Evaluation of Hydrated Lime Stabilization of Sulfate Bearing Expansive Soils

Ece ÇELİK

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ABSTRACT

Calcium-based stabilizers such as calcium oxide (lime) have been used extensively to improve the soil properties of expansive soils. However, in recent years, it has been reported that the presence of sulfate in lime stabilized soil caused abnormal volume changes in expansive soils due to the formation of the secondary minerals: ettringites. Ettringites are known as the highly expansive crystalline minerals. The increasing sulfate heave problems in lime treated expansive soils prompted an important research need in such areas. This research focuses on the understanding of the behavior of the lime treated soils in the absence and presence of sulfate in the soil and to evaluate the effectiveness of ground granulated blastfurnace slag (GGBS) on the lime-induced heave of sulfate bearing clay soils. In this study, an expansive clay with low sulfate level (640 ppm) was used as a control soil and lime was used as an additive for the treatment of this soil. Three different sulfate concentrations: 2000, 5000 and 10000 ppm were used to evaluate the effect of sulfate on the lime treated soils. In order to eliminate the harmful effect of sulfate in the lime treated soils, ground granulated blastfurnace slag was used. Atterberg limits, linear shrinkage, swell, compressibility, consolidated undrained triaxial CU, and cyclic swell-shrink tests were conducted on the natural, and the lime treated soils with the absence and presence of sulfate. Three different curing times (0, 30 and 365 days), three different mellowing times (1, 2 and 3 days) and two different temperatures (25, 40°C) were used to evaluate the behavior of the lime treated soils in the presence and absence of sulfate.

Test results revealed that lime, in the absence of sulfate, is very effective in reducing the plasticity and the swell potential and increasing the strength of the expansive soil. However, the presence of 5000 and 10000 ppm sulfate concentration in the lime-treated soils caused the plasticity and the swell potentials to increase abnormally due to the formation of the ettringite minerals. High concentration of sulfate eliminated the remedial effect of lime in expansive soil and caused the swell to increase. The swell potential of the lime-treated soil with 10000 ppm sulfate concentration became three times higher than the control soil's swell potential. Test results showed that the formation of the ettringite minerals in the lime treated soil with 5000 and 10000 ppm sulfate concentration was further accelerated with the increase in temperature (40°C). Consolidated undrained triaxial, CU tests, showed that the shear strength of the lime treated soils decreased with the increase in the sulfate concentration and curing time. In the absence of sulfate, the effective stress path of the lime treated soil followed the same trend as overconsolidated clay. However, in the presence of sulfate, the effective stress path of the lime treated soil with 10000 ppm sulfate concentration became similar to that of a normally consolidated soil. The shear strength of the lime treated soil subjected to 10000 ppm sulfate decreased dramatically at 365 days curing time. The statistical ANOVA analysis results also verified the experimental findings that with the increase in sulfate concentration and the curing time, the sulfate concentrations and the cell pressures had statistically significant effect on the shear strength. The detrimental effect of sulfate in the lime treated soils was eliminated by adding slag into the lime treated soil. Addition of 6% slag into the lime treated soils prohibited the formation of the ettringite minerals and the increase in the swell potential values was prevented. In the presence of 6% slag, the swell potential of the lime-treated soil with 10,000 ppm sulfate concentration decreased from 8% to 1%

whereas the lime-treated soil with 5000 ppm sulfate concentration showed no swelling.

In the scanning electron micrograph of the lime treated soil subjected to 10000 ppm sulfate solutions, the growth of the ettringite minerals was easily observed.

Keywords: ANOVA, Effective stress path, Ettringite, Expansive soil, Lime, Mellowing, Slag, Stabilization, Sulfate, Triaxial test.

ÖZ

Kireç gibi kalsiyum esaslı iyleştiriciler şişen zeminlerin zemin özelliklerini iyileştirmek için kullanılır. Ancak, son yıllarda, kireçle iyileştirilmiş zeminlerdeki sülfat varlığı etrenjit mineralini oluşturduğundan dolayı zeminde anormal şişmelere sebep olmaktadır. Etrinjit yüksek şişme kapasitesine sahip mineral olarak bilinmektedir. Sülfat varlığından dolayı kireçle iyileştirilmiş zeminlerde şişmelerin olması bu alanda önemli araştırmaların yapılmasını gerektirmektedir.

Bu araştırmada sülfatlı ve sülfatsız zeminlerin kireçle iyileştirilmesi sonucundaki davranışları ve cürufun sülfat içeren zeminlerdeki kireç kaynaklı şişmeler üzerindeki etkinliği değerlendirmektedir. Bu çalışmada düşük sülfat seviyeli (640 ppm) şişen zemin ve bu zemini iyleştirmek için katkı maddesi olarak da kireç kullanılmıştır. Sülfatın kireçle iyileştirilmiş zeminlerdeki etkisini görmek için üç farklı sülfat konsantrasyonu kulanılmıştır; bunlar 2000, 5000 and 10000 ppm'dir. Kireçle iyileştirilmiş zeminde sülfatın zararlı etkisini ortadan kaldırmak için, cüruf kullanılmıştır. Kıvam limitleri, büzülme, şişme, kompresibilite, drenajsız üç eksenli CU ve şişme-büzülme deneyleri doğal zeminde, kireçle iyileştirilmiş sülfatlı ve sülfatsız zeminlerde yapılmıştır. Üç farklı kür süresi (0, 30 ve 365 gün), üç farklı sıkıştırma gecikme süresi (1, 2 ve 3 gün) ve iki farklı sıcaklık (25°C, 40°C) kullanılmıştır. Test sonuçları kirecin plastisite ve şişme potansiyelini azaltmada ve mukavemeti artırmada çok etkili olduğunu ortaya koymuştur. Bununla birlikte, 5000 ve 10000 ppm sülfat konsantrasyonuna sahip kireçle iyileştirilmiş zeminlerde etrenjit oluşması plastisite ve şişme potansiyelinin anormal artmasına neden olmuştur. Yüksek sülfatlı zeminler kirecin iyileştirici etkisini ortadan kaldırmakta ve şişmeyi

artırmaktadır.10000 ppm sülfatlı zeminde şişme doğal zemine göre üç kat artmıştır. Deney sonuçları sıcaklığın (40^0C) artmasıyla şişme potansiyelini hızlandırdığını ve artırdığını göstermektedir. Drenajsız üç eksenli (CU deneyi) deneyleri kesme kuvvetinin kireçle iyileştirilmiş zeminlerde sulfat konsantrasyonunun ve kür süresinin artmasıyla düştüğünü göstermektedir. Sülfatın olmadığı zeminlerin kireç iyileştirmesi sonrasında aşırı konsolide zeminlerle ayni davranışı göstermiştir. Bununla birlikte, sülfat varlığında, kireçle iyileştirilmiş 10000 ppm sülfata sahip zeminin normal konsolide zemine benzer davranışlar göstermiştir. Ayrıca, 365 gün kür süresine sahip 10000 ppm sülfatlı kireçle iyleştirilmiş zeminde kesme kuvetinde dramatik bir düşüş elde edilmiştir. İstatistiksel ANOVA analizi sonuçları da kür zaman artışı ile, sülfat konsantrasyonları ve hücre basınçlarının kesme gücü üzerinde istatistiksel olarak anlamlı bir etkisi olduğunu deneysel bulgular doğrulamıştır. Kireç iyleştirilmiş zeminde sülfatın zararlı etkisi kireçle iyleştirilmiş zemin içine cüruf eklenmesi ile ortadan kaldırılmıştır. Cürufun kireçle iyileştirilmiş 10000 ppm sulfatlı zemine eklenmesiyle şişme potansiyeli %8'den %1'e düşmüş, 5000 ppm sülfatlı toprakta ise şişme sıfırlanmıştır.

10000 ppm sülfatlı kireçle iyileştirilmiş zeminde taramalı elektron mikroskobu incelemesi sonrasında etrenjit oluşumu rahatlıkla gözlemlenmiştir.

Anahtar kelimeler: ANOVA, Cüruf, Efektif gerilme yolu, Etrenjit, İyleştirme, Kireç, Olgunlaşma, Şişen zemin, Üç eksenli test.

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Chapter 1

INTRODUCTION

1.1 Aim of the Study

Expansive soil causes damage to structures, mainly light buildings and pavements because of the shrinking and swelling under changing moisture conditions (Jones and Holtz 1973). Lime stabilization is a most common and economic technique for stabilization of the expansive soils in highways and foundation layers (Eades and Grim 1960, Eades et al. 1962, Thompson 1966, Choquette et al. 1987).

In the past years, some researchers (Mitchell 1986, Hunter 1988, Puppala et al. 2004) reported abnormal heave after lime stabilization of expansive soils. These heaves appear overnight, following rainfall events or after a few years when used for road construction (Harris 2003). Studies (Jahanshahi 2005, Kinuthia 1999, Harris 2003) have shown that a presence of sulfate in lime treated soils causes abnormal heave after lime treatment. After lime treatment of such soils, sulfate present in the soil reacts with calcium which comes from lime and forms the secondary minerals: ettringites. Ettringite were known as the highly expansive crystalline minerals. Due to the formation of these minerals, dramatic heave was observed in expansive soil after lime stabilization (Harris, 2003).

The main objective of this study is to investigate the behavior of the lime treated soils in the absence and presence of sulfate in the soil and to evaluate the effectiveness of ground granulated blastfurnace slag (GGBS), an industrial by-product, on the lime-induced heave of sulfate bearing soils. In the present study, lime was used as an additive for the treatment of an expansive soil and then the lime treated soils were subjected to three different concentrations of sulfate: 2000 ppm, 5000 ppm, and 10000 ppm in order to see the effect of sulfate on the lime treated soils. Ground granulated blastfurnace slag (GGBS), was used to eliminate the detrimental effect of sulfate on the lime treated soils. The natural expansive clay with low sulfate level (640 ppm) was treated with lime and series of laboratory tests were conducted on this soil. Then, the tests were repeated on the lime treated soils with different concentrations of sulfate. In order to eliminate the harmful effect of sulfate in the lime treated soils, 6% slag together with 5% lime was mixed in the soil and the same laboratory tests were performed on the soil with different concentrations of sulfate. The laboratory testing program of the study includes the sample preparation, compaction, Atterberg limits, linear shrinkage, swell, compressibility, consolidated undrained triaxial CU, and cyclic swell-shrink tests. Consolidated undrained triaxial tests were conducted and the effective stress paths were drawn to investigate the changes in the behavior of the lime treated soils in the absence and presence of sulfate. Three different curing times: 0, 30, 365 days, were used to identify the short and long-term effects of lime on the expansive soil in the absence and presence of sulfate. The effect of compaction delay (1 to 3 days) and temperature (25°C, 40°C) on the behavior of the lime treated soils with different sulfate concentrations were also analyzed.

Mineralogical studies by means of X-ray diffraction and Scanning Electron Microscopy (SEM) were used to verify the research findings observed from the macro test results. And finally, the statistical ANOVA analysis was used to verify the experimental findings.

1.2 Frameworks of the Thesis

The research consists of 5 chapters and the first two chapters present the objective of the study, background, and information regarding the expansive soils and the lime-induced heave of sulphate bearing soils. The second chapter provides a more comprehensive literature review of information connected to the topics covered in Chapter 1.

Chapter 2 presents the review of expansive soils, treatment techniques, mechanism of swell, and formation of ettringite minerals. Also it discusses the effect of sulfate on the lime-treated soils and alternative methods to eliminate the detrimental effect of sulfate.

Chapter 3 provides the information about the soil sample location, sample preparations and the experimental test methods.

Chapter 4 presents the test results and discussion of Atterberg limits, linear shrinkage, one-dimensional swell, consolidated undrained triaxial and cyclic swell-shrink tests for control soil, lime-treated soils and lime-treated soil subjected to different concentrations of sulfate with or without slag. Also statistical analyses of the test results are presented in this chapter. The results of the mineralogical studies are used to verify the findings in the laboratory tests.

Chapter 5 presents the conclusions derived from the laboratory tests and the statistical analyses.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the swelling problem in expansive soils and the stabilization methods for such soils. The swell mechanism of the sulfate bearing soils, the ettringite and thaumasite mineral formations and some case studies related to sulfate induced heave in clay soils have been discussed.

2.2 Expansive Soils

Expansive soils are commonly found in the semi-arid and tropical areas (Erguler and Ulusal 1993). Soils containing a large percentage of clay with primarily expansive lattice-type minerals, for instance montmorillonite, have the highest degree of tendency of swell (Hausmann 1990). The alkaline environment and lack of leaching in the arid and semi-arid climates favour the formation of montmorillonite minerals (Abduljauwad 1993). Expansive soils owe their characteristics to the presence of such minerals which have a huge swell potential. Expansive soils have a high cation exchange capacity, resulting in a high amount of swell upon wetting and a huge shrinkage upon drying. This behavior causes damage to structures, particularly light buildings, roads and pavements.

2.2.1 Treatment of Expansive Soils

Treatment procedure that are available for stabilizing expansive soils are:

- Chemical additives
- Prewetting

- Soil replacement with compaction control
- Moisture control
- Surcharge loading
- Thermal methods

2.3 Chemical Additive: Lime

Lime can be used as a stabilization agent for expansive soils in the form of quicklime (calcium oxide CaO), hydrated lime (calcium hydroxide-$Ca[OH]_2$), or lime slurry. Quicklime is manufactured by chemically transforming calcium carbonate (limestone – $CaCO_3$) into calcium oxide. When quicklime chemically reacts with water, created a hydrated lime. Hydrated lime reacts with clay particles and permanently transforms them into a strong cementations bonds (Hunter 1988).

2.3.1 Soil – Lime Reactions

Addition of lime in the highly plastic clays reduces plasticity index and decreases swell-shrink potential of the soil. Normal lime stabilization increases the permeability by supplying the clay silt-like mechanical properties and also decreases the maximum dry density. Normally, stabilization of soil with lime process has four mechanisms (Thompson 1966):

(1) Cation exchance

(2) Flocculation / agglomeration

(3) Carbonation reactions

(4) Pozzolanic reactions

The first two was known as a short term reaction of the lime treated soils and these mechanisms affect the physical properties of the soils. The second two are long term reaction that produces the increasing bearing strength of the clay. The mechanism of the lime induced heave affect only the pozzolanic reactions (Hunter 1988, Rajasekaran 2005).

2.3.2 Soil-Lime-Sulfate Reactions

When the soil and/or ground water contains sulfates in solution, in the presence of lime, they may come together with the alumina free from clay, or possible present in amorphous form, to form a series of calcium-aluminate-sulfate hydrate compounds, leading finally to the formation of ettringite, $Ca_6(Al(OH)_6)_2)\cdot(SO_4)_3\cdot26H_2O$ (Dermates 1995). Figure 2.1 and 2.2 shows that the reaction mechanism of the C_3S (Calcium Silicate Hydrate)-pozzolanic compound and formation of ettringite during pozzolanic reactions (Uchikawa and Uchida 1986, Ogawa and Roy 1982). If all above specification are present in the sulfate bearing soils which stabilized with lime or cement, pH value of the soils will increased to above 12. Due to the high pH value clay minerals start to break down and aluminum appears into the system (Harris 2003). In the system calcium comes from lime or cement during the stabilization process. Sulfate is also supplied from the ground water, mixing water or soils (Harris 2003, Rajasekaran 2005).

$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^-$ (Ionization of lime)

$Al_4Si_4O_{10}(OH)_8 + 4(OH)^- + 10H_2O \rightarrow 4Al(OH)_4^- + 4H_4SiO_4$

(aluminum hydroxide and silicic acid) (Dissolution of clay mineral at pH>10.5)

These two reactions occur in any lime stabilized clayey soils. Reaction 1 shows that when the soil was treated with lime, the pH values increased and became 12.3 causing the release of large quantity of calcium in the media. If pH level rises above

10.5, clay minerals start to break down into aluminum hydroxide and silicic acid which was seen in reaction 2.

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \text{ (Dissolution of gypsum)}$$

$$6Ca^{2+} + 2Al(OH)_4^- + 4(OH)^- + 3(SO_4)^{2-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2 \cdot (SO_4)_3 \cdot 26H_2O$$
(Formation of ettringite)

In this system sulfate ions come from the dissolution of gypsum. Water is only other elements to necessary for formation of ettringite. All these criteria were available in the system where ettringite starts to grow.

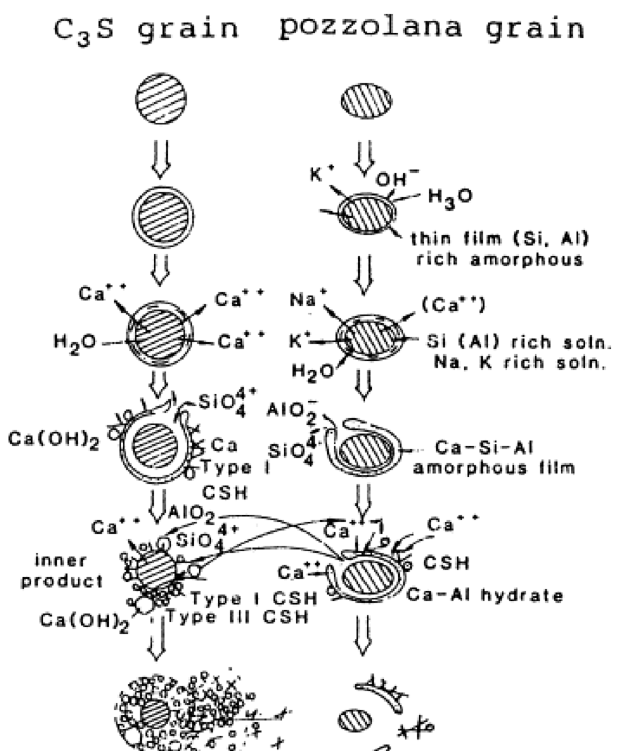


Figure 2.1 Reaction mechanisms of the C_3S -pozzolanic compounds (Rajasekaran 2005)

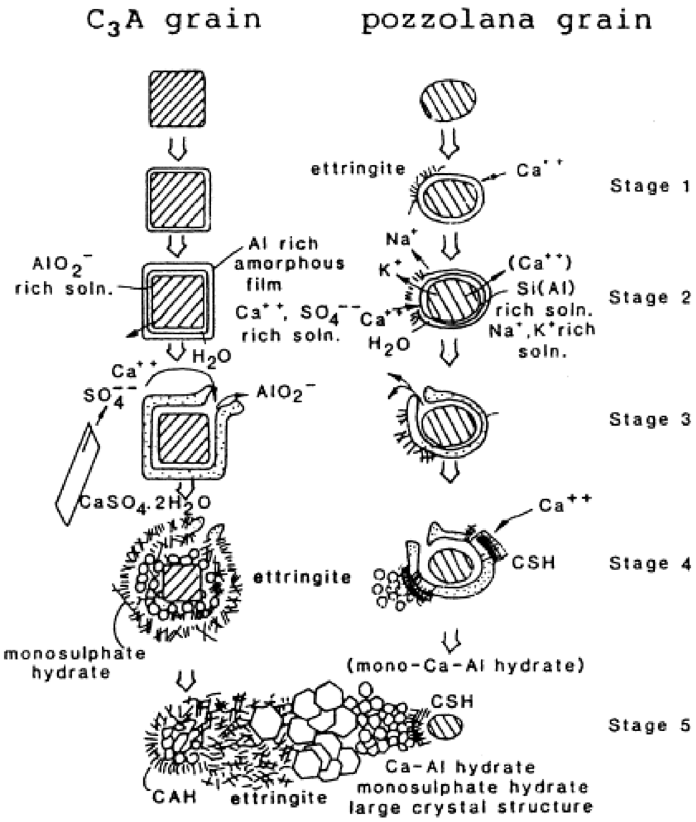


Figure 2.2 Formation of ettringite (Rajasekaran 2005)

2.4 Possible Swell Mechanism

There are two separate swell mechanisms that could be responsible for extensive swelling generally associated with ettringite and thaumasite: swell due to crystal growth, and swell due to hydration and water adsorption

2.4.1 Swell Due to Crystal Growth

Ettringite expansion occurs after additional water is introduced into the system. However, that does not necessarily suggest that water hydration is expansion mechanism. Aluminum, calcium, and sulfate ions present in solution could concentrate around the ettringite nucleation sites and combination to induce ettringite crystal growth (Dermates 1995). Ettringite crystals grow, they exert significant pressures to the restraining media due to growth and interlocking, and when these pressures are high enough, swelling of the media can develop (Dermates 1995).

Figure 2.3 shows the typical scanning electron micrograph (SEM) of the ettringite crystals. The needle-like habit of ettringite can easily be observed in the figure.

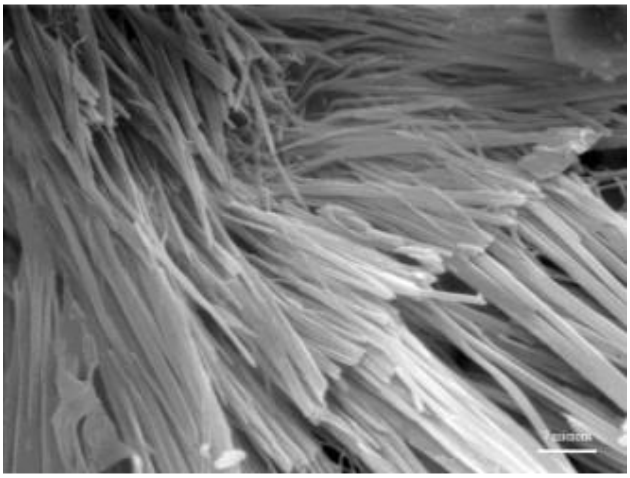


Figure 2.3 Ettringite crystals (Binici, 2012)

2.5 Factors Affecting the Sulfate Attack

2.5.1 Sulfate Level

It is known that lime treatment is very effective in decreasing the volume change of expansive soils (Basma 1991, Nalbantoglu and Gucbilmez 2001). However, literature review indicates that in the sulfate bearing clay soils, lime may not be the ideal solution to the volume change problems (Mitchell 1986, Hunter 1988). The soluble sulfate level of the soil was less than 0.3% or 3000 parts per milllion (ppm) potential of a harmful reaction are low due to the lime stabilization of the soils. The harmful reaction becomes moderate when a total soluble sulfate level is between 3000 ppm and 5000 ppm. However, total soluble sulfate levels between 5000 ppm and 8000 ppm become moderate to high risk. When total soluble sulfate levels are greater than the 8000 ppm, risk becomes high for stabilization of sulfate with lime (Technical Memorandum 2000). However, in Texas region, sulfate concentration as low as 3000 ppm has caused problems with heaving (Harris 2003). Hunter recommended that, sulfate is the key ingredient for the cause of heave. If the sulfate levels are greater than 2000 ppm in soil, calcium-based stabilizers for subgrade stabilization should not be used (Hunter 1988).

2.5.2 pH

Generally Portland cement and lime treatment increase the soil pH to above 12. When pH increase is greater than nearly 9, solubility of silica and alumina also rise exponentially as a function of the pH value (Rajasekaran 2005, Rollings 1999). This is an important factor in freezing material from the clay particles to participate in pozzollanic reactions necessary for gaining strength in lime treatment; however it also produces the chemically active alumina essential for the formation of ettringite during sulfate attack on treated materials. Formation of the ettringite depresses the pH drastically. The high pH media that liberated alumina for formation of ettringite will always exist in the ordinary Portland cement and lime treatment (Rollings 1999).

