the direction of heat flow (Duarte et al., 2006). The low thermal conductivity in fine-grained soils and varies with volumetric water content and degree of saturation. This has been attributed to it being dependent on the minerology and pore sizes of the soil. In addition, Penner (1962) and Bi et al., (2018) suggest that a soils' thermal conductivity is also greatly influenced by particle size, porosity, dry density and hysteresis effects. Generally, thermal conductivity in undisturbed samples of sensitive marine clay will be higher than that in remolded soil samples (Penner, 1962) because of the difference in the structure of the two samples and the anisotropic thermal conductivity of minerals such as mica. The structure of Leda clay in its undisturbed form has been previously discussed, as well as that in a remolded and compressed sample in which particle parallelism occurs. Thermal conductivities measured in soils with changed structural arrangement that has been measured in the same direction as the pressure applied would be less than those occurring in naturally occurring flocculated structures. Penner (1963) later indicated that the parallel alignment of soil particles causes the clay sediments to become anisotropic to thermal conduction.

Heat flow primarily occurs in soil particles because soil particles have a higher thermal conductivity compared to water and air. Although this is the case, Leda clay particularly has low thermal conductivity unlike other similar fine-grained soils as reported by Penner (1962). This was attributed to its high clay content although its mineral composition was suggested to have significance. Brydon & Patry (1961) found mica in appreciable amounts in Leda clay which (Penner, 1962) likened its thermal conductivity to that of water. The thermal conductivity of Leda clay which is relatively low is therefore, not surprising due to this.

2.1.5.3 Hydraulic conductivity

Pavement performance is considerably affected by moisture redistribution within the subgrade soils which results in stiffness changes. Hydraulic properties such as hydraulic conductivity and its influence on movement of moisture within the subgrade therefore, becomes very important to understand. Hydraulic conductivity, also known as coefficient of permeability, is the rate at which water flows through a soil's interconnected voids. It is a significant geotechnical engineering property in soils due to it being essential in performing flow analysis and stability calculations (Penner, 1962). Additionally, Nader (2014) indicates that it influences mechanisms and problems such as migration of pollutants from waste disposal facilities, consolidation of clay foundations and, groundwater regime in stratified deposits near natural and excavated slopes. Hydraulic conductivity largely depends on the soil type of which, in clays it is relatively low compared to sands and gravel. Porosity and permeability of sands and gravel lead to higher hydraulic conductivity due to the larger pore spaces of these soil types.

Flow of water within the subgrade soils is determined by a hydraulic gradient (Fredlund et al., 2012b; Lu & Zapata, 2016) which forms the driving potential. The gradient value describes the available energy allowing the water to flow. And so, the difference in hydraulic head between two points causes flow of water from which the hydraulic conductivity is determined. In view of Das (2008) hydraulic conductivity of a soil is assumed to be constant value in saturated soil conditions. It will however, vary immensely with the soil's stress state. The hydraulic conductivity will decrease as a soils' liquid phase becomes discontinuous due to desaturation and it will increase when the liquid phase is continuous. Since water only flows through void spaces filled with water, the decrease in conductivity was attributed to the decrease in the cross sectional area of the water by Fredlund et al., (2012b).

Panikom (2020) states that in hydraulic conductivity of sensitive marine clays, porewater density and viscosity, grainsize distribution, void ratio, roughness of clay particle surfaces, ion concentration, thickness of water layer adhering to clay particles and the amount of undissolved gas in the pore water, are taken into account. It will generally decrease in sensitive marine clays as stress increases because of change in the pore volume. When there is an initial increase in stress applied, the clay structure and porewater bear the load which consequently resists compression. Hydraulic conductivity decreases consistently with reduced pore size according to Nader (2014) and Panikom (2020). This is when the soil structure cannot withstand the strain. The card house structure eventually collapses resulting in the decreased hydraulic conductivity. In addition, the hydraulic conductivity would decrease with depth along a soil matrix. This would be attributed to increasing geostatic pressure from the overburden which would therefore, cause changes in pore size. Decreasing change in the pore sizes would subsequently result in the liquid phase of the soil being discontinuous hence, the aforementioned decreasing hydraulic conductivity.

To prevent moisture induced damages such as premature deterioration of pavement surfaces, it is vital to have comprehensive understanding of flow behavior and hydraulic conductivity in the subgrade soils such as sensitive marine clays. This may also be related to other foundation structures other than pavement subgrades.

2.1.5.4 Shear strength

The capacity of a soil to resist failure and sliding along a plane within its structure when under stress is known as shear strength (Panikom, 2020). Strength of a soil changes when the stress state changes. Therefore, failure in soils would occur when the stresses applied onto them exceed their shear strength. According to Fredlund et al., (2012a) bearing capacity, lateral earth pressure and slope stability are examples of geotechnical applications that depend on a soil's shear strength, and so, it is an important parameter to understand for construction of engineering structures. Shear strength is expressed as shown in Equation 2-1 (Fredlund et al., 2012a) using the *Mohr-Coulomb failure criterion*.

$$\tau = C + \sigma tan\emptyset \qquad \text{Equation 2-1}$$

Where; τ is the shear strength, C is the cohesion, σ is the normal stress, and $\emptyset$ is the internal frictional angle.

Cohesion results from forces between soil particles that hold them together and cementation from deposition of dissolved clay minerals within the porewater. Within the soil, the greater the cohesion and internal frictional angle, the greater the resulting shear strength would be. It should then be noted that when a soil is disturbed, significant decrease in cohesion and internal frictional angle would consequently result in decrease of the soil's shear strength. Another factor that would contribute to increased shear strength and affect volume change in these soils is increased effective stress. An increased effective stress resulting from the overburden, leads to dissipation of excess pore water pressure from the soil particles which equally contributes to flocculation and soil stiffness.

Figure 2-8 obtained from Mayne et al., (2019) shows compiled results from vane shear tests conducted by various researchers which shows a similar trend.

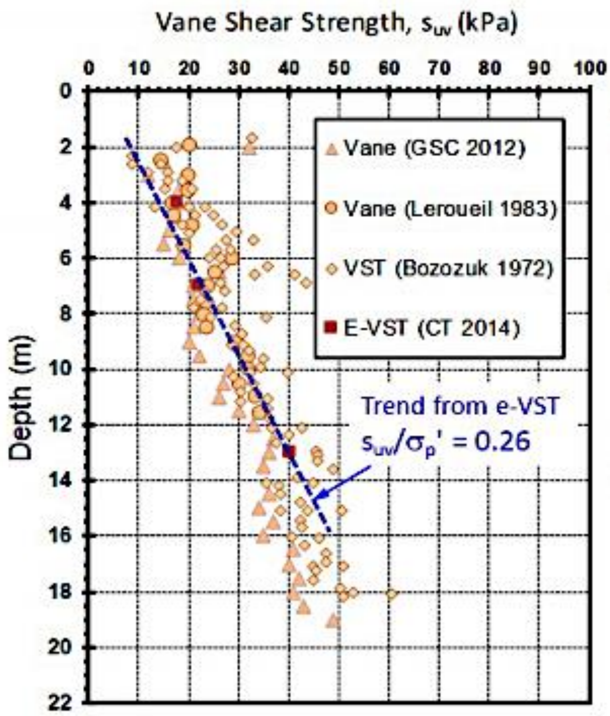


Figure 2- 8. Complied vane shear test results for different sites in Ontario (Mayne et al., 2019)

It can be seen that the shear strength in the sensitive marine clay soils increased with depth due to increased self-weight pressure and consolidation of the soil. Previously, it was discussed that salinity increases with depth which entails increased flocculation of soil particles along the depth. It can therefore, be said that in addition to increasing self-weight of the soil, the shear strength in sensitive marine clays increases with depth. Nader (2014), Abdulrahman & Rayhani (2019) and Panikom (2020) agree on increasing shear strength in sensitive marine clay as salt concentration increases with depth in the soil matrix.

2.1.5.5 Sensitivity

Sensitivity of Leda clay has been discussed briefly in sections prior to this, of which previous researchers suggested an existing relationship with porewater salinity. Salt content within the porewater increases flocculation of the soil particles, resulting in limiting the sensitivity. Due to the effect salt has on flocculation, soils with high salt contents cannot achieve high sensitivity. Although the relationship was suggested, Penner (1965) disagreed with authors suggesting sensitivity is not necessarily related to salinity, but rather electrokinetic potential. Based on the work he performed, he opined that soil sensitivity increases consistently with increasing electrokinetic potential. Electrokinetic potential and sensitivity were suggested to be consistent with a theory referred to as “interparticle repulsion”. Repulsion of soil particles would result in deflocculation which would increase the sensitivity of the soil. In spite of the disagreement, it was concluded by all that sensitivity in Leda clay is of tremendous significance. This is because sensitivity characterizes the soil and its distinctive behavior. It should also be noted that moisture content relative to the liquid limit, percentage of clay content and grain size distribution, greatly influence the sensitivity of a soil as well.

Soil sensitivity is categorized into eight groups depending on the level of sensitivity. Table 2-2 presents classification categories into which soils are generally classified.

Table 2- 2. Soil classification based off sensitivity (Canadian foundation engineering manual, 2006)

Sensitivity range	Classification
< 2	Low sensitivity
2 - 4	Medium sensitivity
4 - 8	Extra (High) Sensitivity
> 16	Quick

When remolded, clays having high sensitivities tend to flow like liquids and so, being known as quick clays. Remolding by a disturbance such as loading causes the engineering properties of the soil to change considerably. The soil losses its shear strength upon remolding which increases its sensitivity. According to Crawford (1968) Leda clays usually have a sensitivity greater than 20 making them hazardous. This will however, vary widely depending on the location and depths from which the soil is obtained. Based off the relationship of sensitivity varying with salinity, quick clay behavior will therefore, occur in clays where salt content within the porewater has significantly decreased due to leaching. Leaching which may be caused by either rain/snowfall or flooding destroys soil particle bonding systems.

2.1.5.6. Thixotropy

Thixotropy is the time dependent strength gain of clay on its own under constant water content and volume conditions (Park, 2011; Ren et al., 2021). It is a process in materials such as sensitive marine clay that occurs after softening by remolding and it is said to be a structural effect that is accompanied by dissipation of internal energy. When a soil is remolded, its shear strength is reduced as a result of the disturbance. Figure 2-9 illustrates the thixotropy effect in which, after a period of time while under constant conditions, the reduced shear strength increases. In a material that is partially thixotropic, the shear strength would not be reverted back to the original after sometime like it would in a fully thixotropic material.

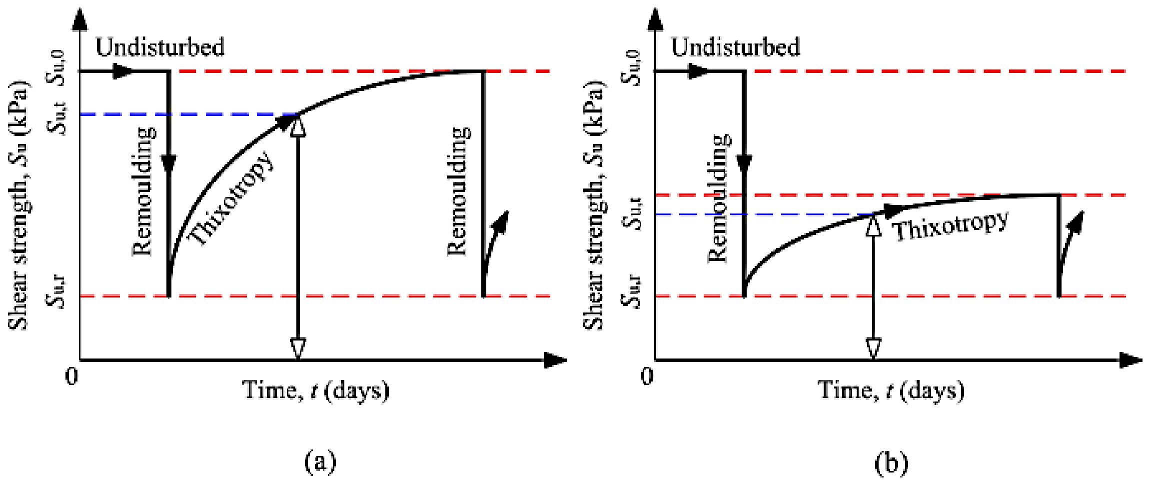


Figure 2-9. Illustration of thixotropic process for a) fully thixotropic material and b) partially thixotropic material (Ren et al., 2021)

Ren et al., (2021) summarized the process as a mechanism of microstructure recovery alongside an increase in flocculation which is formed through reorientation and rearrangement of particles, change in adsorbed water structure and redistribution of ions. Therefore, the degree of thixotropy would depend on the grain size, gradation, presence of electrolytes and mineralogical composition. Although the process is believed to have a great effect on the soil's strength recovery at water content close to the liquid limit, Ren et al., suggested ambiguities still remain. In soils with high activity, the thixotropy effect is significant because of the clay minerals whose crystal structures vary. The thixotropic effect of a soil reduces in high salt concentrations. This is because the thickness of the electrical double layer shrinks, thereby, restricting the rearrangement of particles.

2.2 Background review on pavements

Pavements are engineered structures constructed to provide smooth surfaces which enable users to drive vehicles safely under any given climatic condition for a specified design period. They date back to roman times and have significantly evolved since then. Pavement designs vary based on regional experiences especially in terms of weather because other than loads applied onto them, weather patterns affect their behavior tremendously.

2.2.1 Pavement system and typical pavement types

Pavement structures are made up of a number of layers whose thicknesses are dependent on design methods under consideration (Christopher et al., 2006). In addition to design methods, the region, in situ soils and pavement type also help to determine the layers and thicknesses the structure as a whole would have. Figure 2-10 presents a typical cross section of a pavement structure showing its components.

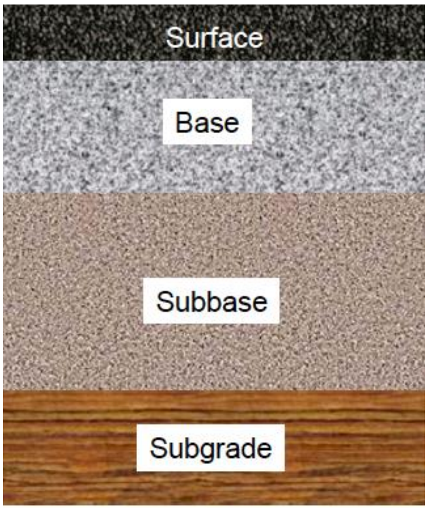


Figure 2- 10. Components of a typical pavement system (Christopher et al., 2006)

Subgrade is the natural soil onto which the structure is laid. This layer is assumed to be infinite in both the horizontal and vertical directions. According to Christopher et al., (2006) the function of the subgrade is to support the whole structure without incurring deflections that would affect its overall performance. It is essentially the foundation which is compacted to prescribed standards to increase strength, stiffness and stability (Christopher et al., 2006; Garber & Hoel, 2009). It should therefore, be noted that if the subgrade is constructed poorly, or if improvement methods are not considered for weak soils, the structure would perform poorly incurring significant maintenance costs during its intended design life.

The subbase is the layer that sits on the compacted subgrade. Christopher et al., (2006) states that this pavement layer is usually included as part of the structure when either very poor quality soils form the subgrade or when base layer materials cannot be obtained locally, therefore, expensive. In view of Garber & Hoel (2009) the subbase layer can be removed from the structure when the quality of the subgrade material meets the requirements of the subbase material. Exclusion of this layer often happens in construction of rigid pavements. However, if incorporated into the design, its function would be to support the base layer which would be located immediately above it and would contribute to the structural capacity of the pavement. Secondary functions of this layer are to prevent intrusion of fine-grained subgrade soils into the base layer to minimize the damaging effect of frost action and to provide drainage for free water that may infiltrate into the pavement structure. In some instances, the subbase material would be stabilized with Portland cement, asphalt, lime or fly ash, to improve its strength and stiffness (Christopher et al., 2006; Garber & Hoel, 2009) because this layer can be of lower quality compared to the base layer.

The base layer is that which is placed directly on top of the subbase layer or the subgrade, if subbase layer is omitted, to provide support to the surface course layer. In flexible pavements, this layer provides a significant portion of the structural capacity and in rigid pavements it improves the stiffness of the foundation (Christopher et al., 2006). Both Christopher et al., (2006) and Garber & Hoel (2009) agree on the specifications for the base material having stern requirements in terms of gradation, stiffness, strength, degree of compactness and plasticity, compared to the subbase material. Similar to the subbase materials, base materials without required engineering properties can be stabilized with Portland cement, lime, fly ash and asphalt to improve their strength and stiffness characteristics.

The uppermost layer in the pavement structure which is constructed above the base layer to accommodate traffic loads is the surface course, sometimes referred to as wearing course. This layer can either be an asphalt layer in flexible pavements or a Portland cement concrete (PCC) layer in rigid pavements. Other than accommodating applied traffic loads, this layer should be able to withstand high tire pressures, provide skid resistance and resist abrasive forces from traffic (Christopher et al., 2006; Garber & Hoel, 2009). Moreover, this layer should provide a smooth driving surface and be capable of preventing infiltration of surface water into the sub layers. This is achieved by including a crown with 2% grade for the asphalt and ensuring good gradation of the asphalt aggregate. However, it should be noted that there are asphalt pavements known as popcorn mixes designed for water to infiltrate rather than run off. The surface course thickness varies depending on the expected traffic for the given structure. Essentially, in high traffic volume roads this layer would be thicker than in low volume roads. That being so, Christopher et al., states that in low volume roads, this layer is often placed directly above the constructed subgrade. However, this approach or technique is not recommended by MTO.

The typical components of a pavement structure have been described. To gain further understanding of pavements including their design lives and performance, understanding the different types that can be constructed becomes vital. There are three conventional pavement types including flexible, rigid and composite pavements (Figure 2-11). Although the three pavement types exist, the most common type constructed is the flexible pavement.

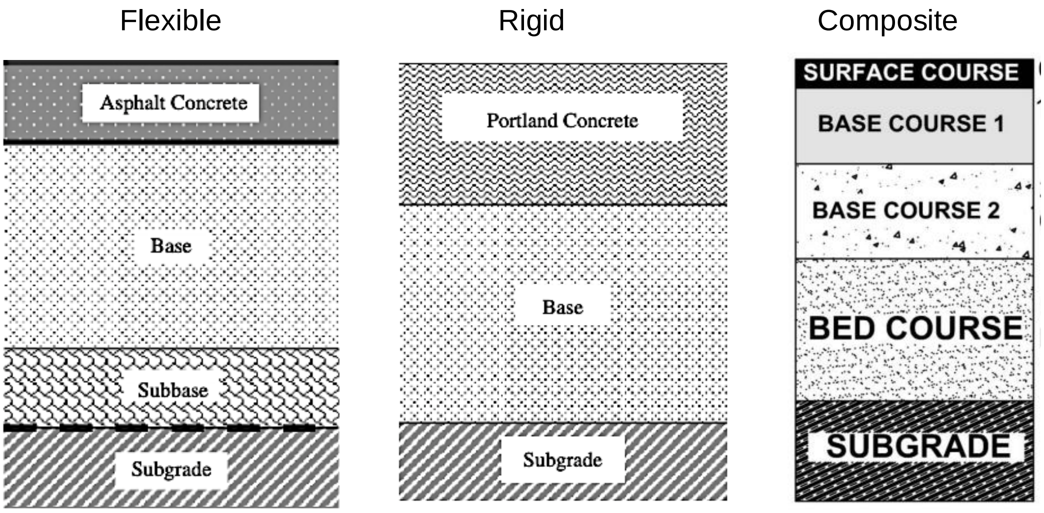


Figure 2- 11. Typical pavement types (Papagiannakis & Masad, 2007; Mezhoud et al., 2017)

As a typical example, in the composite pavement shown in Figure 2-11, the surface course is the Hot-mixed asphalt (HMA), Base course 1 is the asphalt concrete base, Base course 2 is the cement-treated base and the Bed course is the graded crushed rock.

Flexible pavements are those that consist of an asphalt layer which forms the surface course. These structures according to Garber & Hoel (2009) are multi-layered elastic systems having layers that are characterized by physical properties such as poisson's ratio, resilient modulus and modulus of elasticity. In order to achieve satisfactory performance of the structure, it is crucial to attain proper compaction of the asphalt, base and subbase layers. Excessive rutting in the asphalt layer, cracking of the asphalt and failure of underlaying layers may result due to improper compaction. Christopher et al., (2006) states the rutting may occur due to densification under traffic, cracking due to the bituminous binder becoming brittle from air and water exposure and failure may occur due to moisture infiltration. The design life is the intended time that the pavement structure is expected to last before rehabilitation may be done. In flexible pavements this time is typically 10 to 15 years.

Rigid pavements are those that have a surface course consisting of Portland cement concrete. The concrete layer is unreinforced or slightly reinforced due to low stresses induced by traffic and environmental effects which are relative to the tensile strength of the Portland cement concrete (Christopher et al., 2006). Rigid pavements, although used for residential and local roads, are designed to carry heavy traffic loads. These pavements sustain beamlike action across minor irregularities in the underlaying material. This is attributed to some flexural strength they have (Garber & Hoel, 2009). There are four types of rigid pavements that may be constructed including Jointed Plain Concrete Pavements (JPCP), Jointed Reinforced Concrete Pavements (JRCP), Continuously Reinforced Concrete Pavements (CRCP) and Prestressed Concrete Pavements (PCP). Dowel bars in the reinforcement material are a load transfer mechanism which transfer loads from one slab to the adjacent and subsequently, to the roadbed. The design life of these pavements is 30 years or more if properly designed and constructed. Compared to flexible pavements, they usually are less expensive to maintain overtime.

Composite pavements are multi-layer structures constructed as a combination of both rigid and flexible pavements. Papagiannakis & Masad (2007) suggested these pavements being a typical result of rehabilitation work. They may consist of the asphalt layer over the PCC or the PCC may be laid over the asphalt layer. According to Mezhoud et al., (2017) composite pavements are cost effective alternatives for high-volume roadways. The flexible layer provides road users a safe, smooth and quite driving surface while the rigid layer provides the structure with the needed stiffness and strength.

2.2.2 Geotechnical design considerations

Design of the pavement structure and how well each key pavement layer functions would contribute to determination of the pavements' overall performance during its intended design life. The major factors to particularly consider in achieving satisfactory performance of the structure are environmental conditions such as moisture which has a tendency of causing significant distresses and improvement of underlaying weak layers by use of stabilization methods to improve stiffness and strength. Geotechnical designs have to therefore, be implemented in the design process of pavement structures to achieve overall satisfactory performance. These geotechnical designs are discussed hereafter.

Christopher et al., (2006) and Garber & Hoel (2009) show that the layers above the subgrade are required to be of very high quality. This is so because stresses from traffic loads applied on the pavement are greater at the top and decrease with depth (Figure 2-12). And so, there would be more distresses such as rutting, longitudinal or transversal cracks, fatigue cracking, occurring in the upper layers if poor quality materials are used or if construction is poor. However, the subgrade although may have a lower quality layer, needs adequate construction methods in order to sufficiently support the structure it being the foundation. Foundation failures in pavements tend to result in total reconstruction of the whole structure which incurs major expenses, in comparison to rehabilitation of upper unbound pavement layers that provide majority of the structures' structural capacity.

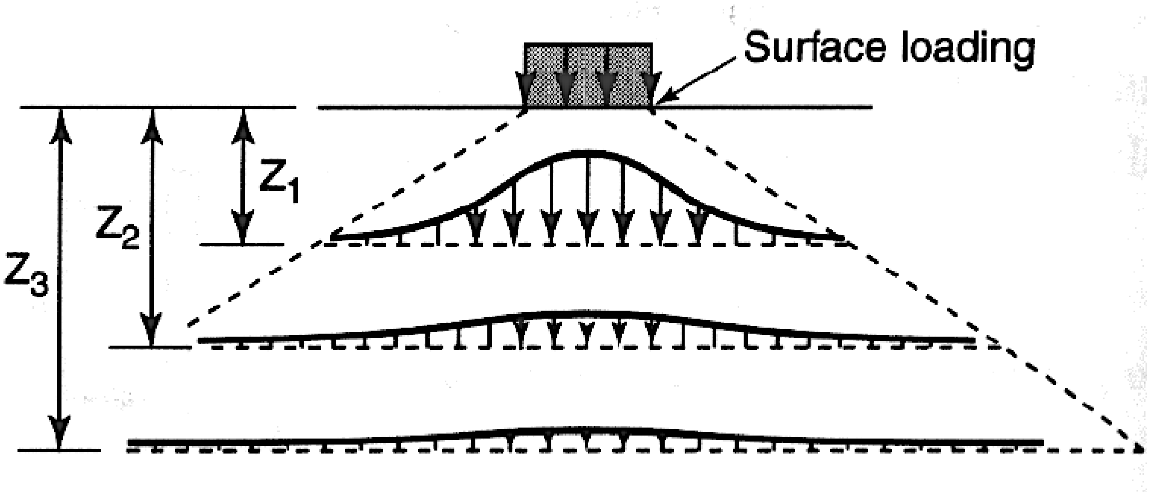


Figure 2- 12. Stress distribution on pavements due to traffic loads (Christopher et al., 2006)

Soil stabilization is a chemical technique used to improve the engineering properties of natural soils. In pavement design and construction, this technique would be considered for construction of the base, subbase and subgrade layers. Methods of soil stabilization can be categorized into two groups including mechanical and chemical. Mechanical stabilization is the method in which different soil grades are mixed and compacted to attain a required soil grade while chemical stabilization is the method in which chemical binders are mixed with the natural soil to improve their engineering properties. Some benefits of stabilization of the subgrade are to improve load-carrying and stress-distributing characteristics, reducing frost susceptibly, and controlling soil shrinkage and swelling (Garber & Hoel, 2009; Maaitah, 2012). As a consequence of stabilizing the soil, the subgrade would be able to perform its intended engineering use without incurring failure that would lead to total reconstruction of the pavement structure.

Moisture control systems in a pavement are equally vital to mitigate premature loss of serviceability due to deformations and failure caused by moisture. According to Christopher et al., (2006), moisture and temperature are two specific environmental variables that can significantly affect the performance of the pavement structure. In this case, the pavement layers would perform poorly and the subgrade properties would deteriorate. There are many ways that moisture may enter the pavement structure. Rising water table, seepage from higher ground, infiltration from surface water, evaporation of ground water and capillary action are all ways moisture may move into the structure. Moisture greatly reduces strength and stiffness of materials, affects the soil structure through destruction of cementation between soil particles, asphalt mixture in the surface course may be stripped off and structural integrity in cement bound materials may be affected (Christopher et al., 2006). Therefore, adequate pavement drainage systems should be designed and constructed to prevent such effects due to moisture especially in soils termed as being "problematic".

Surface and subsurface drains are incorporated into the pavement construction to reduce infiltration of surface moisture into the structure and to lower the ground water table. Jones & Jefferson (2012) suggested vertical and horizontal barriers be employed also during design and construction to control moisture. These would be placed along the depths and base of the subgrade, to prevent moisture effects on the subgrade. The said moisture control techniques result in durable and high performing subgrades, thus, improves constructed pavements.

2.3 Chemical binders

Chemical binders which can also be referred to as cementitious binders are chemically active compounds that are used to improve weak soils' engineering properties. Properties of the soil tend to be improved through distinct chemical reactions that occur when the binder is mixed with soil and water typically inducing a hardening process through production of stable solid hydration products. These improved engineering properties relate to the mechanical behavior of the soil, which will consequently enable pavement structures constructed on them to be supported adequately. In addition, the possibility of permanent deformation occurring in the pavement structure is decreased. Penner (1965) referred to binders as glue that holds solid particles together at surfaces and may additionally take up a role of a filler to improve the soil properties. These binders can either be organic or inorganic (Bye et al., 2011; Gartner & Macphee, 2011; Tabbaa & Stegemann, 2011) where their use is significantly dependent on the type of materials to be bound together and the surface areas.

Pulverized Fly Ash (PFA), Ground Granulated Blast Furnace Slag (GGBS), lime, silica fume and cement are all typical examples of chemical binders that can be used in soil improvement techniques. It should be noted that silica fume has only been listed herein to show that it is binder that can be used for the purpose of improving soil properties but has not been discussed further. This is only because it is similar to fly ash and GGBS. However, the other binders mentioned will be discussed. The aforementioned binders fall under the inorganic category. These binders undergo similar chemical reactions to achieve stabilization, the only difference is the rates at which they gain strength. Moreover, their effectiveness is essentially dependent on how well the voids in the soil are filled with the chemical reaction products and densification of the soil. According to Ardah et al., (2017), lime and cement are manufactured products, while, pulverized fly ash is a by-product obtained from coal combustion. GGBS and silica fume, just like fly ash, are equally by-products from blast furnaces in making iron and of ferrosilicon industry, respectively.

2.3.1 Lime

Lime exists in various forms, however, quicklime and hydrated lime are generally used as chemical binders. Quicklime is produced by heating chalk or limestone, while hydrated lime is produced from reactions occurring between quicklime and water (Dowling et al., 2015). The typical chemical composition of lime is provided in Table 2-3 which shows a breakdown of the chemical compounds it contains. Production of lime subsequently entails some of the properties it will possess, such as the reactivity which will significantly depend on the particle size. Finely produced lime reacts more rapidly due to increased surface area, which would result in greater contact with water and so higher hydration rate. The main constituent of lime is calcium oxide (CaO), and the total amount present indicates the purity of the lime (Hwidi et al., 2018).

Table 2- 3. Typical chemical composition of lime (Janz & Johansson, 2002).

Mineral	Percentage (%)
CaO	94
SiO_2	1.5
Al_2O_3	0.8
Fe_2O_3	0.4
MgO	1.7
K_2O	0.1
Na_2O	0.05

2.3.2 Cement

There are various types of cements that are used for numerous applications. In soil treatment for example, Portland cement is the most commonly used type. The cement characteristics may differ from one plant to another depending on the manufacturing process (Aïtcin, 2016). Typical chemical composition of the Portland cement is presented in Table 2-4. According to Bye et al., (2011) and Tabbaa & Stegemann (2011), the main raw materials in the production of Portland cement are clay or shale and limestone or chalk which are calcareous in nature. The raw materials provide alumina and silica. Alumina and silica are two products necessary in chemical reactions that occur during soil stabilization. The necessity is due to the primary strength gain of Portland cement occurring significantly through the hydration of alumina and silica. Fineness of the cement plays a tremendous role in how reactive it will be as a binder. However, Yi et al., (2014) notes significant environmental impacts Portland cement has which include high energy consumption during production and use of non-renewable resources. Hence it is replaced with other binders or can be incorporated fully or partially with other industrial by-products before use in construction.

Table 2- 4. Typical chemical composition of cement (Janz & Johansson, 2002).

Mineral	Percentage (%)
CaO	60 - 70
SiO_2	17 - 25
Al_2O_3	2 - 8
Fe_2O_3	0 - 6
MgO	0 - 6
SO_3	1 - 4
K_2O	0.2 – 1.5
Na_2O	0.2 – 1.5

2.3.3 Fly Ash

Tabbaa & Stegemann (2011) describe PFA as a siliceous and aluminous material that when finely grounded, in the presence of moisture will react chemically to form compounds with cementitious properties. It has the potential to reduce CO_2 emissions and improve the durability of cement, hence gaining attention (Cho et al., 2019). Pozzolanic properties are vital in enabling a binder to become suitable for use as a stabilizing agent. This is due to the fact that pozzolanic properties will aid long term strength gain of a soil stabilized with a suitable binder. Tabbaa & Stegemann further explain fly ash exists in different forms and not all will exhibit worthy pozzolanic properties. Therefore, the process of production significantly affects the suitability of fly ash as a binder in soil stabilization. Furthermore, Janz & Johansson (2002) state that the combustion and filtration processes further affect the pozzolanic properties. Rapid cooling which allows for rounded particles and high vitreous content, improves the suitability of fly ash as a binder in improving the properties of poor soils. Table 2-5 presents an example of the chemical composition of fly ash which corresponds with the typical chemical composition detailed by Janz & Johansson (2002) in their study.

Table 2- 5. Typical chemical composition of Fly ash (Cho et al., 2019)

Mineral	Percentage (%)
SiO_2	55.4
Al_2O_3	22.2
Fe_2O_3	6.84
CaO	5.12
MgO	1.84
SO_3	0.71
K_2O	1.55
Na_2O	1.26
LOI	3.70

2.3.4 GGBS

Tabbaa & Stegemann, (2011) describes GGBS as a latent hydraulic cement that is most available in the UK. It obtains it's cementitious properties from the additives including limestone, silica and alumina which make up Portland cement, during iron production process (Oner & Akyuz, 2007; Tabbaa & Stegemann, 2011; Yi et al., 2014). The rate of reactivity which is an important property of the binder is dependent on the rapid cooling after extraction from the furnace and the finesse of the slag after is it ground (Janz & Johansson, 2002). Rapid cooling compared to slow cooling, produces highly reactive GGBS suitable for soil stabilization. Oner & Akyuz (2007), Celik & Nalbantoglu (2013) and Yi et al., 2014) show GGBS used successfully in improving properties of soil such as swell potential and strength. Its chemical composition is presented in Table 2-6.

Table 2- 6. Typical chemical composition of GGBS (Celik & Nalbantoglu, 2013).

Mineral	Percentage (%)
CaO	42.7
SiO_2	36.5
Al_2O_3	11.9
MgO	7.7
S	0.9
FeO	0.3

Na_2O	0.2
K_2O	0.5
MnO	0.4
TiO_2	0.5

The chemical compositions of each binder are of noteworthy in order to determine their properties and performance in the intend use.

2.3.5 Rate of binder hydration

There are several factors that affect the hydration process of a binder in chemical soil stabilization. Binder fineness, water-binder ratio, curing time and temperature, are some. Binders with finer particles have increased surface area which increases the surface contact with water and the soil particles, therefore, increased hydration rate and improved overall soil strength and compressibility. Compressibility according to Maaitah (2012) contributes significantly to a structures' safety as much as shear strength does. Chemical stabilization's impact on it should therefore, be emphasized just as much. Water-binder ratio when low, increases the rate of hydration which in turn can reduce porosity and increase strength gain results (Ghirian, 2016). The time and temperature required to cure a subgrade soil-binder mix allows for an increase in the rate of hydration. The longer it is allowed to cure, the more hydration occurs improving soil strength. Higher temperature increases the rate of hydration through increased kinetics of the chemical reactions. Figure 2-13 shows stages in the hydration processes with curing time and the heat generated from this process.

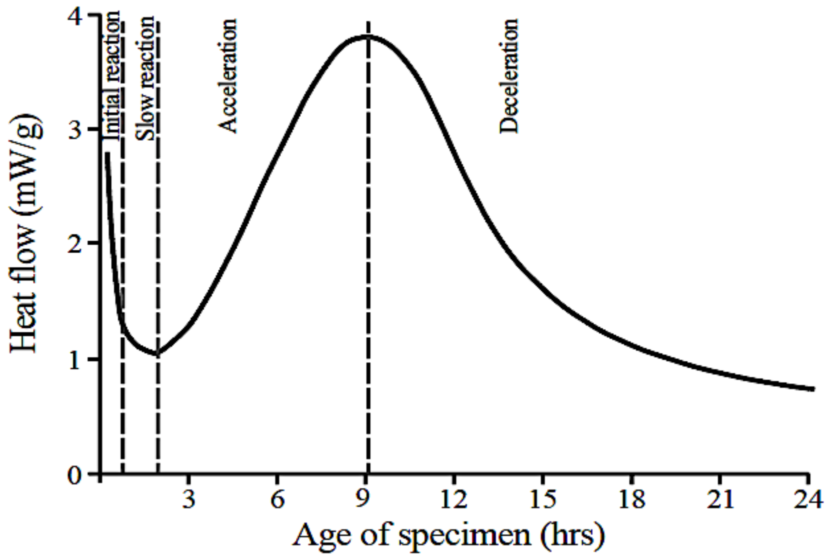


Figure 2- 13. Rate of hydration with curing time (Cui, 2017)

Almost immediately after water is added to the binder during mixing, the initial reaction occurs. It results in the generation of significant amounts of heat. The heat generated decreases during the slow reaction phase and according to Ghirian (2016), it is due to the mixed paste being plastic. During this second stage, hydration products are initially formed. The third stage – acceleration, in which setting occurs is that where significant amounts of heat are generated again due to the reaction of tricalcium aluminate (C_3A). Cementing gels are continuously produced in this stage which subsequently leads to strength gain and reduction of porosity. The final stage in hydration of a binder is hardening. In this stage, it is expected for heat generation to reach its peak then begin to decrease gradually. The products of hydration gradually fill up the pores resulting in further pore refinement. Higher strength and very low porosity are achieved in this stage.

2.3.6 Traditional binders

While having various types of binders, Pourakbar & Huat, (2016) and Ardah et al., (2017) stated that lime and cement are more traditional and have been used for this purpose since the early 1940's. When mixed with granular materials, subbase in pavements achieved high strengths and thereafter, use of lime and cement became popular. Aldaood et al., (2014) further explained how lime has been traditionally used in varied civil engineering works, but mainly in pavement construction since the Roman times when it was applied to roadbed soils (Qubain et al., 2000). In cement, according to Janz & Johansson, (2002), Abu-Farsakh et al., (2015), Pourakbar & Huat, (2016) and Firoozi et al., (2017), hydration occurs quicker enabling strength attainment to be more rapid and immediate compared to lime. However, in a study conducted by Kennedy et al., (1987) to attain compressive strength in expansive soils with high plasticity, the result of treating the soil with lime was more favorable compared to treatment with cement. In soils with low plasticity on the other hand, cement treatment produced significant strength gain. It was also shown that treatment of soil with lime was more resistant to moisture damage when compacted. Moreover, Little & Nair, (2009) recommend lime as an appropriate stabilizer for medium, moderately-fine and fine-grained cohesive soils, while cement being well suited for well graded aggregates. Jones & Jefferson (2012) also added on suggesting lime being the best chemical binder when dealing with soils of high plasticity. In each instance, the properties of the soils were improved adequately for the intended use.

Lime as a chemical binder was therefore, used in this study to stabilize the subgrade sensitive marine clay. This is because lime would have much more of an advantage considering the properties of the marine clay compared to cement.

2.4 Soil stabilization

Soil stabilization has earlier been described as an improvement technique for soil in which binders are used or in which different soil grades are mixed and compacted. For soils with poor engineering properties including bearing capacity, strength, stiffness, compressibility, these techniques are used to improve the said properties. Although mechanical stabilization can improve a poor soils' engineering properties, it is not sufficient enough, therefore, chemical stabilization is opted for (Maaitah, 2012). Chemical stabilization is essential in weak road subgrades because distresses and permanent deformations are frequent in foundations founded on weak soils. In this section, chemical stabilization with lime as a binder will be discussed in detail. However, it should be noted that chemical reactions, processes and products of the reactions will be the similar in the case where other binders are used instead of lime.

To achieve improved soil properties, the lime modification optimum (LMO) needs to be determined firstly before the stabilization processes is started. The optimum content is that which effectively allows for chemical reactions to begin occurring in the lime-soil mix. Beyond the optimum content, in practice, there would be no further changes in the plastic limit of a soil when more lime is added (Maaitah, 2012). A pH test, ASTM 6276 – 19, in which a value of

12.4 gives an indication of the optimum content, can be performed as a determinant of these values. In case of plastic soils such as Canadian sensitive marine clay stabilized with lime, 4% - 5% is usually the optimum value (Choquette et al., 1987; Locat et al., 1990; Qubain et al., 2000; Maaitah, 2012). However, this value will differ significantly for other soil types based on their specific properties. Figure 2-14 shows product formation in lime stabilization that prompts cementation between clay particles in both high and low water contents.