2.5.3 Temperature

Mitchell and Dermatas (1992) indicated that the temperature was the major parameter affecting swelling of lime stabilized and cement stabilized soil mixture exposed to sulfate attack (Rollings, 1999). The amount of ettringite formation and swelling increased within the summer periods and high temperatures (Rajasekaran 2005, Rollings 1999).

2.5.4 Clay Content

The clay content of the soil is also an important factor for evaluating acceptable sulfate levels for treated materials, (Rollings 1999). Sherwood (1982) mentioned that the loss of strength due to the ettringite growth was not important for soils which have lower clay content. Also Hunter (1988) reported that high sulfate level and small clay content (<10%) soils after lime stabilization have less swelling. Mitchell and Dermatas (1992) observed that kaolinite have more possibilities to higher ettringite formation than montmorillonite. When the clay content increases in lime stabilized soils, swell potential will also increase. Kaolinite is an alumina rich clay and in high pH environment its releases more alumina to the media for rise the posibilities of ettringite formation. Rollings (1999) found out that Bush‘s road stabilized with calcium based stabilizers and heave problem was observed afterwards in this road. This road has clayey sand and clay particles nearly <10%. But this clay mineral in the clay faction was halloysite. This mineral was well known as the alumina rich clay mineral which is the ready source of formation of ettringite.

2.6 Effect of Mellowing Time on Swell

Compaction delays have been shown to affect certain properties of soil–lime mixtures (Osinubi 1998). Harris (2003) studied the effect of traditional (no mellowing) lime stabilization and mellowing time on different levels of sulfate concentrations. This study demonstrates the effectiveness of mellowing on double application, and higher molding moisture content (Harris 2003). The result of the tests represented that up to 3000 ppm sulfate level soils were safely treated with lime in a traditional way, but soils with 5000 ppm sulfate level needed one day mellowing period and 7000 ppm sulfate level required two days mellowing to reduce the swell.

Pupalla et. al. (2013) studies the mellowing effect of two different soils in which one of them have an approximately 30000 ppm and the other has more than 30000 ppm of sulfate level. The result of the swell tests shows that 3 and 7days of a mellowing period decreased the swell value below the natural swell value which is less than 30000 ppm soil, but the swell value of the sulfate level soils were greater than 30000 ppm which is greater than the natural swell value for all the mellowing periods.

Lucian (2013) evaluated the effectiveness of the mellowing period on the two-stage lime-cement treatment to stabilization of expansive soils. A reduction was obtained in the free swell test which was near the zero value for 4 hours of the mellowing period treated with 4% lime and 2% cement treated soils.

Talluri et. al. (2013) studied six different expansive soils with different level of sulfate. Mellowing periods within this study was 0, 3 and 7 days. Four of the six soil samples were effectively stabilized using mellowing. The sulfate levels of these four soils were below 30000 ppm and the other two were above the 30000 ppm.

2.7 Case Studies: Heave Problems in Sulfate Bearing Soils

Lime stabilization of expansive soils have been used extensively in roads and foundation layers as an economic technique of providing a appropriate pavement and fill material (Eades and Grim 1960, Eades et al. 1962, Thompson 1966, Choquette et al. 1987, Al-Mukhtar et al. 2012, Cuisinier et al. 2011). However, it has been reported that the presence of sulfate in soils caused abnormal volume changes in the lime-stabilized soil (Mitchell 1986, Hunter 1988, Puppala et al. 2004, Wild et al. 1999). Sulfates may exist within the soil naturally, or may be produced from the oxidation of sulfate minerals (Sherwood 1962). Sulfate-induced heave problems occur when sulfate rich soils are treated with calcium based stabilizers for example lime and Portland cement (Hunter 1988, Mitchell and Dermatas 1990, Petry and Little 2002, Puppala et al. 2004).

However, reports on sulfate-induced heave in subgrade soils established little interest until the mid 1980’s. Calcium components of stabilizers are known to react with free alumina and soluble sulfates in soil to form ettringite mineral (Hunter 1988). Field observations show that the reactions can be very fast and occur overnight following a rainfall event, or it may take years for the problem to signify itself (Harris 2003). Among the most common naturally occurring sulfate within the earth's crust are calcium sulfate which occurs as gypsum [or selenite ($CaSO_4·2H_2O$)], sodium sulfate [as thenardite ($Na_2SO_4·10H_2O$)], potassium sulfate [as arcanite ($K_2SO_4·10H_2O$)], and magnesium sulfate [which occurs as epsomite ($MgSO_4·7H_2O$)] (Wild 1999). Ettringite, a weak sulfate mineral, will undergo significant heaving when subjected to hydration. This sulfate induced heave is known to severely affect the performance of highways, runways, parking lots, residential and industrial buildings, and the other earth structures built on lime or cement stabilized sulfate rich soils (Hunter 1988, Rollings et al. 1999, Puppala et al. 2001).

The subbase construction of an approximate five kilometer section of major Arterial Street in Las Vegas, Nevada in 1976 uses lime treatment for its expansive silty clay soils. The finished construction appeared of good quality and initial performance was perfect (Mitchell 1986). However, in the beginning of 1977 fall season, signs of distress were observed in the form of surface cracking and heaving. By 1978 spring season, the distress in some location had grown, with heaves increasing upto several inches in some places. For a better understanding of the problem, the treated and untreated soils were tested to monitor the changes in their chemistry and composition. Test results indicated that the untreated soil contained significant amount of soluble sodium sulfate. Also the untreated soil contained large amount of gypsum, calcite and dolomite. Test results of the treated soil indicated that significant amount of ettringite, and thaumasite were detected by X-ray diffraction in both failed and unfailed zones along sections of the street where heaving failures predominated (Mitchell 1986).

In 1985, Hunter reported that, after two years of lime stabilization, Stewart Avenue and Owens Street in Las Vegas, Nevada, were heaves which exceeded 12 in. by the undesirable chemical reactions between salt and lime in the natural soils (Hunter 1988). In heaved area found that to contains abundant thaumasite, complex of calcium-silicate-hydroxide (CSH) mineral (Hunter 1988). Calcium-aluminum-hydroxide-sulfate-carbonate-hydrate mineral a solid solution series with ettringite formed thaumasite, (Hunter 1988). In the presence of aluminum, first ettringite was growth and chanced by thaumasite only at temperature below 15^0C (Hunter 1998).

Kinuthia et al., 1999 found out that the consistency and dynamic compaction properties of an industrial kaolinitic clay soil was changed by monovalent metal sulfates of sodium and potassium, and divalent calcium and magnesium. The results show that the addition of sulfate in the lime-stablized kaolinite decreased the liquid limit depending on the nature of the sulfate cations. And plastic limit increased by divalent cations but the monovalent cations decreased the limit of plastic. However, plasticity index of the soils was decreased for both cases. The divalent metal sulfate decreased the maximum dry density (MDD) and increased the optimum moisture content (OMC). The low concentrations of the monovalent metal sulfate decreased MDD and increased the OMC but at high concentration these actions had reversed.

Rollings et. al. (1999) reported that in Georgia unexpected swells were observed in the 3.4 km road six months after its construction. First investigations showed that the cause of problem occurred in the cement-stabilized based course. After laboratory investigation, ettringite minerals were observed in the samples which were taken from the area. These results indicate that the cause of the swell was the ettringite minerals.

Puppala in 2004 used four different natural sulfate rich soils. These soils contained varying amount of sulfate which is one of them contain below 1000 ppm, second one between 1000-2000 ppm, third one between 2000-5000 ppm and last one greater than the 5000 ppm. Sulfate-resistance cement was used as a stabilization material. Experiments was performed on both control (with no sulfate) and cement stablized sulfate soils to study the compaction properties, Atterberg limits, linear shrinkage and free swell strain potentials, unconfined compressive strength and low shear moduli properties. The test results demonstrated that, sulfate-resist cement stabilization improve the physical properties, reduced plasticity and linear shrinkage value, decreased free swell and raises strength of all sulfate rich soils of varying sulfate levels. The results showed that, the treated soil samples compacted at wet of optimum moisture content yielded higher strength and lesser swell properties than soil compacted at optimum water content. This was attributed to more moisture presence in the compaction soils at wet of optimum condition, which facilitated the strong chemical reaction, particularly hydration related reaction between cement stabilizers and soils (Puppala et al. 2004).

Sivapullaiah et. al. (2000) mentions that the strength behavior of the lime-treated montmorillonitic soil in the presence of sulfate concentration after curing for periods of up to 365 days. The results show that presence of sulfate in lime-treated soils considerably decreased the shear strength of soils at long curing times.

2.8 Suppression of Swelling in Lime-Stabilized Sulfate-Bearing Clay Soils

The ever-increasing lime-induced heave problems within sulfate-bearing soils in construction projects prompted an important need of research in order to address new stabilization methods for the modification of sulfate-rich soils (Puppala 2004). With these methods, the formation of ettringite minerals in sulfate-bearing soils should be mitigated and heave potentials should be reduced. The use of ground granulated blastfurnace slag (GGBS), an industrial by-product, is well established as a binder in several cement applications (Wild et al. 1998). Tasong et al. (1999) used blastfurnace slag and studied the microstructure and mineral phase changes of compacted specimens. Wild et al. 1998 studied the effect of GGBS on the strength properties of lime-stabilized sulfate-bearing clay soils. They discovered that substitution of lime with GGBS in stabilizing gypsum containing clays produced significant improvements in the development of its strength. In other studies of Wild et al. 1999, they reported that substitution of lime with GGBS produced significant reduction in linear expansion of lime-stabilized clay soils (Wild et al. 1998). Puppala et al. (2004) investigated the effectiveness of sulfate-resistant cement treatment methods using Types I/II and V cement. They found out that both cement Types I/II and V improved both the physical properties by reducing plasticity index values and engineering characteristics by enhancing unconfined compressive strength and by decreasing free vertical swell potentials of the sulfate rich soils.

The objective of this research study was to investigate the effect of GGBS on plasticity, strength and swell potential of the lime treated expansive soil with different sulfate concentrations and provide a comprehensive stabilization of sulfate-rich soils. Evaluation of the GGBS was addressed by measuring and analyzing plasticity, linear shrinkage, strength and swell potential of the lime-treated expansive soil with different sulfate concentrations in the absence and presence of GGBS.

Chapter 3

MATERIALS AND METHODS

3.1 Introduction

In this study, the tests were designed to evaluate the effect of calcium based stabilizer to an expansive soil in the absence and presence of sulfate soils. The soil investigated in this study was obtained from a site located in Değirmenlik village in North Cyprus (Figure 3.1). Değirmenlik soil had a high swell potential and low sulfate level of 640 parts per million (ppm), therefore this soil was selected as a control soil in this study. Calcium based stabilizer has been used to treat the control soil. Hydrated lime was used for the stabilization of soil and sodium sulfate (Na_2SO_4) was used to increase the sulfate level of the control soil. Ground granulated blastfurnace slag (GGBS) was used to eliminate the harmful effect of sulfate in the lime treated soil with different sulfate concentration.

Figure 3.1 Location of the Değirmenlik Village

3.2 Değirmenlik Soil (Control Soil)

In Değirmenlik region, because of the expansive soil problems, serious structural damages were reported on pavements, roads and buildings (Figure 3.2 a and b). For this reason, this site was selected for the study. According to the Unified Soil Classification System (USCS), the soil was classified as CH, which is clay with high plasticity. The soluble sulfate content of Değirmenlik soil was 640 ppm.

a)

(b)

Figure 3.2 Pictures from the Değirmenlik region a) Expansive soil b) damaged buildings

Değirmenlik soil was used as a control soil in order to understand the behaviour of the different sulfate levels in the soils. For the study, three different sodium sulfate concentrations: 2000, 5000, and 10000 ppm was used to artificially raise the sulfate level in the soil. Sodium sulfate (Na_2SO_4) was used in the lime treated control soil. Sodium sulfate powder was mixed with the calculated amount of water and different sodium sulfate+water concentrations were prepared. Then the prepared sodium sulfate mixture was added into the soil. In this study, three different curing times: 7, 30 and 365 days were used.

3.3 Additives

In this study, calcium based stabilizer lime, and GGBS were used. Lime was used for the stabilization of the control soil. The aim of using lime in the study was to reduce the plasticity and decrease the swelling potential of the Değirmenlik soil. GGBS was used for lime treated soils in order to eliminate the harmful effect of sulfate.

3.3.1 Lime

In the literature, three different types of lime were used to stabilize the soils such as hydrated lime, quicklime and slurry lime. In this research, hydrated lime was selected as a calcium based stabilizer for the stabilization of the soil. In the study, naturally available commercial high calcium hydrated lime [($Ca(OH)_2$] was used as a chemical additive. Table 3.1 shows the chemical composition of the lime used in the study. The density of lime used in this study was 510 kg/m^3.

Table 3.1 Chemical composition of lime

Oxide	**(%)**
$Ca(OH)_2$	82
SiO_2	2.5
Al_2O_3/FeO	0.9
MgO	3.5
SO_3	0.9
H_2O	0.6

3.3.1.1 Determination of Optimum Lime Content

Lime is a chemical material which reacts with soil and increases the workability and the strength, and decreases the plasticity and the swell of the soils. In lime stabilized soils, before adding lime to a soil, the optimum lime content of the soil should be determined so that the maximum effect of lime will be achieved. McCallister and Petry (1992) defined the term "lime modification optimum (LMO)" as the lowest percent lime to produce a pH of 12.4 below which only flocculation occurs and above which pozzolanic reactions are possible. In this study, in order to determine the sufficient amount of lime to be added to the soil, different percentage of lime was applied into the soil and the pH values of these soils were measured. The percentage of lime giving the pH value of 12.4 was determined to be the lime modification optimum for this soil.

In this study, 3, 4, 5, 6 and 7% of lime were used to determine the optimum lime content of the control soil. The lime modification optimum of the soil was determined according to ASTM-D6276 (2006) standard. From the result of the test, the lime modification optimum of the soil was determined to be 5%.

3.3.2 Ground Granulated Blastfurnace Slag (GGBS)

The ground granulated blastfurnace slag (GGBS) used in this research was supplied by the cement factory in Boğaz Endüstri Madencilik Ltd., Iskele, North Cyprus. Table 3.2 gives the chemical composition of GGBS used in this study. The aim of adding GGBS into the soil was to prevent the lime induced heave problem in sulfate bearing soils.

Table 3.2 Chemical composition of GGBS

Oxide	**(%)**
SiO_2	36.5
Al_2O_3	11.9
CaO	42.7
MgO	7.7
S	0.9
FeO	0.3
MnO	0.4
Na_2O	0.2
K_2O	0.5
TiO_2	0.5
CaO/SiO_2	1.2

3.3.3 Sodium Sulfate (Na_2SO_4)

In this investigation, three different sulfate concentrations were used: 2000, 5000 and 10000 ppm. The aim of using Sodium sulfate (Na_2SO_4) in the study was to artificially raise the sulfate level in the control soil. Sodium sulfate powder was mixed with the calculated amount of water and different sodium sulfate+water concentrations were prepared. Then the prepared sodium sulfate mixture was added into the soil.

3.3.4 Water

Distilled water was used in the study.

3.4 Mellowing Times

Mellowing is a method which allows the lime stabilized soil to stay in soft state for a time from one to more days for chemical reactions before compacting a sample to final density. In this research 1, 2 and 3 days were used for mellowing.

3.5 Compaction Characteristics

The compaction characteristics of the soil were determined according to the ASTM-D698 (2012).

3.6 Sample Preparation

The soil was oven-dried for 4 days at 50°C and then pulverized to minus 40 sieve sizes. In this research, the natural expansive Değirmenlik soil (the control soil) was mixed with 5% lime in order to reduce the swell potential. On the natural and lime stabilized soils, standard Proctor compaction tests were conducted and the compaction characteristics; maximum dry density and optimum water content were determined. Throughout the study, all swell and compressibility tests were performed on the soil samples compacted at the optimum water content.

3.7 Test Methods

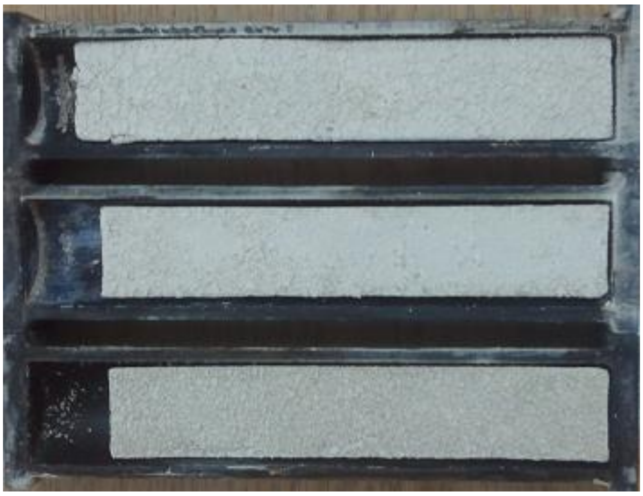
In the study, the following tests were performed: particle size determination, Atterberg limits, linear shrinkage, pH determination, one dimensional swell, cyclic swell and shrinkage, swell tests at different temperatures, and consolidated undrained triaxial (CU) tests. These tests were conducted on control soil, control soil+lime, control soil+lime+sulfate and control soil+lime+sulfate+slag.

3.7.1 Atterberg Limit Test

The consistency of the soils was determined by performing the Atterberg limit tests using ASTM-4318 (2010) method. To observe the changes in plasticity of the control soil, 5% lime treated soil and 5% lime treated soils subjected to different concentration of sulfate with and without slag Atterberg limit tests was performed. The plasticity index was calculated using the liquid and plastic limits determined from the test, and used for the classification of the soils.

3.7.2 Linear Shrinkage Test

Linear shrinkage test was performed for the control soil, 5% lime treated soil and 5% lime treated soils subjected different concentration of sulfate. The test was performed according to BS 1377 Part 2. Figure 3.1 shows the linear shrinkage bars filled with the soil. The soils in the linear shrinkage bars were kept at a temperature controlled room for 2 days and then placed into 50^0C oven. Afterwards, the bars were placed into 110^0C oven for complete drying. At the end of drying, the width and the length of the samples were measured by using a vernier and then the percentage of linear shrinkage value for each soil was calculated.



2000 ppm

5000 ppm

10000 ppm

Figure 3.3 Linear shrinkage bars

3.7.3 Swell Tests

One-dimensional oedometer was used to perform the swell and consolidation tests. Swell tests were performed on control soil, 5% lime treated soil and 5% lime treated soils subjected to different concentration of sulfate with and without slag. These tests were conducted for zero curing, 7, 30 and 365 days. The tests were also repeated with different mellowing times: 1, 2 and 3 days.

3.7.4 Cyclic Swell-Shrink Tests

Cyclic swell-shrink tests were performed by using the modified one-dimensional oedometer test apparatus. The sketch and picture of the modified one-dimensional oedometer test set-up is shown in Figures 3.4 and 3.5, respectively. In order to perform the swell test at 40^0C temperature, flexible heaters were used around the modified oedometer cell. The modified oedometer cell was placed inside a stainless steel container. The outer face of the container was surrounded by a flexible heater which was connected to a temperature controller with the aid of which the test specimen was allowed to shrink at controlled temperature. In order to keep the temperature of the specimen constant throughout the shrinkage process, a thermocouple was inserted into the specimen. The other end of the thermocouple was connected to the temperature controller as can be seen in Figure 3.4. The stainless steel container filled with water and then the specimen is allowed to swell. At the end of the full swelling process, the shrinkage stage had started. Before starting the shrinkage process, the water in the stainless steel container was discharged and the temperature controller was switched on to supply the necessary temperature. After each cycle temperature controller was switched off and sample temperature was allowed to reach the room temperature. This procedure was repeated for several swell-shrink cycles until the sample reached the equilibrium stage. One swell-shrink cycle was represented by the integration of one swelling and one shrinkage cycle.

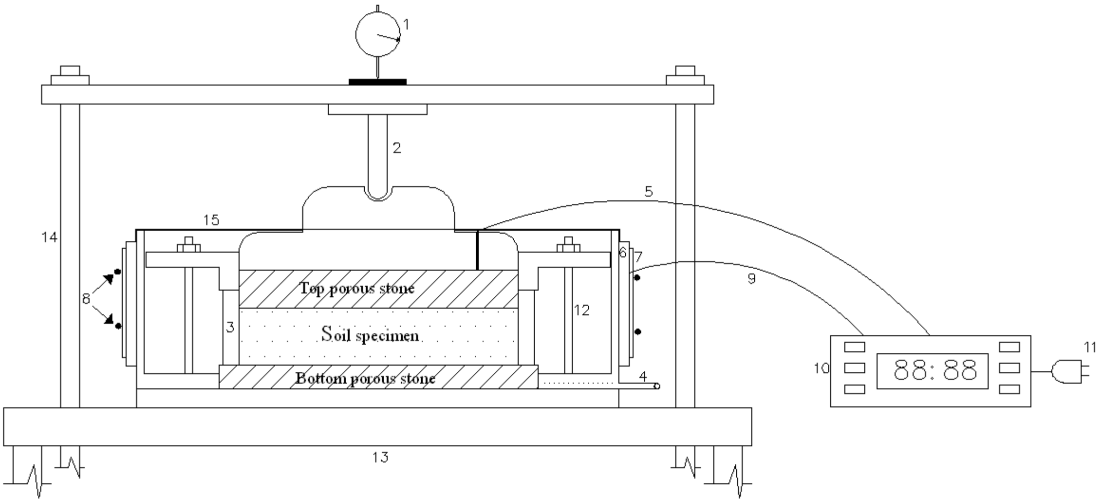


Figure 3.4 The modified consolidometer

1: Dial gauge, 2: Load, 3: Consolidometer ring, 4: Drainage pipe, 5: Thermocouple, 6: Flexible heater, 7: Heat isolator, 8: Thermocouples, 9: Thermocouple, 10: Temperature controller, 11: Plug, 12: Screw, 13: Consolidometer table, 14: Consolidometer arm.


Figure 3.5 The modified consolidometer with temperature controller

3.7.5 Swell Test at 40^0C Temperature

Cyprus is in a semi-arid region and in summer, the temperatures of the soil usually rise to above 40^0C. It is known that (Harris, 2004) the highly expansive ettringite minerals grow after 25^{0}C. In this study, in order to see the formation of these secondary minerals (ettringite), the swell tests were also repeated for all the samples at different temperature: 25^{0}C and 40^{0}C. The reason of using higher temperature was to follow the formation of the ettringite minerals for the lime treated soils. Due to the formation of these minerals at high temperature, higher swell values of the lime treated soils were expected.