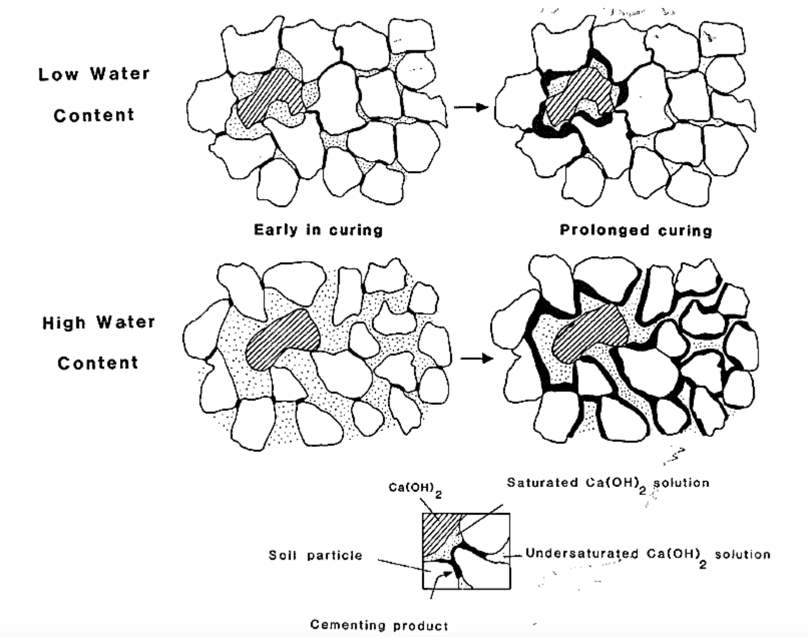


Figure 2- 14. Bonding process in lime stabilization of sensitive clay (Locat et al., 1990a)

When lime is mixed with soil, three mechanisms occur through which the soil properties are improved, including; hydration, flocculation and cementation (Locat et al., 1990; Qubain et al., 2000; Maaitah, 2012; Firoozi et al., 2017). Both flocculation and cementation occur during hydration. Hydration is the process in which lime in the soil reacts with water. When the hydration reaction occurs, the soils' pore water pressure decreases resulting in an increase in the effective stress. This subsequently, causes the shear strength of the soil to increase also. Flocculation is the process where the soil particles rearrange and become closely packed due to cation exchange. These exchangeable ions – Ca^{2+}, are provided by the lime. They migrate to the surfaces of the soil to then displace water ions and other ions. Cementation on the other hand is the process through which cementitious gels are produced through pozzolanic reactions that are time and temperature dependent. Additionally, the soils reactivity in terms of available alumina and silica, affects these reaction rates (Qubain et al., 2000). According to

Zha et al., (2008), during pozzolanic reactions, the high pH in the treated soils causes silica and alumina on the soils' surface to dissolve, thereafter, combing with the calcium from the lime to produce the cementitious gels namely calcium aluminate hydrate (CAH), calcium silicate hydrate (CSH) and calcium silicate aluminate hydrate (CSAH). It should be noted that pozzolanic reactions are exothermic reactions, hence, heat is as a result produced while they occur. Cementation provides the soil with strong cementing bonds that hold the soil particles together, contributing to the increased long term shear strength of the soil after stabilization. Of the three processes, cementation occurs gradually overtime contributing largely to the increased soil strength. This is in comparison to hydration and flocculation which occur almost immediately. These two are short term reactions that contribute to immediate soil improvements such as plasticity, workability, uncured strength and load-deformation properties. Flocculation can be seen in Figure 2-14 occurring as the lime in the soil hydrates. The cementing gels are also increasingly produced with time, improving the soil properties. Low water content soils achieve strength quicker than soils with high water content. However, strength would be achieved except time plays a significant role. The soils' improved properties are suggested to be maintained for over 20 to 40 years according to (Qubain et al., 2000).

Properties of subgrade soils improved through lime stabilization enable pavement structures to perform adequately throughout their design life. This would be without incurring distresses and permanent deformations such as cracking and rutting, which would cause hinderance in the comfortable use of the structure. Moreover, the structure would require minimal maintenance over its service life.

2.5 Thermal-Hydro-Mechanical-Chemical processes in soils treated with a binder

The thermal (T), hydro (H), mechanical (M) and chemical (C) processes are processes that occur continuously at different rates in soils or a porous media containing pores or voids typically filled with a fluid and mixed with a binder. This phenomenon is of great significance in geotechnical engineering due to its ability to influence the behavior of treated soils on which structures are founded. Essentially, soil performance and safety of structures laid on the treated soils overtime can be predicted from understanding these processes. This section describes the THMC processes that occur in soils treated with binders.

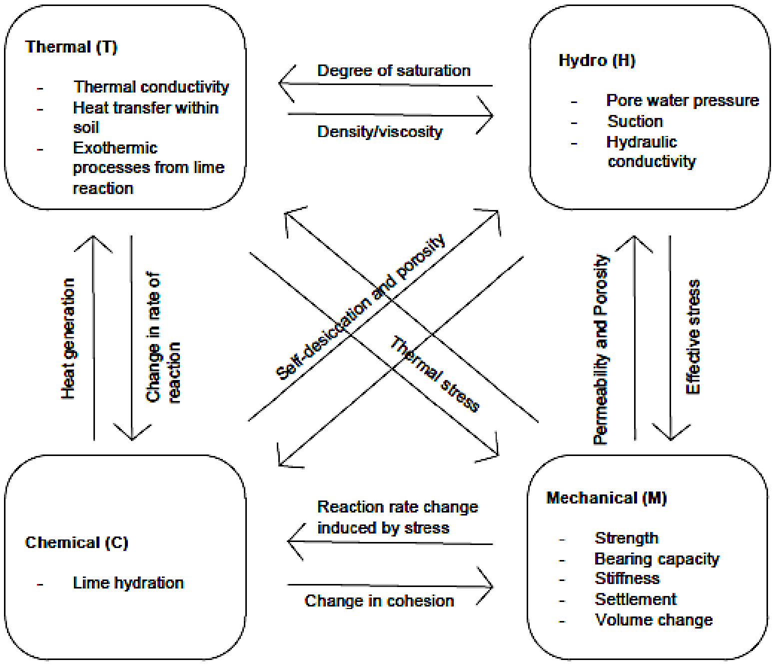


Figure 2- 15. Schematic drawing of the coupled THMC processes

Figure 2-15 illustrates the coupled THMC processes that occur within soils stabilized with a binder. They are known to be coupled processes because of their interdependency and ability to influence each other. Because of the interdependency, the process as a whole cannot be predicted by considering an individual processes independently (Chan et al., 1996) otherwise, Ghirian, (2016) suggested it might lead to misunderstanding the studied phenomenon. Although this is so, in chemically improved soils and other porous medias, two-way interactions between individual processes need to be understood and studied (Rutqvist et al., 2014; Ghirian, 2016). These interactions provide a link necessary for the coupled THMC to be fully understood. In chemically improved soils, an example of a two-way interaction is cementation on the mechanical behavior of the soil. Cementation would lead to a decrease in moisture due to hydration, and could potentially make the soil prone to deformations due to thermal stresses. Some more of the important two-way interactions can be seen in Figure 2-15.

Table 2-7 further provides information on the two-way interactions of individual processes. Lanru & Xiating, (2003) and Ghirian, (2016) described an “agent” and an “object” as being present in these interactions. The agent in the interaction initiates a process in the object. In the coupled CM process that was discussed previously as an example, the C (chemical factor) is the agent that affected the M (mechanical factor). This can be seen in the table represented as M = f_m(C). In this instance, the T (thermal factor) would eventually become the agent while the M (mechanical factor) would be the object because of deformations possibly occurring due to thermal stresses. Therefore, the relationship can be seen as M = f_m (T). It should however, be noted that these processes would affect each other at different rates and strengths (Ghirian, 2016).

Table 2- 7. Effects of interaction between coupling processes (Ghirian, 2016)

Agent / Object	**T**	**H**	**M**	**C**
T	o	T = f_t (H)	T = f_t (M)	T = f_t (C)
H	H = f_h (T)	o	H = f_h (M)	H = f_h (C)
M	M = f_m (T)	M = f_m (H)	o	M = f_m (C)
C	C = f_c (T)	C = f_c (H)	C = f_c (M)	o

(T: thermal, H: hydraulic, M: mechanical, C: chemical)

2.6 Summary and conclusions

This chapter discussed and provided theoretical and technical background on Canadian sensitive marine clay locally known as Leda clay or Champlain Sea clay. These soils are products of sedimentation in lakes during proglacial and postglacial periods. Chlorite, illite, amphibole, quartz and feldspar were found to be the main minerals that these soils are comprised of but they vary in amounts depending on the location and depth of the deposit. They are highly sensitive clays often behaving like quick clay once disturbed and this has been attributed to their salinity which upon leaching, causes the card-house structure they possess to change to a parallel structure. Due to this, road construction on sensitive marine clay without any form of stabilization becomes very challenging because of the nature of the soil.

Background information on pavements including flexible, rigid and composite, as well as chemical binders that can be used to improve weak subgrade soils through a process known as soil stabilization were also discussed. Soil stabilization through the use of chemical binders is achieved through chemical reactions when binder hydration begins. Through three distinct processes including hydration, flocculation and cementation, the weak soil's engineering properties such as bearing capacity, stiffness, compressibility and strength are improved. Hydration reduces the soils pore water pressure whereas, during flocculation, the soil particles tend to rearrange and become closely packed through cation exchange reducing air voids and improving soil compressibility. Cementitious gels (CAH, CSH and CSAH) are produced during cementation which further improves the soils' geotechnical properties with time. Hydration and flocculation occur almost immediately while cementation occurs gradually over time.

Finally, the coupled THMC processes in soils treated with a binder were discussed in this chapter. It was noted that for the complete THMC process to be fully understood, two-way interactions of individual process need to be understood prior. This would provide links that would facilitate understanding the THMC process as a whole.

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Chapter 3: Literature review of previous studies on sensitive marine clays treated with lime

In this chapter, a literature review of previous research work performed on sensitive marine clay treated with lime has been done. A discussion and review on the coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes has also been included.

3.1 Background on sensitive marine clays treated with lime and the coupled THMC processes

Sensitive marine clay properties in Canada have for long been improved by use of lime as a chemical binder. Quigley & Di Nardo, (1978) studied the effect of mineral weathering on Southwestern Ontario soils and how lime and cement stabilization has been made more difficult due to increased activity. The main mineralogical control was determined to have been an increase in smectite content towards the surface caused by oxidation weathering. A study by Choquette et al., (1987), on the mineralogical and microstructure changes associated with lime stabilization of Eastern Canada marine clays was performed in which the mechanisms responsible for the soils' strength gain were investigated. The gained strength and the affected pore size distribution were both related to the production of cementing gels, calcium aluminate silicate hydrate (CASH) and calcium silicate hydrate (C-S-H). Bryhn et al., (1984) further studied the process of stabilizing sensitive marine clays by use of hydroxyl-aluminum which they compared to slaked lime. The extents of improving the sensitive clays was described by shear strength measurements. Locat et al., (1990) focused on the shear strength development of lime stabilized sensitive clay which was conducted through laboratory investigations. The strength properties of the soil were improved to significant levels due to reactions that occurred when enough time and lime were provided. In addition to the mechanical properties, Locat et al., (1996) through a comprehensive study, demonstrated that at less than 3% lime content flocculation dominates therefore, higher hydraulic conductivity. However, higher lime content increases the amount of secondary minerals which can reduce the hydraulic conductivity behavior of the lime treated clay. Focusing on the fabric and mineralogy of lime treated marine clay, Rajasekaran et al., (1997) obtained results that were indictive of an improved structure which resulted in a highly open structure due to formation of crumbs of aggregates, increasing the porosity. It was further noted in the study that lime stabilization was effective in improving the mechanical properties of the marine clay. Mathew & Rao, (1997) studied the effect of lime on the cation exchange capacity (CEC) of marine clay through lime columns installed in a bed of marine clay. The CEC was noted to increase through the pH which equally increased.

Further focusing on the general mechanical behavior of high water content clayey soils from eastern Canada, Tremblay et al., (2001) conducted a study on soils when treated with lime or cement. They made emphasis on the compressibility of the soils. It can be noted that previous literatures on lime stabilized sensitive marine clay show that the main focus of the work performed was to understand the effects of lime on the mechanical behavior of the sensitive marine clay. Although this is vital and the studies did show significant improvement when the soil was treated with lime, the studies did not consider or address the coupled THMC processes which indeed do occur within stabilized sensitive marine clay and impact their properties. Moreover, the effects that environmental conditions (e.g., temperature) have on the coupled processes in the lime treated sensitive marine clay were not evaluated.

Despite studies showing lime stabilization as being effective in improving sensitive marine clay's properties, Holt, (2010) reported that improving soils with lime is a process that has not been utilized widely in Canada as it has been in many other parts of the world. The weak geotechnical properties of sensitive marine clays make these soils unsuitable for engineering applications such as pavement construction without chemical treatments such as lime stabilization, or other appropriate mechanical improvement techniques or soil removal and replacement. The former is a preferred method due to soil properties being sufficiently improved at reasonable costs in comparison to the other methods (Maaitah, 2012) such as mechanical stabilization or soil removal and replacement. This is especially in construction of road subgrades before pavements are laid. Soil removal and replacement is a technique that is particularly not cost effective in terms of pavement construction due to their large lateral extents. Moreover, this technique as a means of improving the soil properties preconstruction, increases demand for renewable resources and adds on to the environmental footprint of the specific project, therefore, not being sustainable if considered. Chemical treatment technique therefore, results in overly satisfactory improvement of the sensitive soils' engineering properties due to reactions between lime and water when mixed with the soil. It also works out to be a more cost effective improvement method for sensitive marine clays (Holt, 2010).

Although there has been some work on sensitive marine clay stabilization with lime in Canada, Locat et al., (1990) opined scarcity of detailed geotechnical investigations related to lime stabilization of these sensitive marine clays being in existence. Because of this, it is somewhat a challenge to know the success rate in the field, outside laboratory investigations that have proven to be very successful. Holt (2010) further agreed and stated soil stabilization in Canada has been used to a limited extent due to harsh weather conditions which consequently, bring about concerns with the efficacy of material durability. Little, (1999) however, suggested that even in severe environmental conditions, long term durability and strength gain can still be achieved in sensitive marine clay when stabilized with lime. Many parts of Canada are known to experience winters with sub-zero temperatures for long periods which results in deep frost penetration. Furthermore, freeze-thaw cycles could occur during the winter months of which Holt (2010) suggested would typically not be a problem in subgrades stabilized for major highway construction. This is so because of the thicknesses of the overlaying structure which would be sufficient enough to eliminate penetration of frost into the subgrade. However, the stabilized subgrade layer in minor highways, access roads and parking lots would be a problem due to overlaying structures being of lesser thicknesses. Nonetheless, due to autogenous healing, improved geotechnical properties of the soil could still be a success. Thompson & Dempsey (1969) reported that in fact with additional curing after the freeze-thaw cycles and additional freezing and thawing, the terminal strength gain of the soil would be greater than the initial strength gained. Additionally, undertaking extensive laboratory freeze-thaw testing prior to utilizing the method in Canada, increasing binder content in specific projects and incorporating sufficient geotechnical inputs such as drainages, would lead to efficient results being obtained. Moreover, one of the main benefits of soil stabilization in sensitive marine clays during road construction is that it improves the soils' workability. When disturbed during construction particularly due to equipment traffic, the sensitive marine clay loses its strength and integrity which in turn makes construction very difficult. Therefore, stabilization of sensitive marine clays has both short and long term benefits in pavements and construction. While freezing and thawing in lime treated sensitive marine clay have been studied and discussed to an extent, the effects of daily thermal cycles on lime-stabilized sensitive marine subgrade soils have not been evaluated. In addition, the effects that the daily thermal cycles have on the coupled THMC processes occurring within the treated soil and properties of the lime treated sensitive marine clay have not been studied and evaluated, in spite of the subgrade soils being exposed to daily thermal cycles in the field.

Despite there being limited data on projects that utilized lime stabilization in Canada to improve the poor soils, Holt (2010) detailed the Chatham wind project in Southwestern Ontario as a success. Access roads to the additional wind turbines were required and treating the soil with lime was opted for instead of the traditional soil removal and replacement method. The process was considered highly successful.

3.2 Coupled THMC processes

Lime stabilization has become a prominent way in which weak soil properties are improved for construction. Although lime stabilization results in improved engineering properties of the soil, coupled processes occurring within the soil tend to become factors that affect how structures laid on the said soil perform over the intended life span. The effectiveness of binder reactions would be dependent on stresses in the environment such as temperature and moisture. As a result, strength gain properties of the soil due to lime treatment would depend on the chemical reactions occurring and environmental stresses. The improved soil properties tend to become a function of the coupled thermal-hydro-mechanical-chemical (THMC) processes. An illustration of the coupled processes and their dependency has been illustrated in Figure 2-14 in chapter 2.

Over the years, these coupled processes have been studied in applications of nuclear waste disposal, CO_2 storage, energy geostructures and cemented paste backfill (Chan et al., (1996); Gatmiri & Delage, (1997); Gens et al., (2007); Ghirian & Fall, (2013); Ghirian & Fall, (2014); Cui & Fall, (2015); Murphy et al., (2015); Li & Laloui, (2016); Lu et al., (2017) and Wang et al., (2021)). The coupled processes that were studied in these applications were noted to not only be THMC, but rather; thermal-hydro-mechanical (THM), thermal-hydro (TH), thermal-mechanical (TM) and even hydro-mechanical (HM). In some of these applications, the chemical process was not a part due to the other processes being the main influence on how the structures would perform. Moreover, the soils were typically not treated in any case. This is unlike the case of the sensitive marine clays that would require the chemical treatment which would prompt THMC coupled processes.

With there being very limited literature on lime treated sensitive marine clay to begin with, these coupled processes that occur within these soils have yet to be investigated and studied widely. In expansive clays for instance (Villar & Lloret, (2004); Guimarães et al., (2007); Schanz et al., (2013) and Darde et al., (2018)) some of these processes have been investigated. However, it is to the best of the authors' knowledge that in fact, the coupled THMC processes are yet to be studied in the sensitive marine clays when treated with lime and when exposed to daily thermal cycles. Thus, the objective of this particular research is to study and understand the coupled THMC processes in lime treated sensitive marine subgrade clay. In Addition, to evaluate the effects that exposure to daily thermal cycles has on the treated subgrade sensitive marine clay properties and the coupled processes.

3.3 Summary and conclusions

In this chapter, lime treated sensitive marine clays were reviewed and discussed. It was reported that although chemically treating these soils with lime as a means of improving their weak geotechnical properties has been done, it has not been done widely in Canada as it has been in many other parts of the world such as the USA. Despite the scarcity noted, available literature showed that use of lime as a chemical binder to treat these soils produced sufficient results even where extreme weather conditions could arise as a concern. The cementing products that are produced due to lime hydration, were noted to significantly improve the geotechnical properties of the sensitive marine clays.

An investigation of the coupled processes was noted to be vital in assessing and understanding the long-term behavior of structures that would be laid on the treated soils. In other applications and soil types, some of these processes that are coupled have been studied. However, it was observed that the coupled THMC process that occur when sensitive marine clays are treated with lime are yet to be studied and understood. The effects that environmental conditions (thermal) have on lime treated sensitive clay and the coupled THMC processes are also yet to be evaluated. Specifically for subgrade construction in treated sensitive marine clay, these coupled processes and the impacts that the thermal cycles have, would tremendously affect the design costs and overall maintenance of the structure post construction.

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Chapter 4: Technical papers

4.1 Introduction

This chapter presents two research manuscripts including technical papers 1 and 2, on the coupled THMC processes in lime treated Sensitive Marine clay subgrade soils experimented in columns. In the first paper, results obtained from studying the coupled behavior are presented. The second paper presents the results obtained from studying the coupled behavior when subjected to daily thermal cycles.

4.2 Technical Paper 1: Column experiments to study the Thermo-Hydro-Mechanical- Chemical behavior of sensitive marine clay subgrade soil treated with lime

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(submitted)

Abstract

Column experiments were conducted in this study on sensitive marine clay subgrade to understand the evolution of the coupled Thermal (T), Hydraulic (H), Mechanical (M) and Chemical (C) processes that occur in the lime treated and untreated marine clay by monitoring the soil samples over a period of 28 days. Three columns in which sensors were placed within the compacted soil samples and a dial gauge at the top, were setup to allow monitoring of the evolution of the THMC processes. Nine other columns were also prepared and setup from which samples for extensive testing were obtained at 1, 3, 7 and 28 days. The mechanical properties of the soil increased significantly due to the lime treatment in which pozzolanic reactions occurred. The study showed that the improved mechanical properties were coupled with the chemical reactions that were monitored through electrical conductivity, temperature evolution within the column and suction which developed with time. Properties such as the hydraulic conductivity were affected, to which pore refinement as a result of lime hydration was attributed. The coupled THMC behavior was noted to have been highly dependent on the hydration of lime. To understand the behavior of treated pavement subgrades, the effects of the coupled process presented in this study need to be understood to further design cost effectively and have pavements of long service lives.

Introduction

Pavements which commonly consist of a surface course, a base course and a subbase, are structures that are laid on subgrade soils. The subgrade soils therefore, form the foundation on which the structure is laid. Subgrades are usually in situ soils such as sensitive marine clays that can be very weak and would require some form of stabilization to improve the soil properties. Sensitive marine clay is found in different regions of the world. In Canada, it is particularly found in the eastern region where it is also referred to as Leda clay or Champlain Sea clay (Al-Umar et al. 2020, 2021). According to Taha & Fall, (2014), these clays are highly sensitive and they tend to pose quick clay behavior. When disturbed, the clay loses its strength, therefore, it needs to be improved before any construction work can be done on it. Improving the soil properties subsequently enables the pavement's traffic loading to be sufficiently supported.

Chemical stabilization is a soil improvement method in which, chemically active compounds are used to improve the soil properties (Maaitah, 2012). Cement, Lime and Fly Ash are examples of such compounds that can be used (Ardah et al., 2017). However, lime as a chemical stabilization compound, is more traditional and is the oldest known (Qubain et al., 2000). It has since been used in many cases during road or highway construction projects to improve the soil stiffness, strength, bearing capacity, durability and settlement (Qubain et al., 2000; Maaitah, 2012; Rout et al., 2012 & Ahmed et al., 2020). The improved soil properties are attained through three mechanisms: cementation, hydration and flocculation (Qubain et al., 2000; Maaitah, 2012). Cementation is a lime and soil reaction that forms various cementitious gels; hydration is a reaction between lime and water; and flocculation is a process in which the clay particles are rearranged to become very closely packed together. The aforementioned mechanisms largely contribute to the enhancement of the mechanical behavior of the subgrade soil, which is however, affected by other processes (Locat et al., 1990; Rajasekaran & Rao, 1997; Abiodun & Nalbantoglu, 2015).

Although chemical stabilization significantly improves the soil's properties, its effectiveness is largely dependent on environmental stresses, such as temperature and moisture infiltration. Climatic changes have become extreme over time. They have led to new challenges in geotechnical engineering which are very critical for development of roads or highways that are sustainable and durable for our societies. In view of Ye et al., (2012), Ghirian & Fall, (2013) and Schanz et al., (2013), the mechanical behavior and stability of these infrastructures or cementing porous media is affected by the mechanical (**M**, e.g., stress), hydraulic (**H**, e.g., pore water pressure, suction), thermal (**T**, e.g., temperature, heat transfer) and chemical (**C**, lime hydration) properties or processes. Pore water pressure (PWP), hydraulic conductivity and suction are hydraulic properties or processes. An increase in the soil's PWP results in increased degree of saturation and decreased air voids which subsequently, reduces the suction (Vanapalli, 2010). However, during the hydration process of lime, suction increases as the excess pore water is being dissipated due to self-desiccation (consumption of water by lime hydration) contributing largely to increased shear strength, bearing capacity and volume change behavior of the soil (Maaitah, 2012; Zhu et al., 2019). Heat capacity and thermal conductivity are thermal parameters of which the latter is more important due to its significance in geotechnical engineering applications (Bi et al., 2018) such as construction of subgrades before pavements are laid. The transfer of heat within the soil together with the different temperature gradients, often lead to changes in the microstructural features of the soil such as shape and size. Additionally, the soil's suction and PWP would be affected thereby, resulting to changes in mechanical behavior. When sensitive marine clay is stabilized chemically, it's improved geotechnical properties tend to become a function of the coupled Thermal-Hydro-Mechanical-Chemical (THMC) processes that take place in the marine clay treated with lime. The THMC processes and their interactions are illustrated in Figure 4.2-1.

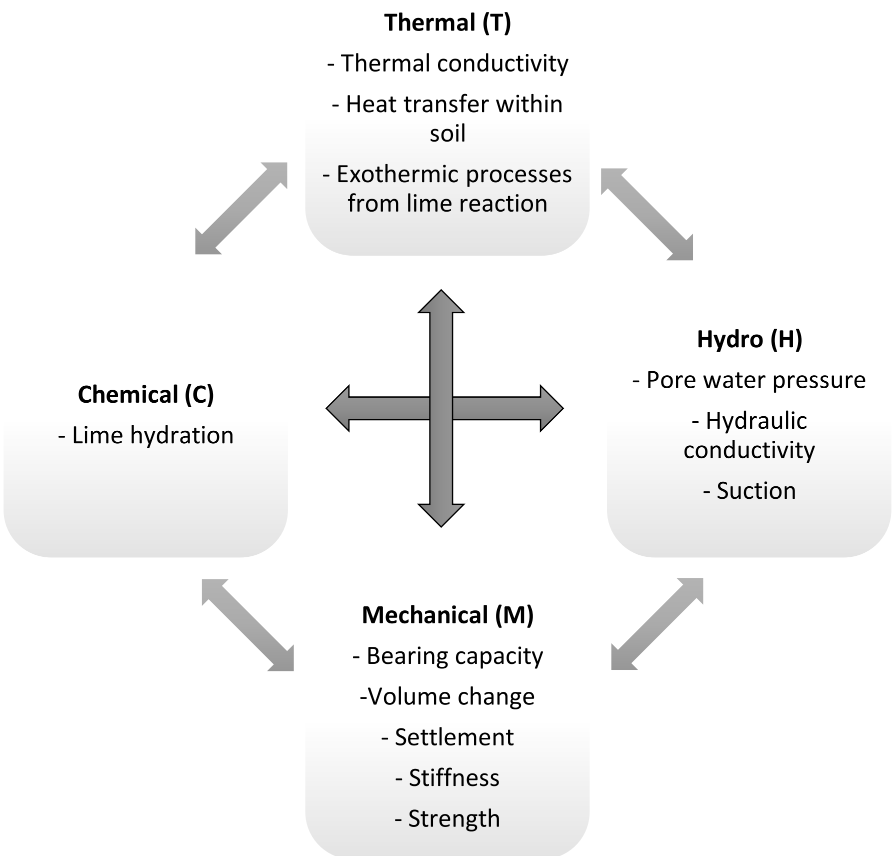

Figure 4.2- 1. Schematic diagram of interactions amongst THMC processes within sensitive marine clays

Understanding these coupled THMC processes that occur in lime treated subgrade soils is vital to an assessment of how these subgrade soils would perform in the field. This would help in achieving construction of roads that are durable, have long service lives, high performance and are cost effective.

Research work has been performed by numerous researchers globally, to prove that the use of lime as a chemical stabilizer improves the geotechnical properties of sensitive marine clay (Choquette et al., 1987; Locat et al., 1990; Rajasekaran & Rao, 1997; Tremblay et al., 2001; Wang & Korkiala-Tanttu, 2020). The focus of these studies were primarily on the effects of the chemical processes on the strength of the marine clay. Furthermore, physical changes of the soil-lime mix were investigated. On the contrary, the coupled THMC processes occurring in the lime treated sensitive marine clay, as well as the effects on its behavior were not taken into consideration. Accordingly, Choquette et al., (1987) describes how the strength gain of the soil - lime mix is due to the immediate chemical reactions occurring at the points of contact at which hydrate gels are formed. As a result of the gain in strength, the microstructure and texture of the mix consequently change.

Equally, Locat et al., (1990), Rajasekaran & Rao, (1997), Tremblay et al., (2001) and Wang & Korkiala-Tanttu, (2020) share the same sentiments arguing that the sensitive soil strength gain is based on the cementation process which is chemical. The researchers additionally showed that for sensitive marine clay to reach significant levels of strength; enough curing time must be allowed for, minimum of 4% lime content must be used and excellent mixing of the lime and soil must be done to achieve maximum dispersion of the lime therefore, complete reactions occurring. It being proven, lime has indeed been used for many years since the early 1960s (Tremblay et al., 2001), to improve subgrade soils for road construction. However, to the best of the authors' knowledge, the coupled THMC processes or behavior of lime treated sensitive marine clays are yet to be studied. The objective of this study is to therefore, conduct various column experiments to assess the THMC behavior of lime treated sensitive marine clay. It will successively contribute to better design of cost effective and durable subgrades for roads or highways.

4.2.1 Experimental program

4.2.1.1 Materials

The materials used during the column experiments include sensitive marine clay, lime and water.

4.2.1.1.1 Sensitive marine clay

Sensitive marine clays are young deposits that originated from sedimentation of glacially ground rock flour (Nader et al. 2013, 2015; Taha & Fall, 2014; Kondo & Torrance, 2005).

Sedimentation occurred in basins that had been depressed by glacial ice sheets which were then uplifted above sea level causing changes to the properties. The high sensitivity in these soils is attributed to the 'leaching theory' which is based on the principle that sedimentation occurred in sea - water (Penner, 1963). Leaching of salt from the soil's pore water causes the soil structure to become inherently unstable, thus, significantly losing its strength when disturbed. Penner (1963), describes the salt-flocculated soil structure as becoming 'metastable', making this soil a geotechnical hazard.

The sensitive marine clay used for the column experiments in this study were collected from Gloucester in the Ottawa region in Canada. Gill (1968), Kondo & Torrance (2005), Taha & Fall (2014) and Li & Fall (2016) describe quartz, feldspar, illite and chlorite to be the prevalent minerals in the sensitive marine clay. According to Taha & Fall, (2014), this mineral composition is typical of sensitive marine clay. The main geotechnical properties of the soil sampled are summarized in Table 4.2-1. In order to determine the properties, standard laboratory geotechnical tests were performed in accordance with ASTM standards. The Atterberg limit tests were performed in accordance with ASTM D4318 to determine the soil's liquid limit (LL), plastic limit (PL), liquidity index (LI) and plasticity index (PI). Additionally, optimal water content and maximum dry density of the soil were determined using the procedure described in ASTM D1557 for the modified proctor test.

Table 4.2- 1. Summary of the geotechnical properties of the sensitive marine clay used

Properties	Value/ classification
Classification	CH
Water content (%)	71.4
Liquid limit (%)	80
Plastic limit (%)	26.5
Plasticity index (%)	53.5
Liquidity index (%)	1.1
Percentage fines	87
Activity	0.6
Natural void ratio	1.2
Optimum water content (%)	25.4
Dry density at optimum (g/cm^3)	1.5

Studies conducted by Leroueil, (1997) suggest that sensitive marine clays in eastern Canada have a LL less than 83% and a PL ranging between 17% and 35%. Tremblay et al., (2001) who carried out work on sensitive marine clay sourced from Quebec, suggested a range of LL being between 22% and 86% and PL ranging between 0% and 34%. Furthermore, Nader, (2014) suggested the range for the LL and the PL of the sensitive marine clay to be 19% - 80.8% and 14% - 28% respectively. The results obtained in this study show the soil's LL to be

66.7% and the PL to be 26.5%. These results match with the findings of Leroueil, Tremblay and Nader. The liquidity index of sensitive marine clay is greater than 1.0, to which, its ability to pose quick clay behavior when remolded is attributed (Law & Bozozuk, 1988; Taha, 2010). When calculated using equation 4.2- 1, the liquidity index of the sensitive marine clay used in this study was 1.1.

$$LI = \frac{W - PL}{LL - PL} \quad [4.2\text{-}1]$$

Where W is the natural water content.

The grain size analysis of the sensitive marine clay used in this study was performed as per ASTM D422. Figure 4.2- 2 shows the results obtained. From these results, it can be noted that an 87% fraction at 2 µm in particle diameter suggests that the soil has a high clay fraction. According to Leroueil, (1997) and Taha, (2010), the Eastern Canadian activity range the for soil is between 0.25 and 0.75 in which the calculated activity for the soil in this study lies. With these results in mind, and the Unified Soil Classification System (USCS), this soil can be classified as inorganic clay of high plasticity (CH).

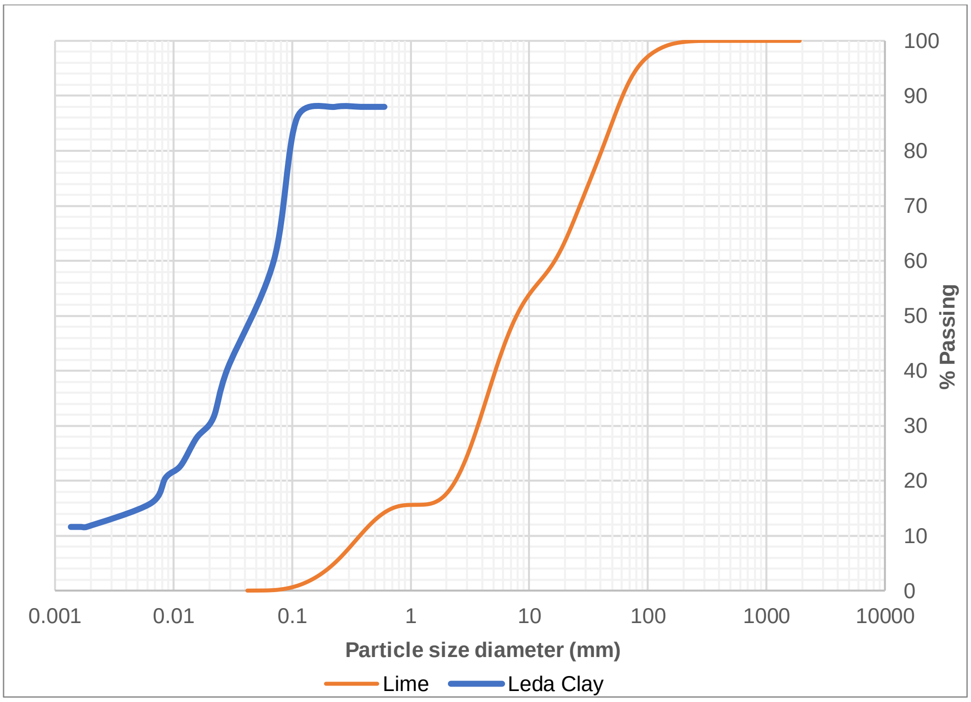

Figure 4.2- 2. Grain size distribution of Sensitive marine clay from Ottawa region and Lime used

The specific gravity of the soil was determined in accordance with ASTM D845. It was suggested by Tremblay et al., (2001) and Taha & Fall, (2014) that the specific gravity range for sensitive marine clay is between 2.7 and 2.8, in which, the determined specific gravity in this study is 2.7.

The chemical composition of the sensitive marine clay used in this study is provided in Table 4.2- 2. X-ray fluorescence (XRF) analysis was used to determine the chemical compositions of the clay.

Table 4.2- 2. Chemical composition of sensitive marine clay

Chemical	**Percentage (%)**
LOI	24.53
Na_2O	2.24
MgO	2.88
Al_2O_3	12.25
SiO_2	46.12
P_2O_5	0.15
K_2O	2.48
CaO	3.78
TiO_2	0.52
MnO	0.08
Fe_2O_3	4.91

4.2.1.1.2 Lime and water

Lime which generally has a chemical composition ($CaCO_3$), was used as a binder to improve the soil properties of the sensitive marine clay. The chemical composition and physical characteristics of the lime used in this study are provided in Table 4.2- 3 and Figure 4.2- 2, respectively. The grain size distribution of the lime was determined by laser diffraction analysis. In the presence of water, pozzolanic reactions and cation exchange occurred producing calcium silicate hydrate or calcium aluminate hydrate cementitious gels. The lime modification optimum (LMO) was determined by using ASTM 6276 – 19. In this study, three different lime contents were used to stabilize the soil; one was equal to the LMO, the other was slightly higher by 1% than the LMO and lastly, 0% lime to serve as part of the control sample. This enabled obtaining results with varying lime contents.

Tap water was used to prepare the soil samples before being placed in the columns for testing.

Table 4.2- 3. Chemical composition of lime

Binder type	Components	Amount (%)
Lime	Calcium Oxide	43.09
	Magnesium Oxide	28.23
	Acid Insolubles	0.71
	Iron & Alumina Oxide	0.59
	Loss on Ignition	26.6
	Carbon Dioxide	2.9
	Hydrated Oxides	94.59

4.2.1.2 Sample preparations

In this study, three soil samples were prepared for testing. Two samples were mixed with lime and one sample was prepared without any lime to act as the control.

The soil and lime mixtures were prepared as per ASTM D3551 - 17. A laboratory mechanical mixer was used during the process. Before mixing the soil sample with lime and water, the sensitive marine clay was firstly mixed very well in order to achieve a homogeneous sample. This was done due to soil characteristics possibly changing slightly, from top to bottom when stored away. The soil and lime (5% minimum and 6% optimum in weight percentage), based on the mass of the soil, were then folded in and mixed for 1 minute until it could be seen that the mixture appeared in a uniform color. By use of the optimum moisture content obtained from the proctor tests, the amount of water to be mixed with the soil and lime was determined. The water was then gradually added to the dry mix, after which, the mixing continued for an additional 5 minutes. This was done until the soil - lime mix was consistent and uniform. To determine the mineralogical and microstructural changes of lime stabilized sensitive marine clay, Choquette et al., (1987) prepared the samples used in the study according to the aforementioned standard and described procedure. In a study performed by Xiao, (2017), in which the stiffness of marine clay stabilized with cement was analyzed, the soil-binder mix was however, mixed for 10 minutes instead of 5 as in this procedure. The soil-lime mixture was then gradually placed and compacted into a 45cm high column in preparation for testing.

4.2.1.3 Experimental set-up of column experiments

Figure 4.2- 3 presents a schematic drawing of the developed experimental set-up for the columns specifically for this study. The columns for monitoring were designed using AutoCAD software and eventually assembled in the laboratory for use. Two exact cylindrical columns, 45cm in height with a diameter of 15.2cm were constructed. The total column height (45cm) was to accommodate the 40cm stabilized subgrade soil (sensitive marine clay) as well as both

the top and bottom caps which held the soil in place. In two columns, sensitive marine clay mixed with lime was placed, while in another one, only sensitive marine clay was placed acting as an experiment control. The height of the column was decided upon by considering the maximum depth which can generally be treated with lime directly in the field. Christopher et al., (2006) indicates this maximum depth range between 0.6m and 1m. Therefore, the column height for this study falls well within the depth directly affected by the lime. The soil-lime mix was carefully poured from the mixing bowl into the column. This was done in four layers. After each layer, the modified proctor test was used in order to compact the mix thereby, achieving a required maximum dry density. The compaction was done manually using a hammer weighing 4.5kg, dropped from a height of about 45cm with each of layer receiving 25 blows. The compaction procedure was equally performed on the soil sample without lime. Fibre glass insulating foam was then wrapped around the column with the compacted mix. Fibre glass with a thickness of 8cm which was used as an insulation material, was wrapped around the columns to limit heat loss from within the columns. Additionally, it was used to prevent the surrounding environmental temperatures from causing any effects within the columns. The columns were subsequently placed on steel frames that were designed to hold them in place for the duration of the tests.

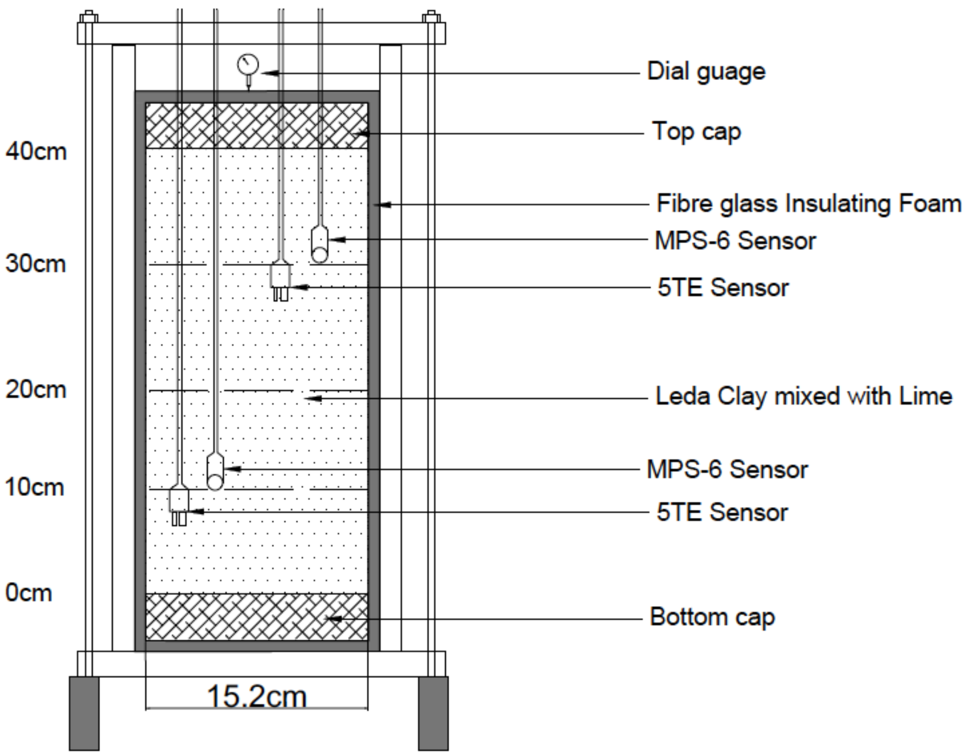

Figure 4.2- 3. Schematic drawing illustrating the experimental column set-up (Not to scale)

4.2.1.4 Column instrumentation and monitoring

In the columns, both a 5TE sensor and an MPS-6 sensor were placed at the depths of 10cm and 30cm to enable measurement of the thermal (temperature), hydraulic (volumetric water content, suction) and chemical (progress of lime hydration) properties as they progressed over the monitoring period. The sensors were placed at the aforementioned depths so as to detail the behavioral changes closer to the top and bottom of the column. The arrangement of the sensors within the column can be seen in Figure 4.2- 3. The MP-6 sensor is a water potential sensor that was used to measure suction in the soil – lime mixture while it developed. This sensor has a measurement range of -9 kPa to -10^5 kPa with an accuracy of ± 10%. The 5TE sensor was used to monitor changes in the volumetric water content, temperature and electric conductivity within the column. The volumetric water content measurement range is between 0% and 100%, and the temperature range of -40°C to 60°C with an accuracy of ± 1°C. Lastly, the electric conductivity (EC) measurement range is between 0 dS/m (bulk) and 23 dS/m (bulk) with an accuracy of ± 10%. The EC whose properties determine transmission of ions, aid determination of lime hydration within the soil-lime mix sample and the rate at which this hydration occurs. Abiodun & Nalbantoglu, (2015) suggest that it is dependent on the soil particle arrangements and the density. Xiao & Li, (2009) further explain that fluctuating increments in EC indicate dissolution of ions within the sample mix as hydration occurs resulting in formation of hydrate gels that lead to improved properties and rapid change in the microstructure. A dial gauge was placed on top of the column to measure settlement of the soil-lime mixture, due to self-weight while the soil- lime mix was being monitored. Over a period of 28 days, the columns were monitored continuously while hydration continued to occur including development of soil suction, PWP and settlement.

4.2.1.5 Testing program

Extensive laboratory tests were performed on the soil-lime mixture samples at different curing times to understand the THMC behavior. The THMC properties of the compacted subgrade soil with lime were determined at 1, 3, 7 and 28 days to understand the evolution of these properties. Soil-lime mixture samples tested were taken from two different heights of the column at 10cm and 30cm to better understanding of the behavior at the top and bottom of the column. To fully understand the evolution of the THMC proprieties of the marine clay - lime mixture, thermal conductivity measurements, hydraulic and mechanical tests, as well as chemical analyses were conducted. The microstructural properties of the lime treated subgrade soils were also determined. The microstructural properties analysis was used to understand the soil – lime mixture pore structure evolution over the testing period. Moreover, water content (gravimetric (ω%) and volumetric (θ%)), degree of saturation (Sr%), void ratio (e), porosity (n) and dry and wet density (ρ) were determined for the soil – lime mixture in the columns. The tests performed to determine the thermal, hydro, mechanical chemical and physical properties of the soil – lime mixture are described hereafter.

4.2.1.5.1 Mechanical tests

California bearing ratio (CBR) and Resilient modulus (M_R) values characterize pavement material stiffness and strength (Christopher et al., 2006). The horizontal tensile strain at the bottom of the asphalt layer and the compressive vertical strain at the top of the subgrade, due to loading, are influenced by the stiffness of the subgrade soils. It is therefore, vital to perform mechanical strength tests on the subgrade soils to assess deformations potentials such as rutting within the subgrade and fatigue cracking on the asphalt layer. The unconfined compressive strength (UCS) test was conducted to measure the strength properties as per ASTM D2166 by means of a computer-controlled mechanical press. To ensure the accuracy of the results, each UCS test was repeated twice. Additionally, for strength gain properties, the samples were compacted in the column manually using a hammer according to ASTM D1557. This enabled attainment of the target dry density and optimum moisture content. The CBR of the soil – lime mixture was estimated from the obtained UCS value by using existing correlations expressed in equation 4.2- 2 (Saputra & Putra, 2020), which were developed for clays. The M_R of the subgrade soil was predicted from the CBR. Heukelom & Klomp, (1962) suggested the correlation M_R = 1500CBR, which was said to be reasonable for fine-grained soils and fine sands compared to granular materials. It was further suggested that CBR values less than 20 would provide better M_R values. However, Christopher et al., (2006) suggested not using this correlation as a means of determining the M_R and CBR of the soil. Therefore, in this study Equation 4.2- 3 for cohesive soils (Powell et al., 1984) was used to determine the sensitive soils' M_R from the CBR.

$$CBR = 0.1325UCS \quad [4.2\text{- }2]$$

$$M_R = 17.58(CBR)^{0.64} \quad [4.2\text{- }3]$$

4.2.1.5.2 Saturated hydraulic conductivity tests

Hydraulic conductivity is necessary in understanding flow behavior in the subgrade due to hydraulic gradients. It is used to determine material moisture profiles and to estimate drainage characteristics of the subgrade soil (Christopher et al., 2006). The hydraulic conductivity tests on the subgrade samples were performed in accordance with the ASTM D5084 – 16a. This is the flexible wall technique in which the falling head method was opted for. The system was able to maintain ± 5% constant hydraulic pressures or better, as stated in the standard. Suction within the mix sample was monitored with an MPS-6 sensor as discussed earlier.

4.2.1.5.3 Determination of thermal conductivity

According to Christopher et al., (2006), thermal conductivity assess distribution of temperature along the depth of the subgrade as heat is dissipated with time. Soil particles tend to have higher thermal conductivity compared to water and air, therefore, heat flow occurs in them (Bi et al., 2018) which consequently induces water migration. Thermal conductivity of lime-treated subgrade materials are needed in calculating the moisture, temperature, and frost regime throughout the pavement and subgrade soil (Mallela et al., 2004). The thermal conductivity of the soil – lime mix was determined by use of existing correlations based on the moisture content of the mix. Many existing correlations have been proposed based on varying soil parameters such as soil type, minerology, porosity, degree of saturation and dry density (Côté & Konrad, 2005; Zhang & Wang, 2017; Lyu et al., 2020) which strongly influence the soil's thermal conductivity. Equation 4.2- 4 shows the correlation used to determine the thermal conductivity of the sensitive marine clay based on the moisture content (w) in this study.

$$K=[0.9\log(w) -0.2]10^{0.017} \qquad [4.2\text{- }4]$$

4.2.1.5.4 Microstructural analysis and tests

Mercury intrusion porosimetry (MIP), X-Ray diffraction (XRD) and Thermal gravimetric/differential thermal gravimetric (TG/DTG) analysis were conducted on the soil – lime mixture to examine the pore structure and evolution of the binder hydration products (C-S-H and C-A-H), respectively. The samples to be tested or analyzed were firstly oven dried at 50°C before the analysis could be performed. MIP analysis through a porosimeter (PoreMaster 33, Quantachrome Instruments) was used to assess the porosity and pore size distribution of the samples. Prior to MIP testing, the sample was dried and cut into small pieces, 2cm x 2cm. XRD was used as a method to analyze the structure and mineralogical content of the samples thereby, revealing the chemical composition. This analysis was performed using an X-Ray diffractometer, the soil – lime mix was scanned with a 2θ range of 5° - 90° in steps of 2θ = 0.02°. Finally, the TG/DTG analysis was performed to determine the soil - lime mix sample's change in weight as the temperature fluctuated. It was performed by use of a thermogravimetric analyzer SDT 2960, in which the sample was heated under a nitrogen confined space at 10°C/min rate up to 1000°C. The sample for both the XRD and TG/DTG were oven dried and ground finely to a powder passing through an ASTM sieve number 40 before the analyses could be done.

4.2.2 Results and discussions

4.2.2.1 Evolution of the mechanical properties (M)

4.2.2.1.1 Unconfined compressive strength (UCS)

The UCS tests were performed on a total of 24 samples for different curing times and lime contents. It was expected that no significant variations would be seen in the control sample due to the absence of lime to cause any mechanical improvements to the clay. A minor increase in the strength of the sensitive marine clay with time, however, can be expected due to the thixotropy effect (Ren et al., 2021). Figure 4.2- 4 shows the variations of UCS against the sample curing times of 1, 3, 7 and 28 days. Curing time and the amount of lime added, evidently had a positive effect on the strength gained by the soil. In the initial stage in which hydration occurs, Ali & Mohamed (2018) suggested the clay characteristics change immediately due to immediate increase in strength. Longer curing time during the monitoring period allowed for lime hydration to progress continuously thereby, increasing production of cementitious gels which contributed to the gained strength. This can be seen from the peak UCS recorded at axial failure.

For samples from the top of the column, the UCS increased significantly from 101 kPa in untreated sensitive clay sample to 223 kPa in the sample treated with 5% lime and 286 kPa in that treated with 6% lime, at 7 days. This is in comparison to the peak UCS values at 1 and 3 days. The UCS of the sample treated with 6% lime was almost three times that of sensitive clay in its natural state. At the bottom of the column, the UCS also increased similarly, however, samples collected at the top of the column presented higher UCS values compared to those from the bottom of the column. This can be attributed to the fact that, due to gravitational forces, moisture movement within the column was in a downward direction which stimulated a partially drained condition at the top. This enabled higher strength gain at the top compared to the bottom of the column. This is supported by suction development in the column which was also higher at the top and lower at the bottom, as discussed in the Section 4.2.3.2.2. Moreover, evaporation occurred from the top of the column which meant more moisture lost from the upper layers of the column subsequently resulting in higher UCS.

After 28 days, the UCS of the sample with 6% lime increased linearly to 370 kPa and 325 kPa at the top and bottom, respectively. The higher strength gain seen after 28 days is due to cementation which occurs gradually over time. Maaitah (2012) and Ali & Mohamed (2018) also note increased UCS in the soil overtime to which reactions in the long term stage were suggested to be the cause of the increase in their respective soil samples. There however, was no linear increase in the UCS for the sample with 5% lime. At axial failure after 28 days, the peak UCS recorded was 163 kPa and 120 kPa at the top and bottom, respectively. The drop in the UCS seen in this soil sample may be due to the 5% lime being the retention or fixation point. Earlier in the experimental work, it was noted that a minimum of 5% lime was required for reactions within the sensitive marine clay in this study to begin occurring. Therefore, after the initial stages of the reactions occurring in this sample, pozzolanic reactions which should have been sufficient for the long term cementation did not occur due to the lime content being the minimum amount required to initiate the pozzolanic reactions. The drop in the UCS was thus noticed after 7 days. This is in comparison to the soil sample that was treated with 6% lime which was in excess of the threshold quantity for the pozzolanic reactions to occur. A linear increase in the UCS in this soil sample was subsequently noticed. Ho & Handy, (1963) and Diamond & Kinter, (1965) detail this lime retention characteristic in montmorillonitic clay in which behavior noticed in this study was equally seen. In addition, it was noted by Al-Mukhtar et al., (2014) and Ali & Mohamed, (2018) that in the reaction stages following the initial in which hydration occurs, the reaction rates are slower and are dependent on lime availability among other variables such as moisture. This is the phase in which cementation occurs. Therefore, it can further be suggested that a significant amount of lime reacted during the fast initial reaction which led to a high initial strength gain of up to 223 kPa at 7 days but consequently, resulted in the dropped UCS after the initial reaction phase i.e. at 28 days.

Although a drop in UCS was noticed in the soil treated with 5% lime after 28 days, it can be suggested from the results that lime content plays a significant role in achieving high strength gain in sensitive marine clay immediately after pozzolanic reactions begin to occur, more so after curing is allowed. However, more detailed microstructure and chemical studies should be conducted in the future to obtain a more in-depth insight into the mechanisms responsible for the aforementioned decrease in strength.

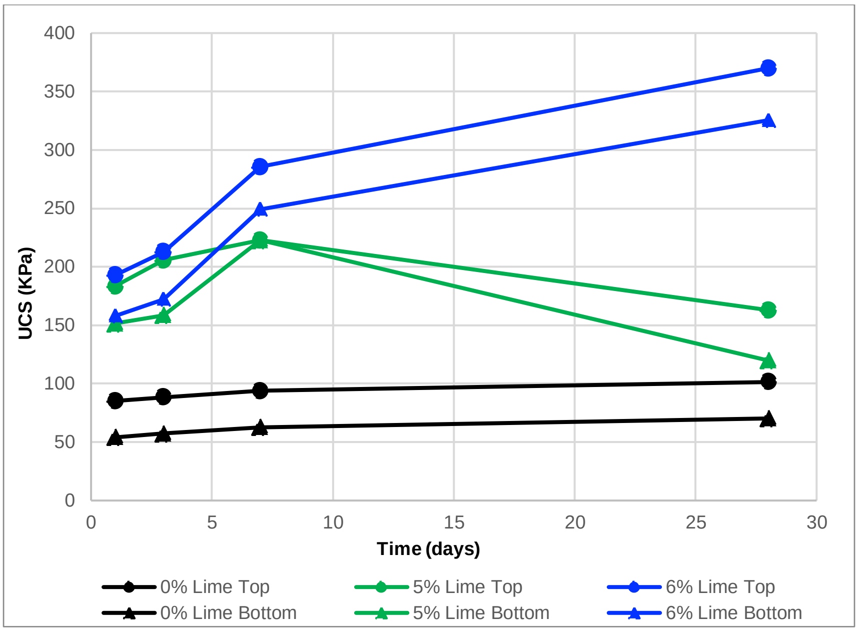

Figure 4.2- 4. Variation of UCS with time.

Void ratio is suggested to be one of the basic parameters that affects the mechanical behavior of soil (Jongpradist et al., 2011). It can as well be considered in describing the volume change behavior that soils undergo. Figure 4.2- 5 demonstrates the variation of UCS against void ratio. A general relationship in which the void ratio decreases with increasing peak UCS values can be seen in the soils. The soil samples treated with 5% lime after 7 days are an exception to this relationship because of the decreased UCS. As discussed earlier, it was suggested that a significant amount of the lime may have been consumed in the initial stages hence the reduction in UCS values after 7 days. Although this was the case, it could still be noticed that the void ratio decreased with time. The decrease of void ratio with time in the treated soil is due to the lime hydration products filling up the pore spaces, as supported the results of microstructural tests and analyses presented in Section 4.2.3.4.2. This resulted in change of the soil structure, and thus, the increased soil strength.

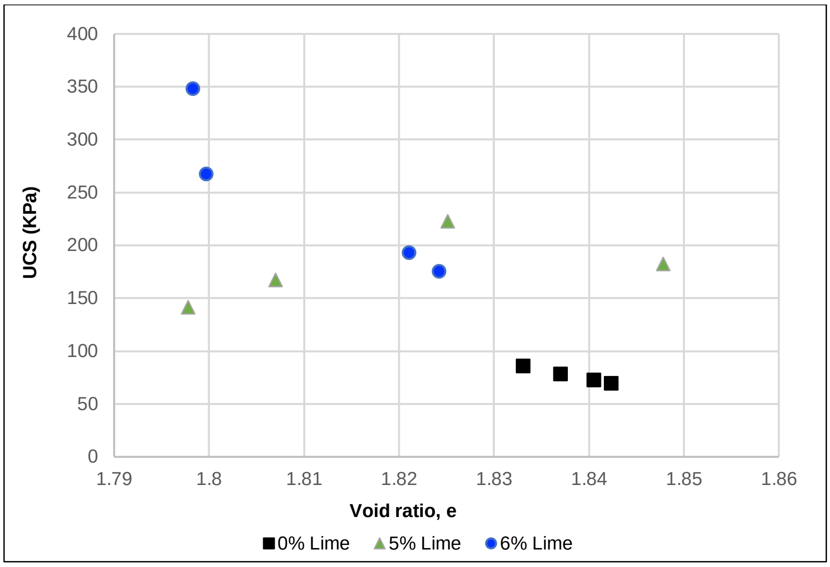

Figure 4.2- 5. Variation of UCS with void ratio

4.2.2.1.2 Vertical settlement

The vertical settlement in all three columns was recorded after 1, 3, 7 and 28 days during the monitoring period. Figure 4.2- 6 shows its variations with time. The column with untreated sensitive marine clay showed no settlement during the period for which it was monitored. On the other hand, very small settlements both less than 1mm, were recorded in the treated soil. 0.05mm was recorded as the maximum in the soil treated with 5% lime and 0.1mm was the maximum recorded in the soil treated with 6% lime. Although very small, the settlement behaviour can be attributed to the changes in moisture content due to hydration of the lime and self - desiccation of the soil in the column. The self-weight pressure of the material in the column according to Ghirian & Fall, (2014) can equally contribute the settlement in that it consolidates the pore spaces within the material generated due to self – desiccation. However, with time and the continuous cementation due to hydration, the settlement would reach an almost constant value. During this process, the soil stiffness and strength would increase hence the constant settlement with time. It should however, be noted that if additional pressures were applied on the top of the soil, significant values of settlement would have been recorded specifically during the initial stages when effective stress of the soil would have been at a low owing to excess pore water pressure in the soil. The column set up being undrained would have contributed as well.

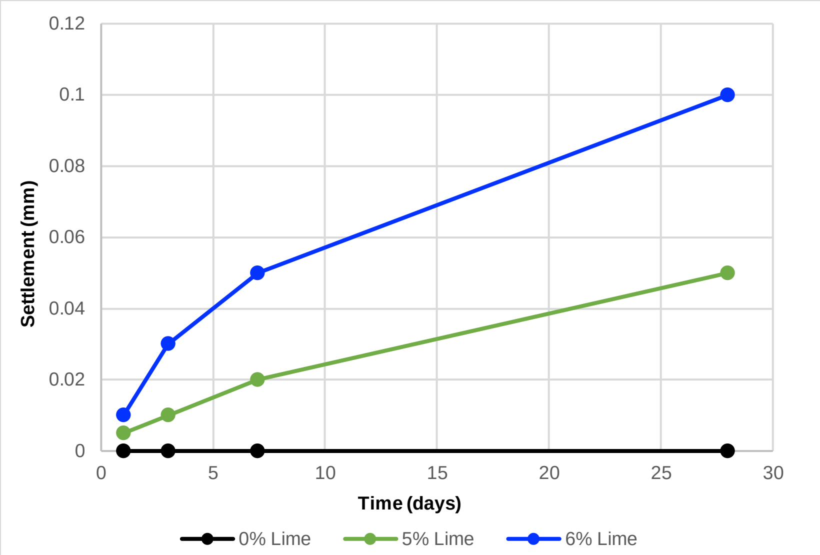

Figure 4.2- 6. Evolution of settlement with time.

4.2.2.1.3 Resilient modulus (M_R) and California bearing ratio (CBR)

Resilient modulus which is defined as the unloading modulus in cyclic loading (Christopher et al., 2006), is the method by which stiffness in unbound pavement material is characterized. While M_R characterizes soil stiffness, CBR test measures subgrade soil strength based on the resistance to penetration. According to Christopher et al., (2006), soil stiffness is considered the most important property of unbound materials in pavements. This is so because the stiffness of the soil would dictate how the stresses and strains within the pavement layers would be distributed and thus, would determine the pavement response to deformations such as rutting in the subgrade layer and fatigue cracking on the asphalt layer. Strength of the soil would however, only ensure traffic load can sufficiently be supported when applied.

Figure 4.2- 7 and 4.2- 8 illustrate the variation of M_R and CBR with peak UCS respectively, recorded over a 28 - day monitoring period. Formation of the lime hydration products resulted in the increase of the two parameters indicating the effect lime had on the sensitive soil. M_R increased almost linearly while the CBR increased linearly, as the UCS increased with time. At the top of the column, the maximum values of M_R recorded after 28 days for 0%, 5% and 6% were 93 MPa, 180 MPa and 212 MPa, respectively. A significant increase in M_R was noticed when the soil was treated with 5% lime which was almost twice that of untreated soil. This increase indicates how well the soil's stiffness was improved, thus, demonstrating the ability of the improved soil to withstand deformations in the unbound pavement layer due applied stresses, all this while the UCS increased too. The results are consistent with Qubain

et al., (2000) who noted that lime treated subgrade soils' M_R and CBR increase upon stabilization. He further showed an immediate increase in these parameters by a factor of four to five without curing. With increased lime content from 5 to 6%, an additional M_R 32 MPa was gained. Although not as significant as when the soil was initially treated with 5% lime, this increase further shows how the soil stiffness would increase with increasing lime content. A similar behavior was observed at the bottom of the column except, the M_R recorded was lower than at the top of the column.

The increase in both soil mechanical properties was as a result of the lime hydration which enhanced the cementation of the soil particles as well as reduced the PWP in the soil. Reduction in the PWP therefore, resulted in increased suction to which more specifically the CBR indicating strength gain, correspond.

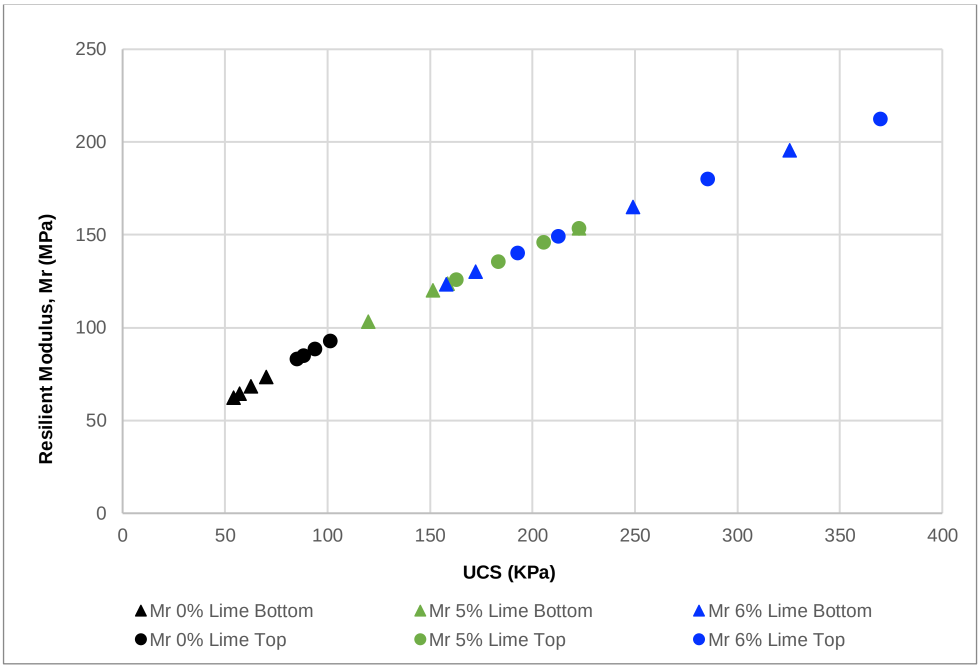

Figure 4.2- 7. Variation of M_R with UCS

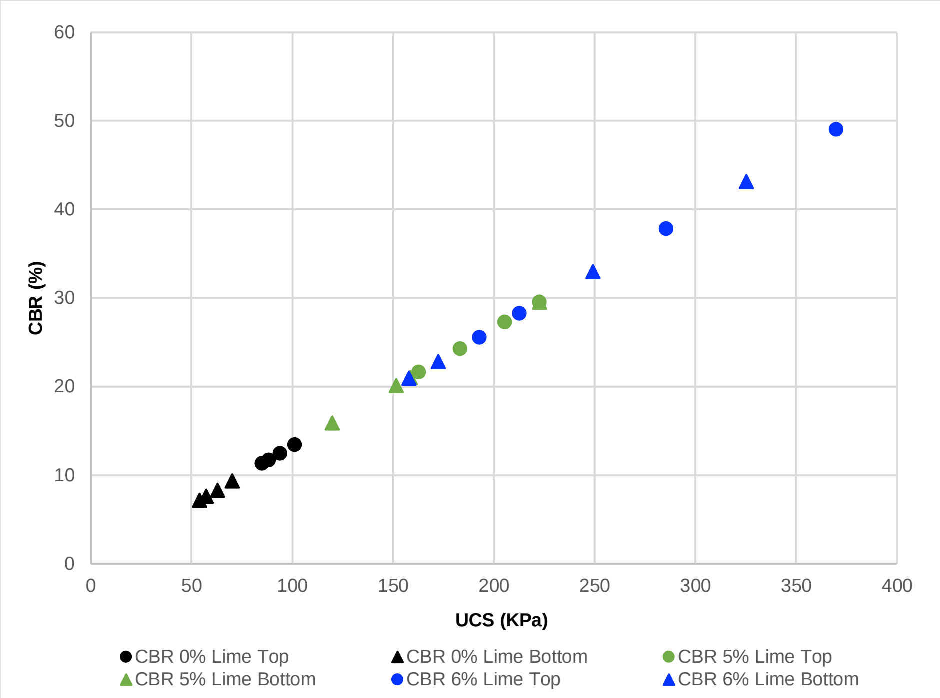

Figure 4.2- 8. Variation of CBR with UCS

Development of M_R in the columns is shown against CBR development in Figure 4.2- 9. The two soil mechanical properties show an almost linear relationship in their evolution. Soils' strength development due to the effects of cementitious products from lime treatment and curing time allowed, correspond with the characterized stiffness from M_R that the soil develops. The effects of lime portion used in the treatment is notable with much more effective results obtained. Therefore, in treated soils the stiffness which controls analysis of deformation in the pavement layers, increases as the soil develops its strength.

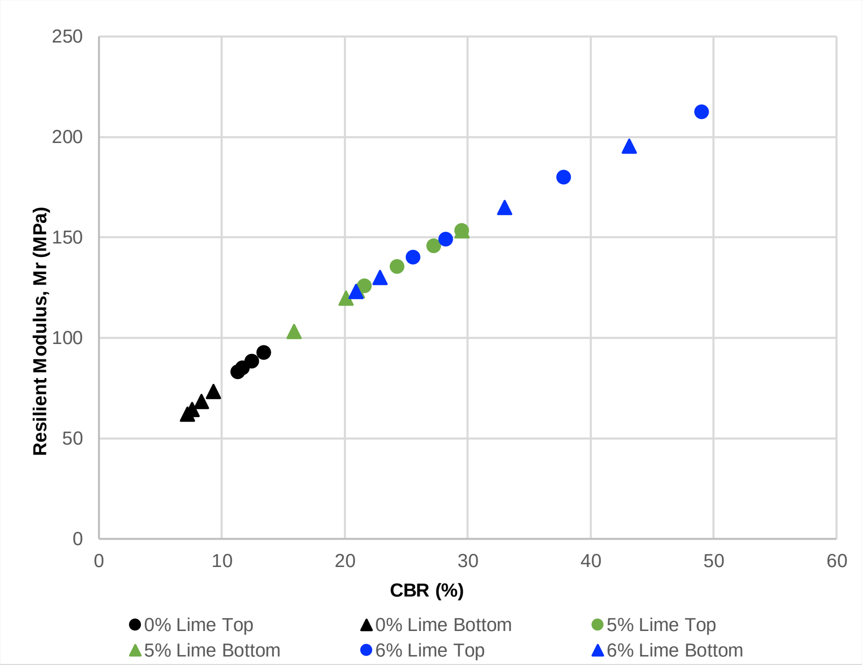

Figure 4.2- 9. Variation of M_R with CBR

4.2.2.2 Evolution of the hydraulic properties (H)

4.2.2.2.1 Change in volumetric water content (VWC)

Figure 4.2- 10 shows the variation of the volumetric water content (VWC) from the three columns with varying lime content. The figure shows that the soils treated with lime have lower VWC than the soil without lime and the VWC decreased as the lime content increased. This is due to the fact that the hydration reactions of lime consume water (i.e. self-desiccation), thereby leading to the decrease in the VWC of the soil treated with time. A higher initial lime content is associated with more consumption of water, i.e. more intense self-desiccation. The untreated soil thus retained more water within its pores compared to the soil that was treated. Indeed, the soil samples treated with a higher portion of lime content showed a lower VWC in comparison to the other soil samples. It can then be said that the VWC decreases with an increased proportion of lime. Eyo et al., (2022) and Thudi, (2006) have the same conclusion regarding the VWC behavior when soil is treated with a binder.

The determined VWC behavior corresponds to suction development in the soil samples which is dependent on moisture content. It essentially increases as the moisture decreases, thus, the higher strength gain developed in the soil sample with 6% lime proportion compared to the other two samples.

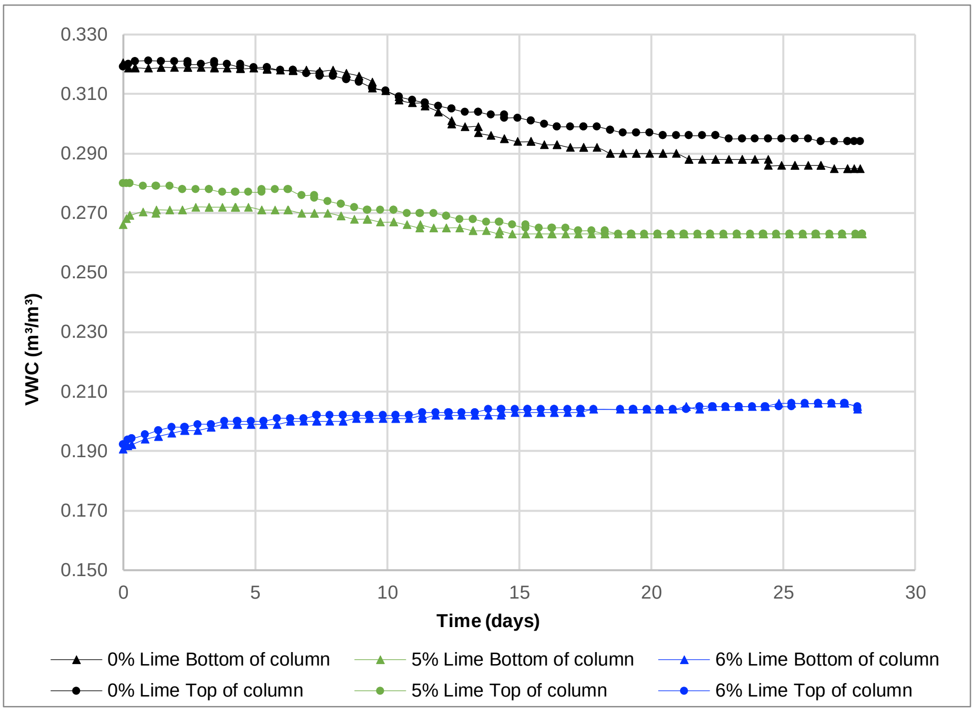

Figure 4.2- 10. Evolution of volumetric water content with time

4.2.2.2.2 Suction

Figure 4.2- 11 shows the evolution of suction both at the top and bottom of the columns with 0%, 5%, and 6% lime mixed with sensitive marine clay. The suction in the soil samples was noticed to have increased overtime, but more especially in the soil sample with a higher portion of lime. This was attributed to the lime hydration process which occurs over time, resulting in moisture content within the sample decreasing due to the self-desiccation mechanism. Albeit suction increased within each column, the top compared to the bottom showed differences but more so in the columns with treated soil. The higher suction at the top was associated to evaporation of moisture while the lower suction at the bottom was associated to drained water from the upper layers to the bottom layers.

While suction development occurs, water tension forces at menisci perimeters increase affecting the shear strength. And so, other than the amount of lime added to the sensitive marine clay, suction also contributed significantly to the time-dependent strength gain of the subgrade soil. It can be seen that a coupled hydro - mechanical relationship exists due to this. Figure 4.2- 12 shows the variation of the soil suction with UCS. From this figure, changes in UCS are seen to increase with increasing suction in the soil treated with 6% lime. In the sample with 5% lime, a decrease in the UCS which was attributed to the threshold lime quantity not being sufficient to enable pozzolanic reactions for long term cementation, was is noticed after

7 days. This resulted in the reduced mechanical strength in this particular sample. Lastly, the untreated soil sample showed no increment in mechanical strength due to there being no hydration and undeveloped suction.

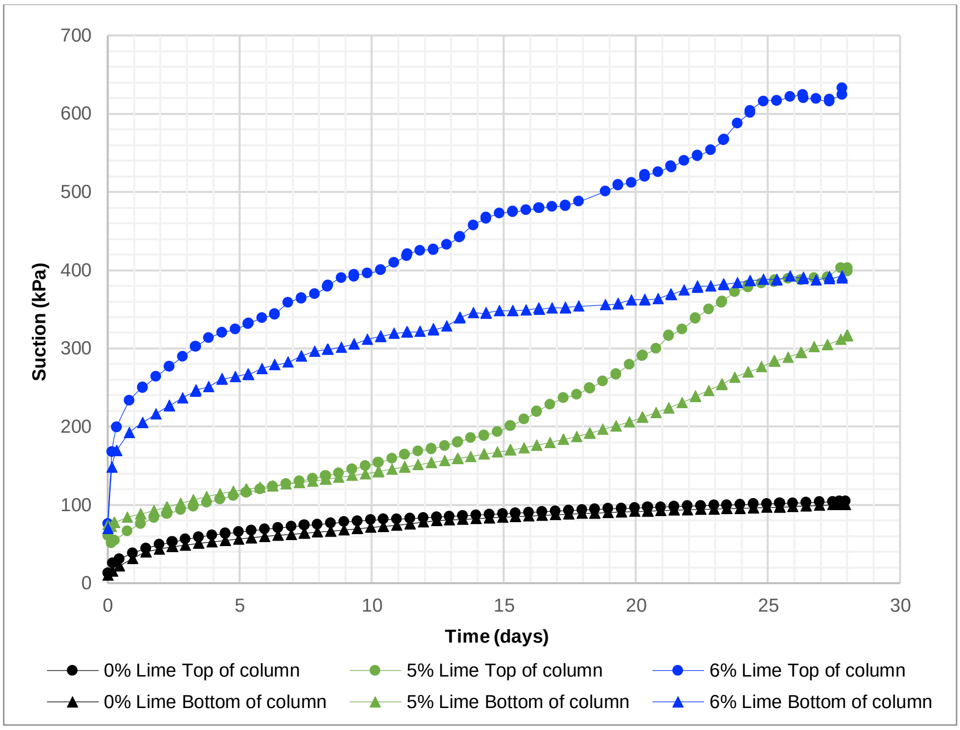

Figure 4.2- 11. Development of suction with time

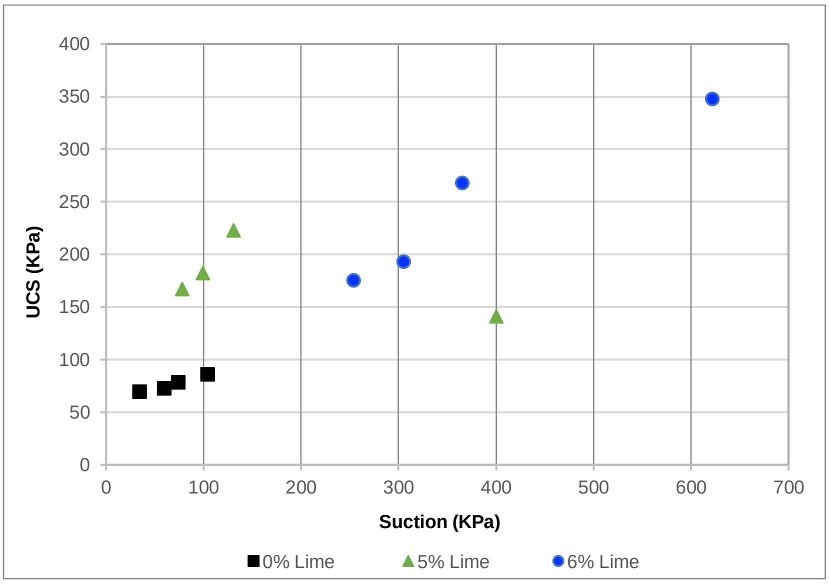

Figure 4.2- 12. Variation of UCS with Suction

4.2.2.2.3 Saturated hydraulic conductivity

Saturated hydraulic conductivity is an important parameter to consider because it can be used to determine moisture flow behavior within the subgrade soil. In Figure 4.2- 13, the evolution of hydraulic conductivity with time is shown for all three samples. Interestingly, the hydraulic conductivity pattern observed in the treated soil samples was contrary to expectation. It initially showed a constant decrease in both treated samples until after 7 days when an increasing pattern was observed. However, the untreated soil sample showed a constant hydraulic conductivity lower than that in the treated samples. This decrease during the first 7 days is attributed to pore refinement due to lime hydration in the treated soils, as supported by the MIP test results discussed in Section 4.2.3.4.5. The LMO according to Locat et al., (2011) is related to the hydraulic conductivity as much as it is to the strength gained by the soil. Furthermore, the results obtained in their research indicated a strong relationship between hydraulic conductivity and the lime portion rather than curing time for which its effects were less pronounced. It was suggested that at values lower than the LMO, the hydraulic conductivity in treated soils would increase due to flocculation without apparent cementation. At values equal to or higher than the LMO, the opposite was to be expected and thus, the general decreasing behavior noticed in the first 7 days. Nalbantoglu & Tuncer, (2001) and Di Sante et al., (2020) agree with lime portion significantly affecting the hydraulic conductivity in the treated soils. However, they indicate curing time equally has its effects. They further indicate that increasing hydraulic conductivity in lime treated soils is typical, which can be noticed in Figure 4.2- 13. The change in the soil structure which becomes more open, explains the increased hydraulic conductivity with time. Due to lime hydration and pozzolanic reactions, stronger lime particle aggregates are formed which result in the soil becoming more coarser in nature (Nalbantoglu & Tuncer, 2001). As a result, an even more open structure is developed which subsequently, increases the hydraulic conductivity in treated soil. Tran et al., (2014) also found that hydraulic conductivity increases in lime treated soils due to an increase of inter-aggregate pore sizes. Intra-aggregate pore sizes on the other hand do not change after lime treatment. The soil treated with 5% lime showed hydraulic conductivity increasing higher than the soil treated with 6% lime at 28 days due to the sample having less hydration products as a result of insufficient lime which does not exceed the minimum required for long term reactions to occur continuously. Thus, having a coarser pore structure compared to the soil treated with 6% lime as can be seen in the MIP results in section 4.2.3.4.5.