3.7. 6 Consolidated Undrained Triaxial Test, (CU)

Consolidated undrained triaxial (CU) test was performed on control soil, 5% lime treated soil and 5% lime treated soils subjected to different concentrations of sulfate. In this test, the dimensions of the specimens were 38 mm diameter and 76 mm height. Soil specimens were coated with filter paper and then placed in the latex membrane and afterwards the porous stones were placed on top and bottom of the specimens to allow water to run in and out of the specimen. The prepared soil samples at OMC were placed in the triaxial cell. The cell was filled with de-aired water and this initiated the saturation process. In the first stage that is the saturation stage, cell pressure was applied to the sample and after 10 minutes, percentage of saturation (B-value) was checked. After applying the back pressure, this procedure was repeated until the B-value had reached a greater value than 0.95. After the saturation processes, consolidation stage had started. After completion of the consolidation stage, axial load was applied to the sample. For consolidated undarined tests, three different confining pressures: 500, 600 and 700 kPa were used. The consolidated undrained triaxial test specimen is shown in Figure 3.6. Figure 3.7 shows the consolidated undrained (CU) test setup and the specimen placed on the test apparatus and Figure 3.8 shows the pressure panel of the triaxial test apparatus.

Figure 3.6 Triaxial cell

Figure 3.7 Consolidated undrained triaxial test setup


Figure 3.8 Triaxial pressure panel

3.8 Chemical and Mineralogical Analyses

3.8.1 pH Determination

In the determination of the pH value of the soil, a 1:1 ratio of dried soil to distilled water was used in this method. This test was performed for the control soils and the lime treated soils with and without slag. The test was performed according to ASTM D 4972 (2012) standards.

3.8.2 X-Ray Diffraction Test

To identify the types of minerals in the soil, X-Ray diffraction technique was used. This technique determines the type of the minerals in the soil. CuKα radiation was used in the test and the samples were subjected to this radiation. The scanning speed of the counter was 2 degrees per minute.

3.8.3 Scanning Electron Microscopy

Scanning electron microscope (SEM) was used to obtain the structural changes in the soil. The scanning electron microscopy study on natural and treated specimens was performed on piece of specimens which were dried in an oven at 110 °C. The operation voltage of SEM was 20 kilovolts (kV).

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the physical and index properties of the natural soil (Değirmenlik clay) selected for this study, were presented, and the results were displayed in the figures. The natural expansive soil was treated with 5% lime and the effect of lime on the physical, index and swell properties of the soil had been tested. Then, the effect of different sulfate level in the lime stabilized soils was investigated and the results were presented. To prevent the lime induced heave problem in sulfate bearing soils, slag was introduced to the soil-water environment to prevent the heaving problem. The tests performed on the natural, and the treated soils were the particle size determination test, hydrometer analysis, Atterberg limits, linear shrinkage, Standard Proctor compaction, swell, cyclic swell- shrink tests, one dimensional consolidation, and the Consolidated Undrained triaxial tests (CU). To study the microstructure of the natural and the treated soils, the soils were investigated under the scanning electron microscope in order to detect any changes in the soil structure.

4.2 Control soil (Değirmenlik soil)

In this study, the Değirmenlik soil was selected to be the control soil with a low sulfate level of 640 ppm. To increase the sulfate level of the soil, sodium sulfate (Na_2SO_4) was added to the soil so that the lime induced heave problem could be modeled and studied in the laboratory.

4.2.1 Hydrometer Test

To determine the particle sizes, sieve analysis and hydrometer tests were performed on the control soil. Depending on the hydrometer test results, the control soil has 60 percent clay and 40 percent silt particles. Figure 4.1 shows the hydrometer test results for the control soil.

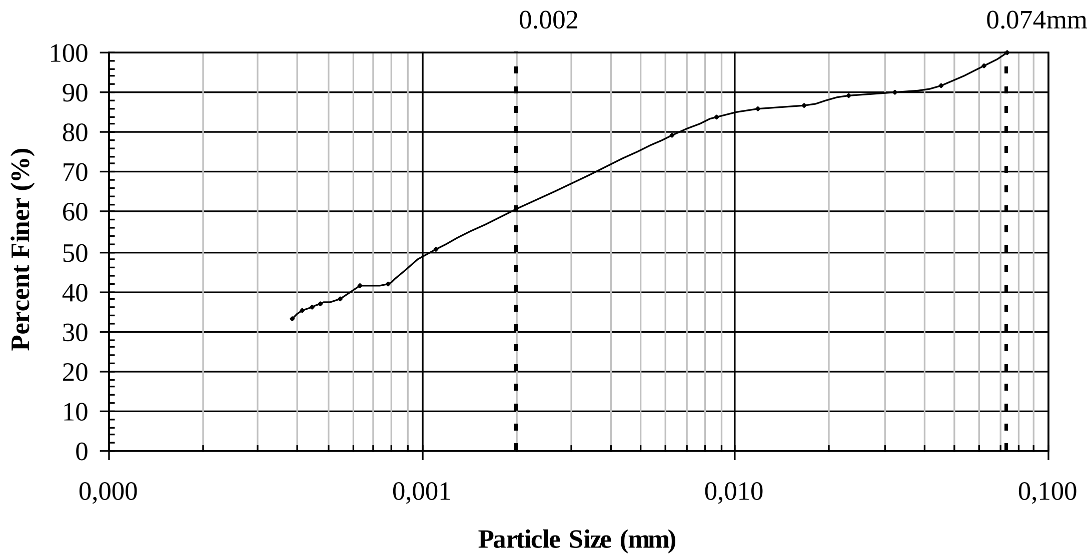


Figure 4.1 Hydrometer curve for the Control soil (CS)

4.2.2 Atterberg Limits and Linear Shrinkage Tests

In Table 4.1 the liquid limit, plastic limit, and the plasticity index of the control soil was given. According to the particle size distribution curve and the Atterberg limit test results, the control soil was classified as CH, clay with high plasticity, (Unified Soil Classification System, USCS).

Table 4.1 Atterberg limits of the control soil (CS)

Soil properties	%
Liquid Limit	56
Plastic Limit	25
Plasticity Index	31

The linear shrinkage of the control soil was obtained as 9%.

4.2.3 Standard Proctor Compaction Tests

In the study, the optimum water content and maximum dry densities of the control and the treated soils were determined according to ASTM Test Method for Laboratory Compaction Characteristics of Soil, (D 698). For the determination of the optimum moisture content (OMC) and maximum dry density of the control soil, the standard Proctor compaction test was conducted. Figure 4.2 represents the standard Proctor compaction test results of the control soil. According to the test results, the control soil gave an optimum moisture content of 23% and a maximum dry density of 1.53 gr/cm^3.

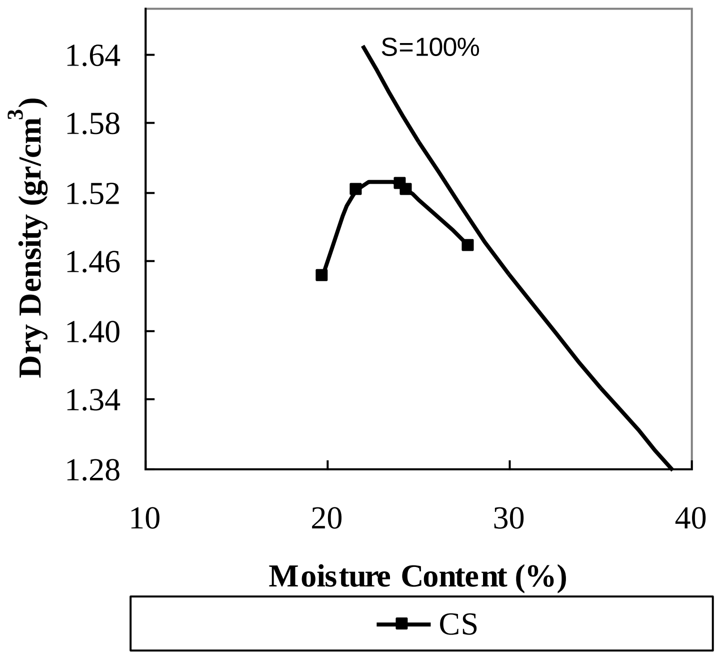


Figure 4.2 Compaction curve for CS

4.2.4 pH value of the control soil

The pH value of the natural control soil was obtained to be 8.3. It is known that a pH value greater than 7 is an indication of good lime reactivity (Thompson, 1966).

4.2.5 Swell tests on control soil

Figure 4.3 shows the swell curve for the control soil. The figure represents that the swell potential of the natural Değirmenlik soil is 3 percent.

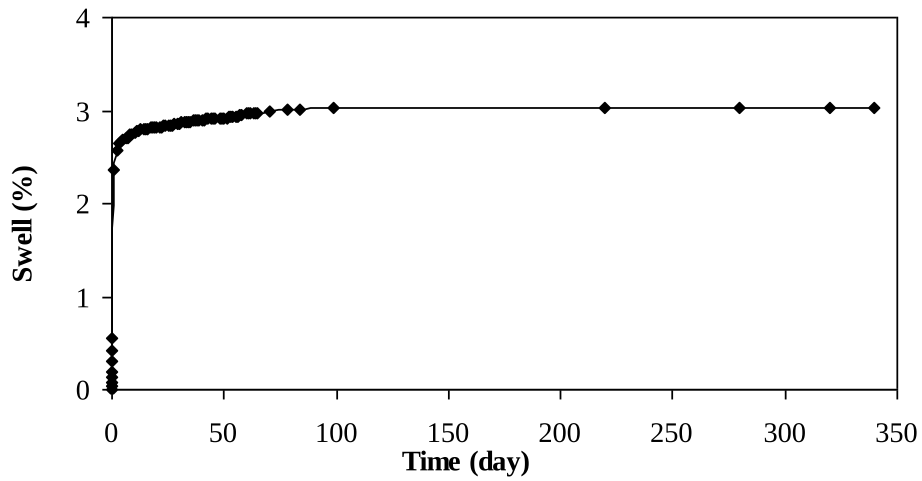


Figure 4.3. Swell curve for the natural Değirmenlik soil

4.3 Değirmenlik soil treated with lime

4.3.1 Hydrometer Test

Figure 4.4 shows the hydrometer test results for the 5% lime treated Değirmenlik soil. The comparison of the hydrometer test results for Değirmenlik soil and 5% lime treated soil is given in Table 4.2. Hydrometer test results show that the clay particle size decreased when the control soil was treated with 5% lime. Test results indicated that the percent clay size decreased from 60 percent to 48 percent with lime treatment.

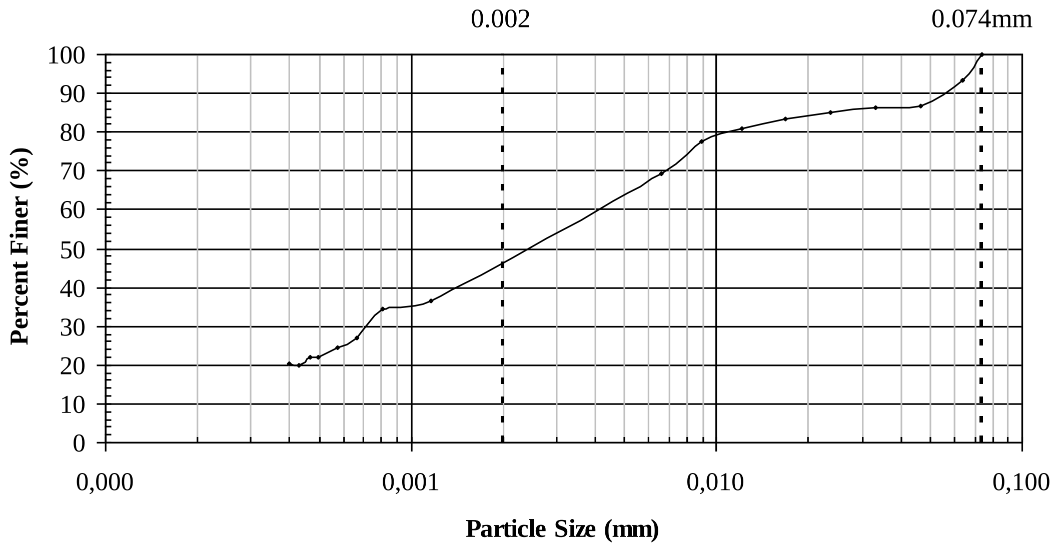


Figure 4.4 Hydrometer curve for 5% lime treated soils

Table 4.2 Hydrometer test results for CS and Control Soil + 5% Lime (CS+5L)

Soil properties	Control soil	Control Soil + 5% Lime
Silt (75 µm-2 µm), %	40	52
Clay (< 2 µm), %	60	48

4.3.2 Atterberg Limits

The liquid limit and plastic limit test results of the control soil and the soil treated with 5% lime showed that, both the liquid and plastic limit values increased after the lime treatment. Increase in both the liquid and plastic limit values resulted in a consequent reduction in the plasticity index of the lime treated soil. Test results indicated that the plasticity index decreased from 31 to 25 percent due to lime treatment.. As Hausmann (1990) stated, depending on the lime addition into the soil, the plasticity index of the soil decreases generally due to the increase in plastic limit. Liquid limit may increase or decrease depending on the soil type. Atterberg limits test results for control soil and lime treated soils are shown in Table 4.3.

Table 4.3 Atterberg Limits of CS and CS+5L

Soil properties	Control soil	Control Soil + 5% Lime
Liquid Limit, %	56	63
Plastic Limit, %	25	38
Plasticity Index, %	31	25

4.3.3 Linear Shrinkage

The linear shrinkage test results indicate that when the control soil was treated with 5% lime, the linear shrinkage value of the control soil reduced from 9 percent to 5 percent.

4.3.4 Standard Proctor Compaction Test

Figure 4.3 presents the effect of lime on the optimum moisture content and maximum dry density of the treated soils. When control soil was stabilized with 5% lime, optimum moisture content increased and maximum dry density decreased. In the lime treated soils, higher amount of water was required to complete the soil-lime reaction. Therefore in the treated soils, higher optimum moisture content was obtained due to the need for higher amount of water consumed by the soil-lime reaction. This water was needed to break the lime into Ca and OH ions which are needed for the soil-lime reaction. Reduction in the maximum dry density can be explained due to the flocculation and agglomeration of the clay particles due to soil-lime reaction.

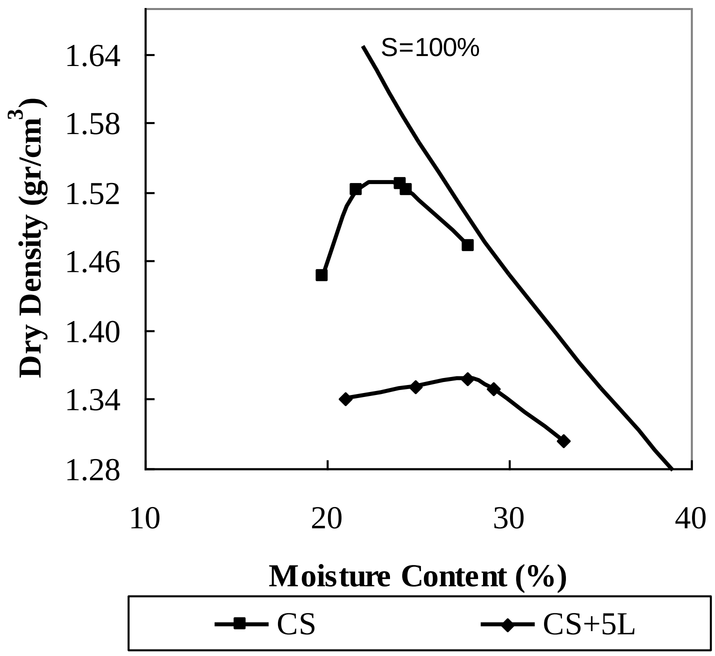


Figure 4.5 Compaction curves for CS and CS+5L

4.3.5 pH value of the control and the lime treated soils

Figure 4.4 indicates that when lime was added into the soil, pH value of the control soil increased from 8 to 12.8. Increase in the pH value of the lime treated soil indicated the high lime reactivity of the lime treated Değirmenlik soil.

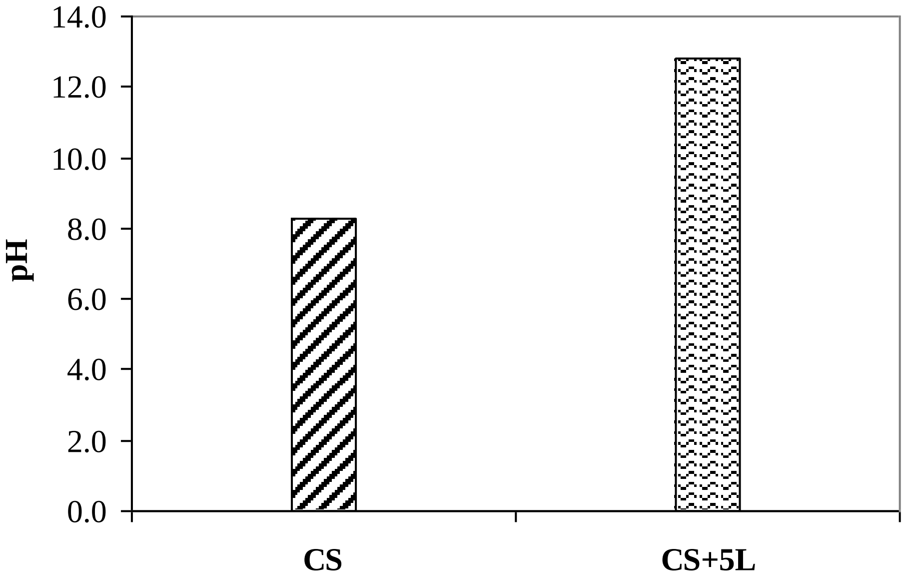


Figure 4.6 pH values for CS and CS+5L

4.3.6 Swell test on lime treated soils

Figure 4.7 shows the swell potential of the control soil and 5% lime-treated soil. The figure indicates that adding 5% lime into the soil results in a reduction in the swell potential. The results show that lime is effective in decreasing the swell potential of the control soil with low sulfate content. In the absence of sulfate in the environment, lime acts as a very good stabilizing agent and reduces the swell potential of the soil.

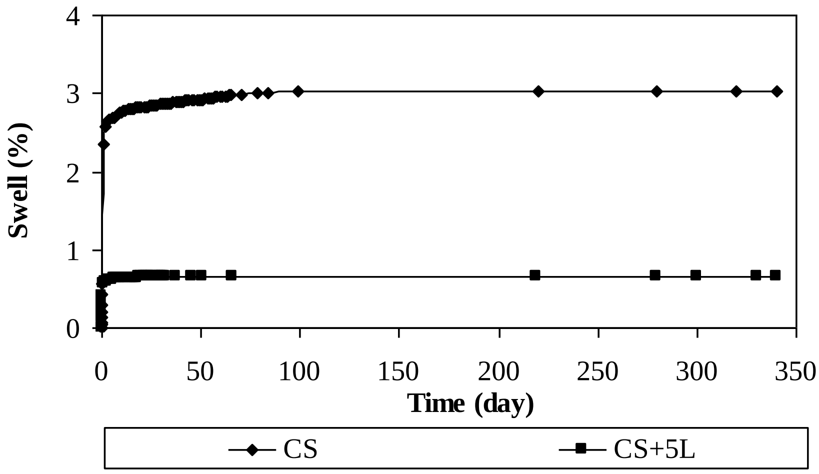


Figure 4.7 Swell percent of the CS and CS+5L

4.4 Effect of Sulfate on lime treated soil

4.4.1 Effect of Sulfate on physical properties

The above test results indicated that in the absence of sulfate, lime is a very good chemical additive for reducing the plasticity and the swell potential of the soil. However, it is known that in the presence of sulfate, the same behavior may not be obtained. So in this part of the study, different concentrations of sulfate had been artificially introduced into the soil-lime mixture and the effect of the sulfate on the lime treated soil was investigated. The plasticity index values of the CS, CS+5L and CS+5L subjected to different concentration of sulfates is shown in Figure 4.8. As it can be seen from the figure, addition of the lime into the soil decreased the plasticity index of the lime treated soil. However, when the sulfate level in the lime treated soil increased continuously, the plasticity index of these soils increased and exceeded the plasticity index of the control soil. The plasticity index of the lime treated soil, which was subjected to 10000 ppm sulfate, reached 38 percent. Figure 4.8 shows that if the sulfate level of the control soil is between 5000 to 10000 ppm, lime will not be a good additive for reducing the plasticity index of the soil and decreasing the swell.

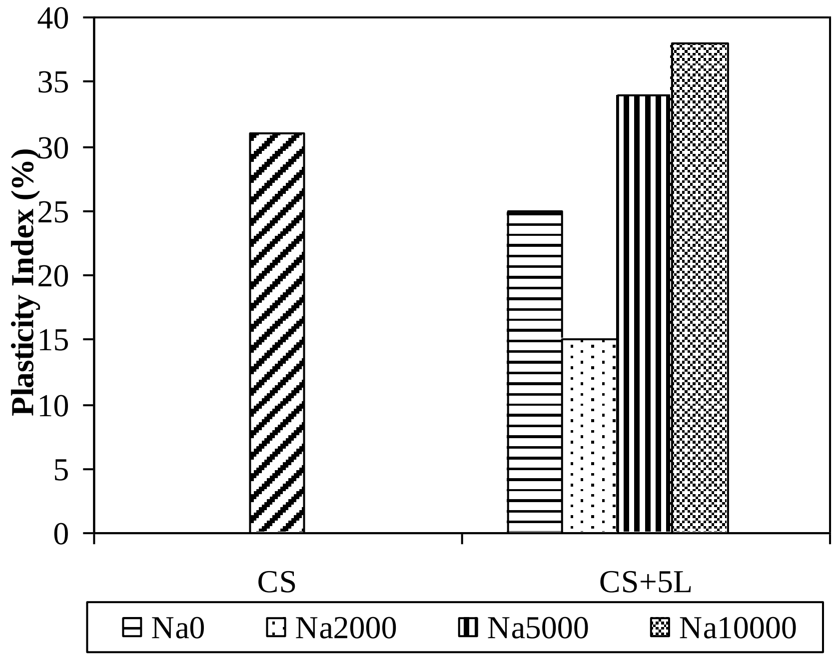


Figure 4.8 Plasticity index of CS, CS+5L and CS+5L subjected to different sulfate concentration

4.4.2 Effect of Sulfate on linear shrinkage

Figure 4.9 shows the linear shrinkage values of the CS, CS+5L and CS+5L subjected to different concentration of sulfates. As it was mentioned earlier, when the control soil was treated only with 5% lime, the linear shrinkage value of the soil decreased from 9 percent to 5 percent. However, in the case of sulfate in the environment, the linear shrinkage values of the lime-treated soil increased and reached a maximum value of 11 percent. The figure indicates that the maximum value of linear shrinkage was obtained for the lime-treated soil with 10000 ppm sulfate concentration.