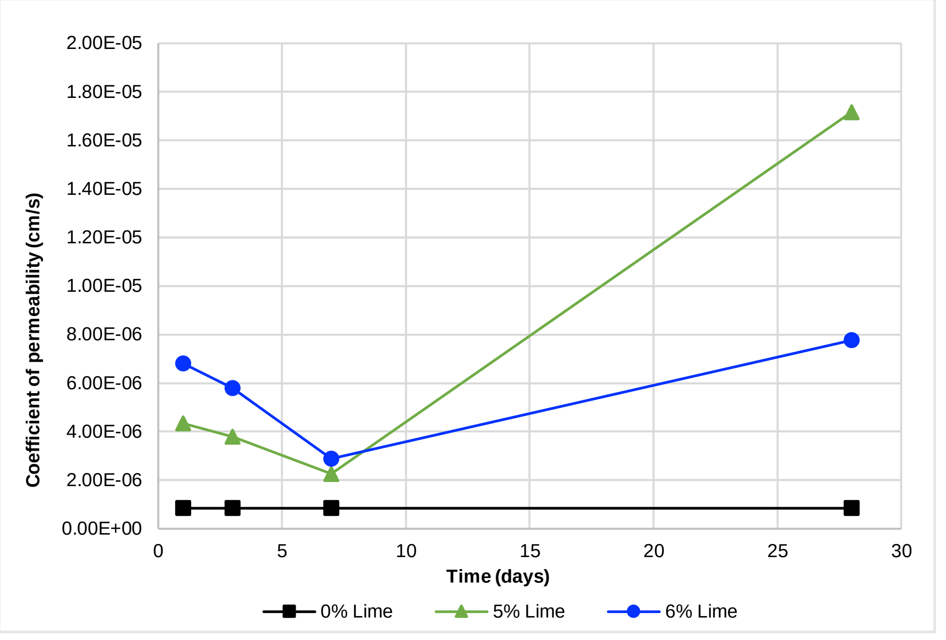

Figure 4.2-13. Variation of Coefficient of permeability with time

Intra-aggregate and inter-aggregate pores are the two types of pores in clayey soils. The pores in-between soil particles within an aggregate or cluster are the intra-pores while those between the aggregates or cluster are the inter-aggregate pores (Quang & Chai, 2015). In size, intra-aggregate pores are normally smaller than inter-aggregate pores. Figure 4.2- 14 shows the variation of hydraulic conductivity with void ratio for the 28-day monitoring period. A general relationship where the hydraulic conductivity increased while the void ratio decreased can be noticed in the samples treated with lime. This relationship has been attributed to the pores within the soil. Although Tran et al., (2014) suggested that the intra-aggregate pores do not change after lime treatment, Quang & Chai, (2015) argued that they do due to cementation products formed by pozzolanic reactions. It can therefore, be said that for the treated soils, the void ratio decreased due to changes in the intra-aggregate pores while the hydraulic conductivity increased as a result of the inter-aggregate pores which increase. The untreated soil samples however, showed no changes in void ratio or hydraulic conductivity for the whole 28 day period for which they were monitored.

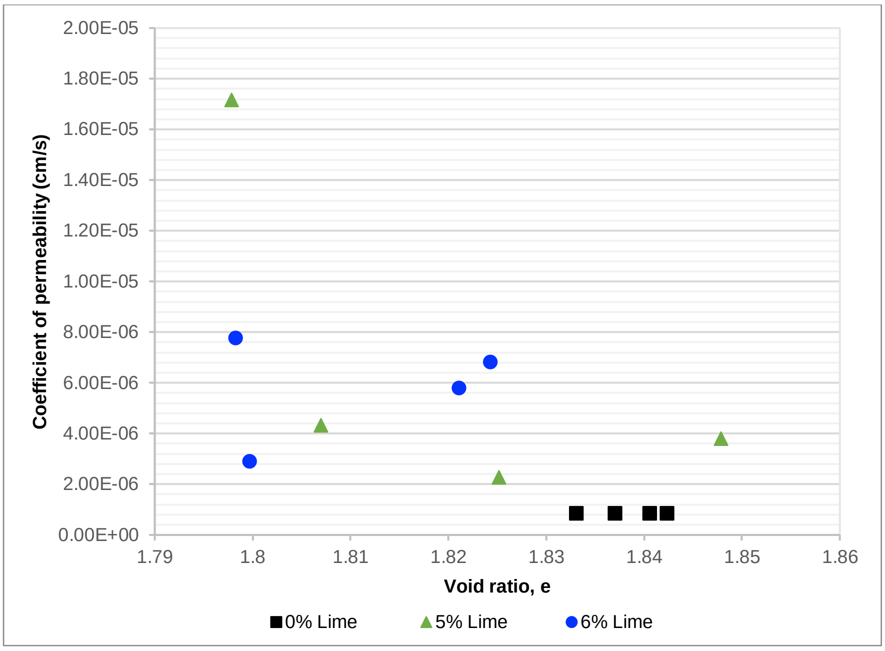

Figure 4.2- 13. Variation of void ratio with coefficient of permeability

4.2.2.2.4 Moisture variation

Moisture variation along the heights of the columns was measured for all three soil samples. Samples at every 10cm from the top to the bottom of the column were taken to enable this determination. Figure 4.2- 15 shows the results that were obtained. Generally, the samples treated with lime have moisture content decreasing with increasing curing time. During hydration, moisture is consumed to form cementitious gels and so, more moisture is lost with increasing portion of lime. Although this is the case, the sample treated with 5% lime was seen to have lesser moisture compared to the soil treated with 6% lime. Rapid initial reactions occurred causing the samples with a 5% portion of lime to become much drier. As moisture is required for hydration to occur, this fact and the minimum lime content in this sample lead to maximum strength not being attained as seen in section 4.2.3.1.1. This is in comparison to the soil treated with 6% lime in which more moisture was available. Maaitah, (2012) explains similar findings in which a higher moisture content in a treated soil sample resulted in higher strength gain.

Along the heights of the columns, samples collected from the surface had lower moisture content compared to samples from the bottom. This observation was attributed to evaporation at the top of the column and movement of moisture downwards due to gravitational forces. The untreated soil had the highest moisture content which remained constant for the entire monitoring period.

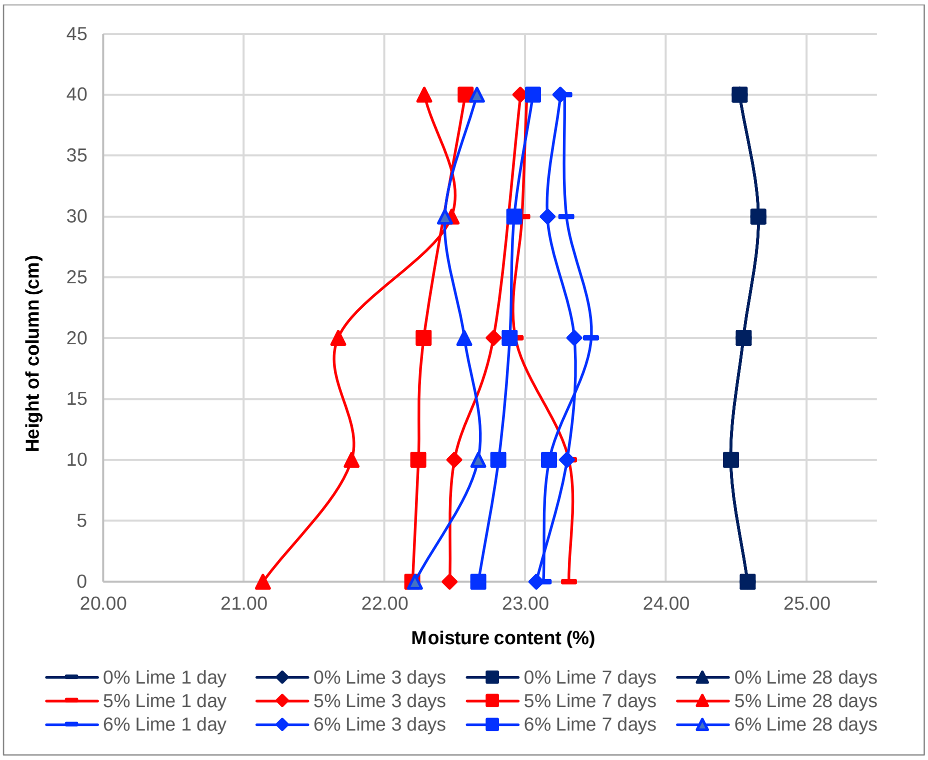

Figure 4.2- 14. Moisture variation along the height of the column

4.2.2.3 Evolution of the thermal properties (T)

4.2.2.3.1 Temperature evolution

Temperature changes within the columns varied with time. Figure 4.2- 16 shows these temperature variations in all three columns. The column with untreated clay showed no significant temperature variations, it was noticed that almost constant temperatures of about 22 °C were recorded for the 28-day monitoring period. Lime reactions are exothermic, and so, the hydration process generates heat which is dissipated. For this reason, the columns with treated soil showed variations in the temperature developed during the monitoring period. Highest temperatures were recorded on the first day as a result of rapid initial reactions, after which constant fluctuations were noticed.

Notable differences in temperature evolution within the columns could be seen between the top and bottom. In the column with untreated clay, lower temperatures were recorded at the bottom of the column while closer to the surface higher temperatures were recorded. In the columns with treated soil, the opposite was the case. According to Ghirian & Fall, (2013), it should be expected to have lower temperatures closer to the surface in these columns because latent heat of evaporation is normally absorbed at the column surface during evaporation hence the lower temperatures.

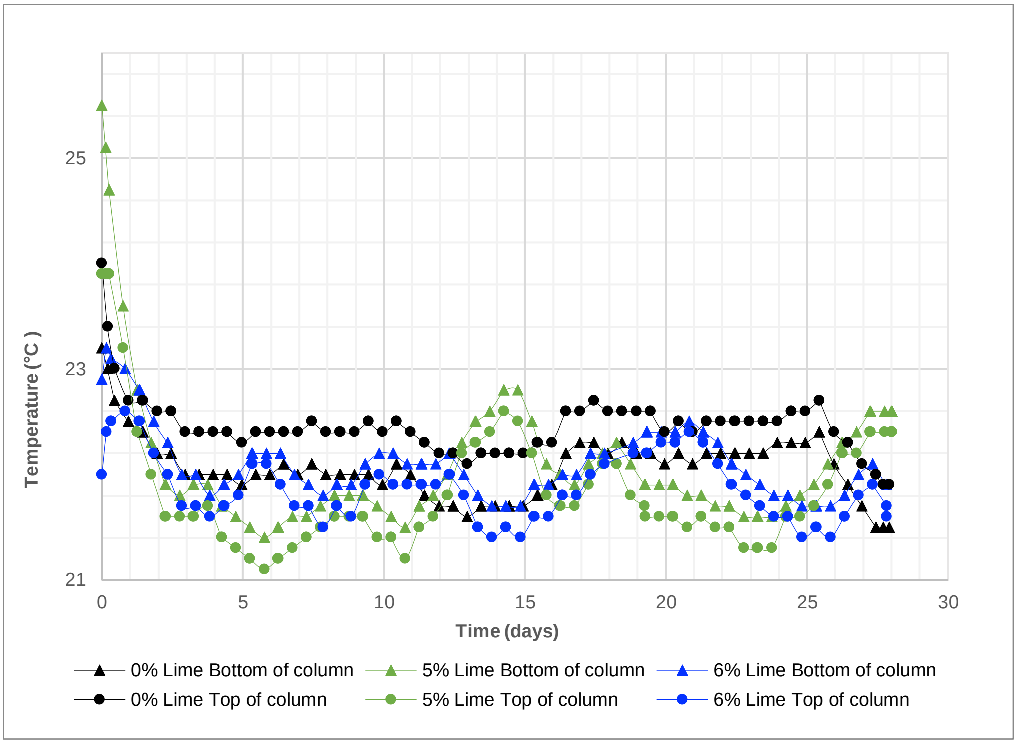

Figure 4.2- 15. Evolution of temperature with time

4.2.2.3.2 Evolution of thermal conductivity

In soils, degree of saturation, porosity, grain size distribution and mineral content are all factors that affect the thermal conductivity. However, degree of saturation has a significant effect (Ghirian & Fall, 2013). Figure 4.2- 17 shows the relationship between thermal conductivity and moisture content for all three columns for the 28-day monitoring period. A direct relationship between thermal conductivity and moisture content can be seen. Soil treated with an increased lime portion resulted in reduced moisture content with time due to the hydration process and so, a lower thermal conductivity. In the case of untreated soil, the moisture content would be high thereby, the soil would have a higher thermal conductivity. A thermal – hydro relationship in this case can be noticed.

Figure 4.2- 18 shows the variation of thermal conductivity with column height for each column. With an established relationship between moisture content and thermal conductivity, the thermal conductivity along the depths of the column containing treated soils reduced towards the top where evaporation occurred. It was higher at the bottom of the column due to

moisture content being higher.

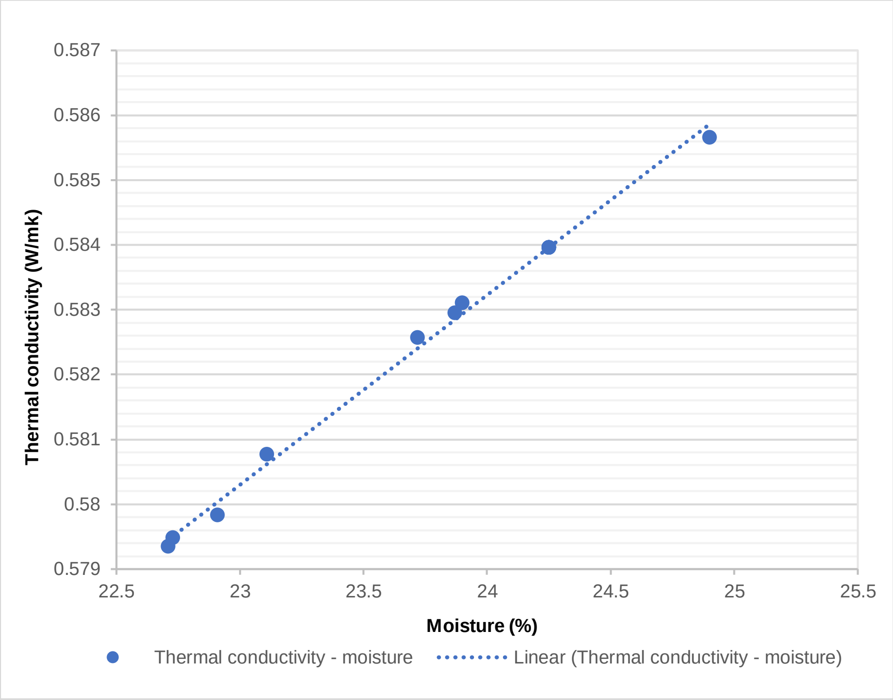

Figure 4.2- 16. Thermal conductivity variation with moisture content

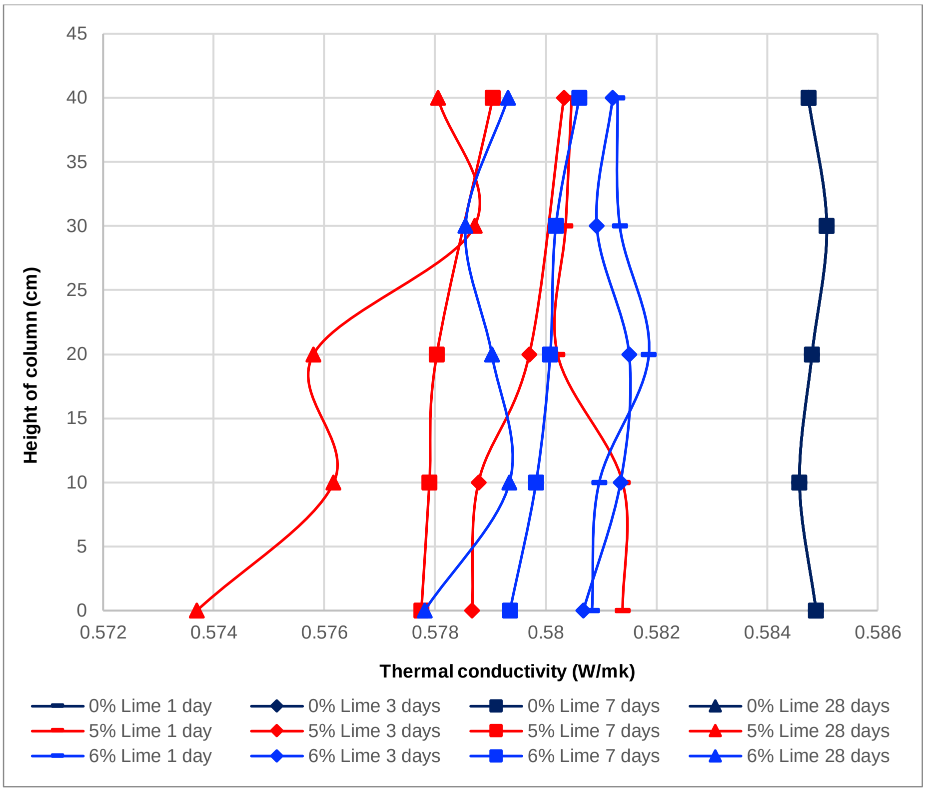

Figure 4.2- 17. Variation of Thermal conductivity along the height of the column

4.2.2.4 Evolution of chemical (C) and microstructural properties

4.2.2.4.1 Evolution of Electrical conductivity

Figure 4.2- 19 illustrates the variations of EC with time in all the three columns. The column with the untreated soil showed a constant EC for the duration of the monitoring period while the columns with treated clay showed decreasing EC with time. The constant EC in the untreated soils illustrates the absence of ions resulting from the chemical reactions of lime. In the treated samples on the other hand, the EC is seen to start at a peak then gradually decrease. The peak shows an increased concentration of ions resulting from lime hydration. The decrease seen in both soil samples treated with different portions of lime is attributed to; lime hydration products that form, consumption of free water and evolution of capillary pores (Tian & Fall, 2021). According to Diamond & Kinter, (1965), the drop in EC noticed overtime in the treated soil samples can be further attributed to adsorption of lime which occurred rapidly. Of the two columns with treated soils, the column having soil treated with 5% lime showed a higher EC compared to the soil treated with 6% lime. This entails an increased concentration of ions which can be related to the UCS (Abiodun & Nalbantoglu, 2015). It was noted in section 4.2.3.1.1 that the soil sample treated with 5% lime had a high initial strength

gain in the first 7 days, to which the higher EC compared to the soil treated with 6% lime can be related.

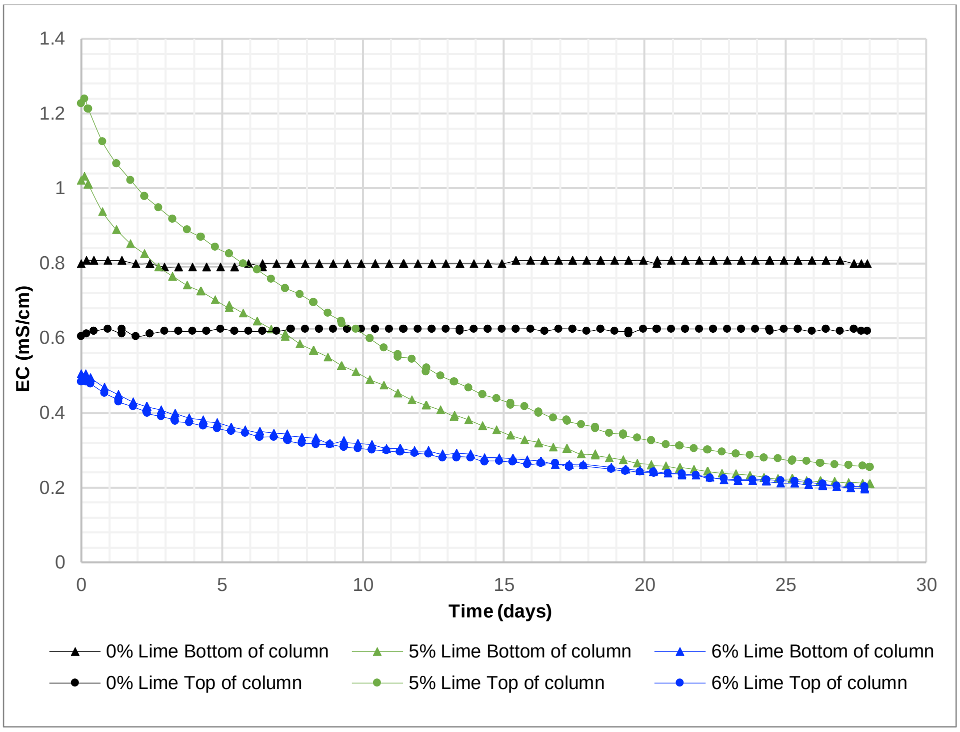

Figure 4.2- 18. Evolution of electrical conductivity with time

4.2.2.4.2 Physical properties

Figure 4.2- 20 shows the variation of void ratio along the heights of the columns. As a result of the pozzolanic reactions, the pore spaces within the soil particles filled up with the cementitious gels that were produced. This led to noticed reduction of pore spaces in the treated soils, whereas, in the untreated soil, the pore spaces remained constant. In addition, flocculation which is a process that also occurs in treated soils, contributed to the change in pore spaces as a result of soil particles becoming closely packed. This process contributed to the gain in mechanical properties of the soil such as strength and stiffness which can be seen in figures 4.2- 4, 4.2- 7 and 4.2- 8. And so, a relationship between the mechanical and chemical (MC) processes can be observed.

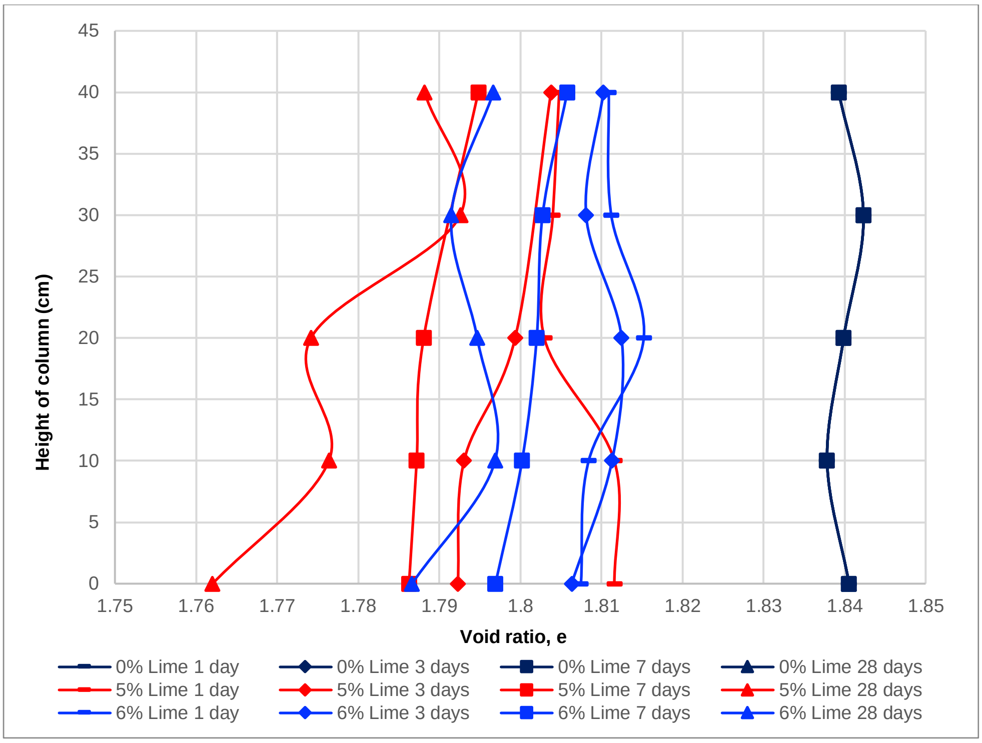

Figure 4.2- 19. Variation of void ratio along the height of the column

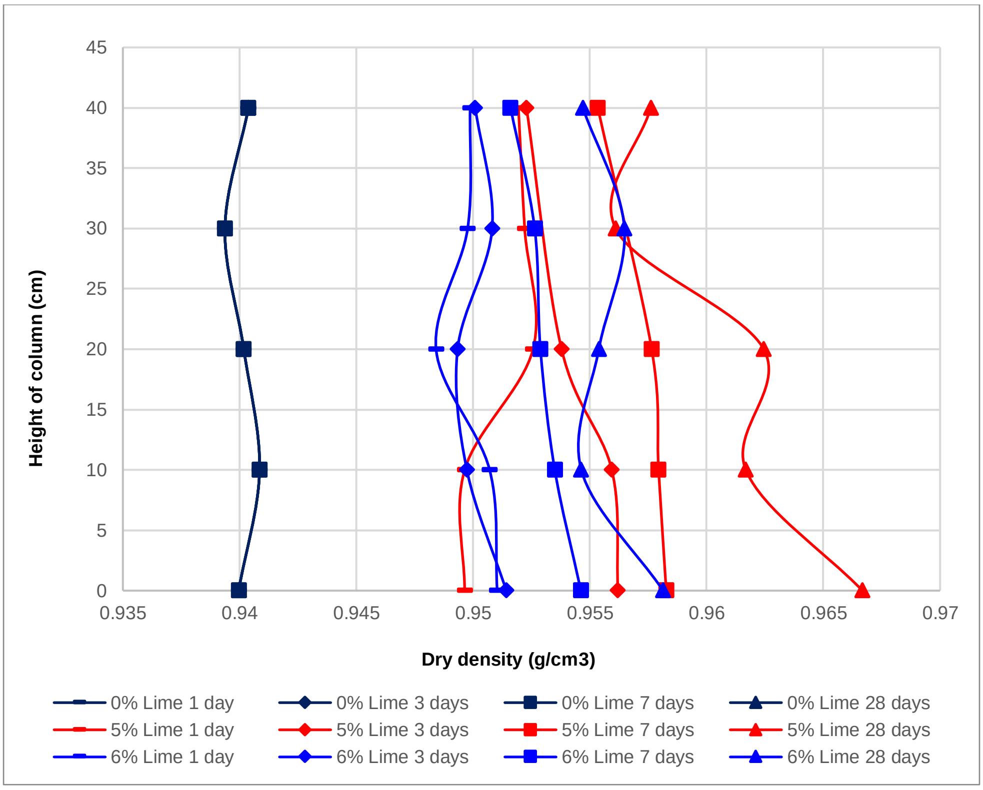

Figure 4.2- 20. Dry density variation along the height of the column

Figure 4.2- 21 presents the variation of dry density along the heights of the column. The dry density of the clay is seen to increase when the soil is treated and additionally, when allowed to cure for a longer time. It is known that as lime hydration progresses with time, more hydration products precipitate into the soils' matrix making the lime treated soil denser. Therefore, increasing the dry density of the soil. Rajasekaran & Narasimha, (1997) had similar conclusion on lime improved soil properties. The portion of lime used in the treatment of the soil also significantly affects the resulting dry density. Along the heights of the column, the dry densities were seen to generally increase from the bottom of the column to the top. Moisture content affects the dry density in that it is lowered when the moisture content is higher and vice versa. The corresponding moisture content at the bottom of the column was high, therefore, the lower dry density which increases towards the top of the column.

4.2.2.4.3 XRD results

The results from the XRD tests performed on the treated and untreated soil samples are presented in Figure 4.2- 22. They show the mineralogical alteration and formation of the new reaction compounds. Alterations in the soil structure can be seen through the intensities observed in the treated soil, which are lower than those in the untreated soil samples. The change in the structure is due to the effect of lime treatment in which destruction of clay mineral layers occurs while pozzolanic reactions develop (Al-Mukhtar et al., 2014). The main lime hydration products are identified as calcium silicate hydrate (C-S-H), calcium aluminate hydrate (CAH) and calcium silicate aluminate hydrate (CSAH). The peaks that correspond to C-S-H, CAH and CSAH are higher in the lime-treated soil than in the untreated soil. These compounds that improve the strength of the clay significantly by binding the clay particles together, form a hardened matrix which corresponds to the UCS (Figure 4.2- 4) of the treated samples in comparison to those untreated. Furthermore, the lime hydration products refine the soils' pore structure i.e. reduces porosity. Similar observations were made by Monsif et al., (2021) in which hydration gels were formed in Leda clay that was stabilized with a binder.

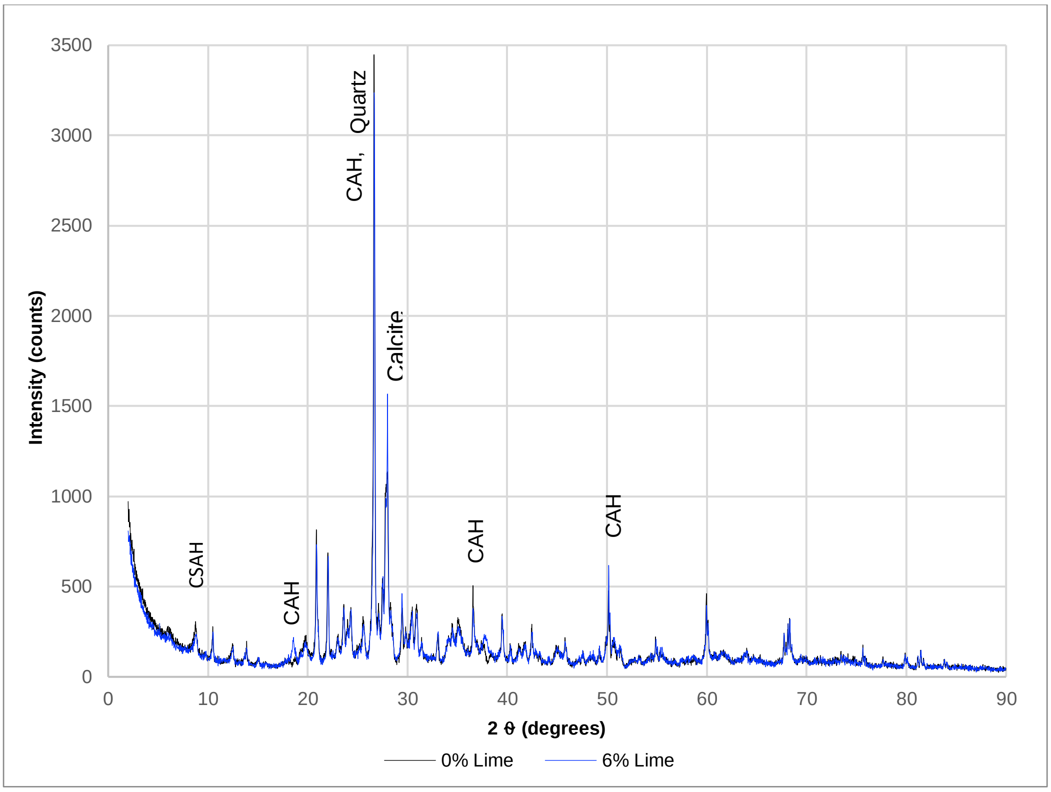

Figure 4.2- 21. XRD results for treated and untreated Leda clay

4.2.2.4.4 TG/DTG analysis

Results of the thermogravimetric analysis performed on the treated and untreated soil samples are illustrated in Figure 4.2- 23 providing a comparison. From the TG curves, the mass loss for the three samples can be seen. There is a significant difference in the mass lost between the untreated and treated samples which can be seen between 10 °C to about 800 °C. The masses lost increase almost continuously with temperature. The soil samples treated with 6% lime lost more mass compared to the samples treated with 5% lime. However, at 700 °C the loss in mass is very negligible. The resulting mass lost in the treated samples is attributed to dehydration of the Ca-hydrates formed from the pozzolanic reactions.

The DTG curves for the three soil samples that correspond to the TG curves show endothermic peaks which correspond to different phases during the hydration process of lime. Three very distinct peaks can be seen with the largest one at almost 750 °C. The first peak which occurred between 100°C and 150 °C was caused by evaporation or removal of free or bound water molecules present in the soil - lime structure. At about 400 °C, the second distinct peak referred to as the main loss by Cardoso et al., (2009) occurs. It shows decomposition of major components in the hydrated lime structure which are known as portlandite. Finally, at nearly 750 °C the final peak occurs in the soil samples which relates to the decomposition of a mineral component of the soil known as calcite into CaO releasing CO_2.

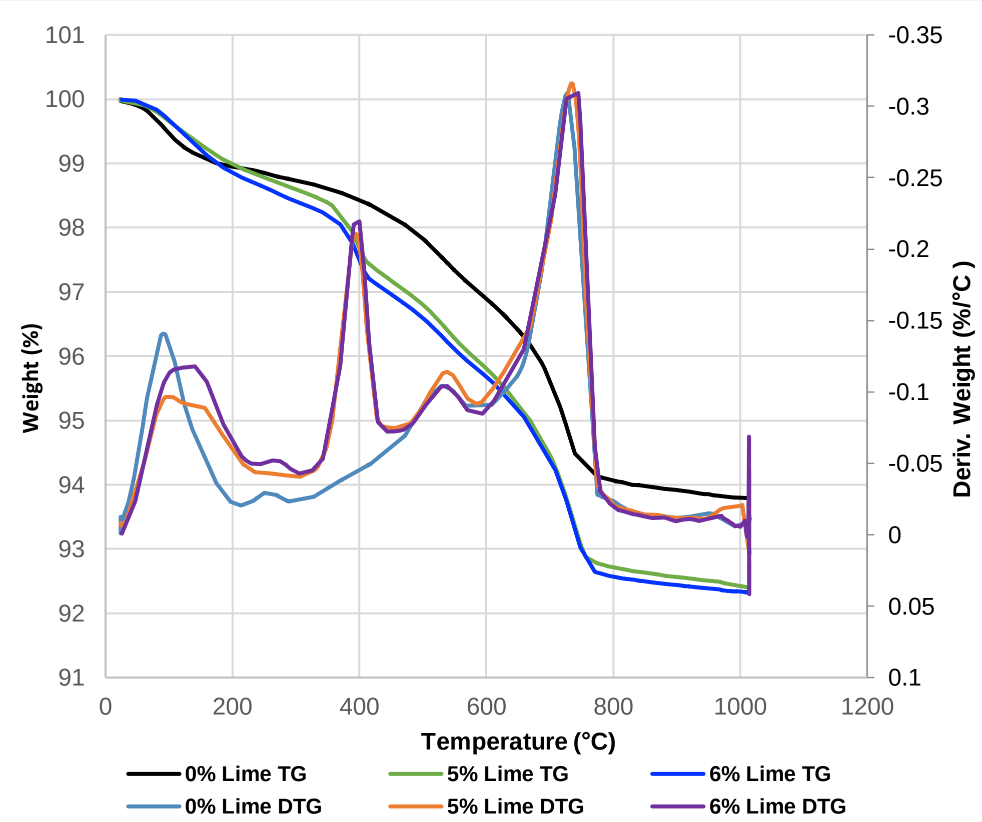

Figure 4.2- 22. Thermogravimetric analysis of untreated and treated Leda clay

4.2.2.4.5 MIP analysis

The microstructure and pore size distribution for the untreated and treated soil, cured for 28 days, were investigated. Low pressure of 50 psi was initially applied to the samples after which higher pressure of 33,000 psi was applied. Figure 4.2- 24 shows the MIP results where the ratio of volume increment injected into a unit mass of sample to the logarithmic pore diameter is plotted against the pore radius.

The pore radius for the main peak in the untreated clay sample was 9.001E-07, in the sample treated with 5% clay it was found to be 0.236E-07 and finally in the sample treated with 6% lime, it was reported to be 0.191E-07. The pore size significantly decreased with addition of lime which further decreased as the portion of lime added increased. The exhibited rate of volume change shown is as well a significant reduction upon addition of lime. Despite the difference in volume change not being as significant as when 5% lime was added, the volume reduced further with an increase in the portion of lime added. Both the reduction in the volume and the change in the pore sizes show the effect of the hydration products that were produced over the monitoring period, i.e. pore spaces were filled up with the products. The void ratios shown in section 4.2.3.2.3 under the hydraulic conductivity can be related to the pore sizes of the samples. It was determined that the void ratios decreased with time just as the pore sizes decreased. However, the hydraulic conductivity which is discussed under the same section, was seen to increase as a result of the inter-aggregate pores which according to Quang & Chai, (2015) have larger pores compared to the intra-aggregate pores which have smaller pores hence causing the change in the void ratios of the samples.

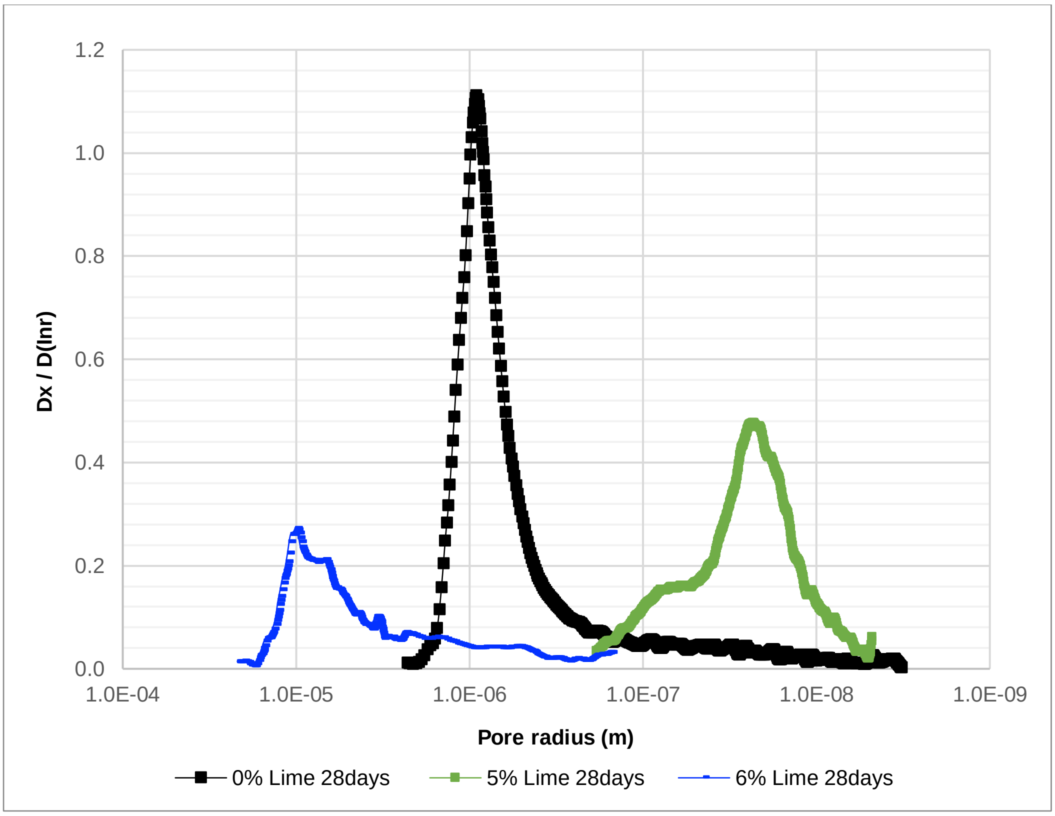

Figure 4.2- 23. MIP results of treated and untreated sensitive marine clay

4.2.2.5 Discussion on the coupled THMC behavior

Figures 4.2- 25 and 4.2- 26 illustrate interactions between the coupled THMC processes occurring in the lime stabilized sensitive marine clay. It should be noted that the illustrations only show the top and bottom of the column treated with 6% lime. However, the behavior is anticipated to be generally the same in all treated columns except with slight variations from top to bottom in the properties due to factors such as evaporation and downward movement of moisture due to gravitational forces. The figures show the temperature variation due to lime hydration – a thermal factor (T), suction and hydraulic conductivity – both hydraulic factors (H), electrical conductivity – a chemical factor (C) showing evolution of lime hydration products, and UCS – a mechanical factor (M), for the duration of the monitoring period.