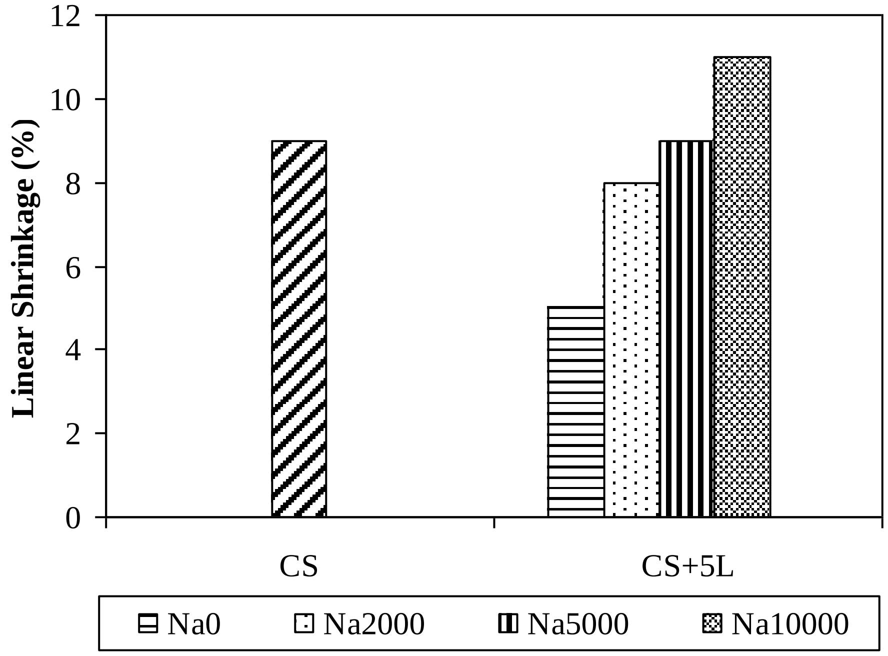


Figure 4.9 Linear shrinkage values of CS, CS+5L, and CS+5L subjected to different sulfate concentration

4.4.3 Effect of Sulfate on swell

Figure 4.10 gives the swell potential of the CS, CS+5L and CS+5L subjected to different concentration of sulfates. The comparison of the test results are given in Figure 4.11. Figure 4.11 indicates that 2000 ppm sulfate concentration is not effective in increasing the swell potential of the lime treated soil. The swelling of the lime-treated soil with 2000 ppm sulfate concentration (CS+5L+Na2000) remains below the swell potential of the control soil. However, when the sulfate concentration of the lime-treated soil increases to 5000 ppm (CS+5L+Na5000) and 10 000 ppm (CS+5L+Na10000), the swell potential of the lime treated soil increases well above the control soil's swell. Figure 4.8 indicates that when there was no sulfate in the soil, the swell potential of the control soil decreased from 3% to approximately 0.5% with only 5% lime treatment. However, when the lime treated soil is subjected to 5000 ppm sulfate concentration, the swell potential of the soil increases above the swell potential of the control soil and reaches to approximately 6%. Figure 4.10 shows that the swell potential of the lime treated soil with 10000 ppm sulfate concentration becomes approximately three times higher than the control soil swell potential and reaches to approximately 8%. The significant increase in the swell potential of the lime treated soils with different sulfate concentrations can be explained due to the formation of the ettringite minerals which are highly expansive in character. The reactions between calcium of the lime stabilizer, reactive alumina in soil, and sulfates in soil solution formed the ettringite minerals which caused an increase in the swelling of the lime-treated soil with higher sulfate concentrations.

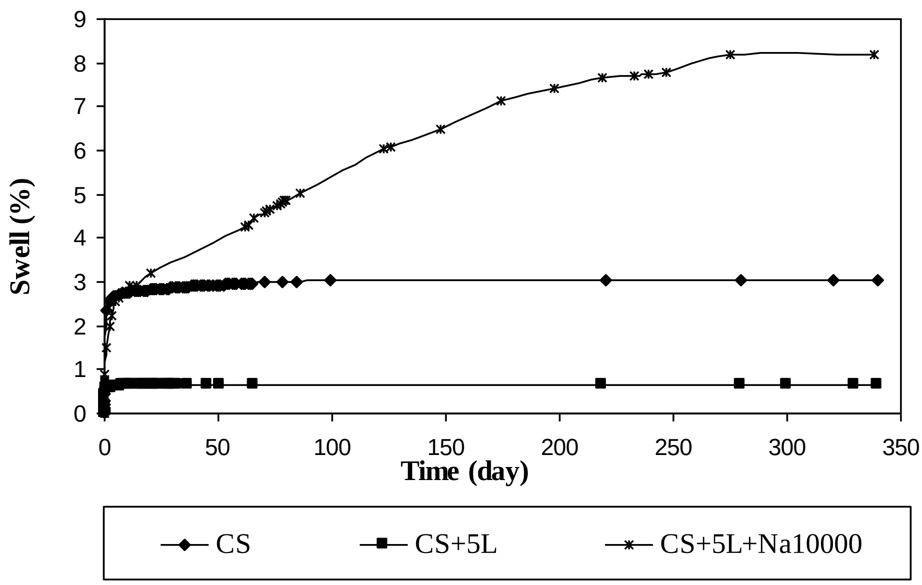


Figure 4.10 Swell values for CS and CS+5L subjected to 10000 ppm sulfate

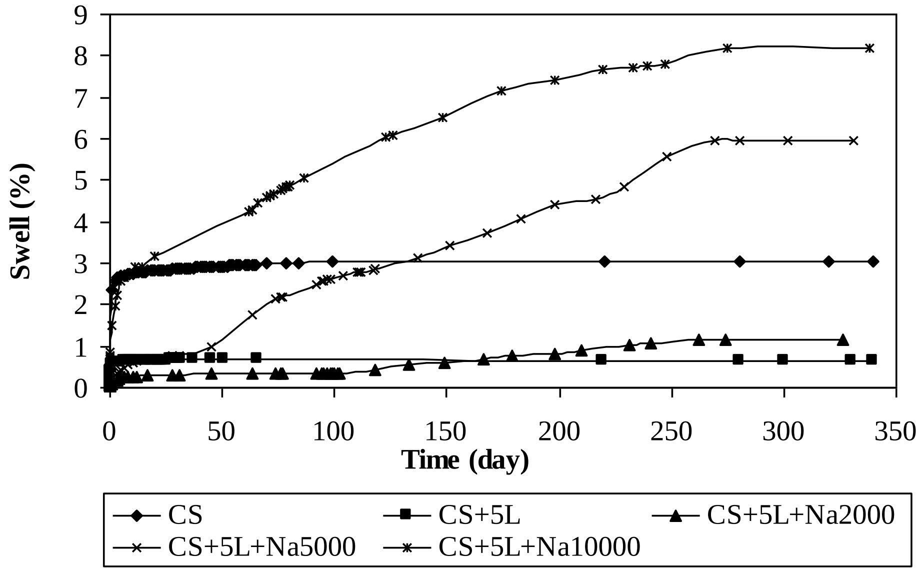


Figure 4.11 Comparison of the swell values of the CS, CS+5L and CS+5L subjected to different concentration of sulfates

4.4.4 Effect of Mellowing Time (Compaction Delay) on Swell Potential

Mellowing means soil mixed with lime and put into protected bag and kept for 1, 2 and 3 days before the compaction (Harris, 2003). Compaction delay has been shown to affect certain properties of soil–lime mixtures and change the engineering properties of the soils (Osinubi 1998). Curing the lime treated soils for 24 hours and then remolding the soil during compaction breaks the cementation bonds and results in different soil properties (Sivapullaiah et al., 2000). Therefore, the effect of mellowing time on the lime treated soil should be well studied and explained. In this study, the effect of mellowing time on the swelling properties of the lime treated soils which have been subjected to different sulfate concentrations will be studied. Figure 4.12 gives the swell potential of control soil, the lime treated soil subjected to 2000 ppm sulfate concentration with mellowing periods of 1, 2 and 3 days. From the figure, it can be seen that when the mellowing time increased, the swell potential of the lime treated soils decreased in 2000 ppm sulfate concentration soils.

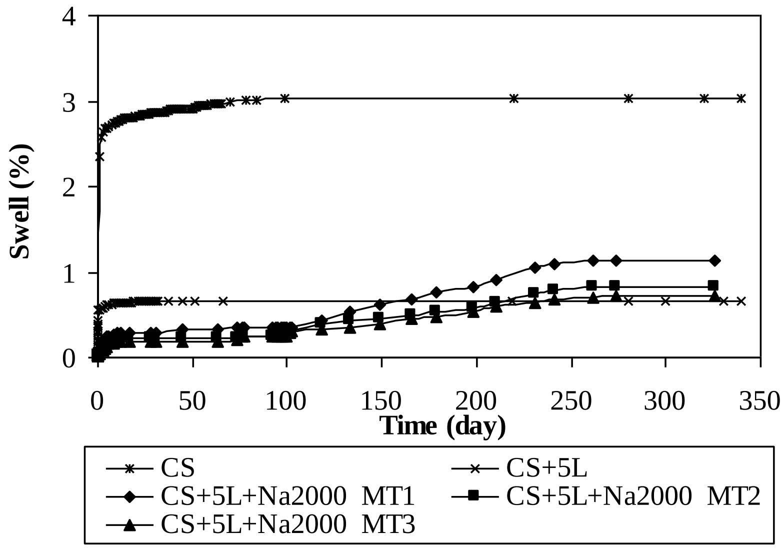


Figure 4.12 Swell potential for CS, CS+5L subjected to 2000 ppm sulfate concentrations with mellowing time 1, 2 and 3 days

The most effective reduction was observed in 3 days mellowing period for the lime treated soil subjected to 5000 ppm sulfate solutions as shown in Figure 4.13. The swell potential of the lime treated soil with 5000 ppm sulfate solution was approximately 6 percent at zero mellowing time but after 3 days mellowing time, the swell potential became 1 percent, because of the broken bonds, in the soil subjected to 3 days mellowing period. In Değirmenlik soil subjected to 5000 ppm sulfate, the mellowing time effectively reduced the swell potential (Harris 2003). Figure 4.4 shows the swell potential of the soil subjected to 10000 ppm sulfate solutions. Test results indicated that applying different mellowing time to the lime treated soils, results in different swell values and soil behaviour. Therefore in lime treated soil studies it is very important to specify which mellowing time has been used in the study.

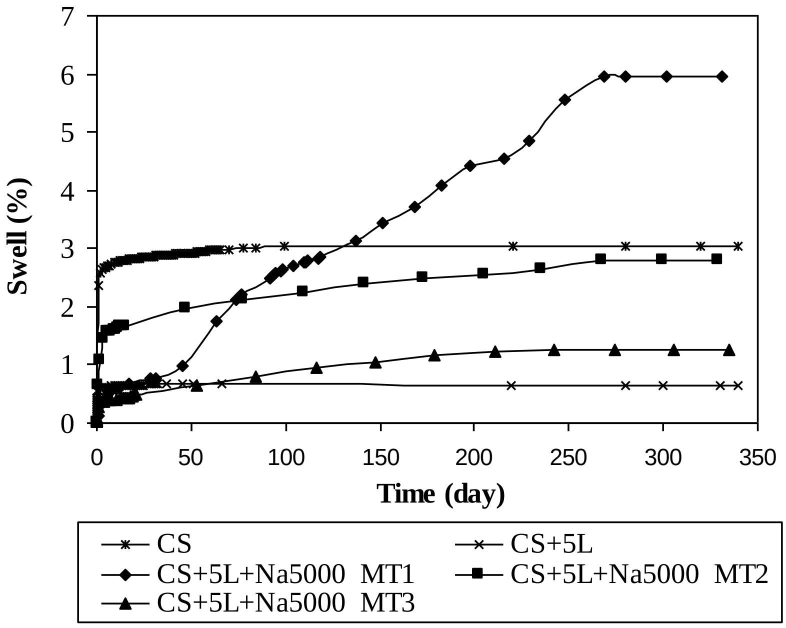


Figure 4.13 Swell potential for CS, CS+5L subjected to 5000 ppm sulfate concentrations with mellowing time 1, 2 and 3 days

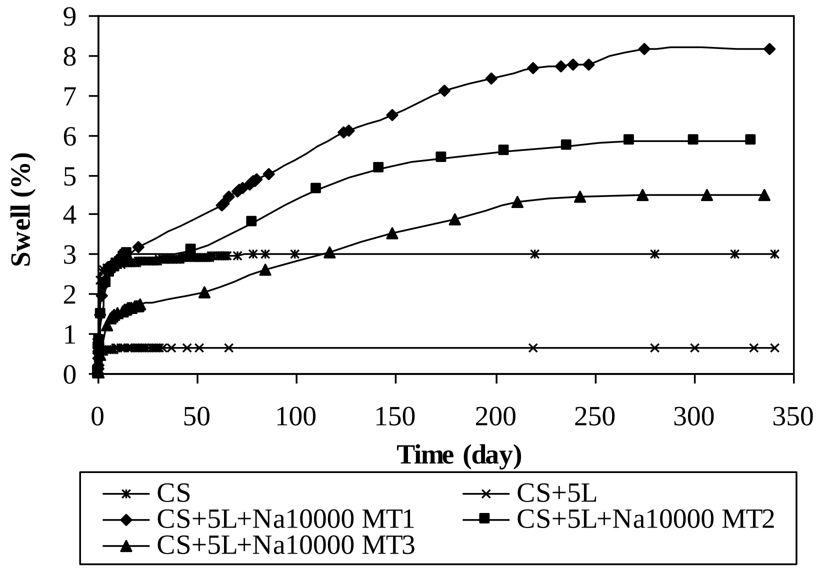


Figure 4.14 Swell potential for CS, CS+5L subjected to 10000 ppm sulfate concentrations with mellowing time 1, 2 and 3 days

4.4.5 Effect of curing time on swelling

Lime was known as the effective agent for decreasing the swell potential of the expansive soils. Figure 4.16 indicates the swell potential of the lime treated soil cured at 7, 30 and 365 days. Test results show that swelling decreases with an increasing curing time. The figure shows that when curing time was 365 days, the swell value become near to zero. Because of the pozzolanic reaction at long curing time, cementation of the particles prevented the swell and caused reduction in swell potential. The results indicated that in the absence of sulfate, lime is very effective in reducing the swell potential.

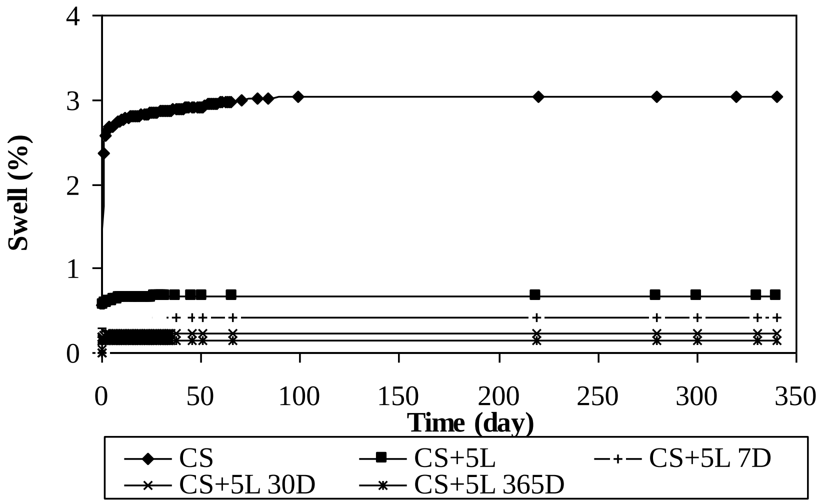


Figure 4.16 Swell potential for lime treated soils at different curing times

However, test results given in Figures 4.17-4.19 clearly show that, the increasing curing time of the lime treated soils with high sulfate levels, does not result in a decrease in the swelling values. Figure 4.17 represents the swell values of the lime treated soils subjected to 2000 ppm sulfate concentration. The figure shows that 2000 ppm sulfate level does not affect the swell values of the lime treated soils. Small increase in the swell value was observed, but this increase was very small.

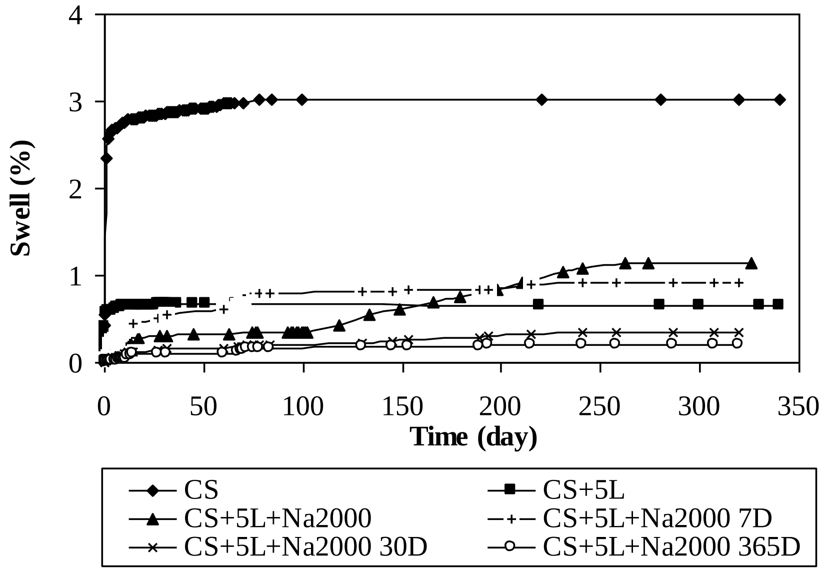


Figure 4.17 Swell values of the lime treated soil subjected to 2000 ppm sulfate with different curing periods

Figure 4.18 represents the swell values of the lime treated soils subjected to 5000 ppm sulfate concentration. The figure indicates that 5000 ppm sulfate level of the lime treated soils needed longer curing period to decrease the swell value. 30 days of a curing period decreased the swell value of this soil below the control soil's swell value and became approximately 2%. The most effective reduction in 5000 ppm sulfate concentration was obtained at 365 days, where the swell became approximately 1.5%. Test results showed that the swell potential of the lime treated soil with 5000 ppm sulfate concentration decreased with increasing curing times. That can be explained because of the pozzolanic reaction between soil and lime. The strong cementation bonds formed after pozzolanic reaction did not allow the soil to swell at long curing periods.

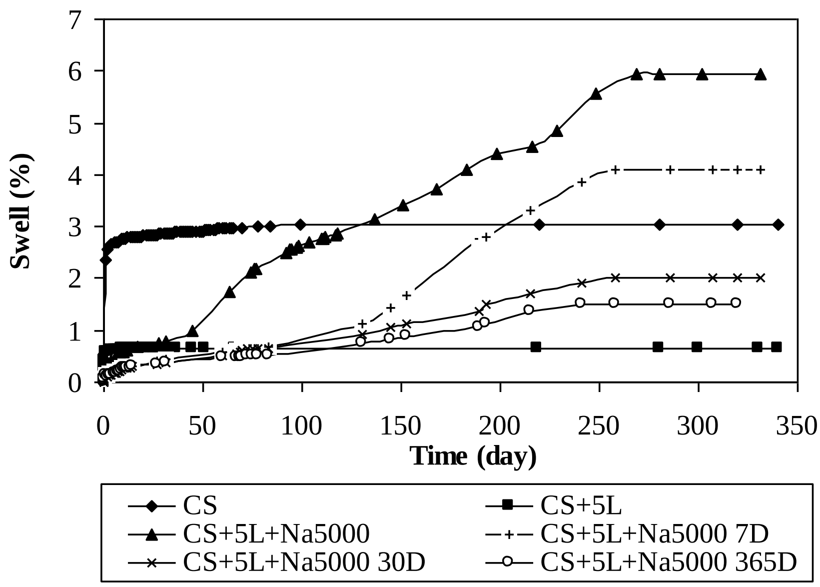


Figure 4.18 Swell values of the lime treated soil subjected to 5000 ppm sulfate with different curing periods

The swell values of the lime treated soils subjected to 10000 ppm sulfate concentration with curing times were given in Figure 4.19. Figure 4.19 indicated that, curing time did not reduce the swell potential of the soil with high sulfate concentration. The formation of the ettringite minerals increased the swell potential of the soil with high sulfate concentration and the remedial effect of lime was prevented.

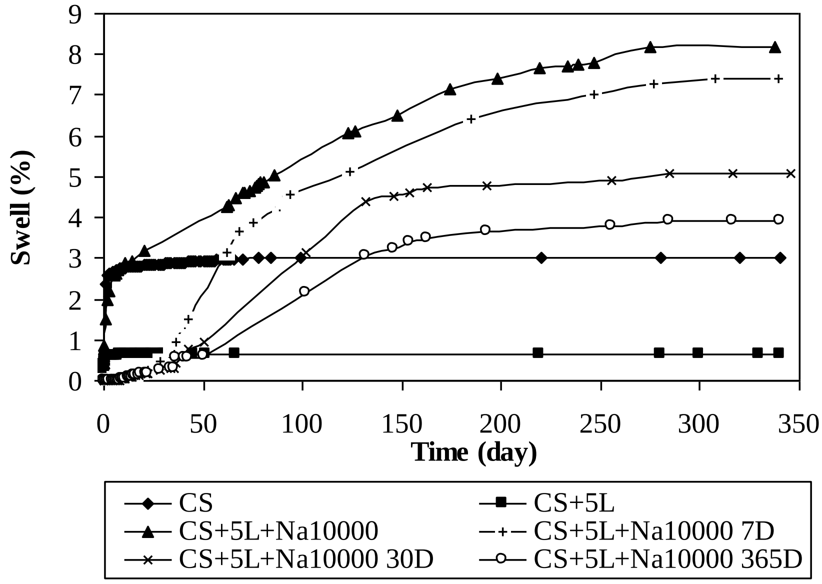


Figure 4.19 Swell values of the lime treated soil subjected to 10000 ppm sulfate with different curing periods

4.4.7 Effect of Temperature

In 1992, Mitchell and Dermates found out that temperature was a major parameter to affect the swelling of lime treated soils subjected to sulfate attack. High temperature accelerates the formation of the secondary minerals, ettringite. In the present study, in order to study the effect of temperature on the swelling of the soils, the swelling tests were performed at 25^0C and 40^0C temperatures. Figure 4.20 indicates the swell values of the lime treated soils subjected to 2000 ppm sulfate at different temperature values. The figure shows that temperature does not affect the swell values of the lime treated soil at low sulfate concentration. Very small increase in the swell value was obtained with the increase in temperature. Figures 4.21 and 4.22 represent the effect of temperature on the swell potential for 5000 ppm sulfate and 10000 ppm sulfate concentrations lime-treated soils. The figures indicate that the swell potential of the soils further increased with the increase in temperature. The formation of the ettringite minerals was accelerated with the increase in temperature.

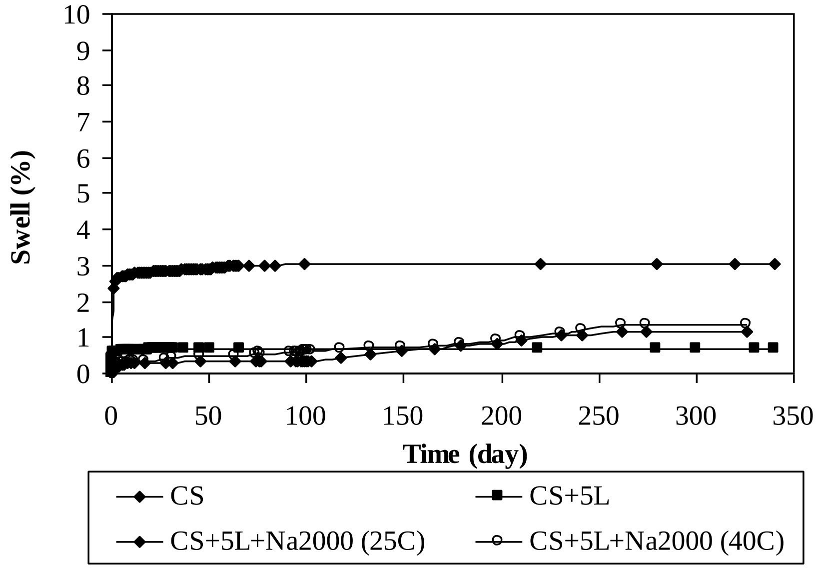


Figure 4.20 Swell potential for lime treated soils subjected to 2000 ppm sulfate at different temperature values

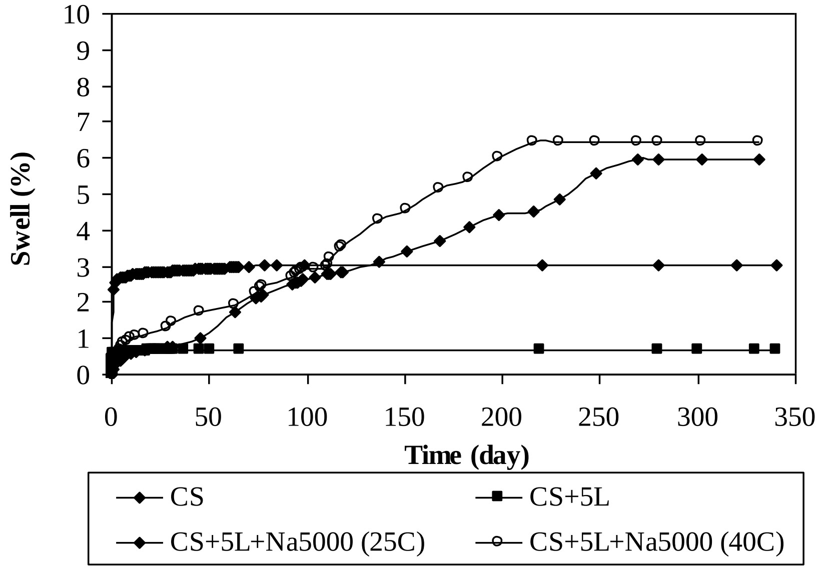


Figure 4.21 Swell potential for lime treated soils subjected to 5000 ppm sulfate at different temperature values

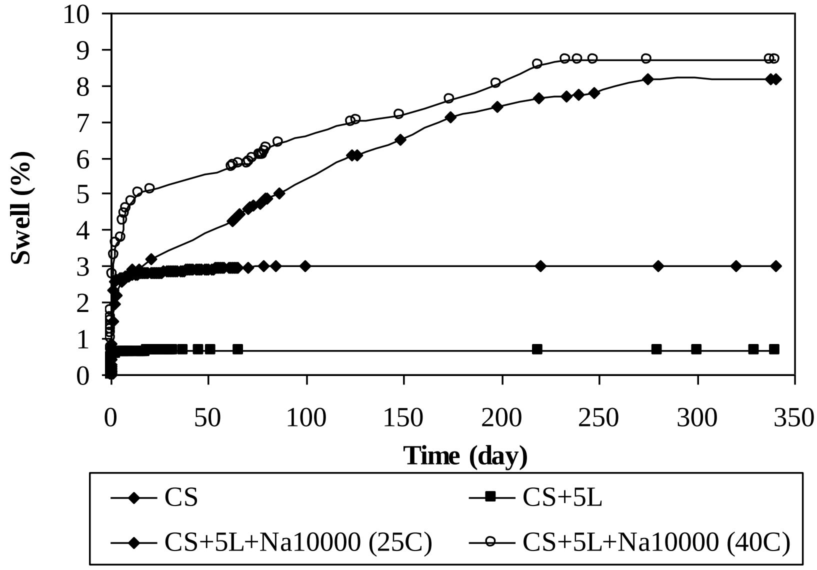


Figure 4.22 Swell potential for lime treated soils subjected to 10000 ppm sulfate at different temperature values

4.4.8 Effect of Sulfate on Consolidation Parameters

4.4.8.1 Compressibility

This part investigated the effect of lime and sulfate on the compressibility characteristics of Değirmenlik soil. The compressibility characteristics were obtained from one-dimensional consolidation tests. The test was repeated at 0 and 30 days of curing periods.

Figure 4.23 represents the effect of lime on the control soil at zero curing time. Figure 4.23 shows that the lime treatment decreased the compressibility characteristics of the soils. The reason of this decrease was due to the flocculation and aggregation process of the lime treated soils. Due to the reaction of the cation exchange, the soil behaved like a granular soil and that reduced the compressibility of the lime treated soils.

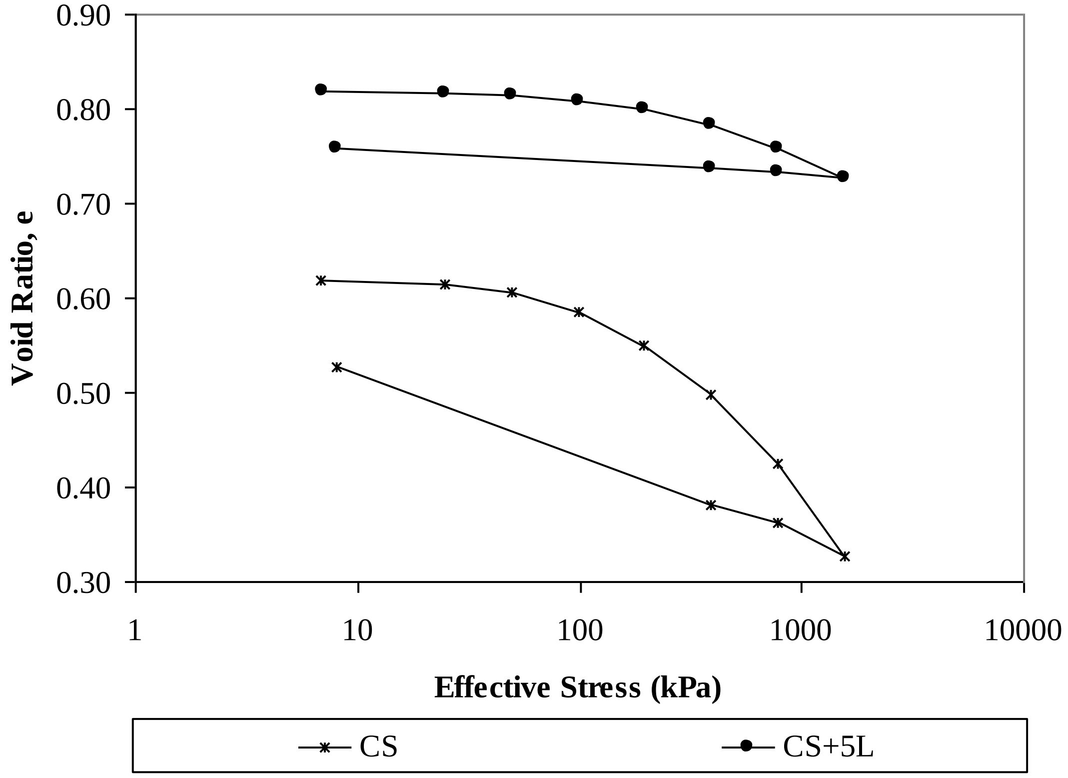


Figure 4.23 Void ratio versus effective stress curves for CS and CS+5L

Figure 4.24 investigates the curing effect on the lime treated soils. The figure shows that the slope of the virgin compression line decreased after 30 days curing periods. That means that the pozzolanic reaction produced stronger fabric and that reduced the compressibility characteristics of the lime treated soils.

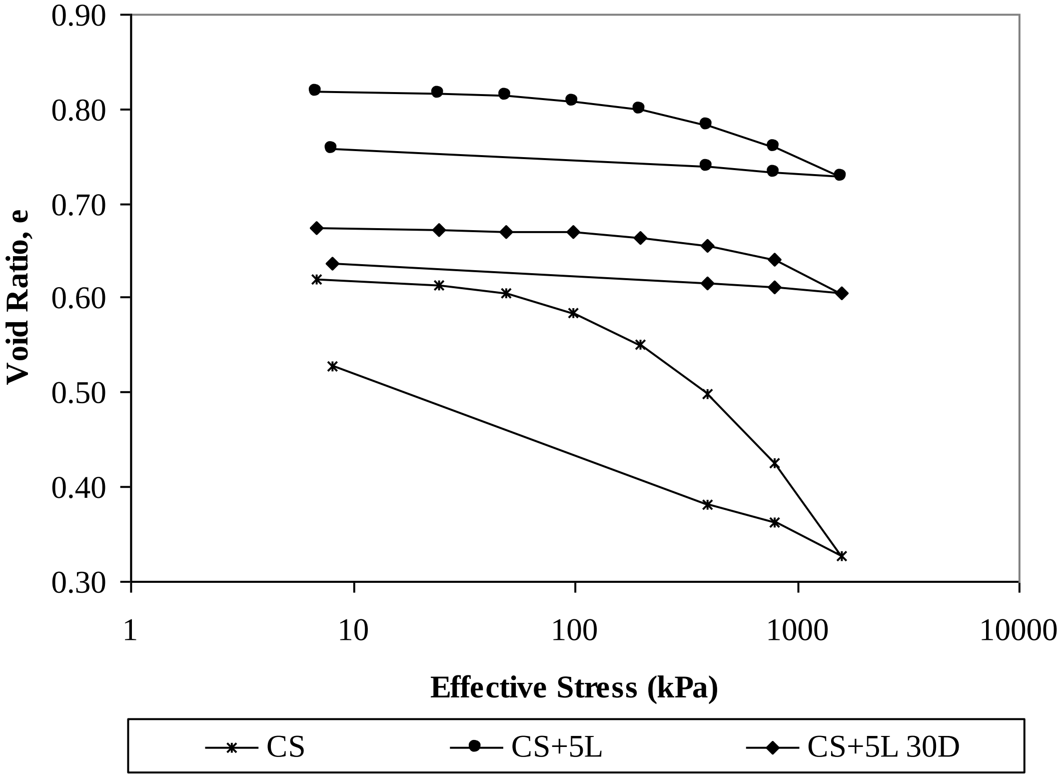


Figure 4.24 Effect of curing time on void ratio versus effective stress curves

The effect of lime and sulfate on the compressibility characteristics of the lime treated soils is shown in Figure 4.25. The figure indicates that sulfate is very effective in increasing the compressibility characteristics of the lime treated soils. An increase in the compressibility characteristics has been obtained with an increase in the sulfate concentration. This can be explained due to the formation of ettringite minerals in the soil media. Alumina and silica reacted with sulfate and formed an ettringite mineral with a high expansive character.

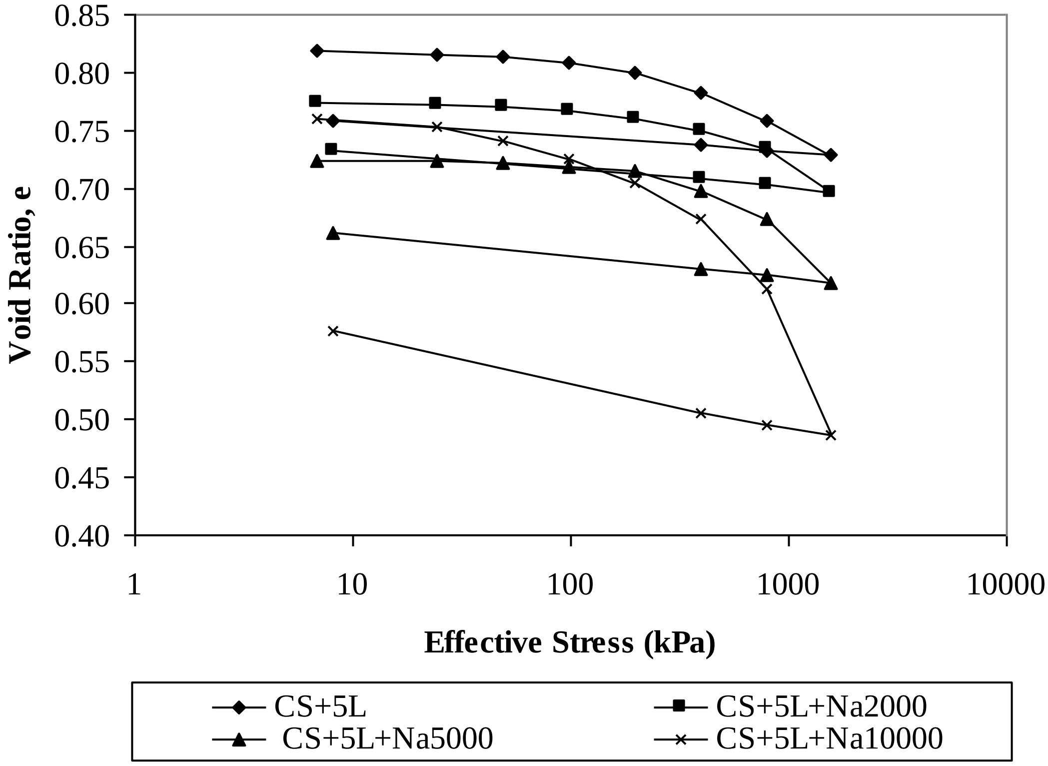
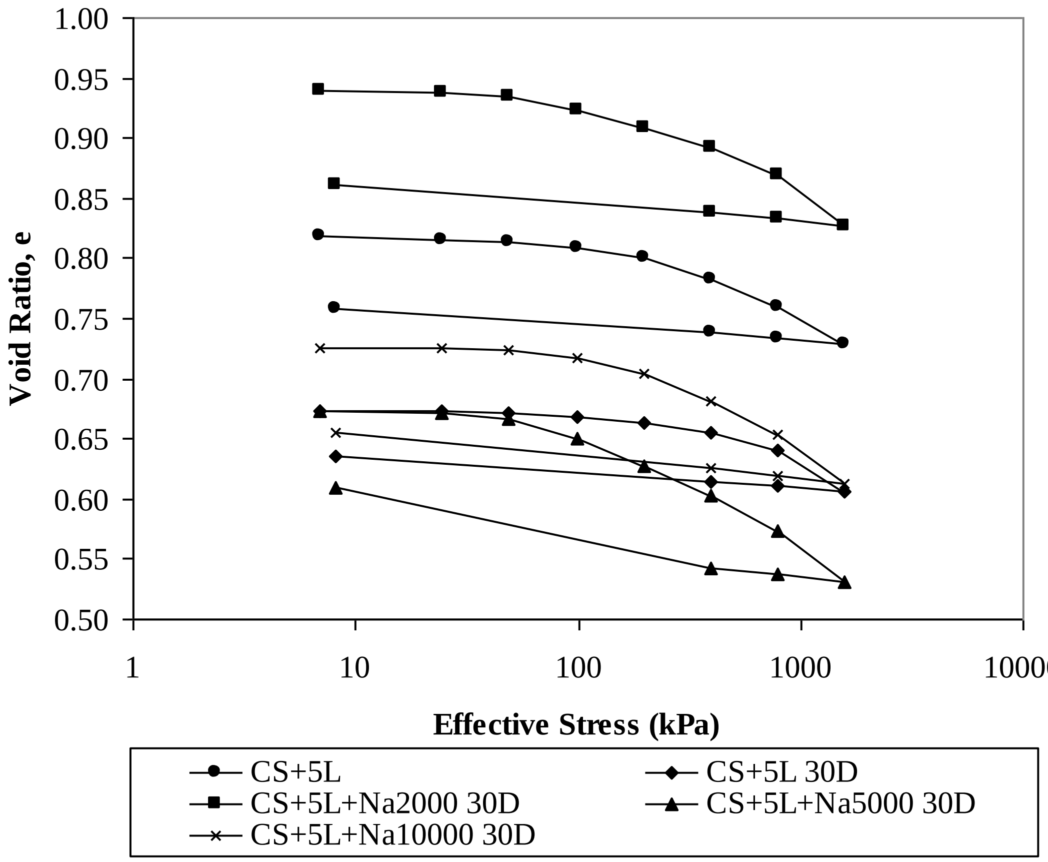


Figure 4.25 Void ratio versus effective stress graph for lime treated soils with different sulfate concentrations

Figure 4.26 shows of the effect of curing time on lime treated soils with different sulfate concentrations. The figure shows that 30 days curing periods decreased the compressibility of the soils for the lime treated soils with 2000ppm, 5000ppm and 10000 ppm sulfate concentrations.



. Figure 4.26 Effect of curing time on lime treated soils with different sulfate concentration

Figure 4.27 indicated the compression index values for the lime treated soils subjected to different concentration of sulfate solutions. Lime treatment usually reduced the compressibility of the expansive soils. However, Figure 4.27 shows that when soil sulfate level was greater than 2000 ppm, lime treatment could not reduce the compressibility of the soils. It is known that the reduction of compression index in lime treated soils was due to the pozzolanic reaction between aluminum, silica from the soil and lime in the environment. Experimental results show that if the sulfate level of the soils was greater than 2000 ppm, due to the formation of the ettringite minerals in the soil an increase in the compressibility index values of the lime treated soils was obtained. The results in Figure 4.27 indicate that the compressibility index of the soils was raised at high sulfate levels and passed natural soil's compressibility index value.

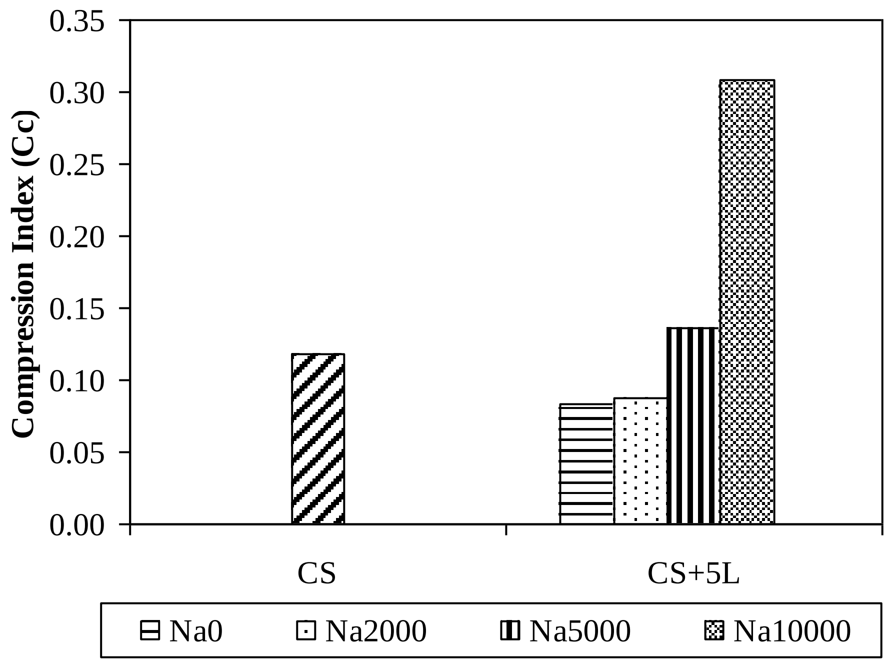


Figure 4.27 Compression index for lime treated soil subjected to different sulfate concentration.

4.4.8.2 Permeability

Figure 4.28 indicates the permeability of the soils subjected to different concentration of sulfate. The figure shows that the permeability of the soils decreased while the sulfate level of the soils increased. In high sulfate levels, the formation of the new ettringite minerals, which are highly plastic and expansive, caused the reduction of the permeability of the soils. The permeability of the soil with high sulfate concentration became less than the control soil's permeability value.

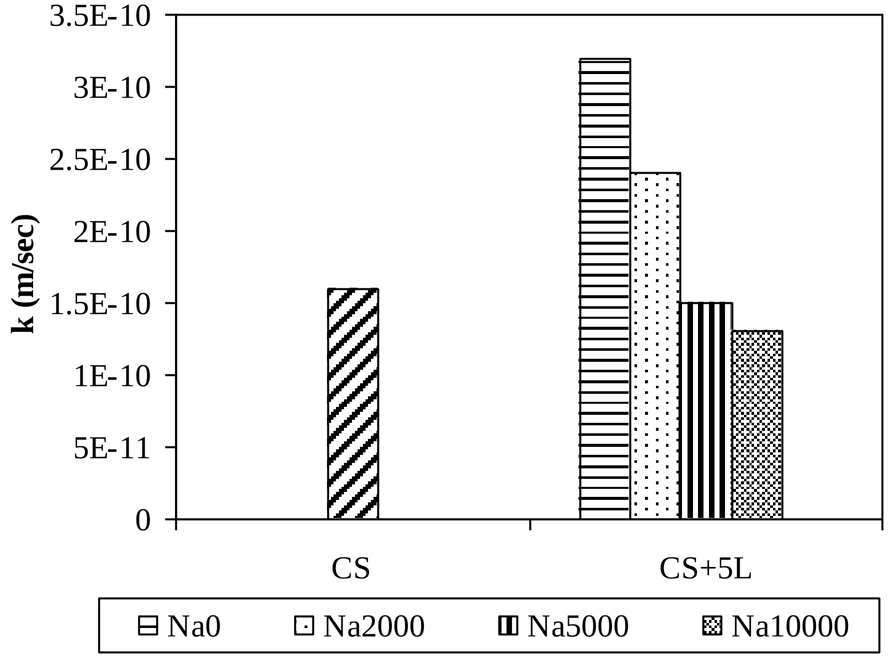


Figure 4.28 Permeability of the lime treated soils subjected to different concentration of sulfate

4.5 Effect of slag on lime treated soil subjected to different sulfate concentration

4.5.1 Effect of Slag on physical properties

It is known that the plasticity index is an effective parameter for controlling the swell potential of a soil. The higher the plasticity index, the higher the swell. The plasticity index values of the lime-treated soil with and without slag are shown in Figure 4.29. The figure indicates that when the lime-treated soil with different sulfate concentration was treated with 6% slag, reduction in the plasticity index values was obtained. The figure presents that the highest slag-induced reduction in the plasticity index had been obtained for the lime treated soil with 10000 ppm sulfate concentration. It can be observed in the figure that, the plasticity index of this soil without slag was 38 percent. When the soil was treated with 6% slag, the plasticity index of the soil decreased from 38 to approximately 8 percent, illustrating the ameliorating effects of slag treatment. The results obtained in Figure 4.29 substantiate the previous findings that slag treatment eliminates the undesirable effect of sulfate on the lime-treated soils and prevents the swelling of the soil. Addition of slag into the lime-treated soil decreases the plasticity index and a resulting reduction in the swell potential of the soil is obtained.