Peak temperature is noted in the early ages where it increased rapidly affecting the rate of the chemical reactions (coupled TC processes). The early ages of stabilization are significant and the reactions occurring between lime and the clay are governed by cation exchange (Al-Mukhtar et al., 2014). The corresponding peak EC in the early ages, which gradually drops indicates an increased concentration of ions resulting from instantaneous chemical reactions. In these early stages, calcium cations are exchanged for cations on the surface of the clay particles, where the high valent cations replace the lower valent cations. The temperature varied for duration of the monitoring period and this was attributed to the reactions being exothermic.

It can be suggested that flocculation and cation exchange may have been prompted in the early ages, positively impacting the mechanical behavior of the sensitive marine clay depicting a coupled chemical and mechanical process. Long term pozzolanic reactions in which cementation occurs are shown by the gradually decreasing EC. They improved the mechanical properties of the soil due to formation of lime hydration products and consumption of free water. The large pore spaces that were filled up with free water were simultaneously filled up with the lime hydration products such as CSH, CAH and CSAH. These long term reactions are characterized by stronger crystal formation and bonding (Al-Mukhtar et al., 2014; Tian & Fall, 2021), hence the higher strength gained and increased stiffness seen in Figures 4.2- 4 and 4.2- 7. The two stages in which long term reactions occur are referred to as skeleton formation and hardening stage.

Development of suction and the high temperatures seen in Figure 4.2- 25 and 4.2- 26, which result from lime hydration show a coupled TH process which contributes to the formation of the skeleton and the hardening stage of the soil. A coupled HM process is noted by the increasing suction which corresponds with the increasing UCS that results from lime hydration in the soil mix. In addition, a further coupled HM process that contributes to formation of the soil skeleton and improved properties is noted between suction and the volume change in the soil as well as reduction in the capillary pore spaces of the soil as seen in figure 4.2- 24.

Increased temperature equally had an effect on the strength development as well as volume change behavior of the soil (TM coupled process). The volume change would occur due to decreased water content and reduced pore spaces resulting from changes in temperature. As a result, the mechanical behavior of the treated soil would be improved as seen in figures 4.2- 25 and 4.2- 26. Another peak temperature can noticed at almost 21 days (Figures 4.2- 25 and 4.2- 26). This peak shows a relationship between the thermal and chemical properties. The peak is attributed the continuous lime hydration process which caused a sharp increase in temperature.

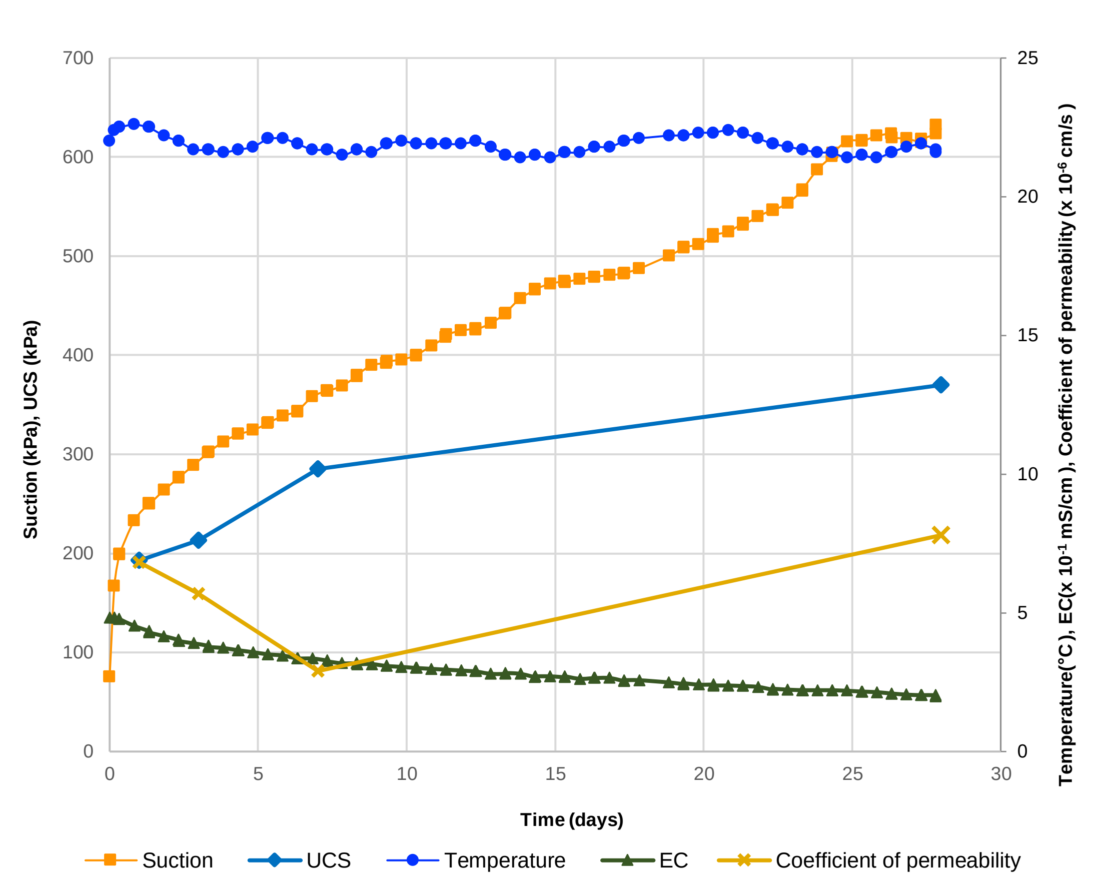

Figure 4.2- 24. Coupled THMC behavior at the top of the column treated with 6% lime

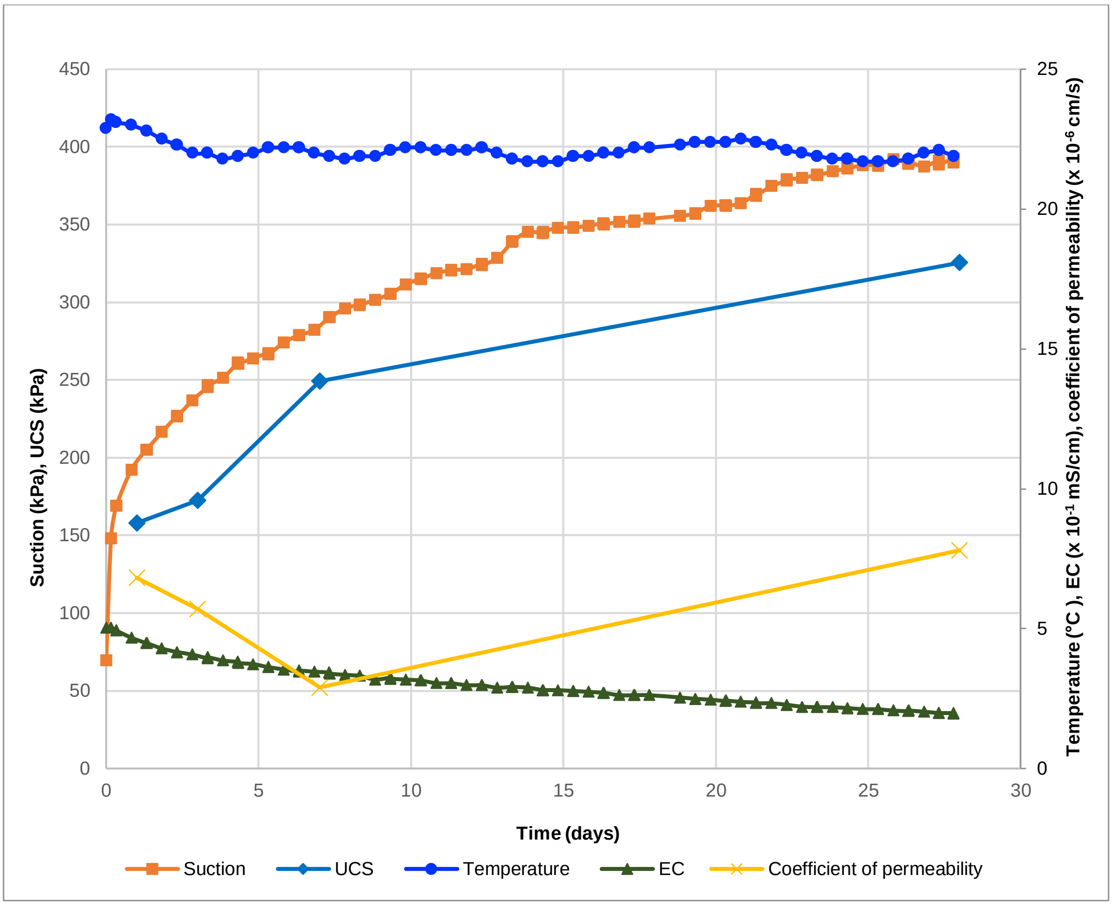

Figure 4.2- 25. Coupled THMC behavior at the bottom of the column treated with 6% lime

4.2.3 Summary and conclusions

In this study, column experiments were conducted at a laboratory scale to monitor the evolution of the coupled THMC processes in lime stabilized sensitive marine clay that is used as the subgrade of pavement structures in regions such as Eastern Canada.

The mechanical properties of the soil developed with an addition of lime content. These properties significantly increased with an increasing portion of lime. From the top to bottom of the column, the mechanical properties, notably, the UCS and stiffness varied due to factors such as evaporation of moisture from the surface of the column and downward movement of moisture. Suction which developed with time had a relationship with development of the mechanical properties. This showed a strong coupled HM process. In addition to development of suction, the results showed that the soils' change in void ratio impacted the UCS. It was also observed that the void ratio affected the hydraulic conductivity of the treated soil due to the hydration products that filled up the voids in the soil.

The results on electrical conductivity show evolution of chemical properties in the treated soil samples while no evolution was seen in the untreated soil sample. Results from the XRD and TG/DTG analysis showed the lime hydration products that formed due to reactions that occurred within the soil. Although the chemical properties were seen to evolve, in the soil treated with 5% lime, the UCS gained after 7 days decreased due to 5% lime being the minimum required to allow for reactions to begin occurring in the treated soil, therefore the lime being insufficient for the pozzolanic reactions in the long term to occur. In addition to the treated soils showing higher hydraulic conductivity values, the sample treated with 5% lime showed an even higher hydraulic conductivity owing to less cementation products in the sample and so, the particles being coarser in comparison to the soil treated with 6% lime.

From the results obtained, it can be seen that the treatment of sensitive marine clay shows a strong coupled THMC behavior. The fundamental mechanisms on the coupled THMC processes have been presented in this study which helps to gain a better understanding on these processes and their coupling. The effects of the coupled processes would be used in effectively designing and constructing cost-effective and durable subgrades, with sensitive marine clay as an in-situ soil. This is so because these effects significantly affect the performance of the pavement structure as a whole.

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4.3 Technical Paper 2: Thermo-Hydro-Mechanical-Chemical behavior of sensitive marine clay subgrade stabilized with lime subjected to daily thermal cycles: column experiments

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(submitted)

Abstract

The coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes occurring in lime treated sensitive marine clay when exposed to daily thermal cycles were studied to understand their evolution and interaction. Two fully instrumented columns were prepared in which the treated clay was placed, compacted and monitored for a period of 28 days. Various sensors were placed at different heights of the column in the compacted clay, with a dial gauge at the top to observe how the coupled processes evolved. At the top of one of the columns, a heating blanket was placed through which daily thermal cycles were applied to the soil to understand the effect the cycles would have on the treated clay. Eight other columns with compacted treated clay were prepared from which samples for testing were obtained from the top and bottom to understand how the properties evolved at two different depths after 1, 3, 7 and 28 days. The results obtained indicate daily thermal cycles significantly affect the chemical (e.g., lime hydration), mechanical (e.g., strength, deformation), hydraulic (e.g., hydraulic conductivity, suction) and thermal (e.g., thermal conductivity, temperature) properties or factors of the sensitive marine clay treated with lime and their interactions. Due to lime hydration, the mechanical properties of the clay were seen to have improved tremendously, however, application of the daily thermal cycles were seen to have improved these properties even more. This was further attributed to the higher curing temperatures which increased the kinetics of the chemical reactions. Temperatures decreased with column height when thermal cycles were applied, while higher temperatures were observed at the bottom of the column compared to the top of the column in the control. Development of the mechanical properties were also influenced by the hydraulic properties, such as suction. The hydraulic conductivity was observed to decrease quicker when thermal cycles were applied. The results presented in this manuscript on the effects of daily thermal cycles on the THMC properties or behavior of lime treated sensitive marine clay subgrade would contribute to cost-effective design and maintenance of pavement structures constructed on sensitive marine clay soils

4.3.1 Introduction

Sensitive marine clay road subgrades are generally poor performing, and this is attributed to the nature and formation of these soils. In Canada, sensitive marine clays are also known as

Leda clay or Champlain Sea clay. According to Penner, (1962), Quigley et al., (1983), Kondo & Torrance, (2005), Taha & Fall, (2013), Mayne et al., (2019) and Liu et al., (2021), these soils are of post glacial marine origin. Leaching changes the salt concentration between the soil particles leading to drastic weakening of the soil and behavior like that of liquid when it is disturbed (Al-Umar et al., 2020, 2021). Additionally, the weak bonds between the soil particles contribute to the change from remarkably brittle to liquid like behavior when disturbed (Liu et al., 2021). The result of road or highway construction on poor soils of this type without remedial methods, would be distresses from within the subgrade layer propagating onto the pavement surfaces. This would in turn result in total failure of the structure as a whole, therefore, not fulfilling its intended engineering use.

Roads and highways are fundamental infrastructure in any given society (Smith, 1994) thus, regions in which poor soils such as sensitive marine clay are predominate, require improvement techniques such as chemical stabilization in order to improve the soil's engineering properties prior to construction works. Chemical stabilization is an improvement technique used in subgrade construction, in which binders such as lime are used to enhance the soil's engineering properties. Rajasekaran & Narasimha, (1997), Qubain et al., (2000), Garber & Hoel, (2009) and Aldaood et al., (2014) indicate that the improvement of the soil properties occur in three fundamental processes including flocculation, cementation and hydration, while the lime reacts with the soil. Flocculation and hydration begin to occur almost immediately after lime treatment and are considered short term reactions. Mathew & Rao, (1997) further suggest that the short term reactions enhance the soils workability and plasticity, and Aldaood et al., (2014) agreed with this. Cementation on the other hand, in which cementitious gels are produced, occurs overtime. Additionally, it is the long term process that Aldaood et al., (2014) suggests is significantly dependent on the rate chemical decomposition, hydration of silicates and aluminates, and temperature. The geotechnical engineering properties that are of immense importance in assessing and predicting the pavement structure's performance over time are bearing capacity, compressibility, strength, and stiffness. In sensitive marine clays, these properties are poor. For this reason, soil improvement techniques such as chemical stabilization are necessary. Consequently, traffic loads applied on the improved subgrade soils will be supported sufficiently without distresses forming within the subgrade layer.

Performance of a road or highway is as well dependent on environmental conditions such as varying temperatures and moisture. Temperature variations evidently affect the mechanical behavior of the soil just as moisture does. Moisture is capable of penetrating in the soil through surface infiltration, seepage from higher ground, rise in the water table, capillary action and evaporation from the water table. Increase in moisture in soil particles results in an increase in the soil's pore water pressure which causes effective stress of the soil to reduce, subsequently, reducing its shear strength. Furthermore, the degree of saturation would increase causing suction between the soil particles to reduce contributing to lose of strength (Figure 4.3- 1). Temperature variations cause heat transfer within the subgrade soils. It influences significant changes such as the composition and structure of the soil which could potentially cause poor performance of the structure. Temperature variations or increase are of significance in a soil's structure. They can influence the soil pore water pressure and fluid transport ability (Geng & Sun, 2018). These temperature changes and heat transfer in soil are highly dependent on the thermal conductivity of the soil (Figure 4.3- 1). According to Penner, (1962) the soil's thermal conductivity is dependent on many factors, including the clay minerals within it as well as the clay content, although, it is said to be largely dependent on the former. In addition to varying environmental temperatures, exothermic reactions in lime treated subgrade soils equally contribute to the temperature changes which affect the pavement structure performance (Figure 4.3- 1). On the other hand, as the temperature changes are being affected by the soil-lime reactions, the strength of the subgrade soils is improved due to the same reactions occurring. As a result; thermal (**T,** e.g. temperature, heat transfer), hydro (**H**, e.g. suction, pore water pressure), mechanical (**M**, e.g. strength) and chemical (**C** e.g. lime hydration) (THMC) processes are determined to be coupled processes that are interdependent (Figure 4.3- 1). Ghirian & Fall, (2014) however, report that the chemical reactions due to binder hydration are one of the crucial factors in the THMC processes due to resulting pore refinement and porosity reduction.

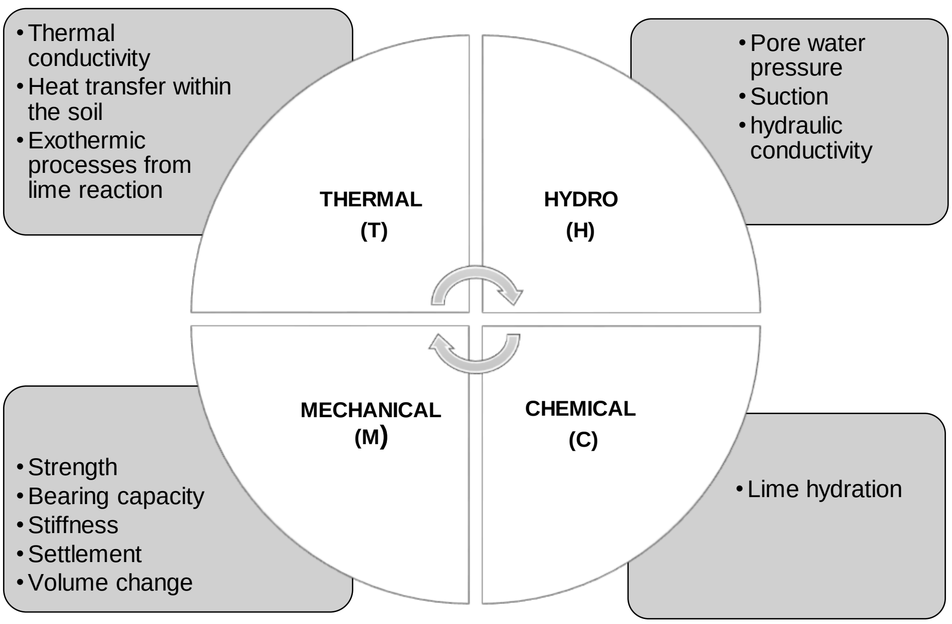

Figure 4.3- 1. Illustration of the coupled THMC processes within sensitive marine clay improved with lime

To the best of the authors' knowledge, the coupled THMC behavior of lime stabilized sensitive marine clay which is the basis of this study, is yet to receive attention in literature. The focus of this study will therefore, be to perform column experiments to understand the coupled processes in sensitive marine clay stabilized with lime when subjected to daily thermal cycles, similar to those that would be experienced in the field. Daily thermal cycles compared to seasonal cycles can cause excessive deformations to soils on which they are applied, and so, of particular interest. Soils subjected to heat stresses undergo degradation and changes to the soils' structure due to diminishing soil resistance, especially in fine-grained soils (Aldaood et al., 2014; Ahmadi et al., 2021). Thermal cycles cause stresses within the soil to occur (Ahmadi et al., (2021)). In addition, daily thermal cycles can affect hydration of lime, water flow and contribute to shrinkage, within the soil and so, assessing the effects they will have on the soil becomes very important. Moreover, the soils' rate of strength gain (e.g., UCS) can be affected by the cycles contributing to the importance of assessing the applied daily thermal cycles. This will aid full understanding of the thermal response of lime stabilized sensitive marine subgrade soils, which will further aid understanding of the pavement structure's performance during its service life. Furthermore, construction of durable and cost-effective roads or highways on the poor soils will be achieved.

4.3.2 Experimental program

4.3.2.1 Materials

4.3.2.1.1 Sensitive marine clay

Sensitive marine clay used in this study was collected from Gloucester in the Ottawa region. The predominate mineral of this marine clay according to Penner, (1962) is Mica. It is suggested to be mainly represented in the silt and sand fraction of the soil. The other minerals composed in the soil are said to be quartz, feldspar, chlorite and amphiboles. Kondo & Torrance, (2003) however, state that the soil's predominate minerals are quartz, feldspar, amphiboles, chlorites and illites without mica. Other than the manner in which the soil was formed, these clay minerals equally play a tremendous role in influencing the behavior of the soil.

The geotechnical engineering properties and grain size distribution of the sensitive marine clay used in this study are summarized and presented in Table 4.3- 1 and Figure 4.3- 2, respectively. ASTM standards were followed in order to perform standard geotechnical tests in the laboratory to determine the soil properties. The Atterberg limit tests were performed according to ASTM D4318 and the optimal moisture content and maximum dry density according to ASTM D1557 – modified proctor test. Plastic limit (PL) and Liquid limit (LL) of the sensitive marine clay in this study match the findings of Leroueil, (1997), Tremblay et al., (2001), Nader, (2014) and Nader et al., (2013, 2015), whose respective researches were equally conducted on Canadian sensitive marine clay. Leroueil determined the PL to range from 17% to 35% and the LL to be less than 83%, while Tremblay et al., (2001) suggested the PL to range between 0% and 34% while the LL between 22% and 86%. Nader suggested the PL and LL to range between 14% - 28% and 19% - 81%, respectively. The grain size analysis of the marine clay in this study was performed according to ASTM D422. It is suggested from the results that the soil has a high clay fraction. The soils' activity which was determined to be 0.6 falls within the range Leroueil, (1997) and Taha, (2010) suggest Canadian sensitive marine clays have. ASTM D845 was used to determine the soil's specific gravity which was found to be 2.7. The results obtained agree with suggestions made by Tremblay et al., (2001) and Taha & Fall, (2014) which state that for sensitive marine clay, it should be between 2.7 and 2.8.

This clay can, therefore, be classified as inorganic clay of high plasticity (CH), from the results obtained and the Unified Soil Classification System (USCS).

Table 4.3- 1. Summary of the geotechnical properties of the sensitive marine clay used.

Properties	Value/ classification
Classification	CH
Water content (%)	71.4
Liquid limit (%)	80
Plastic limit (%)	26.5
Plasticity index (%)	53.5
Liquidity index (%)	1.1
Clay fraction (%)	87
Activity	0.6
Natural void ratio	1.2
Optimum water content (%)	25.4
Dry density at optimum (g/cm^3)	1.5

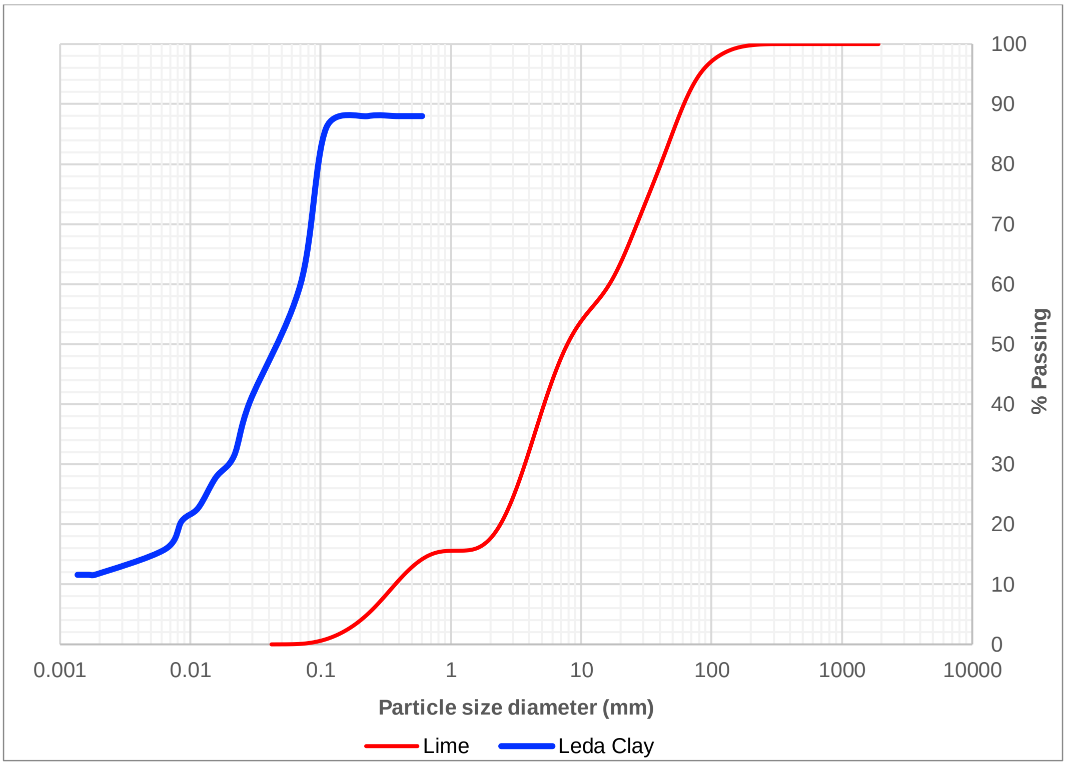

Figure 4.3- 2. Grain size distribution of sensitive marine clay (Leda Clay) from the Ottawa region and Lime used

4.3.2.1.2 Lime and water

In this study, lime was used as the binder to treat the sensitive marine clay. The chemical composition and grain size distribution of the lime are presented in Table 4.3- 2 and Figure 4.3- 2. The lime's chemical composition was obtained from the manufacture while a grain size analysis test was performed to obtain the grain distribution. To determine the lime modification optimum (LMO) which is the minimum amount of lime required to allow for pozzolanic reactions to begin, ASTM 6276 -19 was used. In this study 6% lime was used to improve the soil properties before the thermal cycles could be applied.

Table 4.3- 2. Chemical composition of lime

Binder type	**Components**	**Amount (%)**
Lime	Calcium Oxide	43.09
	Magnesium Oxide	28.23
	Acid Insolubles	0.71
	Iron & Alumina Oxide	0.59
	Loss on Ignition	26.6
	Carbon Dioxide	2.9
	Hydrated Oxides	94.59

Tap water was used to prepare the soil-lime mix before it could be placed into the column for compaction and monitoring.

4.3.2.2 Sample preparation

A soil-lime mix sample was prepared for use in this study with a determined optimum lime content (6%) in accordance with ASTM6276-19. Daily thermal cycles were applied to the soil-lime mix after it was compacted into the column.

ASTM D3551-17 was followed to prepare the soil-lime mixture. Firstly, due to the soil characteristics potentially changing while stored away, the soil was evenly and thoroughly mixed in order to achieve a homogenous soil sample. The mass of the soil required was determined from the dry unit weight obtained by performing standard proctor tests as per ASTM D698-12, and the volume of the cylinder used to make the column. The soil was mixed with 6% lime based on the mass of the dry soil, using a laboratory mechanical mixer for 1 minute. It was ensured that the lime was evenly mixed with the soil before the water could be added. Doing so would enable the lime reactions to occur evenly. The amount of water required was determined from the optimum moisture content determined from the proctor tests. The water was then gradually added to the soil-lime mix which was further mixed for another 5 minutes while ensuring consistency and uniformity before the sample could be placed in layers into the column for compaction.

Researchers such as; Tremblay et al., (2001), Bahador & Pak, (2012), Consoli et al., (2012) and Xiao, (2017), followed this method of soil-mix preparation in their respective studies to achieve consistent and uniform mixes. The only difference was in the time taken to mix the soil and the binder with water.

4.3.2.3 Experimental set-up of the column experiments

The experimental setup designed, developed and used in this study is shown in Figure 4.3- 3. The columns were designed and constructed from a polyvinyl chloride (PVC) pipe in the laboratory specifically for use in this study. The 45cm long and 15.2cm wide columns, were to accommodate 40cm of compacted soil-lime mix including both the top and bottom caps.

In the field, subgrades usually conform to a minimum depth of 30cm. Furthermore, in subgrade soils stabilized with lime, the maximum depth to which the soil can be treated is 0.6m to 1m meter (Christopher et al., 2006; Péterfalvi et al., 2015). For these two reasons, the basis for selecting a column height of 45cm was set. The prepared soil-lime mix was carefully placed into the column in four lifts. After each lift, the soil-lime mix was manually compacted with the same energy to ensure same compaction effort was being applied. This further enabled the soil-lime mix to attain a uniform dry density. A 4.5kg hammer was used during this process. The column was covered in fiber glass to prevent effects from surrounding temperatures and the top of the column was covered with a heating blanket to provide one dimensional thermal migration conditions. The control column was covered with fiber glass and allowed to cure under room temperature.

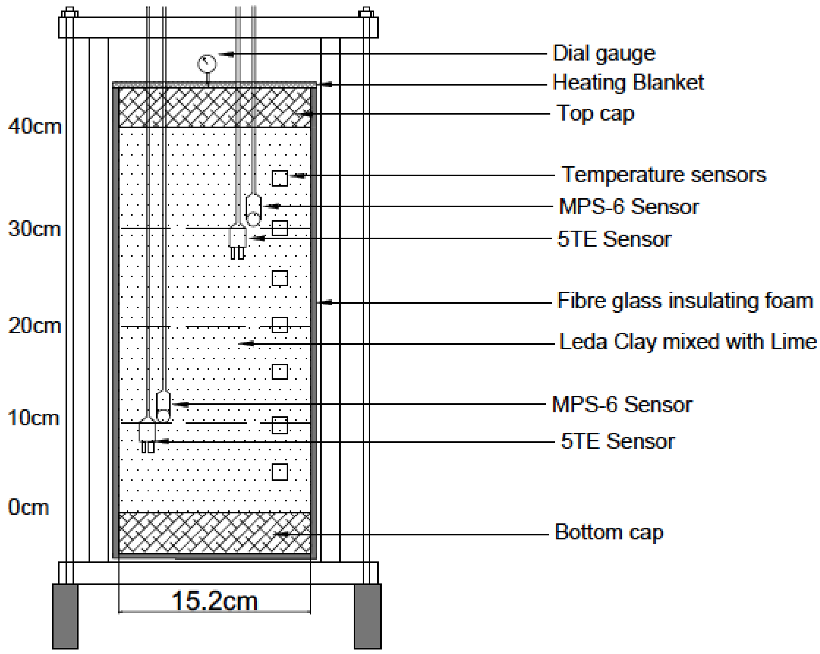

Figure 4.3- 3. Experimental column setup (Not to scale).

4.3.2.4 Column instrumentation and monitoring

The column for monitoring the soil-lime mix was equipped with various 5TE and MP-6 sensors, as can be seen in Figure 4.3- 3. The sensors were used to monitor the variations in the volumetric water content, temperature, electric conductivity and suction. MP-6 measured the suction in the soil-lime mix. Furthermore, the 5TE sensor monitored the volumetric water content, temperature and the electric conductivity. Electrical conductivity (EC), is sensitive to water content changes and has been suggested to have a linear relationship with the water content (Tabbagh & Cosenza, 2007). In addition, Rodríguez-Pérez et al., (2011) suggested that it can be influenced by salt concentration, porosity, clay content, temperature, minerology and phase water retained in the pores. Understanding the effects of water distribution within the soil-lime mass and soil microstructure on the EC help improve inverting the EC data for the sample which controls macroscopic properties such as shrinkage and hydraulic conductivity (Tabbagh & Cosenza). Lime hydration changes the soil particle shape and fabric in that they change as the pozzolanic reactions occur in the soil-lime mix. The effect can be seen through monitoring the EC. Therefore, EC was also monitored to determine the improvement due to chemically stabilizing the sensitive marine clay. During insertion, it was important to ensure contact between the sensors and the surrounding soil mass to avoid effects from air filled gaps (Rowe et al., 2011; Orangi et al., 2019). The sensors connected to a data logger, were placed at depths of 10cm and 30cm to observer the variations closer to the top and bottom of the column. Temperature sensors were placed at intervals of 5cm from the top to the bottom of the column. The temperature sensors were used to monitor the temperature evolution as the lime hydrated while the thermal cycles occurred. Thermal cycles that the soil-lime mix was subjected to were representative of typical summer (June, July and August) field exposure conditions in Ontario, Canada. Immediately after compacting the final layer of the soil-lime mix into the column, and completing the column setup, a dial gauge was placed on top of the column to measure settlement due to self-weight as well as vertical shrinkage due to the hydration process. Additionally, the physical properties of the soil-lime mix samples were observed and determined after extensive physical testing. Gravimetric (ω%) and volumetric (θ%) water content, degree of saturation (Sr%), void ratio (e), porosity (n) and density (ρ) - dry and wet, were determined. These physical properties influence the strength and performance of the treated subgrade soil.

The soil- lime mix compacted to a dry density of 1.54g/cm^3 in the column, was monitored over a period of 28 days.

4.3.2.5 Column thermal boundaries and experimental procedures

According to Environment and Climate Change Canada, (2011), the highest temperature on record in Canada is 49.6°C which was recorded in the summer of 2021 in British Colombia. In the province of Ontario however, the highest temperature on record is 42.2°C which was recorded in 1936 (Environment and Climate Change Canada, 2011). In this study, realistic temperature changes in Southern Ontario, Canada were applied to the column for the duration of the monitoring period of which the maximum temperature was of interest. This was because the maximum temperature would have more effect on the soil-lime mix sample. Soil surfaces on hot days in the field generally experience higher temperatures than the maximum daily air temperatures (Benson & Dirmeyer, 2021). This is attributed to factors such as sunshine durations and solar radiation. Sunshine duration according to Matuszko et al., (2021) is less related to maximum air temperature - because it relates only to one time during the day, than it is to average daily temperature. However, sunshine durations affect air temperature in that the total hours of the sunshine duration cause variances in the air temperature. At soil surfaces Benson & Dirmeyer, (2021) suggest intensified high temperatures due to additional net radiative energy thus, experiencing higher temperatures during hot days. To monitor and determine the effect of the daily thermal cycles on the THMC behavior of lime treated sensitive marine subgrade soils, the temperature controller of the heating blanket was set to varying temperatures for the duration of the monitoring period. Thermal gradients that occur in the field needed to be stimulated by placing the heating blanket at top of the column only, to allow lower temperatures at the bottom.

A soil-lime mix sample to which no thermal cycles were applied was prepared as a control and monitored for 28 days. Another soil-lime mix sample was prepared which was progressively subjected to heat increments over the 28-day monitoring period, until the peak temperature of 48.5°C was reached. The peak temperature was determined by considering the relationship between soil temperature and maximum air temperature. Various models which can be used to help predict soil temperatures exist (Sharma et al., 2010; Bayatvarkeshi et al., 2021). Solar radiation was suggested to be one of the parameters that can be sensitive to soil temperature variations. After applying the peak temperature, temperatures below it were applied for the remainder of the monitoring period. Figure 4.3- 4 provides an illustration of the daily temperatures applied to the soil-lime mix in the column for 28 days. Lime hydration occurs rapidly during the first few days of the reactions occurring, and it is most sensitive to heat during this period (Morsy, 2005). Therefore, peak temperatures occurred within the very first few days of monitoring. Figure 4.3- 5 on the other hand shows how the cycles were applied daily to the sample while being monitored. It should, however, be noted that only the highest temperatures have been shown in this figure due to being of particular interest and that the cycles were continued beyond the third cycle shown. The cycles were done in this manner to mimic field temperature profiles during hot seasons. Heat was typically applied for a period of 12 hours, after which cooling would equally be allowed for another 12 hours. THMC properties were determined on samples from the column to understand the evolution of these properties.

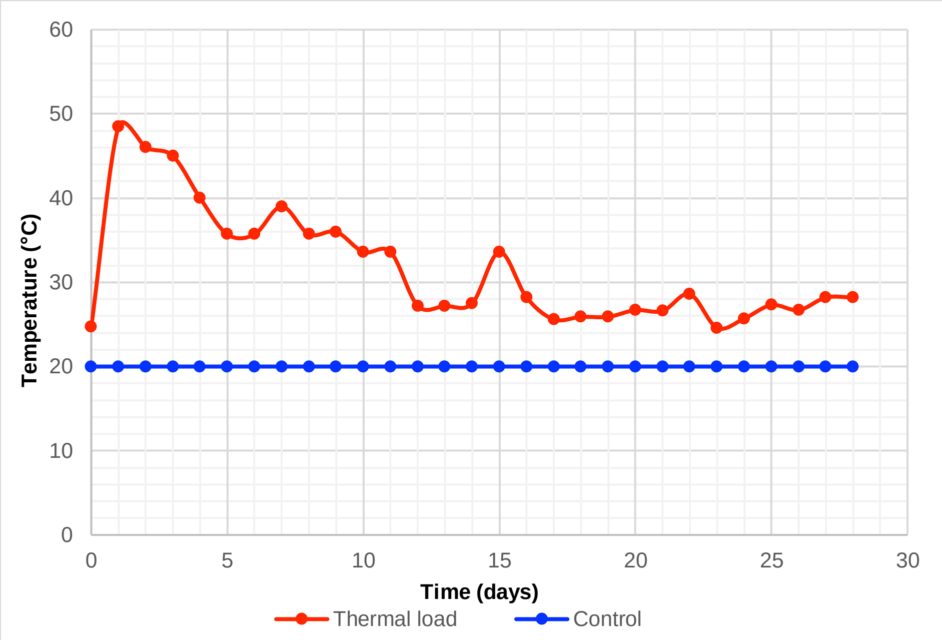

Figure 4.3- 4. Maximum daily temperatures applied to the soil-lime mix sample

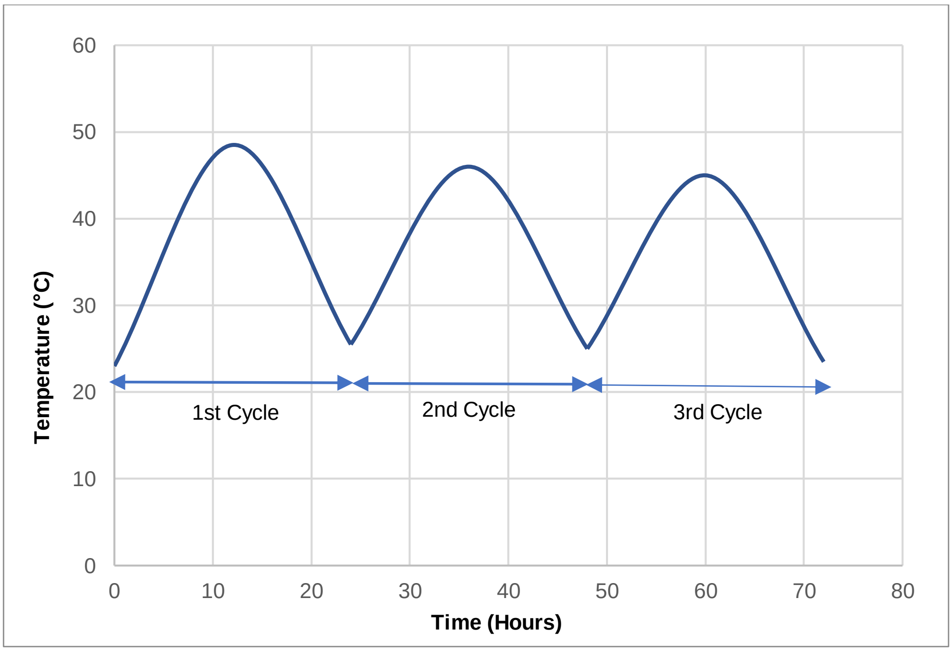

Figure 4.3- 5. Thermal cycles with maximum temperatures applied to the soil-lime mix sample

4.3.2.6 Testing program

4.3.2.6.1 Mechanical tests

The mechanical test conducted on the soil samples obtained at a depth of 10cm and 30cm of the column, was the unconfined compressive strength (UCS) test. The California bearing ratio (CBR) test performed to determine a soil's strength, was calculated from the obtained UCS value using the correlation expression shown as equation 4.3- 1 (Saputra & Putra, 2020). From the calculated CBR of the soil, the resilient modulus (M_R) was determined using an existing correlation expressed in equation 4.3- 2 (Powell et al., 1984). For each test, a minimum of two samples were tested to ensure reliability and consistency in the results. The UCS test to measure strength gain properties was conducted as per ASTM D2166 by means of a computer-controlled mechanical press. Prior to which, the soil-lime mix sample was manually compacted following ASTM D1557, to attain maximum dry density and optimum moisture content.

$$CBR = 0.1325UCS \qquad [4.3\text{- }1]$$

$$M_R = 17.58(CBR)^{0.64} \qquad [4.3\text{- }2]$$

4.3.2.6.2 Hydraulic conductivity tests

The hydraulic conductivity which enables determination and understanding of moisture flow behavior through the subgrade soil, was determined by a flexible wall technique in which the falling head method was used. This procedure was performed following ASTM D5084. ± 5% constant hydraulic pressures or better were maintained through the system as the test was conducted. The test was conducted on at least two soil-lime mix samples after which an average of the results obtained was determined to be the saturated hydraulic conductivity of the sample.