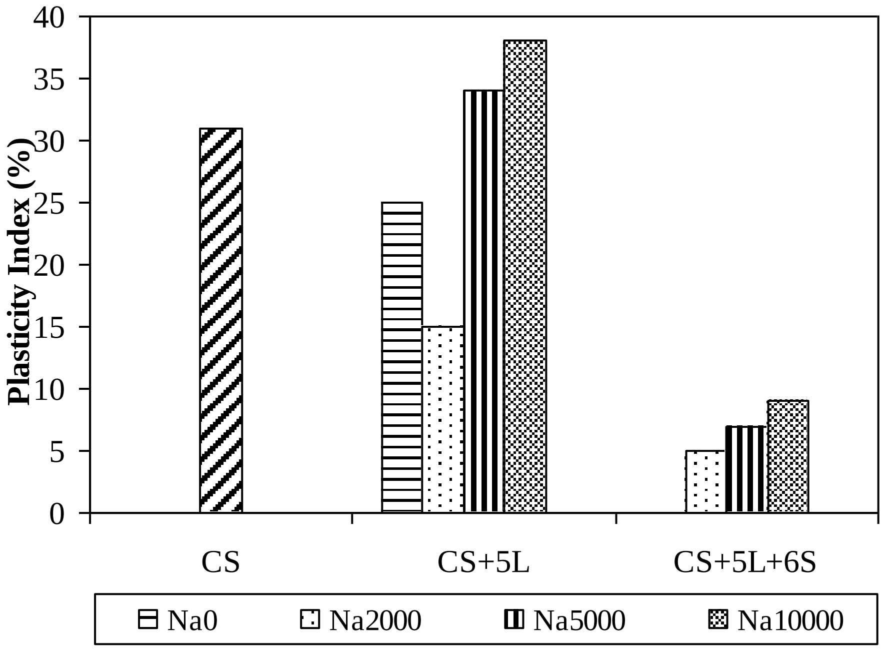


Figure 4.29 Plasticity index of CS+5L soil and CS+5L+6S soil subjected to different sulfate concentration

4.5.2 Effect of Slag on linear shrinkage value

In Figure 4.30, it can be seen that, when the lime-treated soil with different sulfate concentrations was treated with slag, a dramatic decrease in the linear shrinkage values was obtained. The linear shrinkage value of the lime-treated soil with 10000 ppm sulfate concentration decreased from 11 percent to approximately 8 percent. These results are in good agreement with the previous findings. In the presence of the slag, the effect of the sulfate on the lime-treated soils was suppressed and the forming of the ettringite minerals was prevented. Thus, decrease in the plasticity index and the linear shrinkage values and consequently decrease in the swell potential of the soil was obtained.

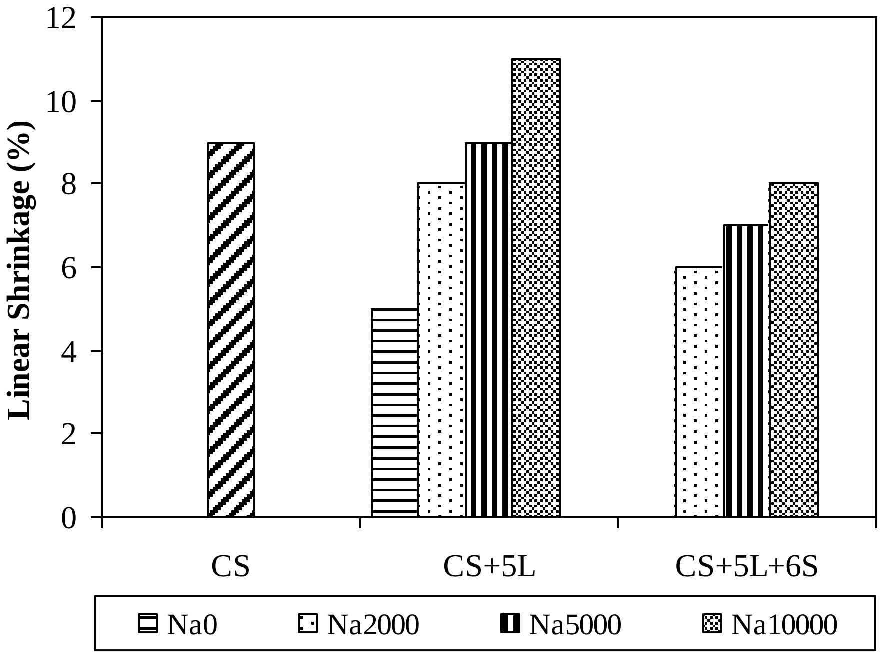


Figure 4.30 Linear shrinkage strain potential for CS, CS+5L and CS+5L+6S subjected to different sulfate concentration

4.5.3 Standard Proctor Compaction Test

Figure 4.31 presents the effect of lime and slag on compaction characteristics of the treated soils. The figure indicates that treatment of control soil with lime and slag decreases the maximum dry density values of the lime and slag treated soils and an increase in the optimum moisture content is obtained.

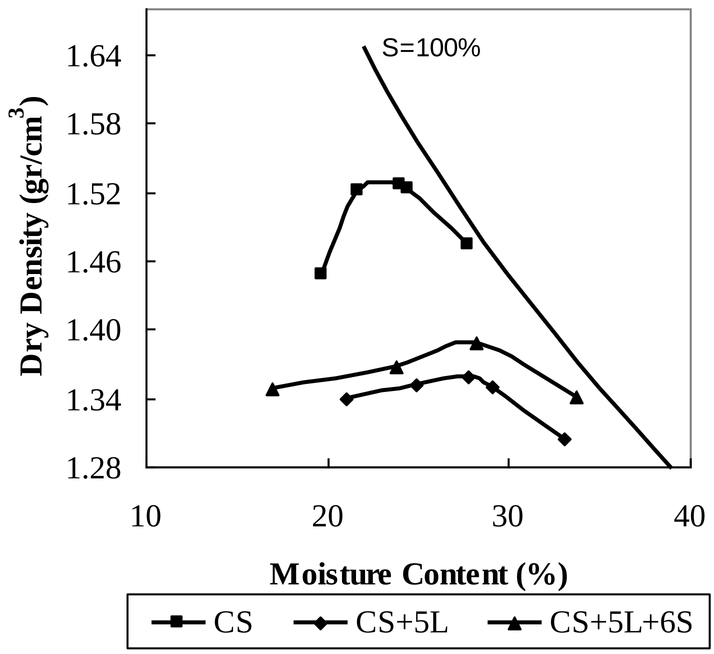


Figure 4.31 Compaction curves for CS, CS+5L and CS+5L+6S

4.5.4 Effect of Slag on Swell value

The effect of slag on swell potential for control soil, 5% lime-treated soil and 5% lime- treated soil with 6% slag and different sulfate concentrations are shown in Figure 4.32. Figure 4.32 shows that when 6% slag was added into the lime treated soils with different sulfate concentrations, instead of a rise in the swell potential, a reduction in the swell potential of the soils was obtained. The figure indicates that, in the presence of slag, the undesirable effect of sulfate on the lime treated soils was suppressed and the swelling of the lime-treated soil was prevented. Addition of 6% slag into the lime-treated soil with 5000 ppm and 10000 ppm sulfate concentrations resulted in a dramatic decrease in the swell potential. In Figure 4.32, in the presence of slag, the swell potential of the lime-treated soil with 10000 ppm sulfate concentration decreased from 8 percent to 1 percent whereas the lime treated soil with 5000 ppm sulfate concentration showed almost zero swell.

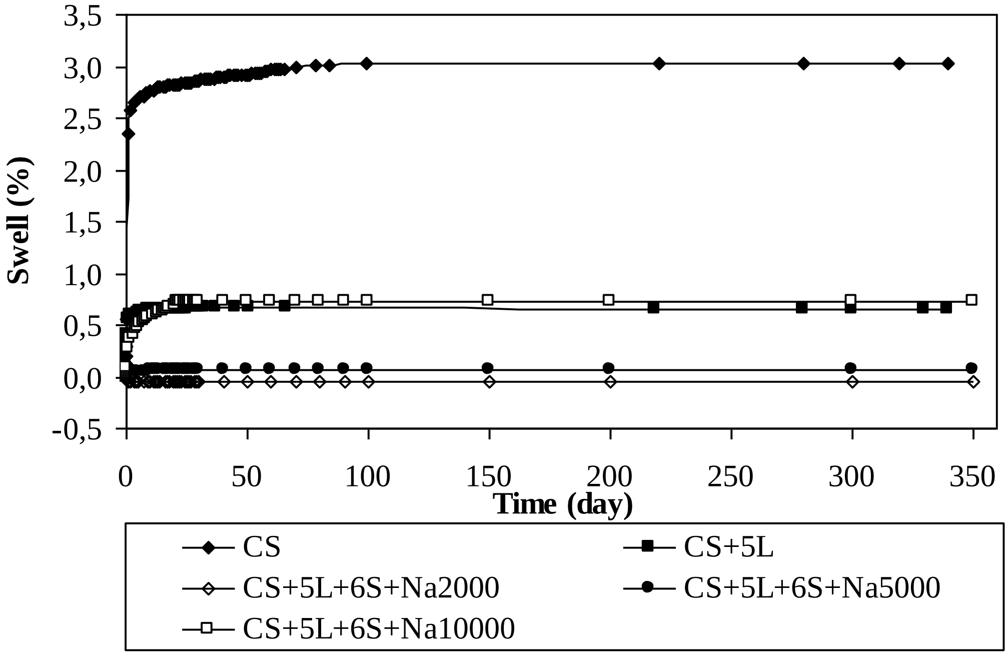


Figure 4.32 Swell potential of soils with 6% slag and different sulfate concentrations

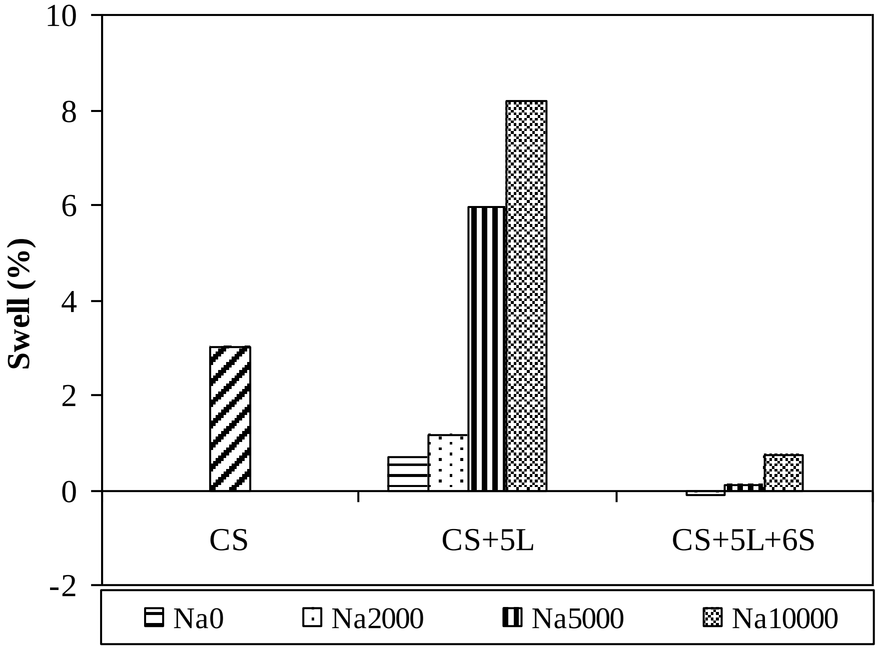


Figure 4.33 Swell potentials for CS, CS+5L and CS+5L+6S subjected to different sulfate concentration

Figure 4.33 gives the summary of the swell potential of the lime-treated soils with and without the slag treatment. The figure clearly shows the effect of slag on the swell potential of the lime-treated soils with different sulfate concentrations. Test results indicate how lime-induced heave of sulfate-bearing soils can be prevented by using slag.

4.5.5 Compressibility

The effect of slag on the compressibility characteristics of the lime treated soils is shown in Figure 4.34. The figure shows that slag is effective in decreasing the compressibility characteristics of the lime treated soils with sulfate. The results shows that the addition of slag into the lime treated soils subjected to different sulfate concentrations, eliminates the effect of sulfate and does not allow the formation of the ettringite minerals.

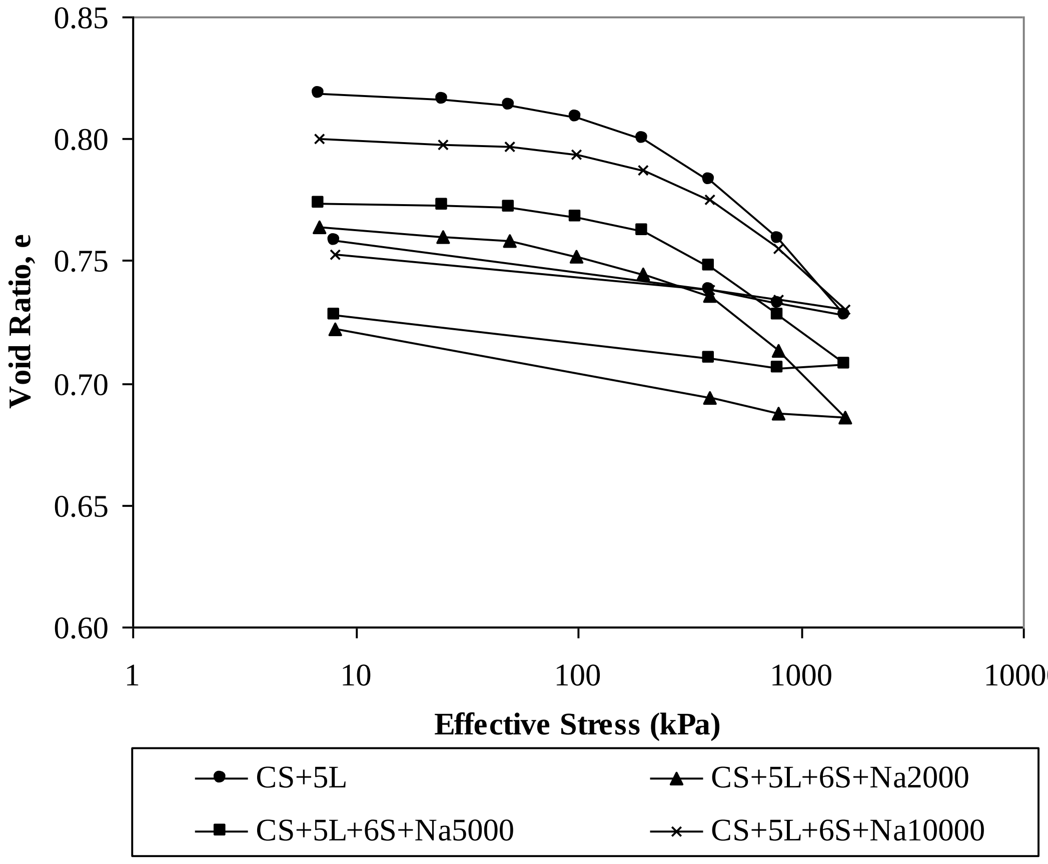


Figure 4.34 Void ratio versus effective stress curves for CS+5L+6S with different sulfate concentrations

4.5.6 Permeability

Figure 4.35 shows that the effect of the slag on permeability of lime-treated soils subjected to different concentrations of sulfate. The figure shows that the permeability of the soils decreased while the sulfate level of the soils increased. Figure also shows that the slag was very effective to destroy the effect of sulfate in lime-treated soils and permeability was not decreased due to the sulfate.

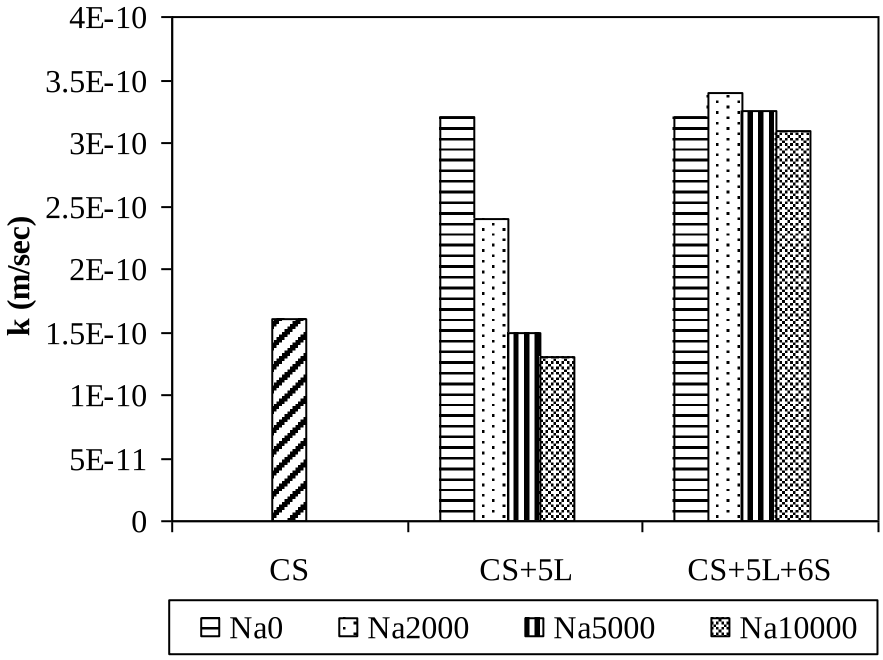


Figure 4.35 Effect of slag on permeability

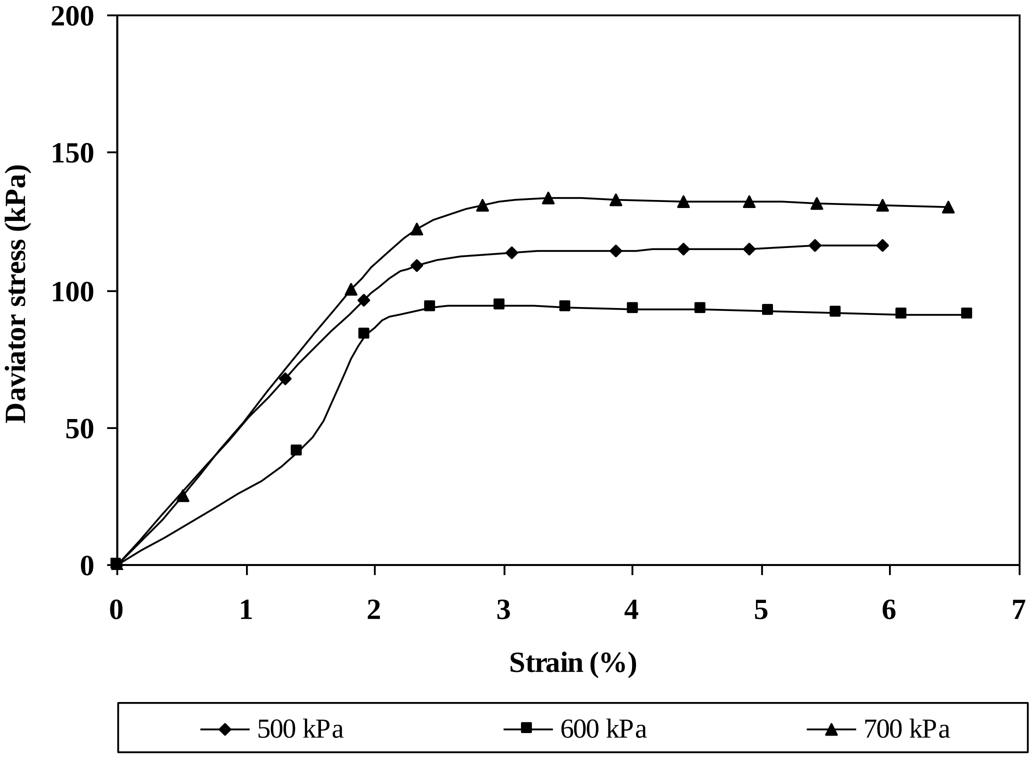
4.6 Consolidated Undrained (CU) Triaxial Test Results

As mentioned in the literature review section 2.7, there is very limited study on the consolidated undrained triaxial test on lime treated sulfate bearing soils. Sivapullaiah (2000) performed consolidated undrained triaxial tests on lime-treated soils subjected to different sulfate concentration and curing periods to determine the effect of the presence of sulfate on strength of the soils at short and long curing times. It was found that the presence of sulfate in lime-treated soils considerably decreased the shear strength of soils at long curing times (Sivapullaiah 2000).

In this study, lime was used to improve the plasticity and the strength of the expansive soils. In order to see the effect of lime on the strength of the treated soils, consolidated undrained triaxial (CU) tests were performed on the control soil and lime treated soils. The lime treated soils were also subjected to different sulfate concentration and the effect of sulfate on the strength of the lime treated soils was exmined. The consolidated undrained triaxial tests were conducted on the soils which were subjected to 2000, 5000 and 10000ppm sulfate concentration with curing periods of 7, 30 and 365 days. Three different cell pressure values were applied: 500, 600 and 700 kPa. Also back pressure values were 400, 500 and 600 kPa, respectively. Deviator stress versus axial strain was plotted by using the test data. The deviator stress-strain curves were ploted by using the total stress values. While drawing the p´- q diagrams effective stress was used. Effective strength parameters, effective cohesion and effective friction angles (c´ and ø´) were obtained from the Mohr's Circles plots.

4.6.1 Deviator stress – strain curves

Figure 4.36 shows the deviator stress-strain curves and pore water pressure-strain curves for the control soil under three different cell pressure values. Figure 4.36 shows that when the cell pressure increased, the peak stress was increased due to the increase in the confinement of the soil. the figure indicates that three of these curves did not have sharp peaks. The shape of the curve of the control soil was similar to a normally consolidated clay soil.



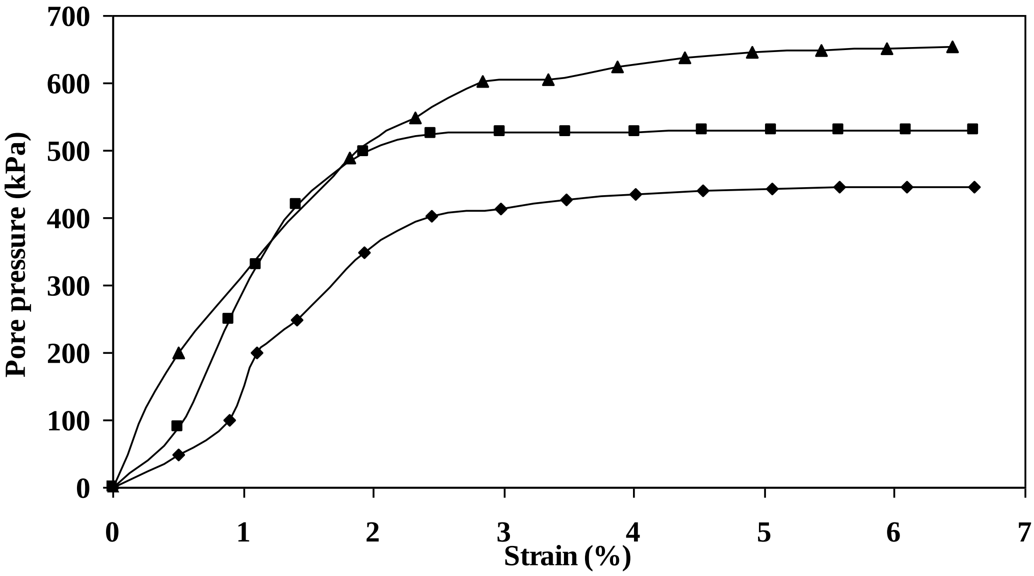


Figure 4.36 Deviator stress-strain and pore water pressure-strain curves for CS with different cell pressures

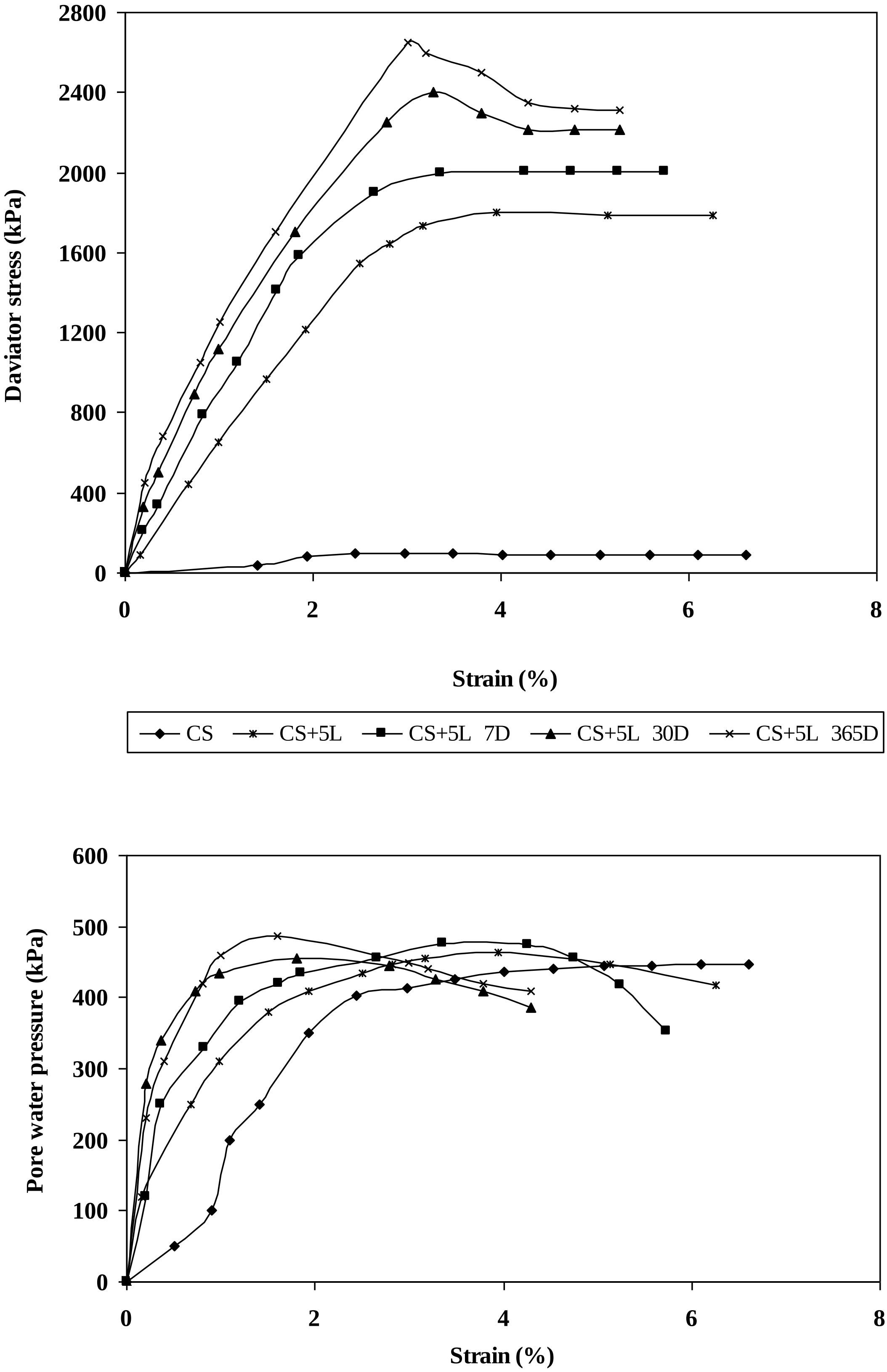


Figure 4.37 Deviator stress-strain and pore water pressure curves for CS and CS+5L (applied cell pressure 500 kPa)

Figure 4.37 indicates the deviator stress-strain relationship for the control soil and the lime treated soil with curing periods of 7, 30 and 365 days for 500 kPa cell pressure. The figure shows that the lime treatment increased the strength of the natural soil. The lime treated soil's strength increased together with the increase in the curing time. This was due to the reaction between the silica from soil and calcium from lime treatment, causing cementation of the soil particles by pozzolanic reactions. The figure indicates that there is a linear increase in the strength of the soils with the increase in the curing periods. The figure also indicates that due to the increase in curing periods, the peak of the deviator stress-strain curves became more pronounced and gave a specific peak. The deviator stress-strain curve obtained in 365 days curing periods, have a very sharp peak, resembling to the behavior of the over-consolidated clay.

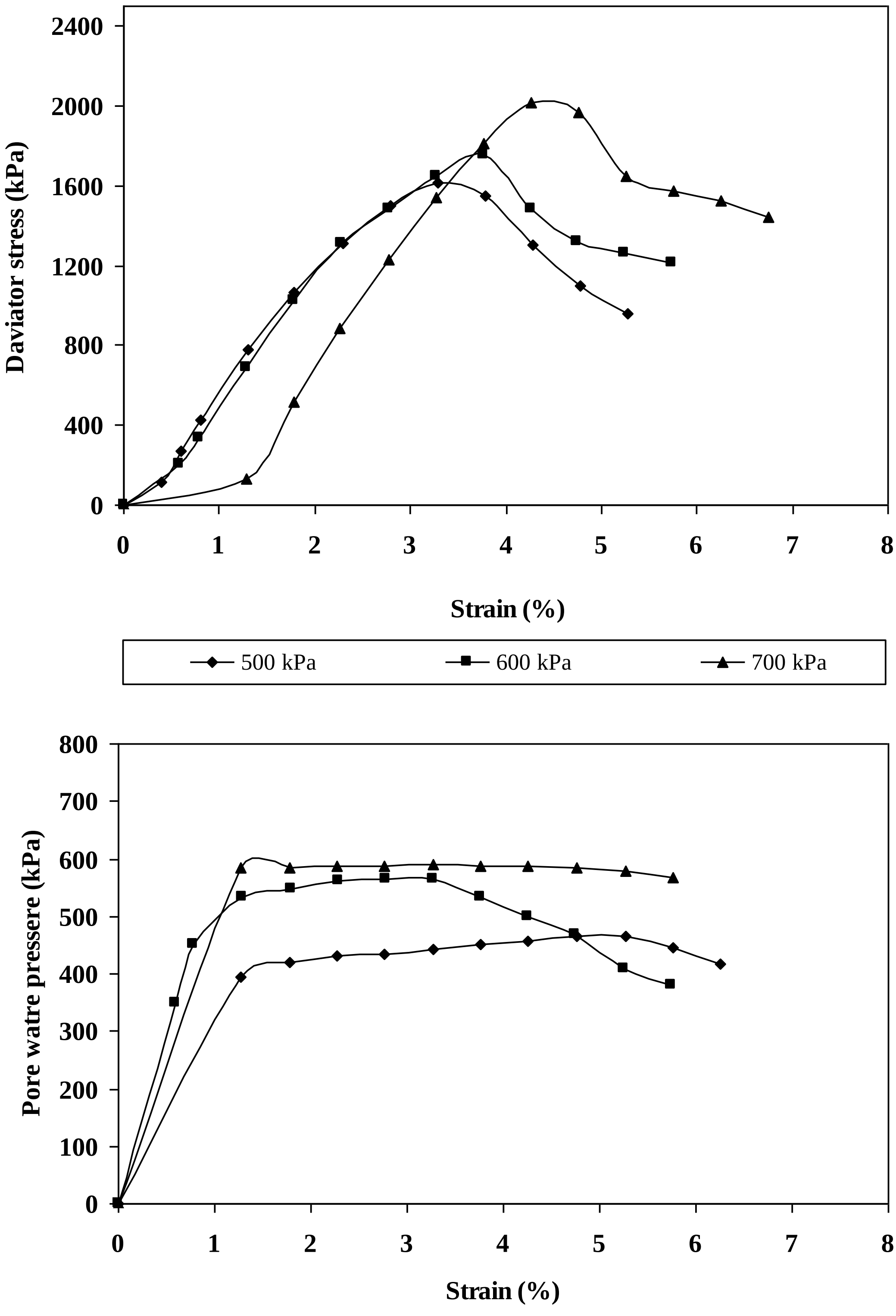


Figure 4.38 Stress-strain curves of lime treated soils subjected to 2000 ppm sulfate

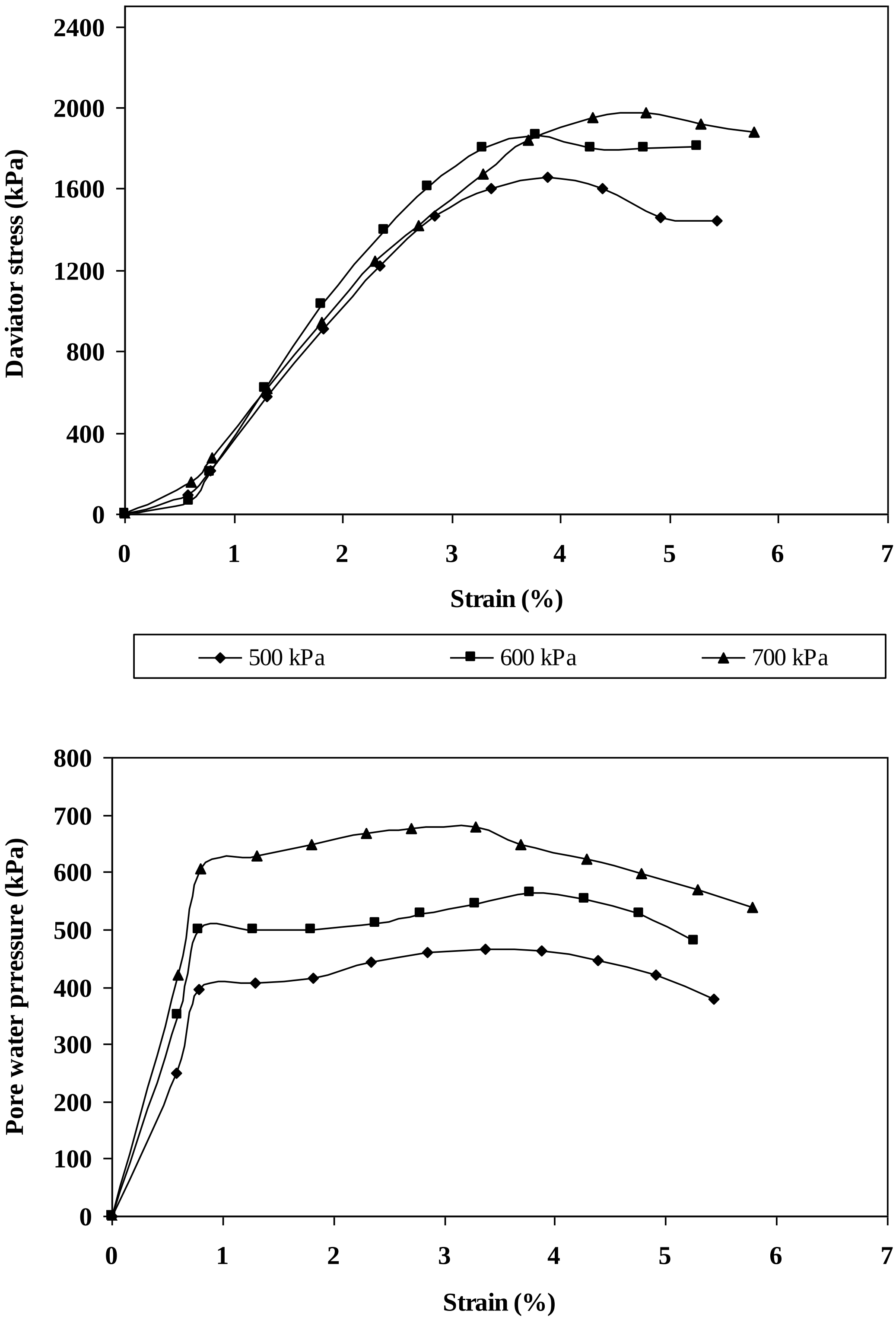


Figure 4.39 Stress-strain curves of lime treated soils subjected to 5000 ppm sulfate

Figures 4.38, 4.39 and 4.40 represent the deviator stress-strain curves for the lime treated soils with different sulfate concentration and different cell pressure values. Stress-strain curves of lime treated soils subjected to 2000ppm sulfate with applied cell pressure of 500, 600 and 700 kPa at zero curing time is shown in Figure 4.38. According to the figure, it was observed that when the cell pressure increased, the deviator stress at failure also increased. The peaks became more pronounced by increasing the cell pressure. From Figures 4.38-4.40, it can be seen that the presence of sulfate in lime treated soil did not affect the nature of the deviator stress-strain curves at zero curing times.

Figure 4.41 represents the effectiveness of the curing time on the lime treated soils subjected to 2000 ppm sulfate. Figure 4.41 shows that the strength of lime treated soils with 2000 ppm sulfate concentration increased continuously with the increase in curing periods of 7, 30 and 365 days. The figure indicates that 2000 ppm sulfate concentration is very low and at such a sulfate concentration, the formations of the ettringite minerals were not possible. Therefore the pozzolanic reaction was not prevented and the strength of the lime treated soil increased due to the cementation.

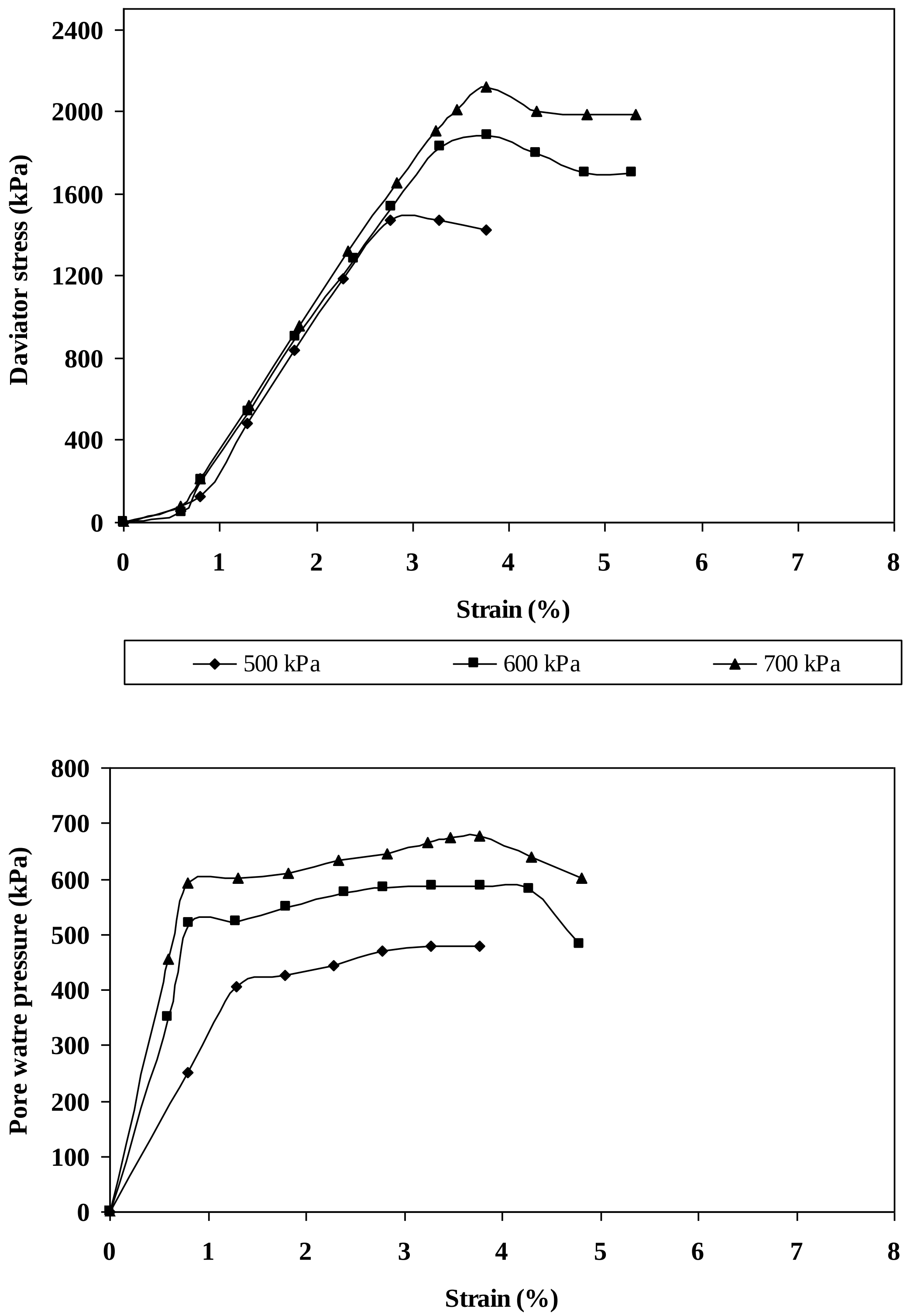
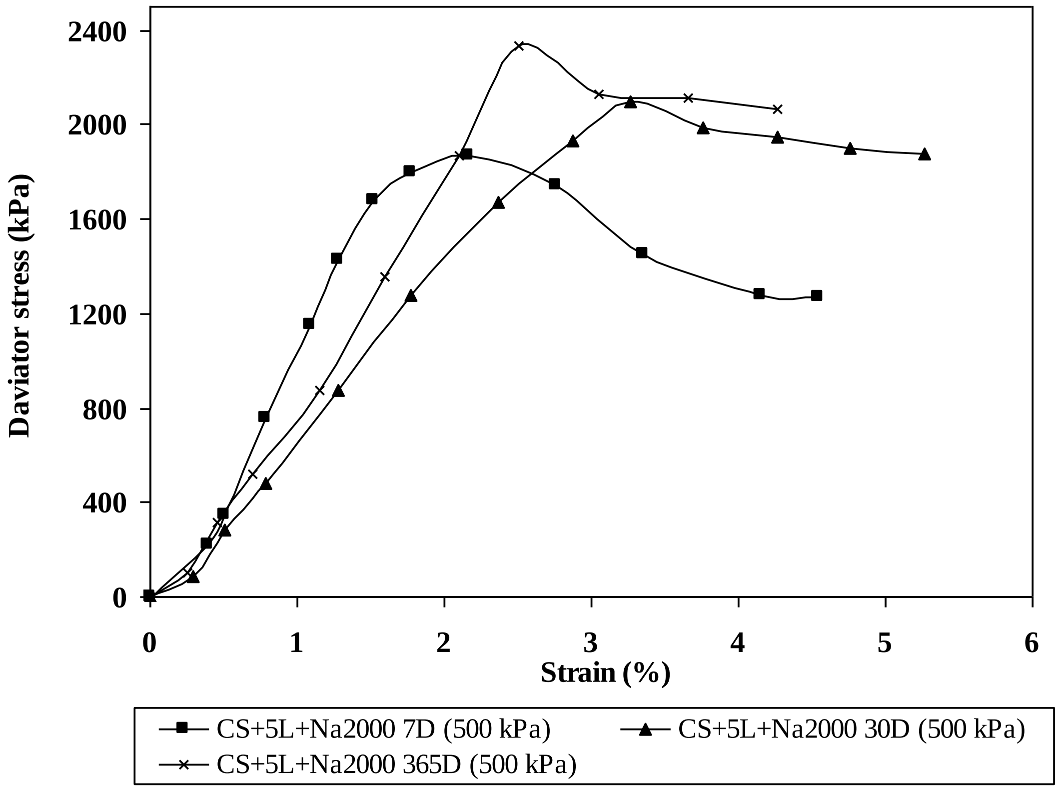


Figure 4.40 Stress-strain curves of lime treated soils subjected to 10000 ppm sulfate



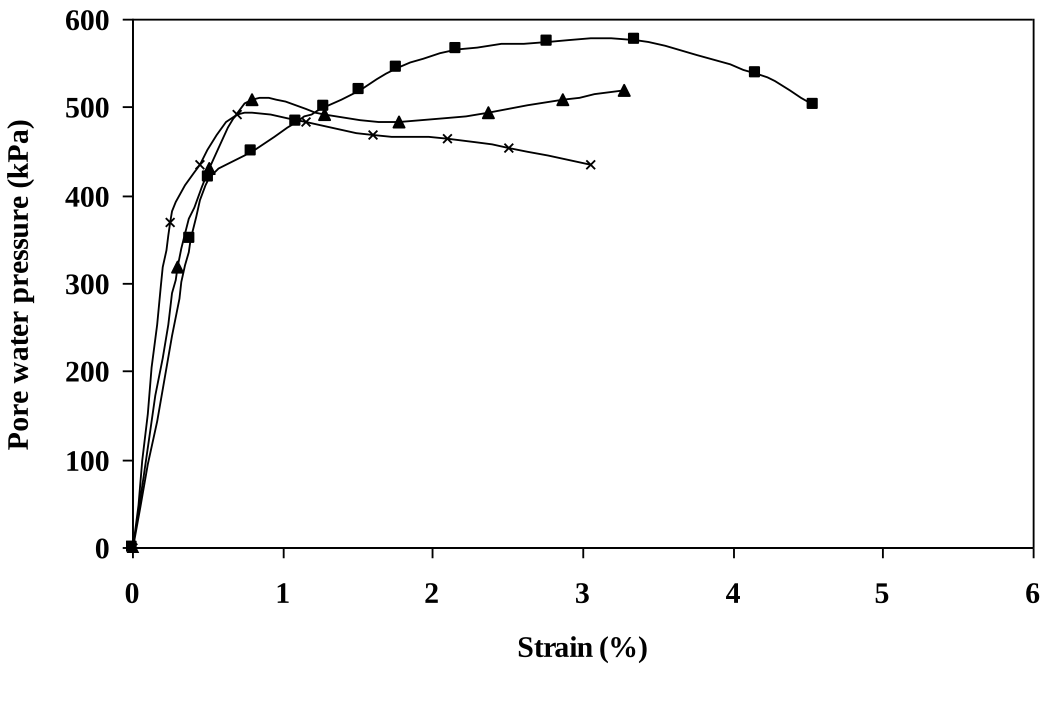


Figure 4.41 Effect of curing time on 2000 ppm sulfate lime treated soils

Figure 4.42 shows that the strength of the lime treated soils with 5000 ppm sulfate concentration increased in 7 days curing periods but then the strength of the same soil decreased regularly in 30 and 365 days. Test results indicated that the stress-strain curves became nonlinear and showed mild peaks while increasing the curing periods. This result showed that after 30 days curing periods of the lime treated soils with 5000 ppm sulfate, the ettringite minerals started to form and prevented the formation of the cementitious compounds and caused a reduction in strength.