4.3.2.6.3 Determination of thermal conductivity

Thermal conductivity of the samples was determined by use of existing correlations based on the moisture content of each individual sample. Varying soil parameter; soil type, minerology, porosity, degree of saturation and dry density can be used to determine the thermal conductivity because of their strong influence on it. Some of these existing correlations have been proposed by Côté & Konrad, (2005) and Lyu et al., (2020). In this study, the correlation shown in equation 4.3- 3 was used to aid determination of the soil-lime mix thermal conductivity.

$K = [\ 0.9\log(w) - 0.2]\ 10^{0.017}$ [4.3-3]

4.3.2.6.4 Microstructural analysis and tests

Evolution of the binder hydration products including calcium aluminate hydrate (C-A-H), calcium silicate hydrate (C-S-H) and calcium silicate aluminate hydrate (CSAH) of the soil-lime mix was determined by conducting various microstructural tests. X-Ray diffraction (XRD) and Thermal gravimetric/differential thermal gravimetric (TG/DTG) analysis were the tests conducted. Prior to the tests being performed, the soil-lime mix samples were firstly oven dried at 50°C.

XRD determined by use of an X-Ray diffractometer, was used as a method to analyze the structure and mineralogical content of the samples which revealed the chemical composition of the sample. The samples were scanned with a 2θ range of 5° - 90° in steps of $2\theta = 0.02°$. Lastly, the TG/DTG analysis was performed to determine the sample's change in weight as the temperature fluctuated. A thermogravimetric analyzer SDT 2960 was used to perform the analysis, in which the soil-lime mix sample was heated under a nitrogen confined space at 10°C/min rate up to 1000°C. Samples prepared for the XRD and TG/DTG were firstly ground to powder form after being oven dried, before they analysis could be done.

4.3.3 Results and discussions

4.3.3.1 Mechanical properties

4.3.3.1.1 Unconfined compressive strength

A total of 16 samples were prepared for UCS testing after 1, 3, 7 and 28 days of curing. Two samples each from the top and bottom of the columns were obtained to determine the UCS. Figure 4.3- 6 shows the results in which the samples to which thermal cycles were applied over the monitoring period are compared to those where no cycles were applied. The maximum strength gained after 1 day in the sample from the top of the column to which the cycles were applied was 257 kPa, whereas that after 1 day in the control sample obtained from the top, was 193 kPa. At the bottom, 253 kPa and 158 kPa were recorded after 1 day in the column to which thermal cycles were applied and in the control, respectively. After 28 days, 714 kPa and 370 kPa were recorded in the column to which heat was applied and in the control respectively for samples obtained from the top of the columns. At the bottom of the column after 28 days, 634 kPa was recorded in the column with applied thermal cycles and

325 kPa was recorded in the control sample. In comparison, the UCS in the column with applied thermal cycles after 1 and 28 days, was almost twice as much that of the control sample i.e. from both the top and bottom of the columns. Noteworthy, the UCS at the top and bottom increased linearly in the columns during the monitoring period because of the increasing time the samples were allowed to cure.

It is evident that application of thermal cycles to the lime treated soil significantly improved the UCS. In addition to the notable differences between the control and the column with applied thermal cycles, each of the columns had significant differences in the UCS at the top and bottom. These differences noticed were due to the heat being directly applied at the top of the column to mimic field temperature profiles. Applying thermal cycles to the treated soil samples accelerated consumption of lime by the pozzolanic reactions, hence the noted differences in strength gained as seen in figure 5. The results of the effect of increased curing temperature on lime treated soils are consistent with Janz & Johansson, (2002), Morsy, (2005), Elkady, (2016), Ali & Mohamed, (2018) and Fiskvik Bache et al., (2022). Pozzolanic reactions result in formation of cementitious gels; calcium silicate hydrate (C-S-H), calcium aluminate hydrate (C-A-H) and calcium silicate aluminate hydrate (CSAH) (will be discussed in Section 4.3.3.4), that fill up pore spaces in the soil and increase inter-cluster bonding strength. The reactions significantly contribute to the evident time dependent strength gained of which maximum activity by the reactions is achieved at higher curing temperatures (figure 4.3- 17) hence higher strength in samples to which thermal cycles had been applied. At room temperature however, the pozzolanic reactions are very slow (Al-Mukhtar et al., 2012), justifying the lower gain in UCS in the control sample as seen.

In addition to the applied thermal cycles during curing, curing time in each of the soil samples contributed to the strength gained. The reactions occur in stages of which in the long term, cementation gradually occurs. In the initial stages of the reactions, quick reactions occur which result in immediate increase in strength gain seen in figure 4.3- 6. The immediate gained strength reflects changes in the characteristics of the clay due to the quick hydration of lime. It can therefore, be suggested reasonably, that initial chemical reactions that occur led to immediate high strength gain. Application of thermal cycles remarkably increase the strength due to an increase in the rate of the reactions. The long-term reactions are slower and are dependent on lime availability and temperature.

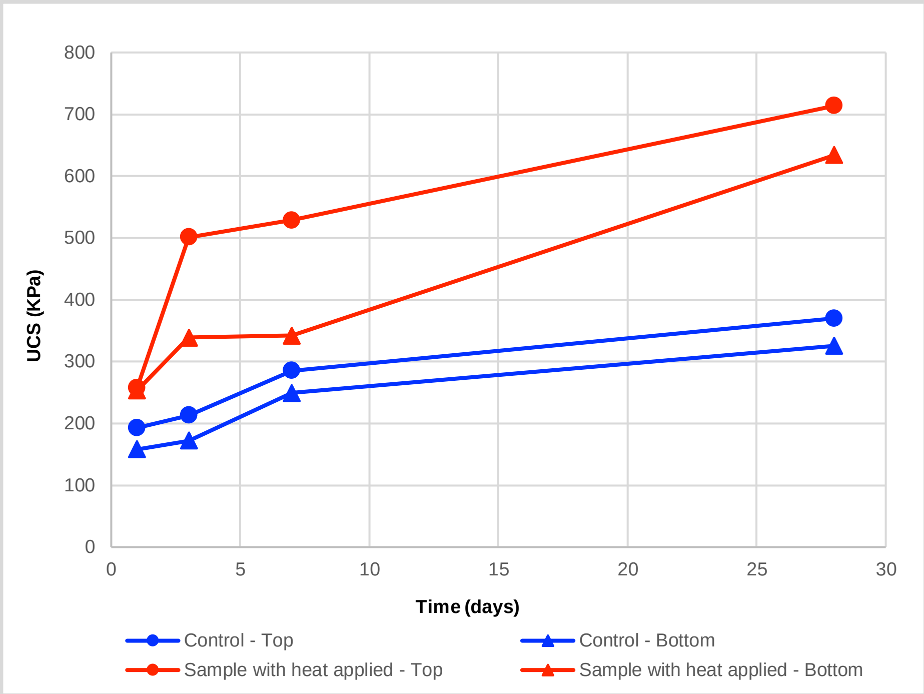

Figure 4.3- 6. UCS evolution with time

Variation of UCS with void ratio in the columns over the 28-day monitoring period can be seen in figure 4.3- 7. Void ratio which decreases due to changes in intra-aggregate pores, is a parameter that contributes to changes in the mechanical behavior of a soil. It can be seen that UCS generally increases with decreasing void ratio. This is so because cementitious gels are produced once reactions begin to occur in the treated soil. The produced gels then fill up the pore spaces within the soil eventually changing the soil structure. As a result, the strength of the treated soil increases. Higher strength gain is noticed over longer curing periods because of the continued lime hydration process, hence further reduction in the void ratio which contributes significantly to the improved mechanical behavior of the treated soil. In comparison, the sample in the column to which thermal cycles were applied at 28 days had the most reduction in the void ratio due to the applied higher curing temperatures increasing the rates at which the reactions occurred. In addition, according to Joshaghani & Ghasemi-Fare, (2021), higher temperatures induce reduction in the void ratio due to thermal loading cycles altering pore spaces which consequently alter the soil fabric.

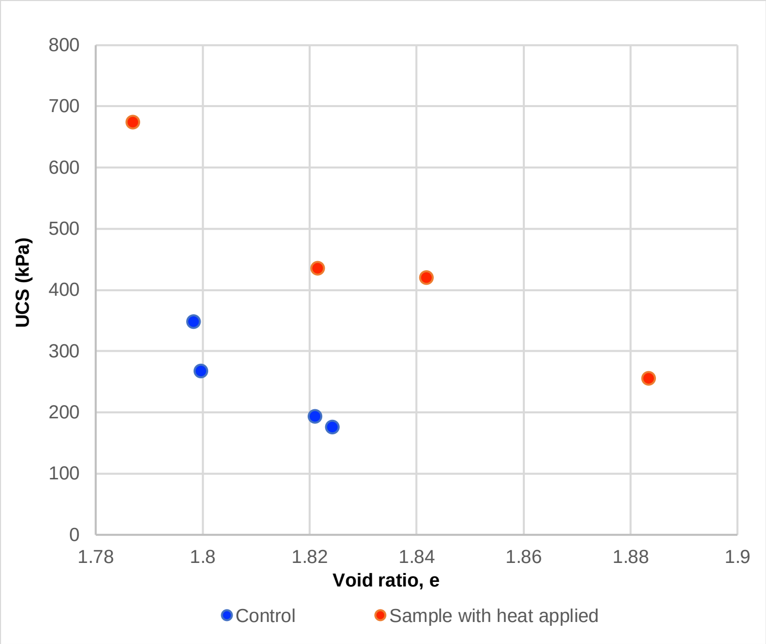

Figure 4.3- 7. Variation of UCS with void ratio

4.3.3.1.2 Settlement

The settlement observed over 1, 3, 7 and 28 days, in columns is shown in figure 4.3- 8. Small increments in the settlements were gradually noticed with the maximum in the column to which thermal cycles were applied being 0.25 mm after 28 days. In the control sample, the maximum settlement noticed after 28 days was 0.1 mm. The gradual changes noticed in the settlements were as a result of lime hydration process and self-desiccation of the soil in the columns which led to changes in the moisture content within the columns. Al-Adhadh et al., (2019) detailed lime as a material that decreased the settlement in clay while the strength (figure 4.3- 6) and bearing capacity increased. In the column with applied thermal cycles, reasonably larger settlements were noticed compared to the control sample. The added effect of thermal cycles caused the notable increment as the higher curing temperature caused quicker changes to the moisture content. Pachideh et al., (2021) shows the effect of low temperatures on settlement of lime treated soil. Low temperatures affected the settlement negatively due to the adverse effect temperature decrease has on the kinetics of the pozzolanic reactions and formation of cementitious gels (Ali & Mohamed, 2018). Changes noticed in the void ratio of the soil samples in section 4.3.3.1.1, support the vertical settlements seen to have occurred. With time, it would however, be expected that the settlements would eventually reach a constant due to increased soil stiffness and strength.

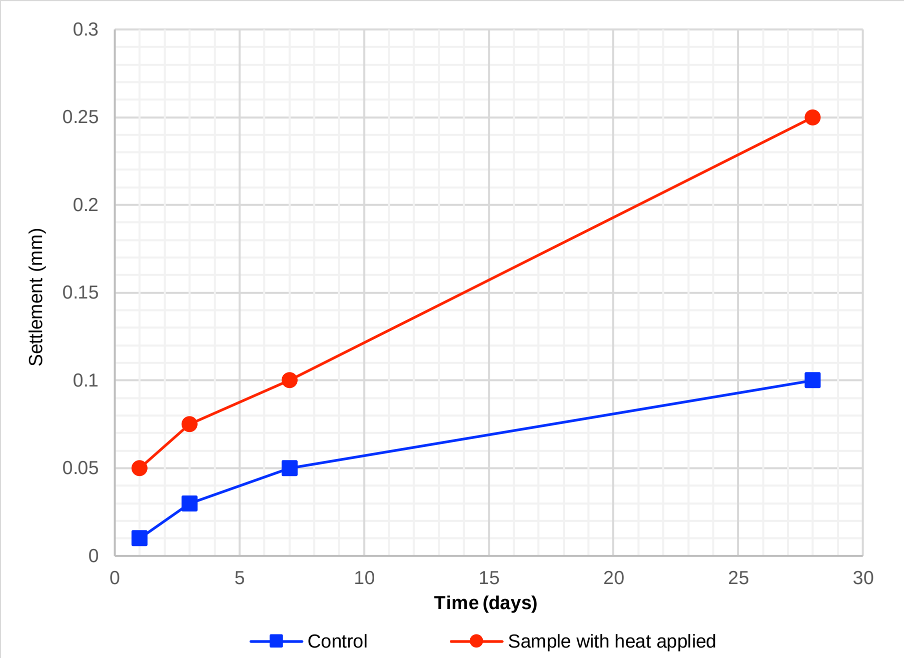

Figure 4.3- 8. Variation of settlement with curing time

4.3.3.1.3 Resilient modulus (M_R) and California bearing ratio (CBR)

Figure 4.3- 9 shows the variation of M_R and CBR with developed UCS over the 28-day monitoring period. It is evident that both M_R and CBR increase with increasing UCS. After 28 days at the top of the column, the M_R recorded in the column to which thermal cycles were applied was 323 MPa in comparison to 212 MPa recorded in the control sample. The CBR increased by 95% after 28 days in the samples from the top of the column to which the cycles were applied while in the control, it increased by 84%. The increase noticed in both parameters is attributed to the lime hydration products (Qubain et al., 2000). Formation of the hydration products was significantly higher in the sample to which thermal cycles were applied, compared to the control due to the noted positive effect temperature has on the formation of the hydration products.

Both mechanical parameters increased over the duration of the monitoring period but there was a difference noticed in these parameters when calculated at the top and bottom of the column. Samples from the top of the column showed higher gain in M_R and CBR compared to the bottom of the column. Application of the daily thermal cycles, evaporation of moisture from the top and formation of a partially drained system are suggested as reasons to why the differences were noticed within the columns. Ability of the treated subgrade soils to resist deformations and sufficiently carry applied traffic loads is thus, demonstrated by the developed stiffness and CBR. This is seen more so when thermal cycles have been applied.

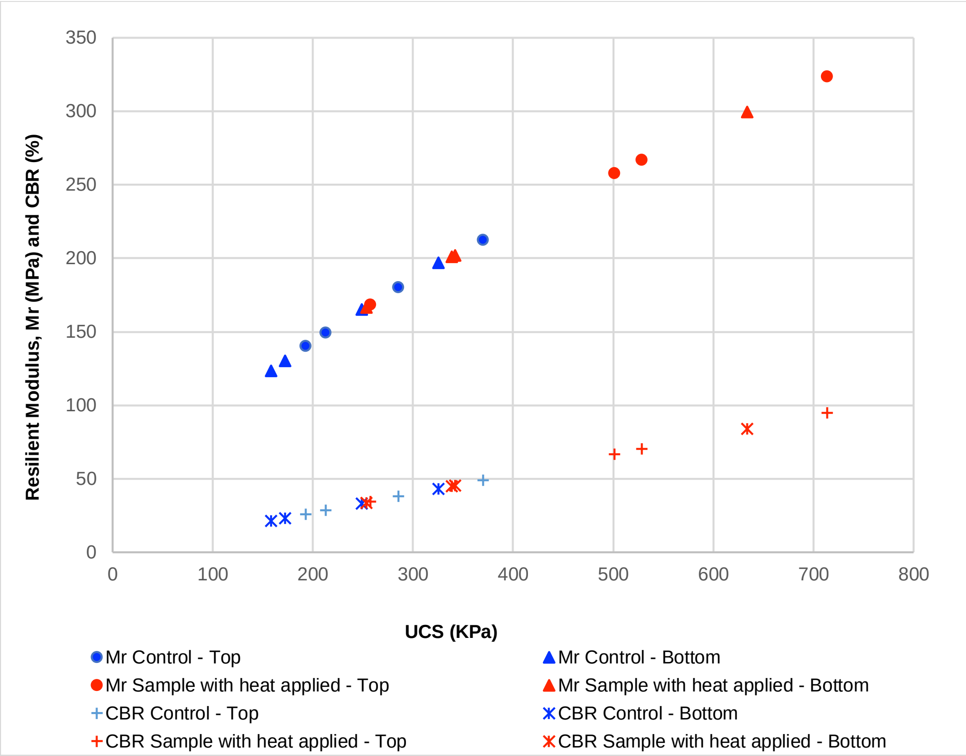

Figure 4.3- 9. Variation of MR and CBR with UCS

Variation of M_R with CBR over the 28-day monitoring period is illustrated in figure 4.3- 10. The treated soil's stiffness is seen to increase linearly with increasing CBR, due to the lime hydration products formed. Although both soil samples were treated with 6% lime, samples in the column with applied daily thermal cycles showed higher M_R with increasing CBR. The difference being application of the cycles which increased production of the hydration products, as discussed later. Curing time and temperature can therefore, be suggested as significant in lime treatment of sensitive marine clay subgrade soils and would result in significant improvement in the subgrade properties.

It is noted that increasing the CBR increased the M_R when the soil is treated. Higher increments in these two parameters are however, noted when thermal cycles are applied which increase the curing temperature. The higher values seen would therefore, enable designing pavement layers with lower thicknesses without having adverse effects on the structural function of the pavement (Mosa et al., 2017). This would subsequently lead to substantial reduction in the cost of construction.

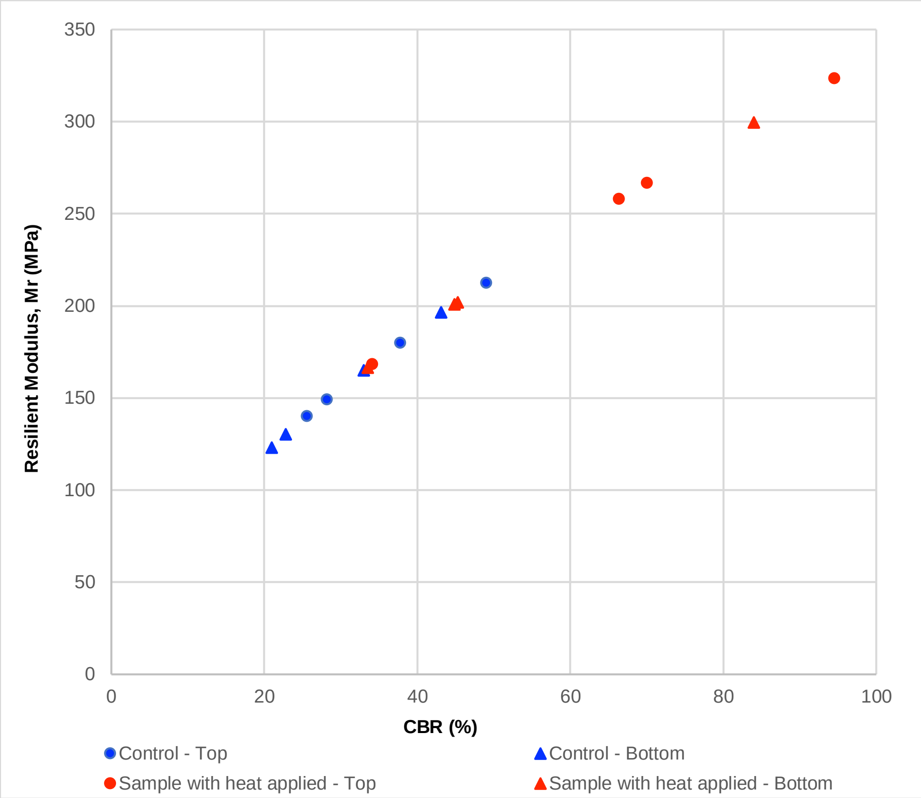

Figure 4.3- 10. Variation of MR with CBR

4.3.3.2 Hydraulic properties

4.3.3.2.1 Volumetric water content (VWC)

Development of volumetric water content in the lime treated soil samples monitored at the top and bottom of the columns is shown in figure 4.3- 11. The development is shown for the 28-day period the columns were monitored. Self – desiccation and application of daily thermal cycles in the soil samples caused changes seen in the VWC.

In the early days of monitoring both of the soil samples, an increase in the VWC was noticed before it started to decrease. The increase was attributed to the self-desiccation mechanism and application of thermal cycles that caused changes in the volume of the sample thereby becoming denser. In becoming denser, suction of the soil samples increased leading to an increase in the soil strength (figure 4.3- 13). With longer curing time, the VWC was seen to decrease due to the lime hydration products which filled up the soils' pore spaces. This effect was seen more at the top of the column especially when thermal cycles were applied to the treated soil.

Self-desiccation is as a result of hydration reactions of lime that consume water. The VWC within the soil can thus be dependent on this process because the volume of water within the void spaces and volume of pores in the sample being reduced (figure 4.3- 7). This was noticed in the soil samples as discussed, but more especially at the top of the columns where evaporation had an added effect. The process can become more intense with an increasing amount of lime and increased time allowed for curing, leading to further reduction in the VWC. At the top and bottom of the column to which thermal cycles were applied, significant differences in the VWC were noticed. This gave an indication of the occurring self-desiccation. At the top, lower VWC was an indication of the changes in the volume of the sample due to the cementing gels which were produced quicker compared to the bottom of the column (figure 4.3- 23). Although the bottom of the column with applied thermal cycles showed higher VWC compared to the control samples, the mechanical properties were significantly higher due to the more densification in the samples.

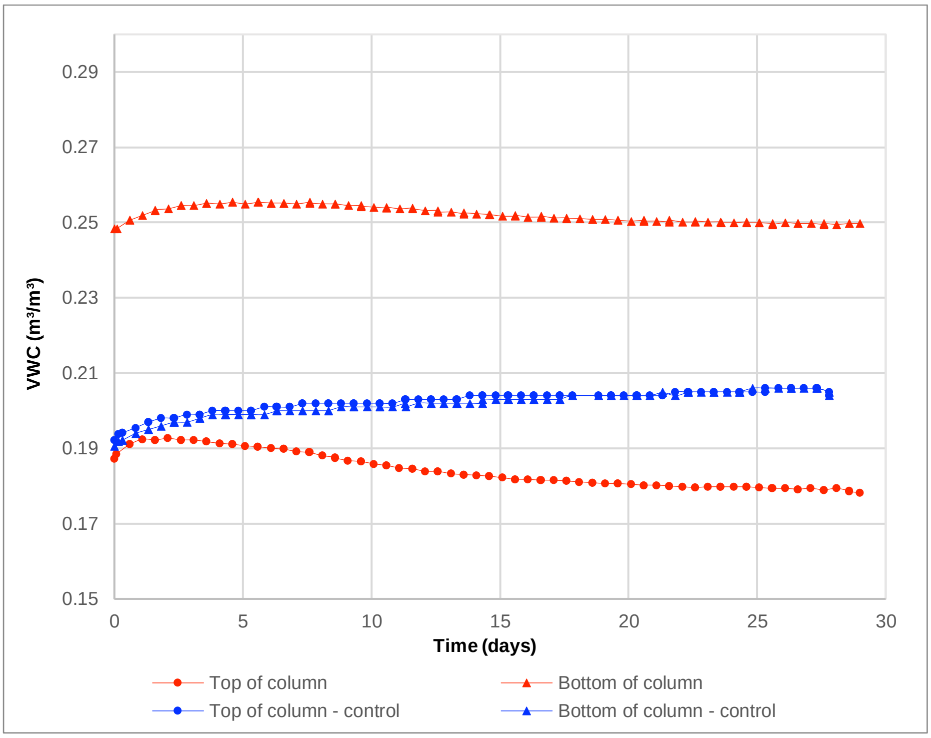

Figure 4.3- 11. Variation of VWC with time

4.3.3.2.2 Suction

Suction development with time in the columns is illustrated in figure 4.3- 12 in which the control sample is compared to the sample with applied daily thermal cycles. The suction within the columns is seen to generally increase with time. Increasing suction with time is attributed to the continuous lime hydration process. Aldaood et al., (2014b) and Elkady, (2016) observed a trend in lime treated soils where suction increases with decreasing moisture content. The observation is consistent with these results presented in figure 4.3- 11 because the intensity of self-desiccation was seen to increase in the columns as the suction increased evidently increasing the mechanical properties of the treated soil. This was seen more in the column to which thermal cycles were applied. Furthermore, increasing curing time equally had a positive effect on the development of suction as continuous lime hydration occurred significantly reducing the moisture content due to the self-desiccation mechanism.

At the top of the control column, higher suction was noticed compared to the bottom. In the column with applied daily thermal cycles however, the suction was observed to be opposite to that in the control column. It was seen to be higher at the bottom compared to the top of the column due to decrease of the surface tension of the water. It initially was anticipated that suction would be higher at the top because of the temperature being higher and the bottom experiencing lower temperatures during curing. Similar results were seen by Yang et al., (2013) where higher temperatures resulted in lower suction values. Treatment of clay with lime is an exothermic reaction. It being so, it contributed to even higher temperatures at the top of the column which consequently decreased the suction.

Although suction is seen to be decreasing at the top in the samples with applied thermal cycles, the corresponding UCS seen in figure 4.3- 6 is higher than that in the control column because it experienced generally higher suction values. In addition, rate of the pozzolanic reactions were quicker than in the control column which heightened production of the lime hydration products. It can be seen that there is no correspondence between the suction and the mechanical properties in section 4.3.3.1 at the top and bottom of the column when thermal cycles are applied. Therefore, it can be suggested that evolution of the mechanical properties which were significantly higher at the top in this column were solely because of the lime hydration that was quickened due to the thermal cycles and the cementing gels that were produced, without suction playing much of a role. However, in general as seen in figure 4.3- 13, the column experienced higher suction values compared to the control evidently showing a coupled hydro-mechanical process.

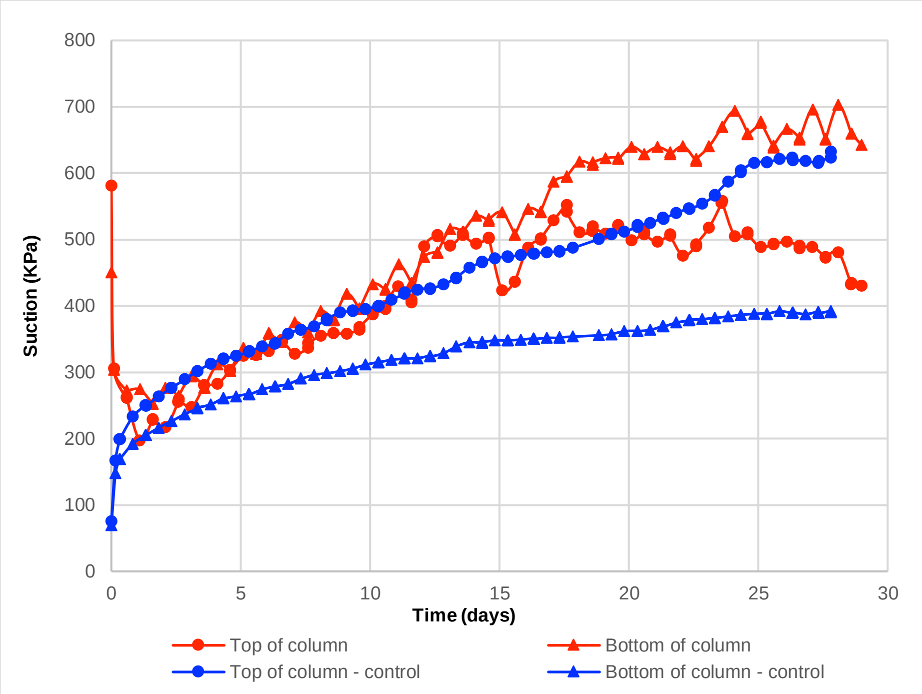

Figure 4.3- 12. Variation of suction with time

Despite the top of the column having lower suction when the thermal cycles were applied, suction development was seen to correspond to the strength gain within the treated soils in the column (figure 4.3- 13). It increased as the UCS increased. In comparison, UCS development with increasing suction was significantly higher in the column to which daily thermal cycles were applied. Due to change in pore water pressure (PWP) which effectively improves the effective stress of the soils, suction noticed over time can be said to have contributed to the strength gained overtime in the treated soil.

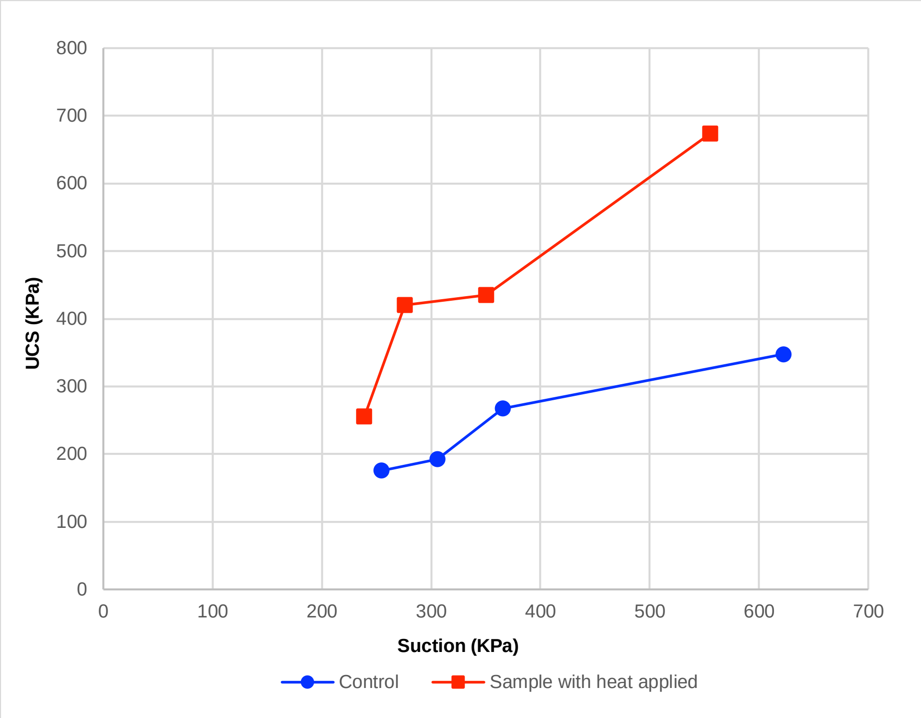

Figure 4.3- 13. Variation of UCS with suction

4.3.3.2.3 Saturated hydraulic conductivity

Figure 4.3- 14 illustrates the evolution of coefficient of permeability for the two lime treated subgrade soil samples over the monitoring period. In the initial reaction stages for both samples, hydration of lime and flocculation due to cation exchange occur which results in the soils having porous structures. An increase in the hydraulic conductivity was thus noticed on the first day in the control and in the first few days for the sample to which thermal cycles were applied. However, in the sample to which the thermal cycles were applied, the hydraulic conductivity was seen to be significantly higher than that to which no cycles were applied. This was attributed to the higher curing temperature accelerating the rates of the pozzolanic reactions in the initial stage, hence the structure being more open compared to the control. This behavior of the hydraulic conductivity in the heated sample was in agreement with the findings of Al-Mukhtar et al., (2012) and Ali & Mohamed, (2018), where an increase was noticed before a decreasing trend was seen in the lime treated clay.

In the stage after the initial, gradual cementation occurred. The lime hydration products filled up the pore spaces in the soil modifying the pore size distribution. Void ratio results shown in section 4.3.3.1.1, in which the void ratio decreased with increasing UCS support these explanations. As a result of the changes in the pore sizes, a substantial drop in the hydraulic conductivity resulted as seen in figure 4.3- 14. In contrast to the hydraulic conductivity that was seen to decrease in the sample with applied thermal cycles after 7 days, it was seen to increase after 7 days in the control. The increase seen in this sample was attributed to an increase in the inter-aggregate pores which resulted from lime hydration and modification of the soil structure. Tran et al., (2014) reported an increase in the soils' hydraulic conductivity when treated with lime as it was seen in this study. However, with even longer curing time, the hydraulic conductivity can be expected to decrease with continuation of the cementation process in which cementitious gels are produced. Treating the soil with lime would eventually decrease the inter-aggregate pores because of gradual cementation. In the sample with applied thermal cycles, the hydraulic conductivity was seen to decrease quicker due to higher curing temperatures that increased the kinetic of the pozzolanic reactions as discussed earlier.

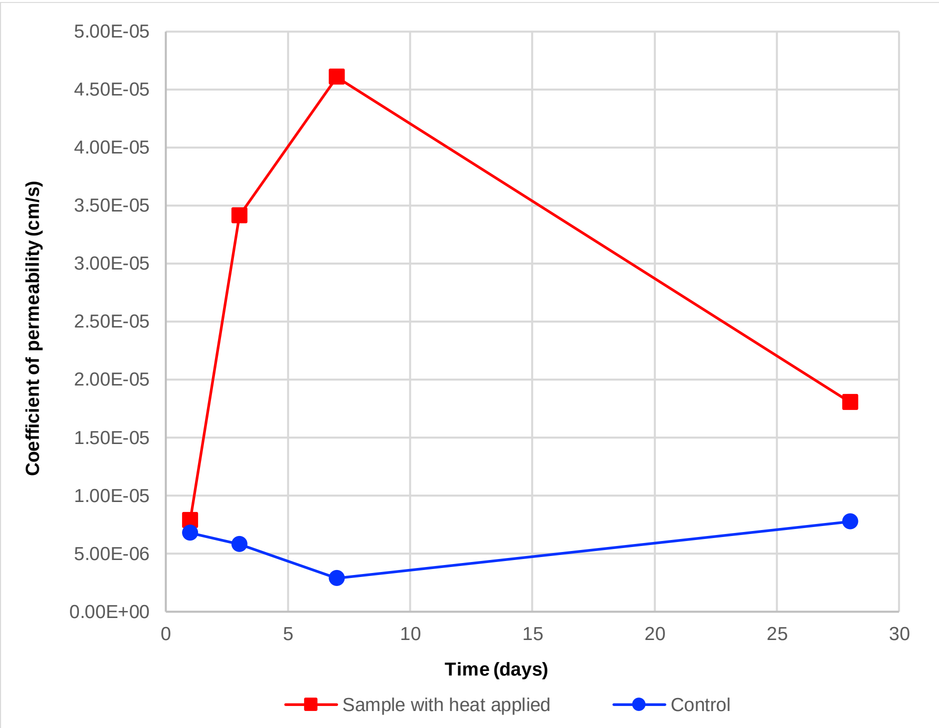

Figure 4.3- 14. Evolution of coefficient of permeability with time

4.3.3.2.4 Moisture variation

Variation of moisture content along the heights of the column are shown in figure 4.3- 15. Samples to determine the moisture content were obtained at every 10cm from the top of the column to the bottom. Understandably so, the control columns had more moisture within them compared to the columns to which thermal cycles were applied. Although this was the case, similar trends in all the columns were observed. Moisture within the columns decreased with increasing curing time because of the lime hydration process. Closer to the surface of the columns, lower moisture content was noted which increased along the height of the column to the bottom. Gravitational forces played a role in moisture moving from the upper layers to the bottom of the column hence the higher moisture content seen. Moreover, evaporation at the surface of the column occurred which led to lower moisture at the top. This was in addition to the thermal cycles being applied at the surface to a set of columns.

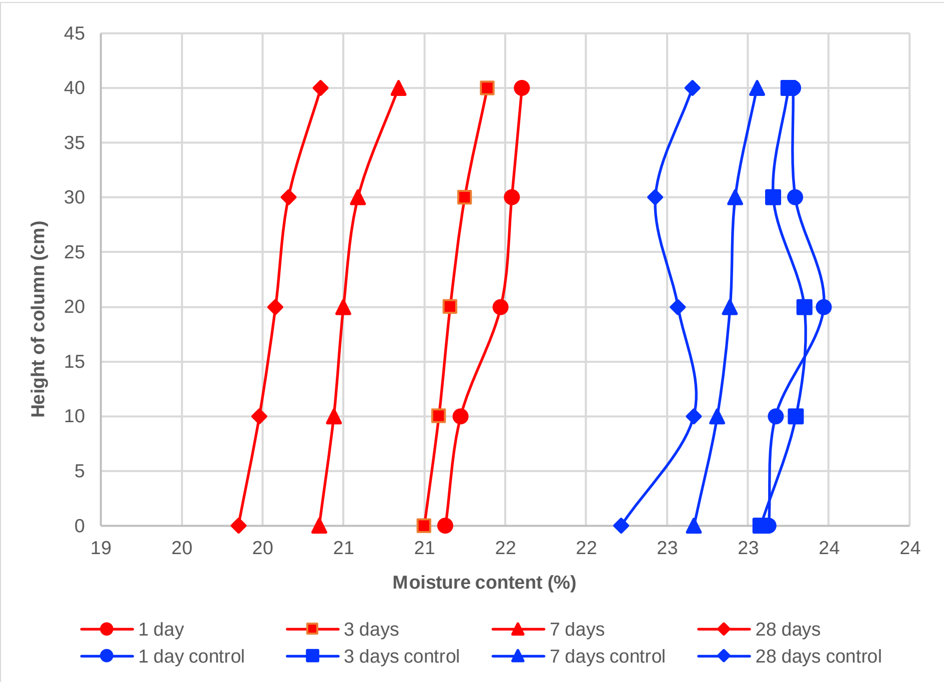

Figure 4.3- 15. Variation of moisture content along the height of the column

4.3.3.3 Thermal properties

4.3.3.3.1 Temperature evolution

Temperature within the columns evolved over the duration of the curing period. The process of lime hydration is exothermic therefore, it contributes to the temperature changes within the columns. Figure 4.3- 16 shows how temperature evolved from the top to bottom of the control column. It should be noted that the temperature variations in this column were observed at 10cm and 30cm only to observe the differences at the top and bottom of the column. Higher temperatures that fluctuated overtime were observed at the bottom compared to the top of the column. A maximum temperature of 23.2°C was recorded in the very early stages of the hydration process after which fluctuations were seen with another peak temperature (22.5°C) being recorded in the advanced stages of the hydration process. The high initial peak was due to the rapid initial reactions. At the top of the column however, the maximum temperature recorded in the early stages was 22.7°C with another peak at the bottom, occurring at the same time it did. The difference noticed at the top and bottom was attributed to latent heat of evaporation which is normally absorbed at the surface of the column during evaporation (Ghirian & Fall, 2013). For this reason, lower temperatures were observed at the top compared to the bottom.

Figure 4.3- 17 shows the temperature variations in the column with applied thermal cycles. In this column, temperature was recorded at every 5cm and 10cm to the bottom. Indeed, due to application of the thermal cycles, temperatures observed in this column were significantly higher at the top decreasing down to the bottom. Just as it was observed in the control column, higher temperatures were recorded during the initial reaction stages. At 10cm, 31.4°C was seen as the highest peak during the early stages, fluctuating throughout the monitoring period. The higher temperatures recorded in this column are reason for the increased kinetics of the pozzolanic reactions which yielded higher mechanical properties seen in section 4.3.3.1. A strong coupled thermal-chemical-mechanical process is thus noticed.

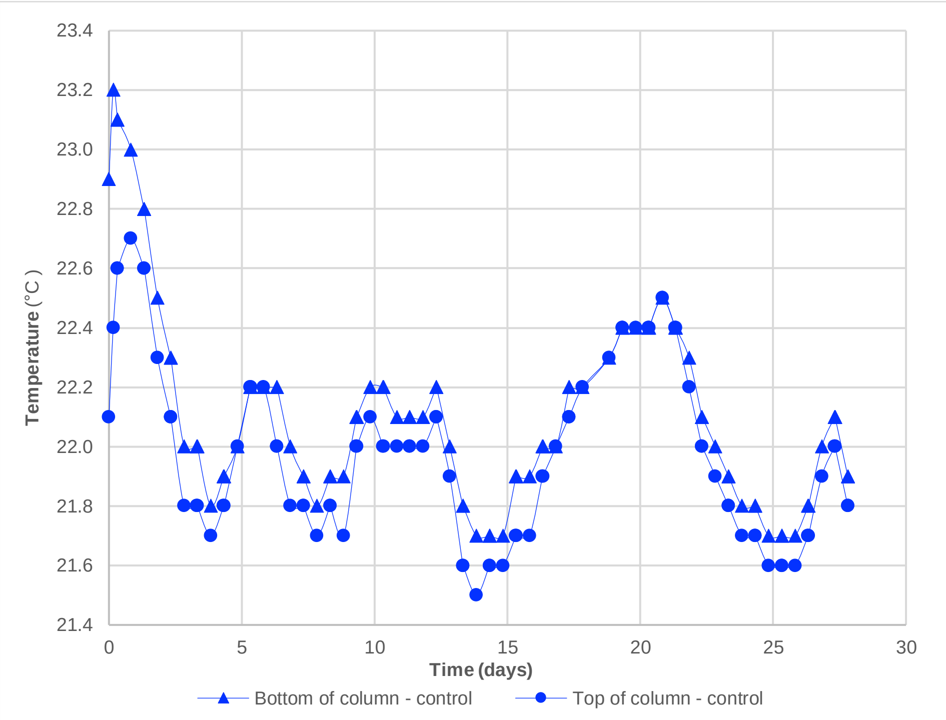

Figure 4.3- 16. Temperature variation with time in control column

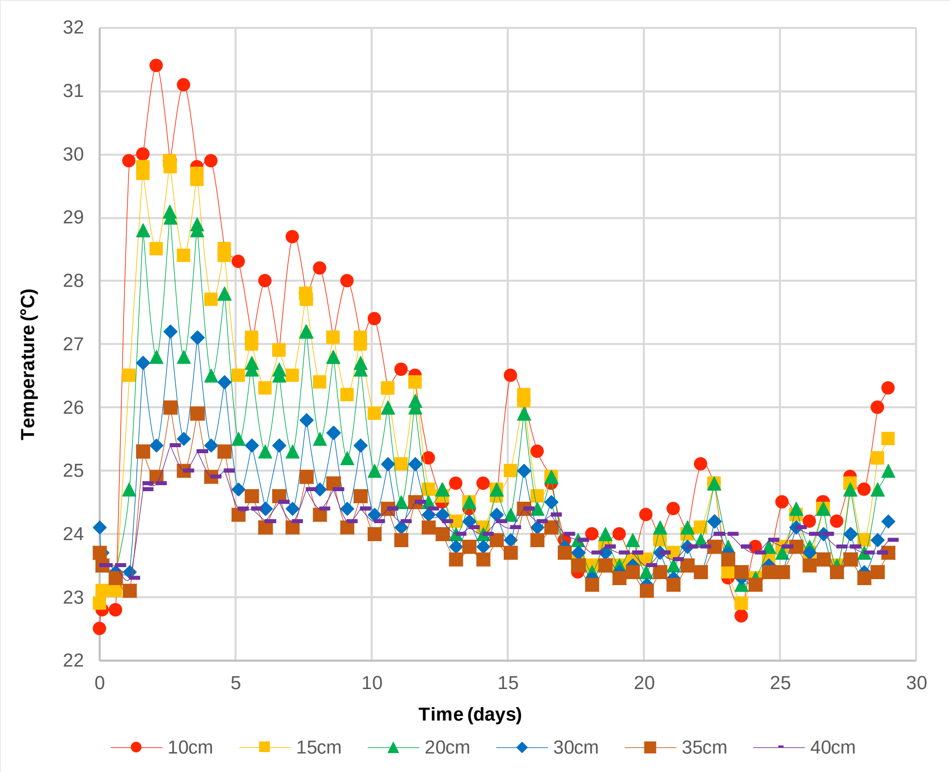

Figure 4.3- 17. Temperature variation with time in column with thermal cycles applied

4.3.3.3.2 Thermal conductivity

Thermal conductivity is a vital thermal property that can be used to assess the effect of temperature on lime treated soils. It becomes an essential parameter in modelling the coupled THMC behaviour in lime treated soils when subjected to thermal cycles. Figure 4.3- 18 shows the variation of thermal conductivity with moisture content in the lime treated marine clay as well as when subjected to daily thermal cycles for the 28-day monitoring period. A relationship between moisture content and thermal conductivity can be seen from the figure. It has been reported by Ghirian & Fall, (2013) that degree of saturation has a significant effect on thermal conductivity despite other factors such as porosity and mineral content affecting the thermal property as well. The thermal conductivity is seen to decrease with decreasing moisture content. The relationship is slightly pronounced when thermal cycles are applied to the column due to higher curing temperatures.

After 1 day, the thermal conductivity was 0.581 W/mK in the control sample compared to 0.575 W/mK in the sample with applied thermal cycles. After 28 days, the control sample was seen to have a thermal conductivity of 0.579 W/mK whereas, the sample with applied thermal cycles recorded a thermal conductivity of 0.569 W/mK. The changes in the thermal conductivity noted overtime are attributed to lime hydration products which increase over longer curing periods. Wang et al., (2016) reported the thermal conductivity of water as being 0.6 W/mK and that of calcium silicate hydrate (C-S-H) as being 0.1012 W/mK. As hydration products are produced, pore spaces within the soil are filled up. Overtime, the pore spaces would be filled up even more. The low thermal conductivity of these products that has been suggested is thus, another reason as to why thermal conductivity of the treated soil decreases with time. It is more so when thermal cycles are applied because of the increased kinetics of the pozzolanic reactions. Noteworthy, if the sample to which thermal cycles were applied was treated with a higher portion of lime, greater changes in the thermal conductivity would have been noticed.

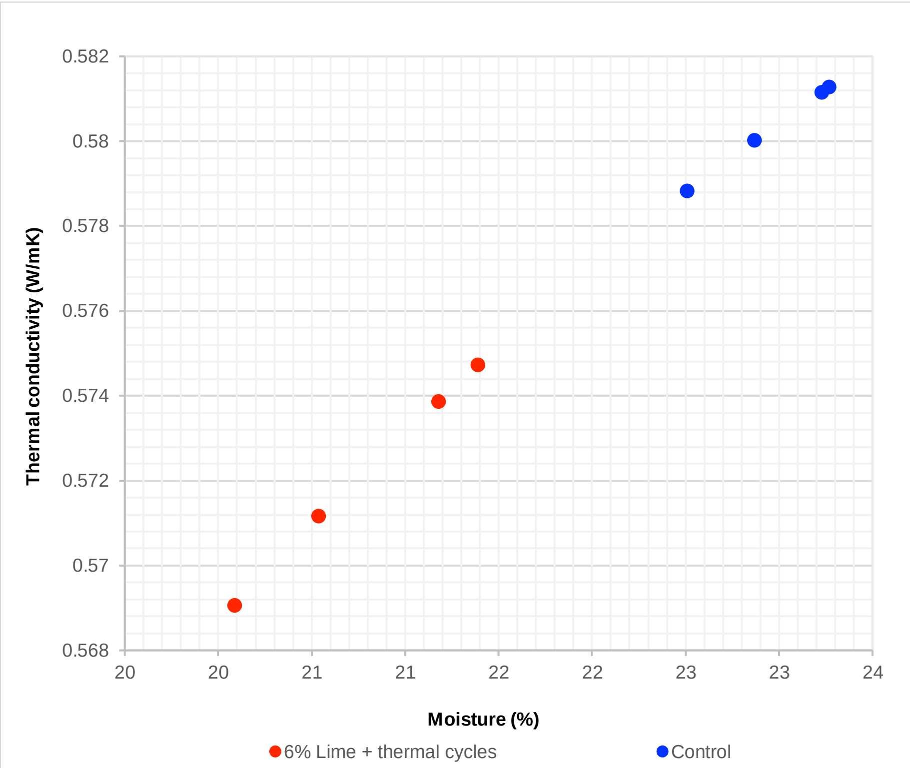

Figure 4.3- 18. Variation of thermal conductivity with moisture content

Variation of thermal conductivity along the height of the column is shown in figure 4.3- 19. The variation shown corresponds with the variation of moisture content along the column height as seen in figure 4.3- 15. This is attributed to the reported relationship between moisture content and thermal conductivity. The thermal conductivity was seen to decrease down to the bottom of the column. In the control sample, higher thermal conductivity was seen in comparison to the sample with applied thermal cycles. Overall, the two samples were seen to have decreasing thermal conductivity values with increasing curing time. A coupled THC process can be noted from the variation of thermal conductivity with moisture content.

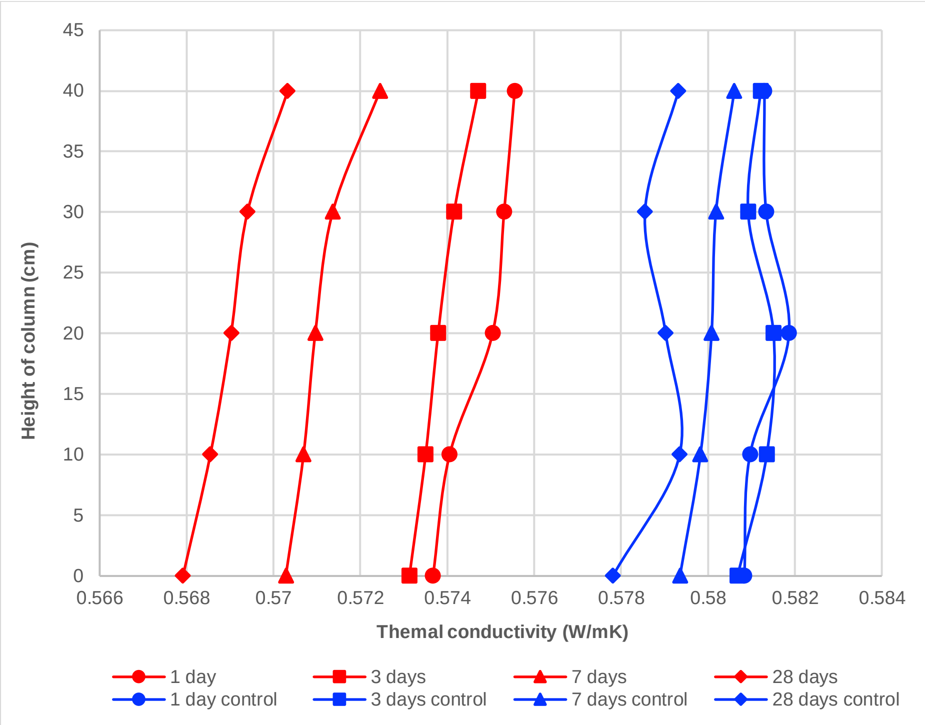

Figure 4.3- 19. Variation of thermal conductivity with column height

4.3.3.4 Evolution of chemical (C) and microstructural properties

4.3.3.4.1 Electrical conductivity (EC)

Evolution of the electrical conductivity in the lime treated soil samples shows formation of ions resulting from the chemical reactions that occur during the treatment process. Figure 4.3- 20 shows the evolution of EC with curing time in the treated soil sample and that with applied thermal cycles. At the start of the monitoring period, the electrical conductivity in the samples with applied thermal cycles is seen to immediately reach peaks of 0.93 mS/cm and 0.71 mS/cm at the top and bottom of the columns respectively. In the control column, the peaks at the start are seen to be 0.49 mS/cm and 0.5 mS/cm at the top and bottom respectively. The results are indictive of higher ion concentration in the early stages of the reactions. These are more so when thermal cycles are applied to the treated soil. High temperatures in the initial stages were observed (figure 4.3 -16 and 4.3- 17) to which increased kinetics of the reactions were attributed. The results correspond to the peak ion concentration shown in figure 4.3- 20. Al-Mukhtar et al., (2010) explained the increasing EC as being a result of additional calcium and hydroxyl ions due to lime dissolution in the treated soil. With time, the EC is seen to gradually decrease and almost coming to a constant in the control sample. After 28 days, 0.19 mS/cm and 0.16 mS/cm were recorded respectively at the top and bottom of the column to which the cycles were applied whereas in the control column, a constant value of 0.2 mS/cm was recorded. The gradual drop in EC with time can be attributed to the lime hydration products that form and the rapid adsorption of lime occurring in the samples (Diamond & Kinter, 1965, Tian & Fall, 2021). In addition, consumption of free water and the evolution of capillary pores cause the gradual change. Al-Mukhtar et al., (2010) who noted similar results, further stated that a reduced amount of Ca^{++} and OH^{-} in the treated soil due to development of the pozzolanic reactions, caused the reductions noted. The strength gain of the treated soil (figure 4.3- 6) corresponds to the evolution of EC overtime.

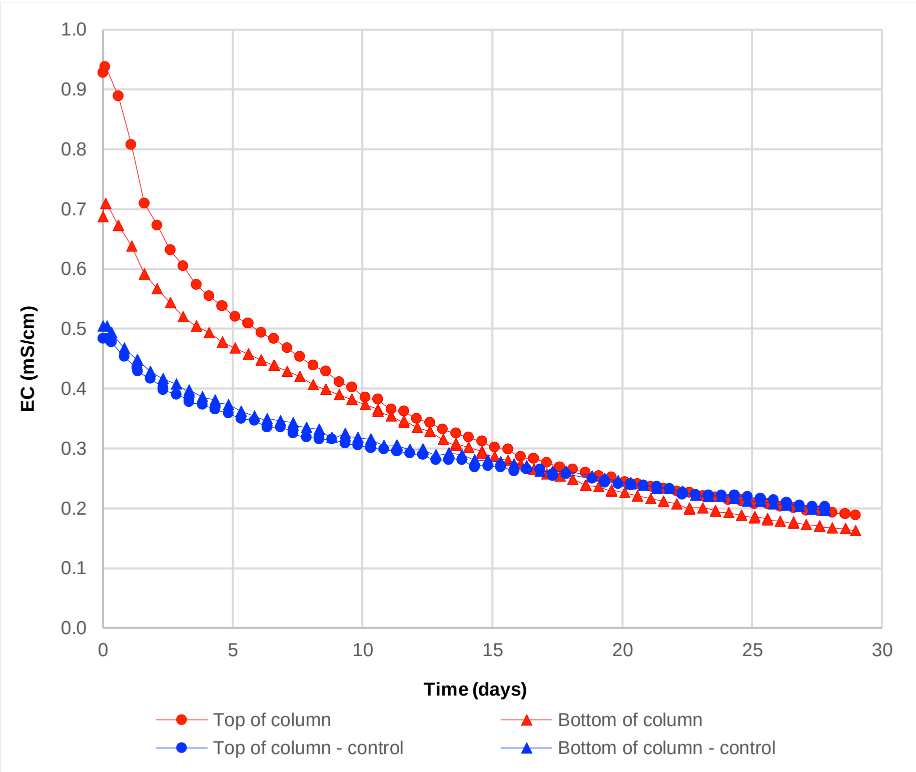

Figure 4.3- 20. Evolution of EC with time

4.3.3.4.2 Physical properties

Figure 4.3- 21 shows how the void ratio in the treated soil samples varied along the height of the column. The hydration products that form as a result of the chemical reactions that occur, fill up pore spaces within the soil eventually reducing the void ratio. This can be seen in the

columns to further reduce with increasing curing time. Moreover, it evident that the applied thermal cycles contributed to the reduction of the void ratio. A relationship between void ratio and the developed mechanical properties of the treated soil can be seen. Therefore, the effect of lime on sensitive marine clay can be seen especially when higher temperatures due to the thermal cycles are applied.

In Figure 4.3- 22, changes of dry density in the columns are shown along the column height. At the top of the control column after 1 day, the dry density was observed as 0.951 g/cm^3 which after 28 days increased to 0.958 g/cm^3. At the bottom a similar increase was equally observed except, lower than at the top of the column. Similarly, at the top of the column with applied thermal cycles, the dry density noted after 1 day was 0.967 g/cm^3 which increased to 0.977 g/cm^3 after 28 days. Dry density was observed to increase which effectively decreased the optimum moisture content. The noted hydration products have an effect on the dry density because they tend to densify the soil as they precipitate into the soil matrix. The results of increasing dry density in the treated soils correspond with the results presented by Rajasekaran & Narasimha, (1997) and Dumpa et al., (2014). The changes in physical properties of the treated soil show the effectiveness of treating sensitive marine clay with lime, which resulted in very notable improvements when thermal cycles were applied.

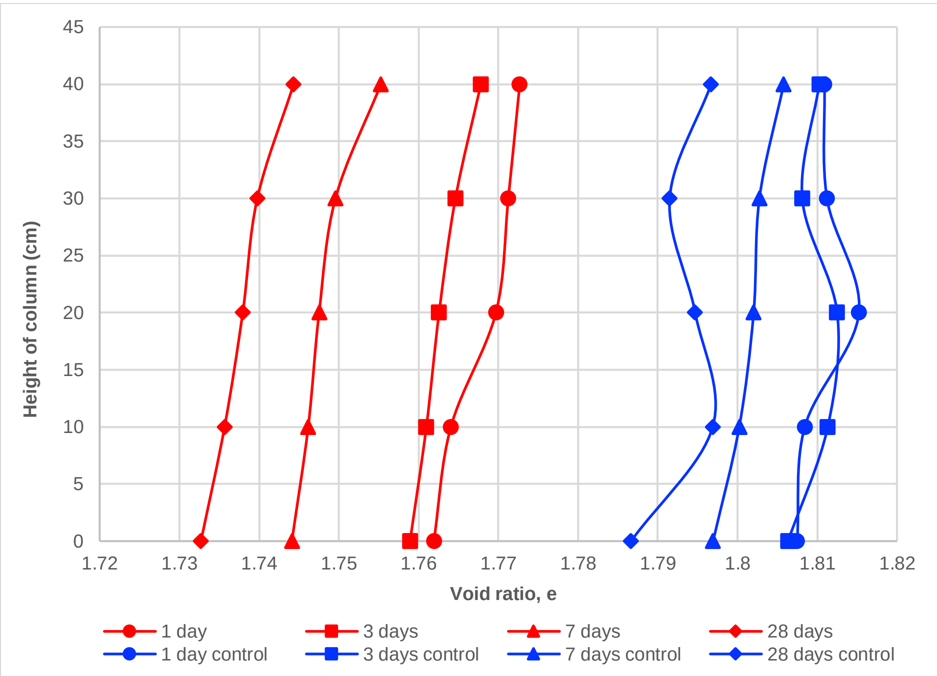

Figure 4.3- 21. Variation of void ratio with column height

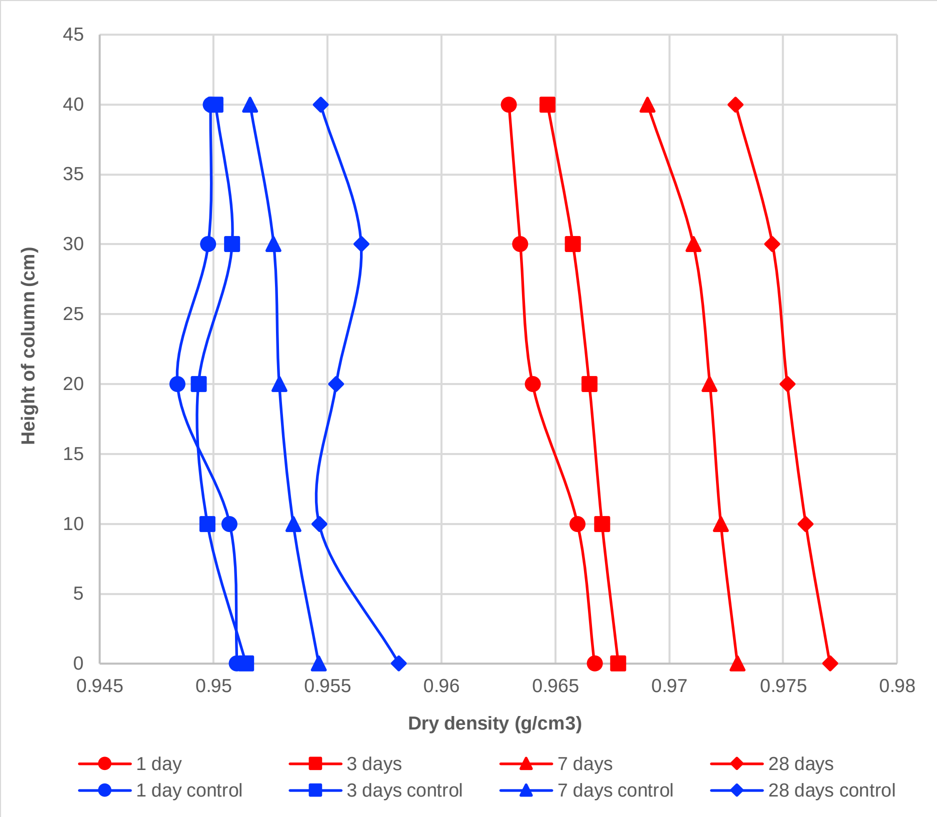

Figure 4.3- 22. Variation of dry density with column height

4.3.3.4.3 XRD analysis

Results obtained from the XRD analysis show formation of the new cementing gels resulting from lime hydration and mineralogical alterations. These results are illustrated in figure 4.3-23 and 4.3- 24 where the samples from the column with applied thermal cycles are compared with the control sample. Changes to the soil structure are shown through the intensity counts. The intensity decreases as the hydration temperature and time increase. At the lime peak shown at 27°, an intensity of 3237 counts after 28 days was seen in the control sample. When thermal cycles were applied to the second column, intensities of 2784 counts and 3326 counts were seen after 1 day at the top and bottom, respectively. After 28 days, 2448 counts and 2502 counts were seen at the top and bottom, respectively. These intensities were seen at lime peak shown at 27°. The results observed correspond with Morsy, (2005) and Aldaood et al., (2014b). Evidently, production of the lime hydration products (C-A-H, C-S-H and CSAH) caused the reduction in the intensities while altering the soil structure. These hydration products form due to the presence of Ca^{+2}, OH^-, SiO_4 and AlO_6 ions. It was suggested in section 4.3.3.3.1 that the high temperature changes that were observed contributed to the increased kinetics of the pozzolanic reactions that led to increased production of the hydration products. This is further supported by the reduction in intensities noted in figure 4.3- 23. Furthermore, the significant increase in UCS gained (figure 4.3- 6) when thermal cycles are applied to the sample are equally supported. Coupling of the thermal-mechanical-chemical is shown through this observation.

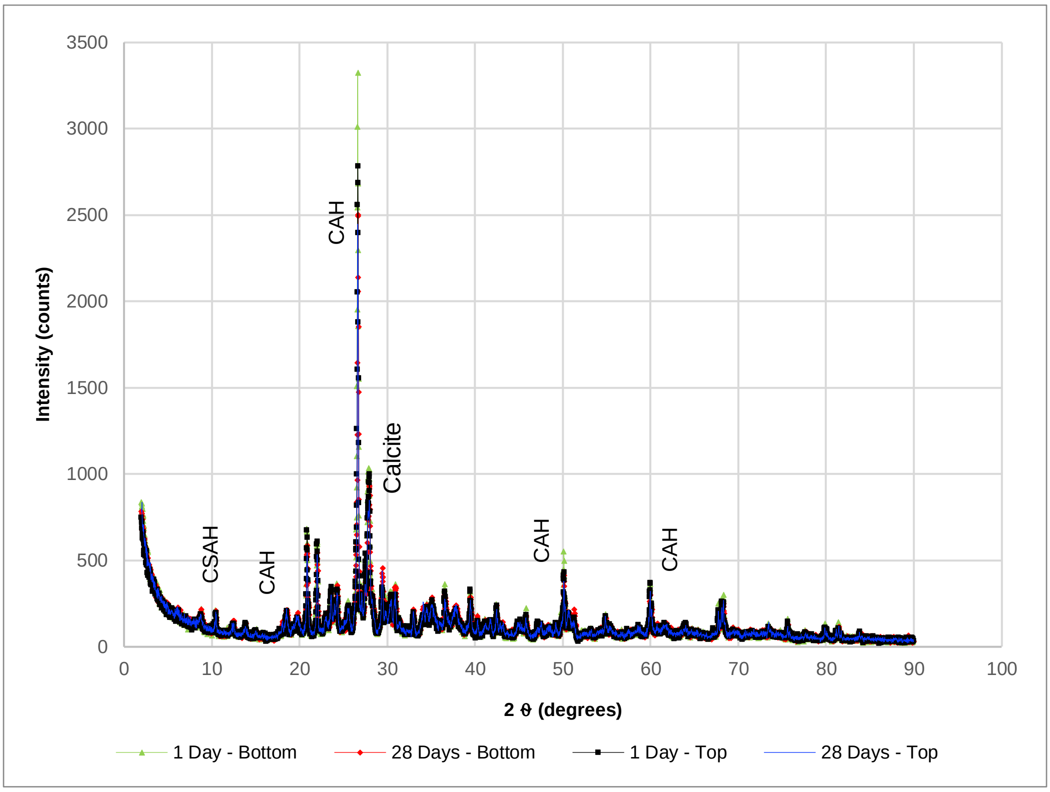

Figure 4.3- 23. XRD analysis of treated Leda clay with applied daily thermal cycles

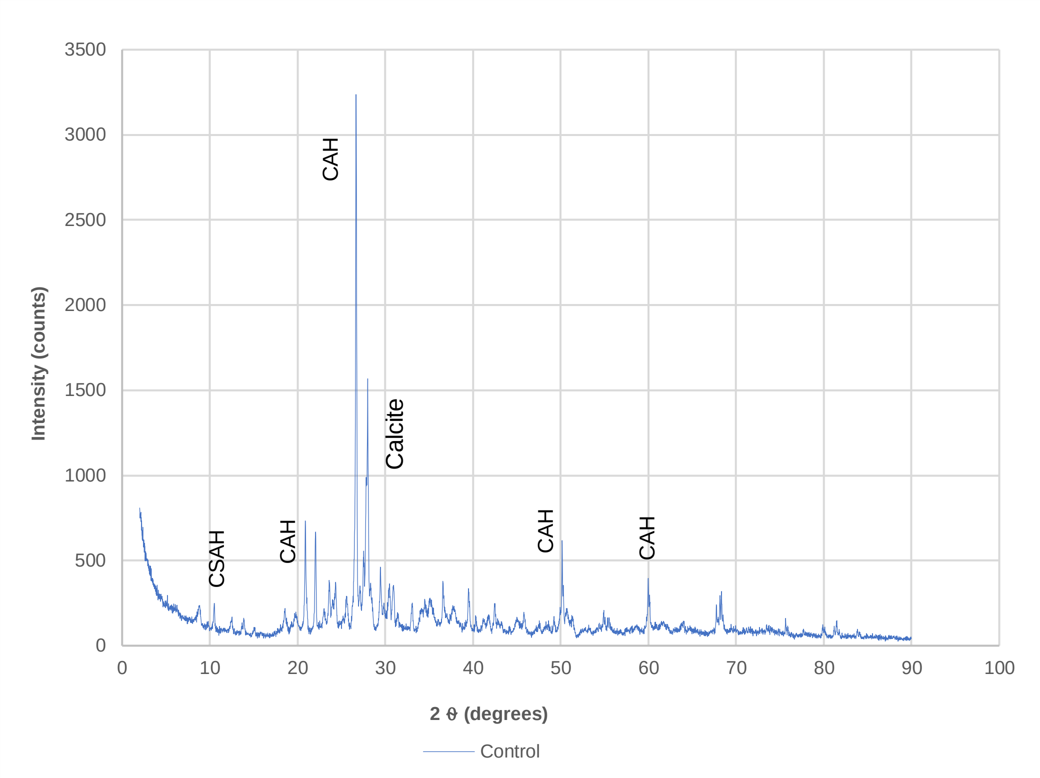

Figure 4.3- 24. XRD analysis of treated Leda clay

4.3.3.4.4 TG/DTG analysis

Thermogravimetric analysis is done on the samples to show their mass loss because of dehydration of Ca-hydrates that result from the pozzolanic reactions that occur. Figure 4.3- 25 illustrates the results obtained for the treated soil samples to which the thermal cycles were applied as well as the control. It is evident that the sample obtained from the top of column with applied thermal cycles lost a significant amount of mass due to the hydration products (figure 4.3- 23) dehydrating. At the top of this column, the samples that experienced longer curing time lost more mass, however, the sample from the top - after 1 day, lost almost as much mass as the sample from the bottom of the column after 28 days. These results are in comparison to the control sample which lost the least amount of mass. The loss of mass in the samples occurred gradually from 26°C until a temperature of almost 800°C.

The DTG results show three endothermic peaks which correspond to different phases that occur during the lime hydration process. The first endothermic peak was observed at 100°C, the second at 400°C and the third was observed at almost 750°C. Evaporation of free water present in the soil-lime mixtures caused the first peak seen. Al-Mukhtar et al., (2012) explained the free water as being interlamellar water that is not linked to the exchangeable cation and water between clay particles. The second peak was as a result of major components in the hydrated lime structure decomposing. This major component is known as portlandite. The third and final peak that was noticed resulted from the decomposition of calcite into CaO.

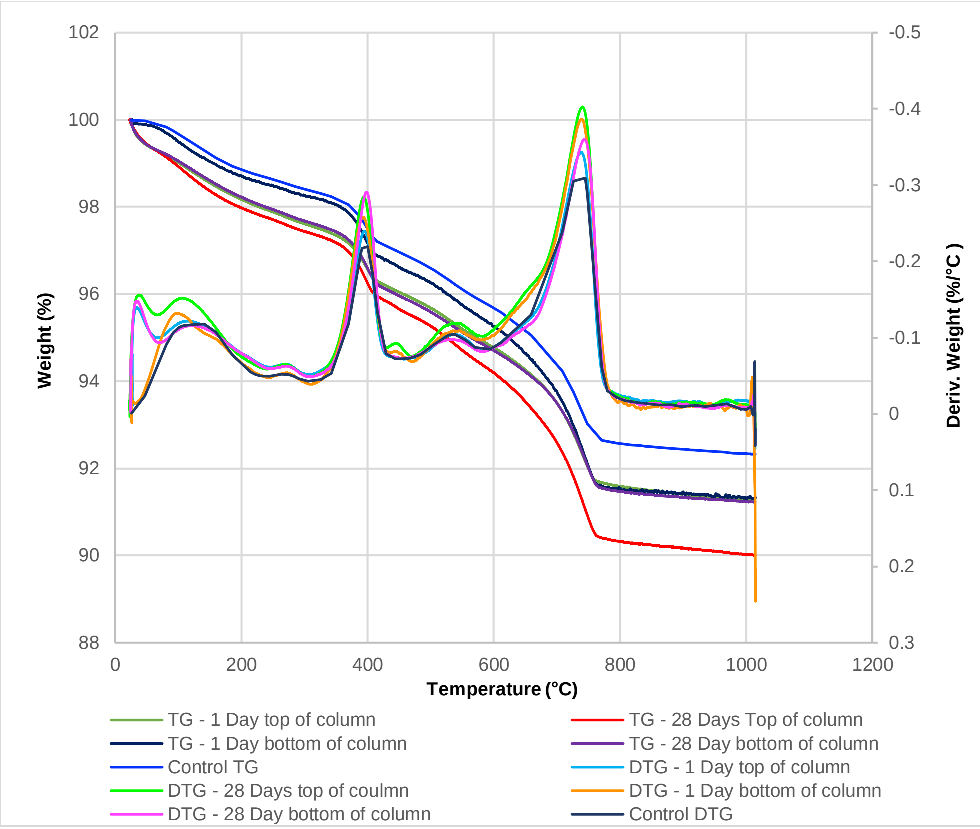

Figure 4.3- 25. Thermogravimetric analysis of treated Leda clay with and without applied thermal cycles

4.3.3.5 Discussion of the coupled THMC behavior

The coupled THMC processes in the control sample and the sample to which thermal cycles were applied are shown in figure 4.3- 26. The EC, temperature, hydraulic conductivity, suction and UCS and shown with the time the samples were cured for. The coupled processes in the figure are shown for samples from the top of both columns. It was expected that similar behavior observed at the top would be seen at the bottom except with variations due to direct application of higher curing temperatures and evaporation of moisture from the top of the column. It could well be seen that the coupled processes in both columns occurred during the time allowed for curing.

Higher temperatures that were experienced during curing of the treated soil samples when the daily cycles were applied, significantly affected the developed mechanical properties (coupled TCM). At higher temperatures compared to lower temperatures, the kinetics of the pozzolanic reactions that occur when the soil is treated with lime are thoroughly increased hence why in the control sample, the mechanical properties that were developed were not as compared to when daily thermal cycles were applied (section 4.3.3.1). In the very first few days, a high initial strength gain can be seen in both columns but more so when the thermal cycles were applied. This resulted from increased lime hydration and flocculation which are the two reactions that occur in the very early stages. A high initial EC in both was as well noticed within the early stages. The high peak in EC which corresponded the initial high strength gain (coupled CM), was due to an increased in ion concentration. The EC gradually decreased showing formation of the cementing gels (C-A-H, C-S-H, CSAH), overtime and consumption of free water during the process. This corresponded to the gain in strength as it can be seen (figure 4.3- 26) where the UCS increased with decreasing EC. It should be noted that the EC when thermal cycles were applied was significantly higher than when no cycles were applied. This indicates the effect that higher curing temperatures from the applied daily thermal cycles, have on the chemical reactions and simultaneously on the gained strength.

The effect of the thermal cycles on the hydraulic conductivity shows a strong coupled thermal, hydraulic and chemical process. In comparison to the control sample, the hydraulic conductivity overtime decreased significantly. The decrease was attributed to increased reduction in pore sizes due to the cementing gels produced filling up the pore spaces. Production of the gels increased with increasing curing time and temperature (figure 4.3- 23), which effectively reduced the hydraulic conductivity. In the control sample however, production of the gels could not be compared to when thermal cycles were applied, hence increasing hydraulic conductivity was seen. However, with even longer curing time, it would be expected that it would gradually decrease. Developed suction contributed to the strength gain properties of the soil (coupled HM process). An increase in suction resulted in an increase in the UCS (figure 4.3- 13). Although a decrease in suction at the top of the column was noticed when thermal cycles were applied, it generally contributed to the strength gain because it increased before it started to gradually decrease after 24 days. Despite the decreased that was noted, the UCS continually increased due to the cementing gels that were produced.

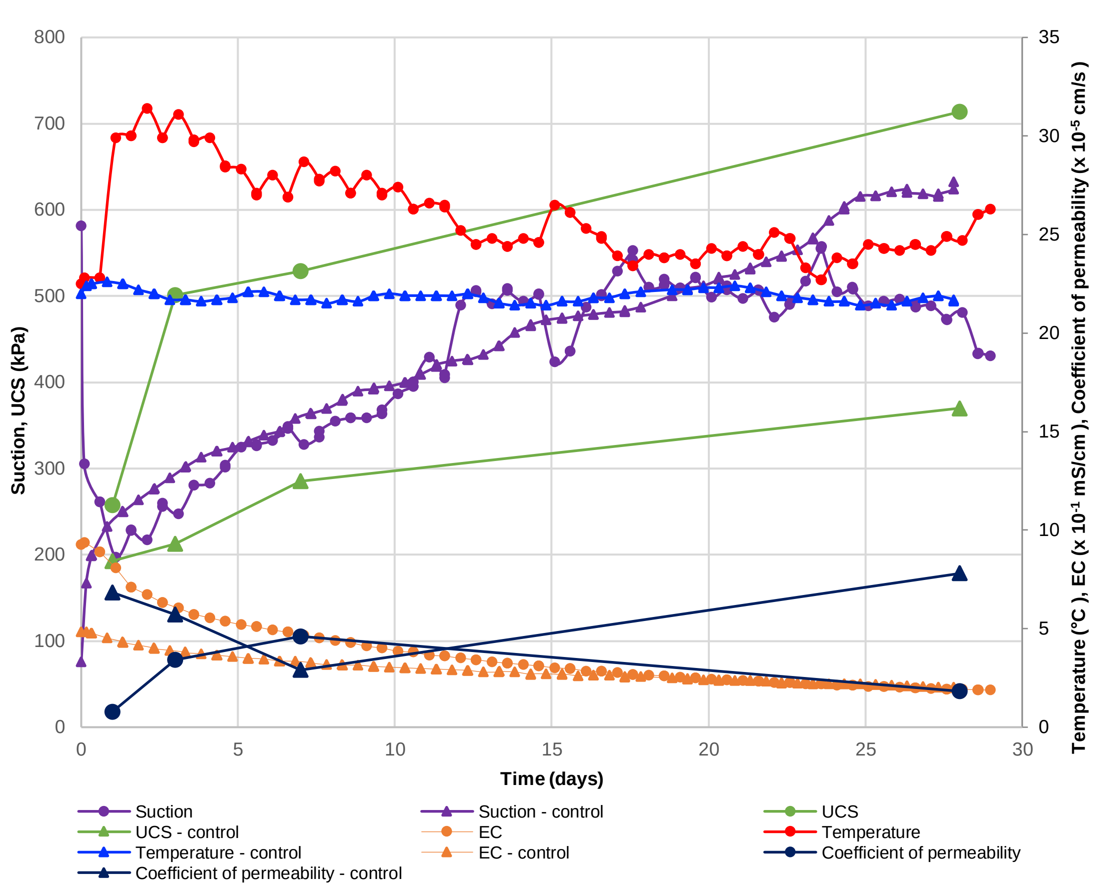

Figure 4.3- 26. Coupled THMC in treated Leda clay with and without daily applied thermal cycles

4.3.4 Summary and conclusion

The effects of treating sensitive marine clay with lime to improve the geotechnical properties were investigated in a laboratory over 28 days. The added effects of applying thermal cycles during curing of lime treated clay were as well observed to gain understanding of how the daily thermal cycles affected the evolution of the coupled THMC processes. It was evident from the results that the thermal cycles had an increasingly positive effect on the treated soil properties.

Due to application of the thermal cycles that stimulated higher curing temperatures, kinetics of the pozzolanic reactions were seen to increase over the monitoring period in one of the columns, resulting in significant production of cementing gels. This was observed through the EC, XRD and TG/DTG results. Temperatures that contributed to the rate of the chemical reactions were seen to decrease with column height when the thermal cycles were applied while higher temperatures were seen at the bottom compared to the top of the column in the control.

The developed mechanical properties were thus higher when cycles were applied to the treated soils compared to when no cycles were applied. The properties were also seen to have increased with curing time due to continuous production of cementing gels. In the two columns with different curing conditions, the mechanical properties gained were seen to vary with column height. At the top, gain in these properties was higher compared to the bottom. When the cycles were applied, significantly higher values were observed for the mechanical properties. Formation of a drained or partially drained system contributed to this observation as much as evaporation of moisture from the top of the column did. The improved mechanical properties not only showed that lime treating Leda clay is effective, it also showed that when thermal cycles are applied, the soil could be improved even more. Thus, as a result of changing environmental conditions when higher curing temperatures are experienced, it can be expected to have very effective results from treating the soil in such conditions.

Development of suction in the columns was observed to correspond with the developed mechanical properties. Due to changes in the intensity of the self-desiccation mechanism, an increase in suction led to an increase in the strength gained by the soil. As it was in the case of the mechanical properties, suction in the soils was higher when thermal cycles were applied to the treated soil. The hydraulic conductivity was noted to significantly decrease when the soil was subjected to the thermal cycles. This was due to cementing gels that modified the pore sizes of the soil at a quicker rate. In comparison, the treated soil to which no thermal cycles were applied was seen to have an increasing hydraulic conductivity at the end of the 28-day monitoring period. It was however, suggested that with even longer curing periods, a decrease in would eventually be seen.

From the results presented on the THMC process in the treated soil, a strong coupled relationship and interdependency could be seen. An even stronger relation in the treated soils was seen when the cycles were applied because of the higher curing temperature. Lime hydration which was the key factor to improving the mechanical (M) properties of the soil largely depended on temperature (T) to increase the kinetics of the reactions. Consequently, the hydraulic (H) properties were improved as well. In the field, this relation could shorten construction periods contributing to cost-effective and durable road construction in poor soils. Therefore, the findings of this manuscript can be used to better understand the mechanism of the coupled THMC process that occur in sensitive marine clay subgrade treated with lime and help design resilient, economical and durable pavement structures. Moreover, the results obtained are valuable for the future development of THMC models and simulation tool to assess and predict lime treated sensitive marine clay subgrade exposed to field climatic conditions.

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4.4 Summary and conclusions

Two technical papers of 1 and 2 were presented in this chapter. Column experiments were performed to understand the evolution and effect of the coupled THMC properties in lime stabilized sensitive marine subgrade clay. Additional experiments were performed to understand the evolution and effect when the treated clay was subjected to daily thermal cycles. The THMC processes that occurred within the columns were then determined. Their relationships were established through various geotechnical experiments performed in the laboratory and experimental monitoring of the treated clay in the columns.

It was observed that the portion of lime used to treat the soil had a significant influence on the soils' gained mechanical properties. A higher portion of lime resulted in much more improved mechanical properties compared to a lower portion of lime. Higher curing temperatures from the applied thermal cycles remarkably increased production of the cementing gels due to increased kinetics of the pozzolanic reactions which subsequently, led to higher strength gain. Development of suction increased over the monitoring period due to the self-desiccation mechanism. It also contributed significantly to the overall strength gain properties of the treated soils. The coupled THMC processes and their interdependency were seen through evolution of UCS, suction, hydraulic conductivity, and electrical conductivity.

Variations in the improved properties were noticed at the top and bottom of the columns. These variations were attributed to evaporation of moisture from the top of the column, formation of a partially drained system, and application of daily thermal cycles. Although these variations were seen, the bottom of the column still showed significant improvements in the geotechnical properties. The developed properties of the soil show how effective treating sensitive marine clay with lime is. Additionally, the effectiveness of lime treatment was further seen after application of the daily thermal cycles when higher curing temperatures were experienced.

Chapter 5: Synthesis of results and implications for road design

5.1 Introduction

The objective of this research was to understand the coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes in sensitive marine clays treated with lime, as well as to gain insight into the impact of environmental stresses (daily thermal cycles) on the processes. Studying and highlighting these processes and their coupling would aid understanding the behavior of pavement structures laid on lime treated sensitive marine clays. The coupled processes that were observed by performing various geotechnical tests and column monitoring are presented and discussed in this section. In addition, implications of the evolution of the THMC process with time on the geotechnical design of sensitive marine clay road subgrades will be discussed herein.

5.2 Coupled THMC behavior in sensitive marine clay treated with lime

Coupled THMC processes were observed to have occurred when the sensitive marine clay was treated with lime. The geotechnical behavior of the treated soil thus, depended on these processes or factors. The processes are known to be interdependent, however, their interactions can either be weak or strong according to Ghirian, (2016). This is because two-way interactions affect each other at different rates and strengths and so, the magnitude of the coupling effect in one direction may differ in the opposite direction. In as much as the weak interactions may affect the behavior of the geotechnical properties, the identified strong interactions would control the geotechnical behavior of the subgrade soil in a pavement structure. Figure 5-1 that was adapted from Ghirian, shows the weak and strong interactions that occurred in the treated soil.

Temperature within the columns increased due to lime hydration which is an exothermic reaction. The daily thermal cycles additionally increased the temperatures when they were applied to the columns. An increase in temperature led to increased development of suction and reduction in pore water pressure (PWP). In figures 5-2, 5-3 and 5-4, this strong T-H interaction can be seen. The effect of this interaction was greatly noticed when daily thermal cycles were applied compared to when they were not. Additionally, at the top and bottom of the columns for the control sample, the interaction could still be seen as strong despite the top of the column having experienced lower temperatures compared to the bottom. Overall, this interaction increased with time because of the hydration process and pozzolanic reactions being continuous in all columns.

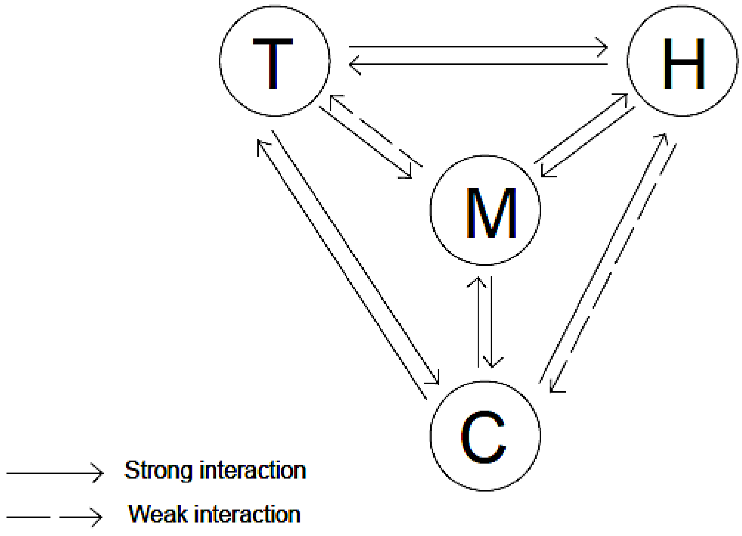

Figure 5- 1. Multiphysics processes in treated sensitive marine clay and their interactions

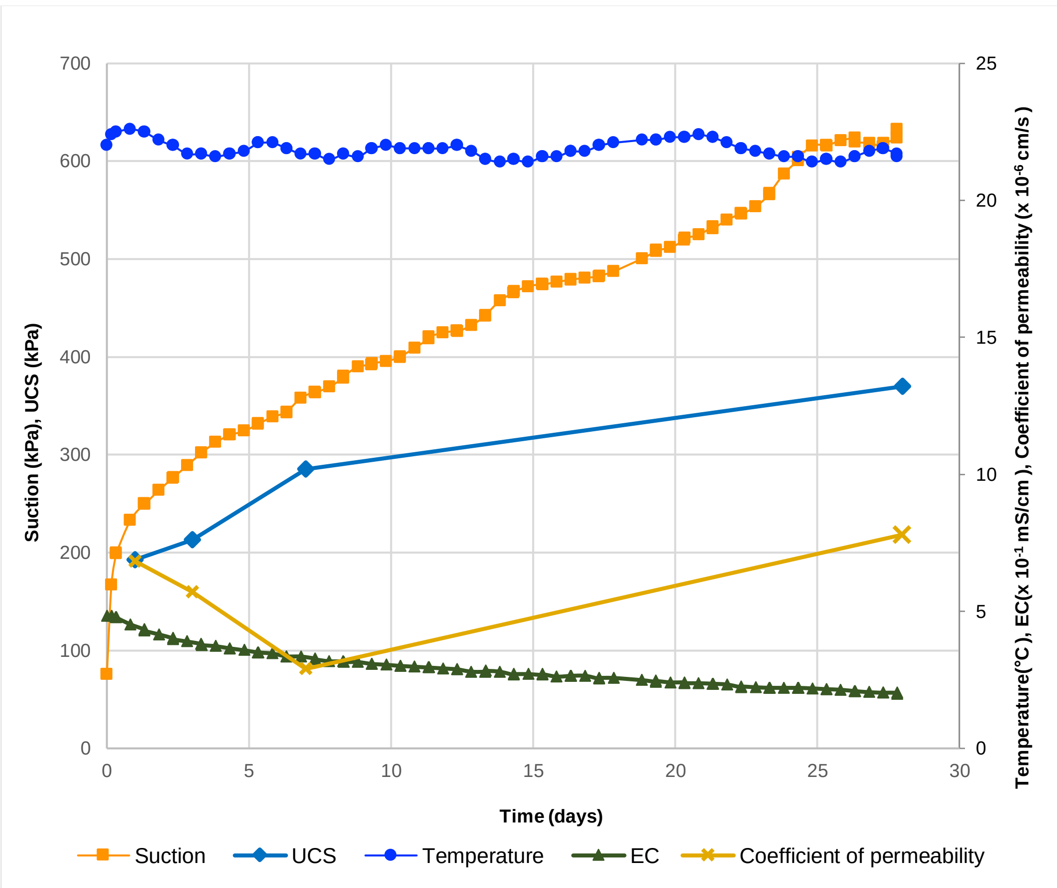

Figure 5- 2. Coupled THMC behavior at the top of the column treated with 6% lime

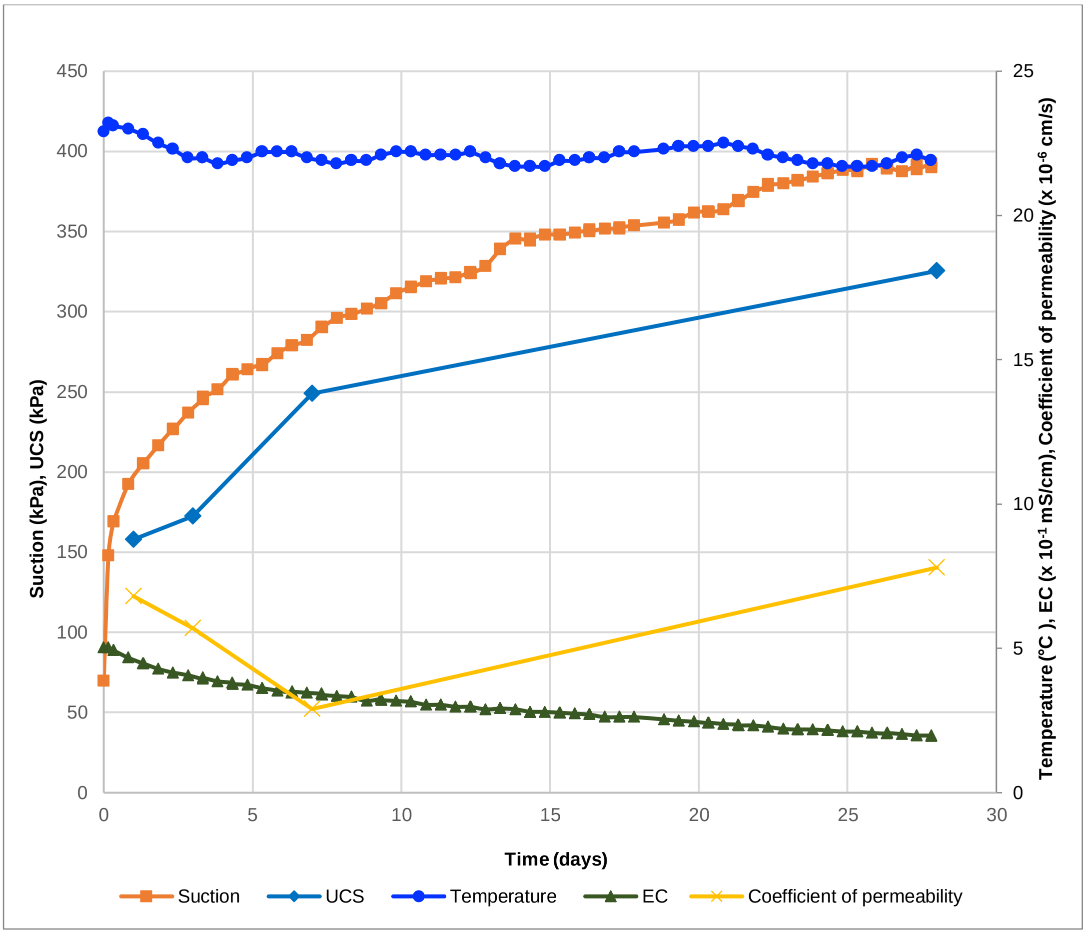

Figure 5- 3. Coupled THMC behavior at the bottom of the column treated with 6% lime

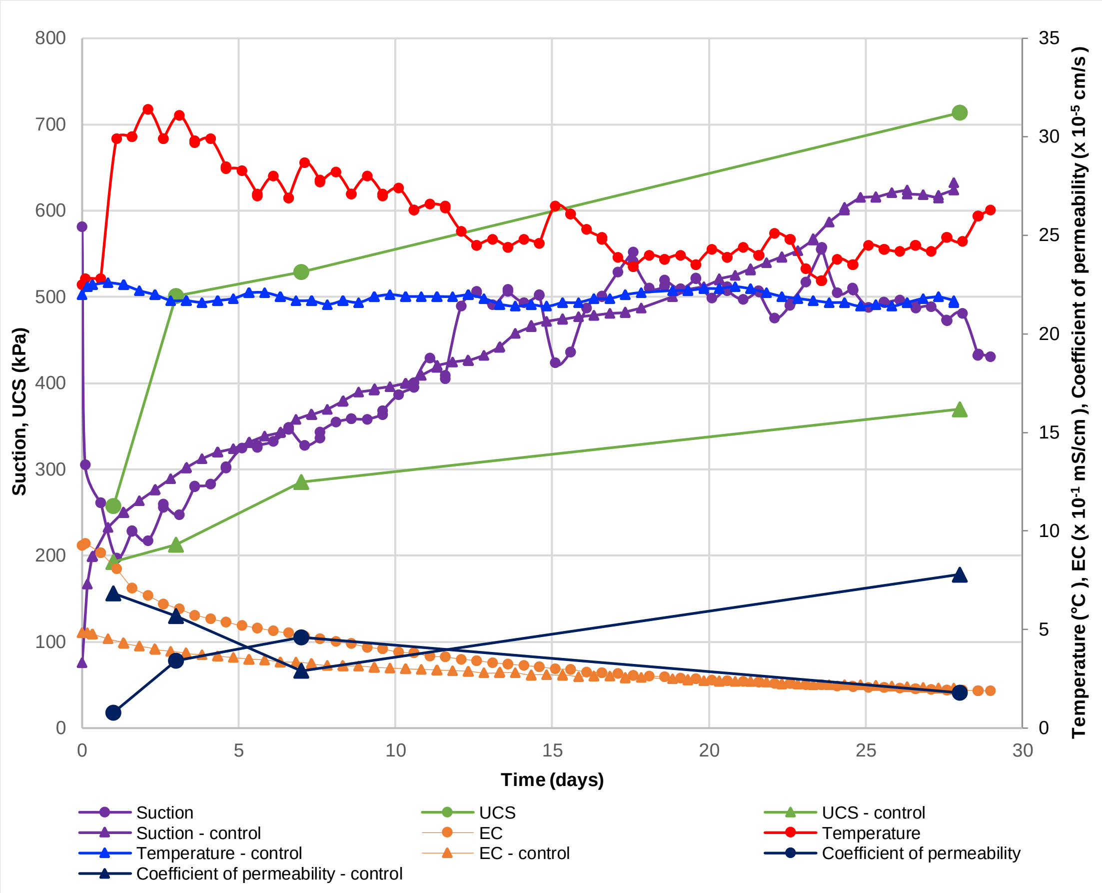

Figure 5- 4. Coupled THMC behavior in treated Leda clay with and without daily thermal cycles

A strong hydro-thermal interaction (H-T) was observed when the sensitive marine clay was treated with lime. The hydraulic conductivity decreased with increasing temperatures (figure 5-4). A further decrease can be expected when an increased curing time is allowed for. Changes in the moisture content due to lime hydration, would affect the soils' thermal conductivity which would subsequently affect moisture flow behavior in the soil.

Temperature was seen to have an effect on the chemical reactions that occurred between the soil-lime mix and water (T-C interaction), essentially affecting the production of cementing gels. In figures 5-2 and 5-3, temperatures are seen to fluctuate through the period the columns were monitored for. Peak temperatures could be seen at the start of the monitoring period where peak electrical conductivity (EC) values could as well be seen showing high concentrations of ions. The gradual drop in EC showed increased production of cementing gels which were positively affected by temperature. In figure 5-4, the effect of this coupling could be seen even more. Higher temperatures due to application of daily thermal cycles led to increased production of cementing gels because of the increased kinetics of the reactions.

The interactions between C-T noticed were due to lime hydration being exothermic as noted earlier. This contributed to increased temperatures within the columns. This interaction is very notable (figures 5-2, 5-3, 5-4) in the early stages in which rapid initial reactions are known to occur.

Reactions that occur during lime treatment of the soil are known to occur in three stages including hydration, flocculation and cementation. Interactions between the factors C and H – hydraulic conductivity precisely, were influenced by these stages. Production of the cementing gels due to lime hydration, represented by EC in figures 5-2, 5-3 and 5-4, strongly affected the hydraulic conductivity due to pore refinement. In the long term, hydraulic conductivity would decrease significantly due to increased production of cementing gels. This was however, seen to occur quicker when daily thermal cycles were applied (figure 5-4) due to higher curing temperatures (strong T-C interaction discussed earlier), hence, quicker production of the cementing gels.

The cementing gels that are shown by the gradual decrease in EC strongly correspond to the increasing unconfined compressive strength (UCS) of the treated soil (figure 5-2, 5-3, figure 5-4). This showed a strong C-M interaction. The cementing gels which provide increased bonding between the soil particles, increased the strength as seen. Other mechanical properties of the soil such as stiffness were equally improved by the hydration products. This interaction could be seen as stronger when thermal cycles were applied (figure 5-4).

Ghirian, (2016), suggests curing under stress increases the binder hydration process, suggesting an M-C interaction. Although this was not investigated in this study, in practice it can be suggested that during the cementation stage when a pavement subgrade is constructed, the hydration process of lime in sensitive marine clay would increase with the application of traffic loads.

The T-M interaction in figures 5-2, 5-3, 5-4, is shown between the temperatures experienced in the columns and the UCS. Higher temperatures resulted in higher gain in strength. Although two-way interactions have been used to further understand the THMC process as a whole, a three-way interaction here can be used. A strong T-C-M interaction can be observed where increasing temperature (figure 5-4) increased the lime hydration process resulting in production of more cementing gels. Consequently, the mechanical properties of the treated soil were seen to increase.

Suction strongly corresponded to the strength gained in the treated soil (H-M interaction). The self-desiccation mechanism increased the suction which led to changes in the soils PWP effectively increasing the effective stress, therefore, increased UCS. The intensity of the self-desiccation process would affect the H-M interaction.

Although the strong interactions within the treated sensitive marine clay have been highlighted and discussed, it should be noted that other interactions do occur – M-T and H-C. The effects that they have on the geotechnical behavior of the treated subgrade soil cannot be compared to that of those outlined in this section, hence not being discussed.

5.3 Implications for road design

Chemically stabilizing sensitive marine clay plays a significant role in cost effectively designing roads. The treatment results in thoroughly improved mechanical properties causing resistance to failure and permanent damage. If done accordingly in practice, Little, (1999) suggests lime stabilization increases soil stiffness significantly. Major distresses such as fatigue cracking, rutting and pavement surface roughness can result from subgrade soils with low stiffness which lime treatment can evidently prevent. The subgrade soils' developed mechanical properties can additionally lead to reduction in the pavement layers above it without altering the pavement's structural integrity. This would subsequently reduce the overall cost of construction and maintenance overtime. Load bearing capacity and stability allowing efficient support of normal traffic loads by the pavement layers would still be achieved. Péterfalvi et al., (2015) and Mosa et al., (2017) detail poor subgrade soils that were chemically treated with binders which eventually resulted in reduced construction costs as a result of the treatment. Moreover, the environmental footprint of a road construction project can be reduced to a great extent by use of treating poor in-situ soils with lime.

In subgrade soils, the parameters such as UCS and stiffness (determined by the resilient modulus (M_R) and California bearing ratio (CBR), respectively) are vital mechanical parameters to consider. They were considered very important parameters in assessing the performance of the subgrade soil because of how susceptible to failure these soils are in their natural state. These parameters in the case of the sensitive marine clay studied in this research, were seen to improve tremendously when treated with lime but more so when daily thermal cycles were applied to the treated soil. The CBR and M_R increased with increasing UCS. It was however, shown that the improved mechanical properties are dependent on the coupled THMC processes (figures 5-2, 5-3, 5-4) that occur within the treated soil.

Higher curing temperatures due to the applied thermal cycles during the monitoring period were seen to accelerate the soils' strength gain due to increased rates of the chemical reactions. This was in comparison to when curing was done with no applied thermal cycles. The environmental conditions would therefore, be important to considered to ensure higher strength gain before the pavement layers are constructed. This is not to mean the sensitive marine soil properties would not be improved when lower temperatures are experienced. They would be improved and the heat generation due to lime hydration would be an added benefit, except the improvement would be at a lower rate which would increase the construction period. The construction period and costs would be reduced when initial strength gain is attained quicker. Quicker generation of the lime hydration products accelerates reduction of the soils' hydraulic conductivity. This cost saving due to fairly shorter construction period is in comparison to methods such as surcharging beforehand or use of wick drains prior to construction which would take a longer period of time. Therefore, it is suggested to have soil treatment done during summer time to benefit from higher curing temperatures.

When the soil was treated, suction was seen to increase with the strength. The existing direct relationship between the two parameters shows the need for suction to be strongly considered in assessing how well the pavement structure would perform. In addition, binder content which was key in achieving the improved soil properties should as well be a huge consideration due to the self-desiccation mechanism having an effect on the soil suction. More than sufficient amount of lime should be used to achieve satisfactory soil engineering properties otherwise, the desired mechanical properties would not be achieved in the long run leading to failure of the structure. Although suction was seen to be directly related to the strength gain, this relationship was in the case where the portion of lime used to treat the soil was more than the lime modification optimum (LMO) thus, the importance in ensuring sufficient lime be used. The implication of this in the field would be avoidance of strain failure due to reduction in the soil stiffness. Moreover, if the binder portion used to treat the soil is less than the LMO, despite having favorable temperatures, sufficient moisture and increasing suction, the structure's long-term performance wouldn't be attained. As a result, the pavements would be more prone to failure.

Poor drainage which in the field could lead to poor subgrade conditions would ultimately result in failure of the pavement structure. This is especially in sensitive marine clays which in their natural state would drastically lose strength if poor drainage was the case. Upon treating the soil with lime, a reduction in the hydraulic conductivity was seen. An escalated reduction was observed when thermal cycles were applied daily to the treated soil. The reduction in the hydraulic conductivity was attributed to changes in the soils' pore structure due to production of the cementing gels. With even longer curing time and higher strength gain, the hydraulic conductivity was anticipated to decrease further.

In addition to long term benefits for pavements, chemical stabilization has short term benefits during construction in sensitive marine clays. When the soil is disturbed due to equipment traffic, the soil loses its strength making constriction difficult. Soil treatment therefore, improves the construction phase due to the improved properties of the soil.

5.4 Summary and conclusions

The coupled THMC processes that occurred in treated sensitive marine clay were discussed and highlighted in this chapter. Their implications on road design were also discussed in detail. It was observed that two-way interactions needed to be understood before the whole coupled THMC process would be understood any further.

Treatment of poor soils (e.g., sensitive marine clay) with lime improves their engineering properties significantly that the soil can be used for engineering purposes without hesitations. This makes the occurring chemical reactions crucial factors in achieving the desired engineering properties. However, due to environmental factors the effectiveness of the chemical reactions in the soil-lime mix would be dependent on thermal and hydraulic factors thus being coupled processes. An increasing portion of lime would effectively result in increased strength properties of the soil.

Thermal factors such as temperature due to thermal cycles that would be experienced in the field, are known to increase the rates at which chemical reactions occur showing a coupled relationship between the two processes. Increasing the kinetics of the chemical reactions results in higher strength gain properties as more hydration products would be produced quicker. This would be in comparison to when no thermal cycles to stimulate higher curing temperatures are experienced.

The chemical reactions also affect the suction and hydraulic conductivity both which are hydraulic factors. Changes in the pore water pressure (PWP), lead to changes in the soil's effective stress which ultimately affect the soil strength. Therefore, the soil suction which increases with increasing lime portion and curing temperatures, contributes to the improved mechanical properties of the soil. The hydraulic conductivity due to lime hydration which would result in pore refinement, would be expected to decrease with longer curing periods. However, if the soil were to experience daily thermal cycles, the hydraulic conductivity would decrease quicker because of the effect higher curing temperatures have on lime hydration.

Strongly coupled THMC processes were observed to have occurred in the sensitive marine clay when treated with lime. Their implications in pavement construction and design are significant because they can lead to reduction in construction time and material, reducing costs of a project. Moreover, overall maintenance costs during the pavements life cycle would be reduced as well because cementation is known to occur for very long periods of time. Therefore, coupled up with the other processes, loss of strength in sensitive marine clay subgrades would be very unlikely.

5.5 References

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Chapter 6: Summary conclusions and recommendations

6.1 Summary

In this study, the behavior of lime treated sensitive marine clay locally known as Leda clay or Champlain sea clay in Canada, was studied as a pavement subgrade soil. Leda clay is a type of soil that is known to have very poor engineering properties due to its origin. The soil drastically changes from being brittle to flowing like a fluid when disturbed. In addition, the soil's structure has pore fluid which is very saline. When leaching of the salts occurs, an imbalance is formed that as well causes the fluid like behavior of the soil. Therefore, for pavement construction to occur on Leda clay, improving the soils would be vital.

Lime treatment is a chemical treatment that was used in this study to improve the engineering properties of Leda clay. The soil-lime mix reacted with water added to it to produce hydration products (C-A-H, C-S-H and C-S-A-H) that improved the soil properties. The improved properties were achieved through hydration, flocculation and cementation. When treated and allowed to cure for varying periods, the soil was seen to have increased mechanical properties – UCS, CBR, M_R, showing how effective lime treatment is on the soil. However, effectiveness of the improved soil properties was determined to have been dependent on thermal-hydraulic-mechanical-chemical (THMC) coupled processes which were the main focus of the research.

Column experiments and monitoring of the treated soil were performed to better understand the evolution of the THMC coupled processes in the lime treated sensitive marine clay. The results obtained from the first technical paper were;

- Temperatures within the columns with treated soil varied throughout the monitoring period due to the lime reactions being exothermic. In the column with untreated soil, the temperature remained constant.
- The soil suction was observed to have increased with an increasing portion of lime. It was determined that the suction contributed to development of the mechanical properties. The hydraulic conductivity was however, seen to increase when the soil was treated and this was due to pore structure change as a result of treating the soil.
- When treated, the mechanical properties of the soil significantly increased. These properties increased further with an increasing portion of lime as did the suction.
- Lime hydration which was monitored through the electrical conductivity was seen to decrease with an increasing portion of lime. The gradual decrease that was observed indicated production of hydration products.

In the second technical paper where coupled THMC processes in treated sensitive marine clay subjected to daily thermal cycles were studied;

- Higher curing temperatures were experienced due to the applied daily thermal cycles. The exothermic reactions contributed to the significantly higher temperatures. As a result of higher temperatures in these columns, the kinetics of the chemical reactions were increased.
- Increased kinetics of the chemical reactions (intense self-desiccation) influenced suction which was increased further compared to when no thermal cycles were applied to the treated soil. It was observed that the hydraulic conductivity decreased at an accelerated rate when the thermal cycles were applied.
- An appreciable increase in the mechanical properties of the treated sensitive marine clay was noted when the thermal cycles were applied. This was attributed to the increased curing temperature which increased the kinetic of the chemical reactions.
- The electrical conductivity when the cycles were applied was seen to have decreased further than it did when no cycles were applied. This showed an increase in the hydration of lime.

An interdependency of the processes was observed in the columns with treated soil through two-way interactions that led to understanding the coupled THMC processes that occurred. Each individual factor had an influence on the behavior of the other factors, hence, the effectiveness of the treated soil depended on the coupled processes. Construction of pavement subgrades in treated sensitive marine clay would therefore, require knowledge and understanding of the coupled THMC processes and what implications they can have on the design, construction and maintenance of the pavement structure.

6.2 Conclusions

Although chemical stabilization has not been utilized to an appreciable extent in Canada to treat sensitive marine clays, this research has shown that indeed treating the soil with lime can help achieve geotechnical properties that would enable the soil to be put to its intended engineering use. In comparison to other methods of improving sensitive marine clay for pavement subgrade construction, lime treatment as a stabilization method would be considered more sustainable. In practice, the coupled THMC processes that would occur in the soil due to treatment can lead to reduction in thicknesses of pavement layers without compromising on the structural integrity of the structure. Furthermore, for the design life, maintenance costs would be reduced significantly due to the ongoing cementation which can continuously occur for years. This would indeed allow for the coupled processes to as well occur for years. Therefore, this method of stabilizing sensitive marine clay can be used in practice more often as it would prompt very satisfactory results in pavement construction.

6.3 Recommendations

This research detailed the coupled THMC processes in sensitive marine clay when treated with lime and exposed to daily thermal cycles contributing to further understanding of soils' behavior. While this was the case, recommendations for further research would be;

- Studying these processes when soil is exposed to freezing and thawing given that Canada is a country that experiences extreme winters. This would establish the coupled behavior in sensitive marine clay during winter and spring seasons.
- In addition, the theory of autogenous healing after freezing and thawing cycles which was noted in literature, can be studied on lime treated sensitive marine clays to understand the evolution of higher terminal strength gain. The effects of the THMC processes that would occur can be incorporated in this as well.
- Samples for testing the mechanical properties and hydraulic conductivity from the columns can be done after 1, 3, 7, 14, 21 and 28 days to have an even better understanding of the change in properties after the suggested days.

Appendix

Laboratory pictures of test samples and equipment used in research.

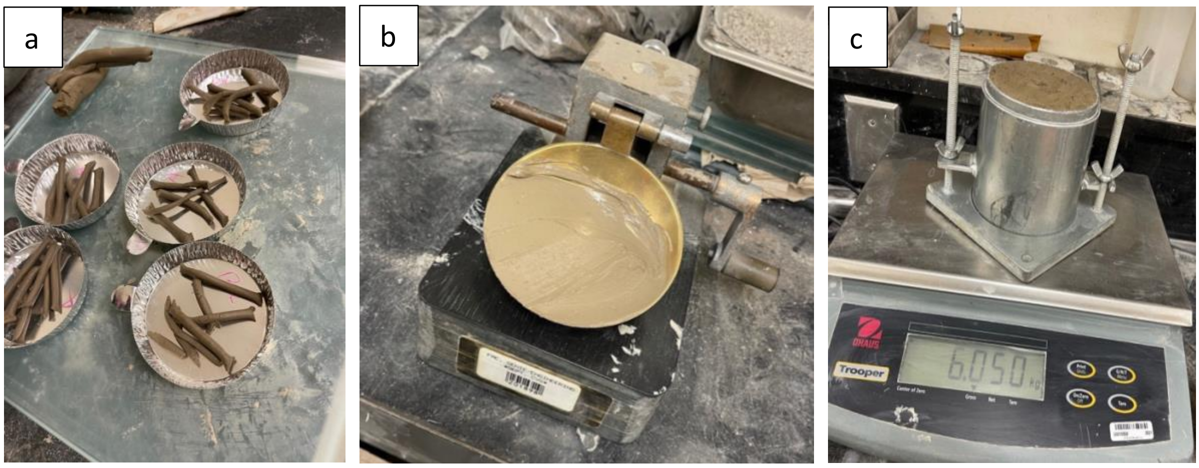

Figure 6- 1. Atterberg limit (a – plastic limit, b - liquid limit) and proctor tests (c) performed on Leda clay.

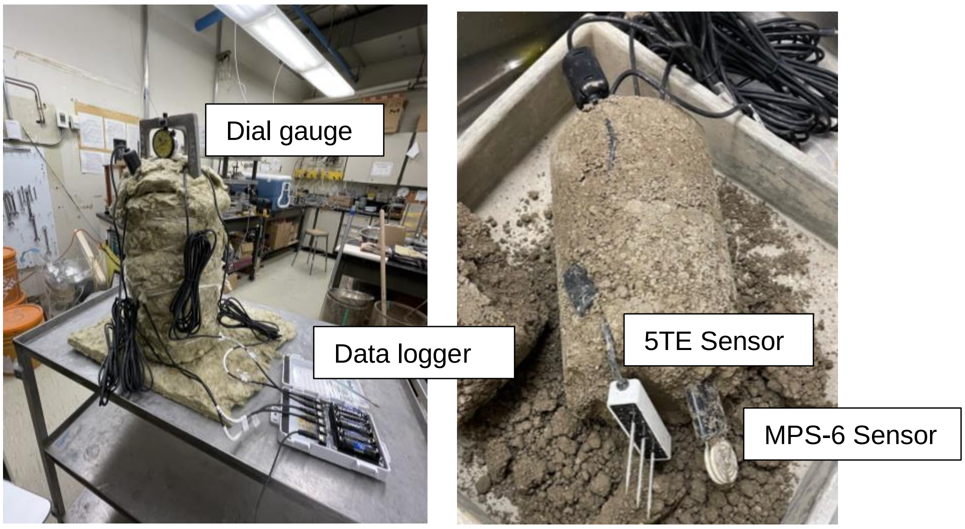

Figure 6- 2. Column setup with sensors placed in compacted Leda clay

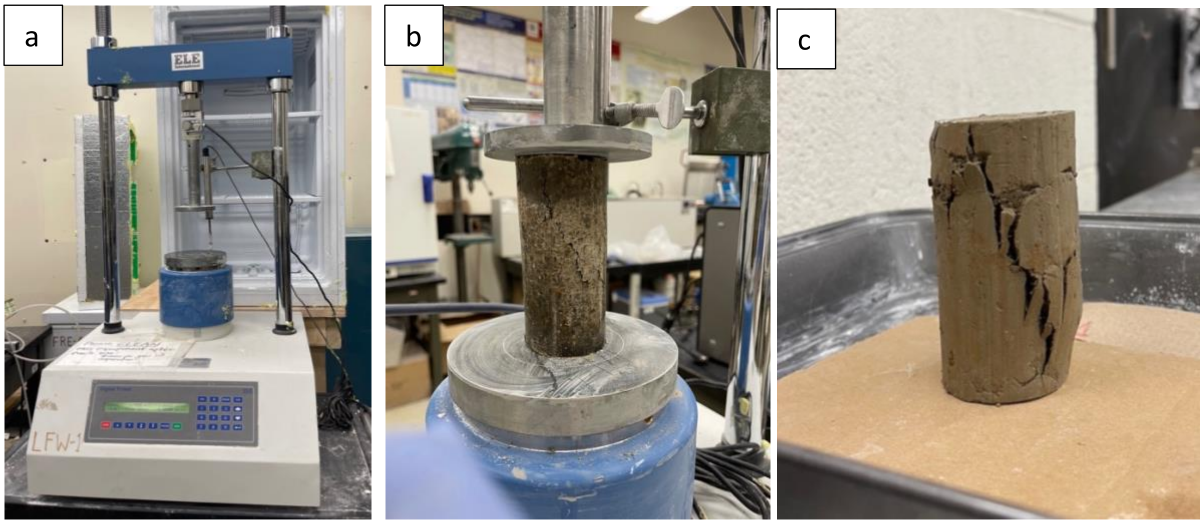

Figure 6- 3. a) UCS machine used on treated and untreated soil samples, b) treated Leda clay sample during testing, c) untreated Leda clay after testing.

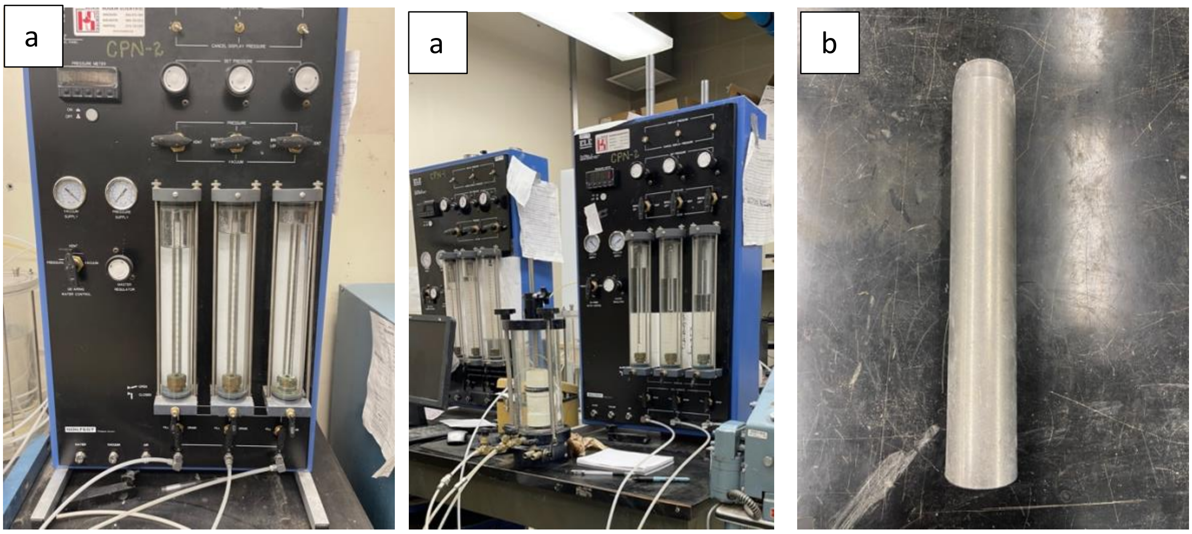

Figure 6- 4. a) Equipment used to determine soil sample's hydraulic conductivity b) Tool used to extract soil samples for testing from column.