Figure 4.43 indicated the effect of curing time on the strength of the lime treated soils subjected to 10000 ppm sulfate under 500 kPa cell pressures. After curing of 7 days, a decrease in the strength was observed within the lime treated soil with 10000 ppm sulfate concentration. The same reduction in the strength of the same soil was obtained at 365 days curing period. Test results indicated that 10000 ppm sulfate level was high and this concentration of sulfate accelerated the formation of the ettringite minerals which caused reduction in the strength of the lime treated soils. The figure shows that the availability of high sulfate level in the soils causes gradual reduction in strength of the lime treated soils at longer curing periods. This reduction in the strength was resulting from the formation of secondary minerals of ettringite. Formation of the ettringite minerals does not allow the pozzolanic reaction to be completed. In lime treated soils without sulfate pozzolanic reaction is successfully completed after the reaction of soil silica and calcium. However, sulfate in lime treated soils react with soil silica and aluminum to form the ettringite minerals. These highly plastic minerals do not allow the cementation of soil particles. Consequently, after longer curing periods, at high sulfate levels, the stress paths become similar to normally consolidated soils due to the broken cementation of the particles.

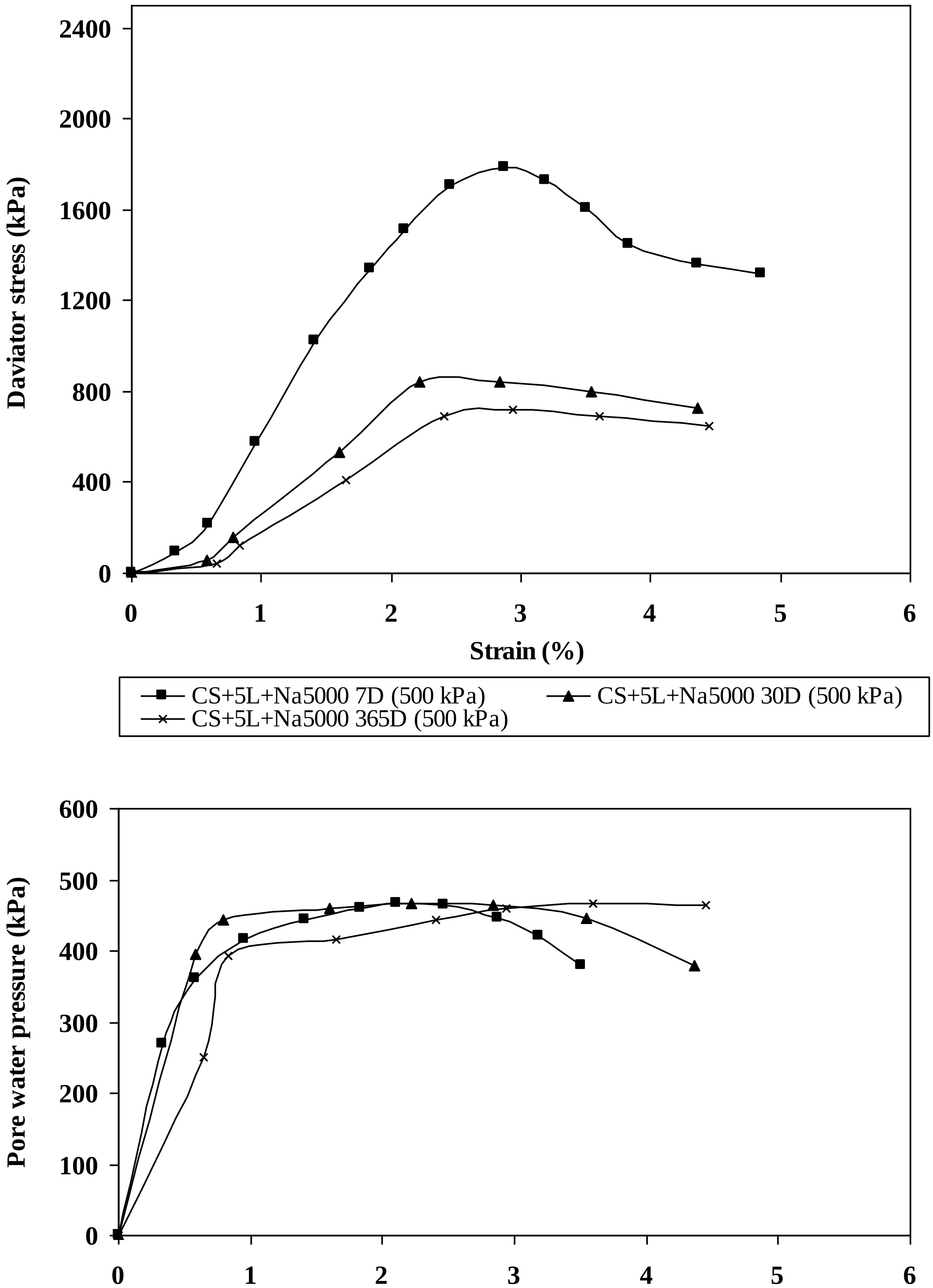


Figure 4.42 Effect of curing time on 5000 ppm sulfate lime treated soils

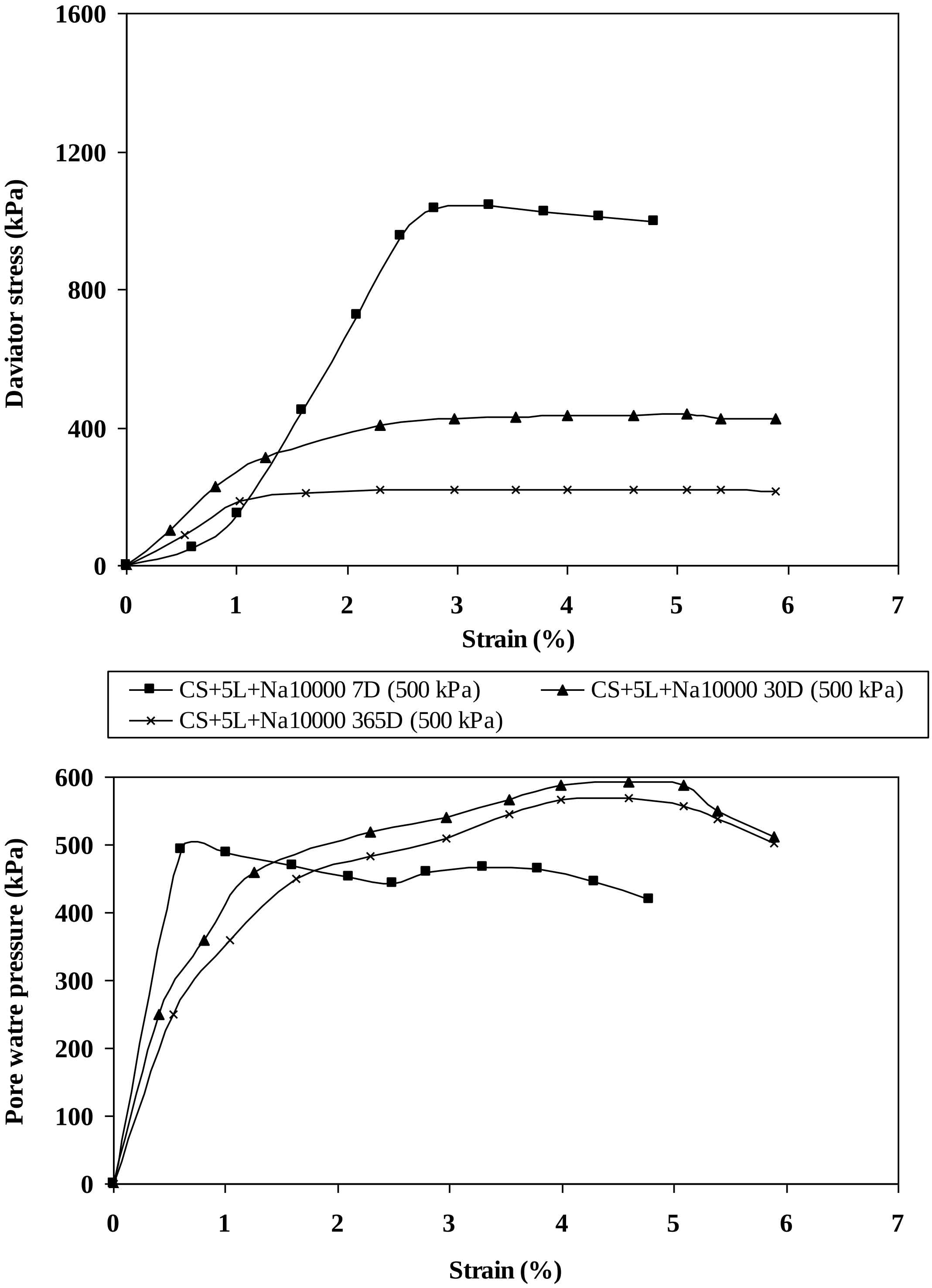


Figure 4.43 Effect of curing time on 10000 ppm sulfate lime treated soils

4.6.2 Effective Stress paths

The cementation characteristic of the soil was examined by using the effective stress path curves. The effective stress paths of the control soil are shown in Figure 4.44. The figure indicates that the stress paths of the control soil are curved toward the left side. Since the stress paths became curved toward the left side, the soil was comprehensive to be normally consolidated. From the figure, it can be seen that the stress paths curve roundness was increased by increasing the cell pressures which was a typical behavior for the normally consolidated clay.

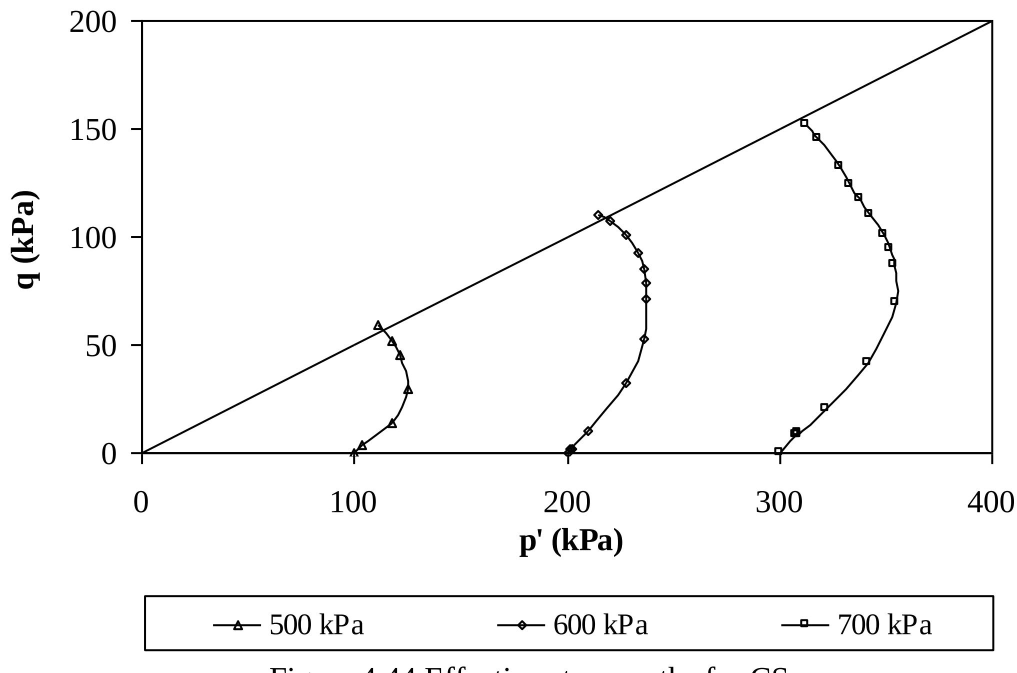


Figure 4.44 Effective stress paths for CS

Figure 4.45 shows the effect of the lime treatment on the stress paths. Figure indicates that when the soil was treated with lime, stress paths tended to become linear and looked like over-consolidated clay soils stress paths. This indicates that when the soil particles are cemented, the effective stress paths start to become linear and change its direction. For over-consolidated soils which are similar to the cemented soils, stress paths are mostly linear towards the right side. Test results indicate that the result of the lime treatment leads to an increase in the cementation of the soil particles and causes the soil to behave like over-consolidated clays.

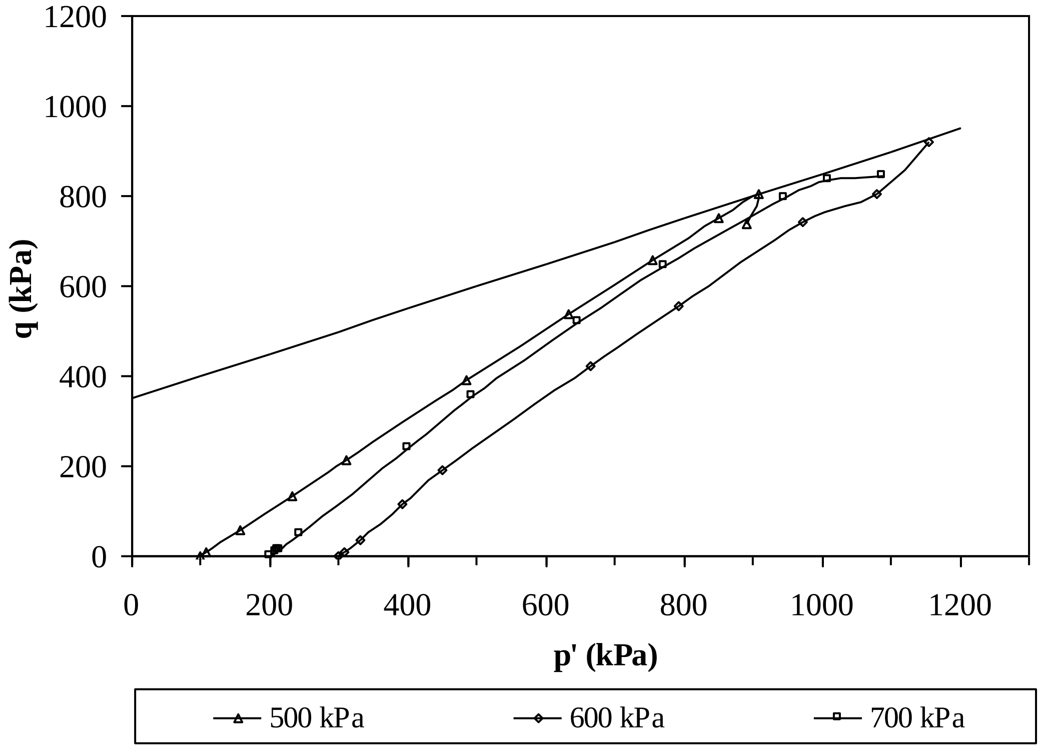


Figure 4.45 Effective stress paths for lime treated soils

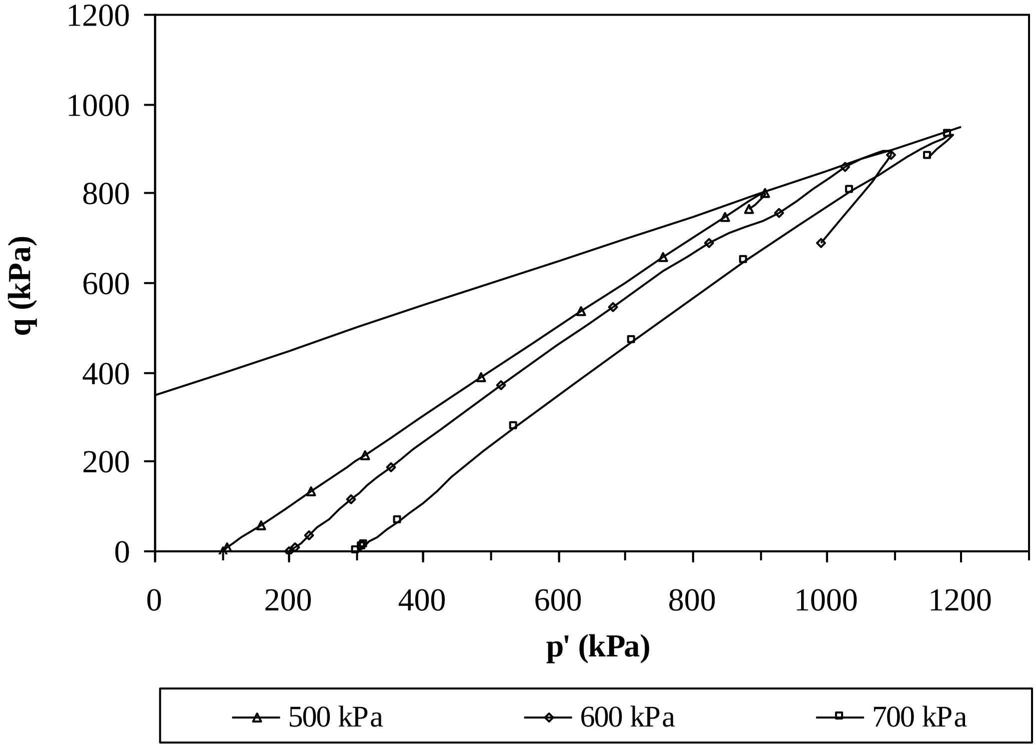


Figure 4.46 Effective stress paths for lime treated soils subjected to 2000ppm sulfate

The effect of sulfate on stress paths for lime treated soils is shown in Figures 4.46, 4.47 and 4.48. Figure 4.46 indicates the effect of 2000 ppm sulfate on the stress paths for lime treated soils at different applied cell pressures at, zero curing time. From the figure, it was observed that 2000 ppm sulfate level was not high enough to change any characteristics of the lime treated soils. The soil at this concentration behaved like an over-consolidated soils which was similar to the behavior of the lime treated soils. Also for 5000 ppm and 10000 ppm sulfate soils, no changes were observed on the effective stress paths at zero curing time.

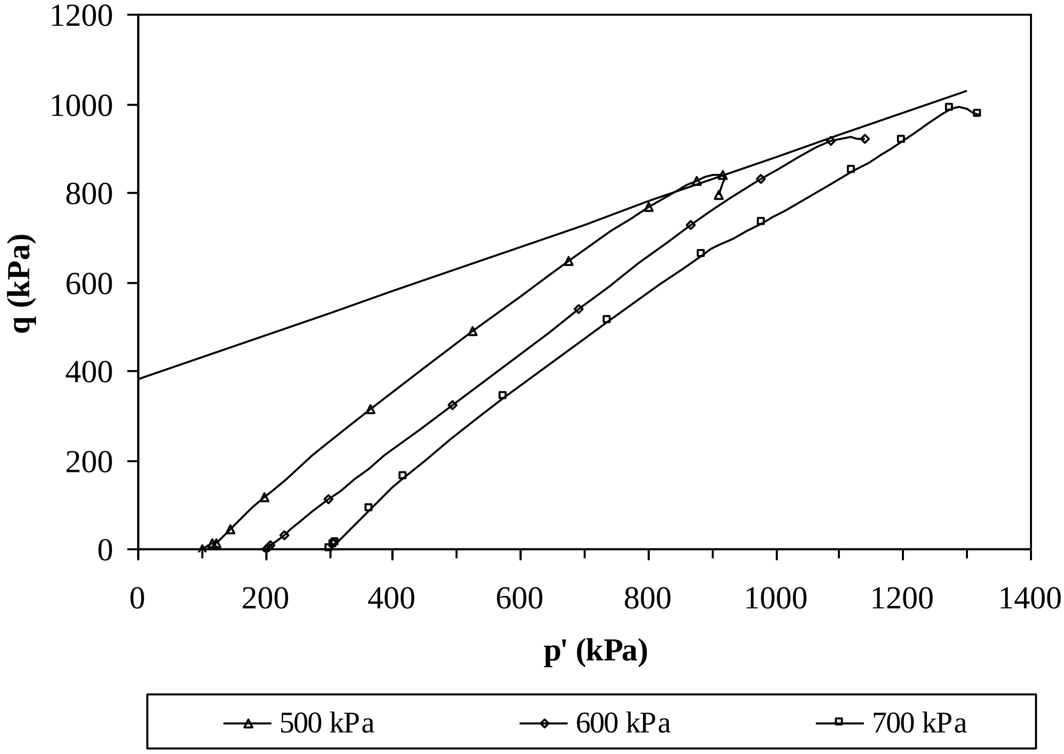


Figure 4.47 Effective stress paths for lime treated soils subjected to 5000 ppm sulfate

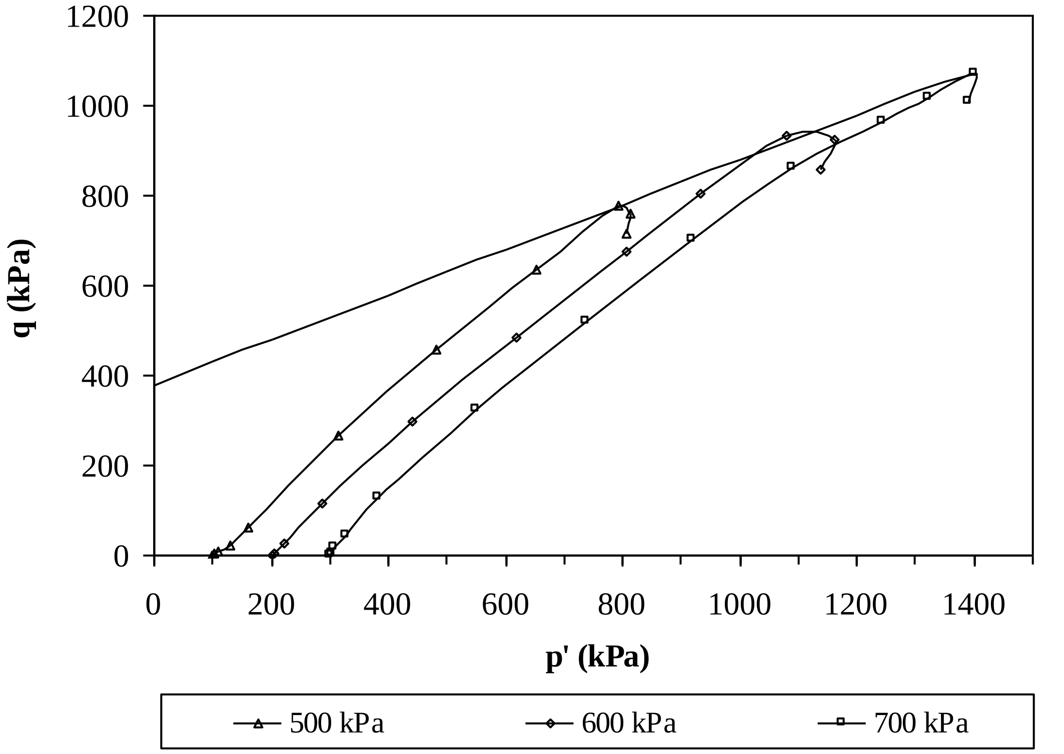


Figure 4.48 Effective stress paths for lime treated soils subjected to 10000 ppm sulfate

4.6.3 Effect of Curing Time on Effective Stress Paths

It is known that the effective stress paths of the lime treated soils are similar to the cemented soils that are the over-consolidated clay and the stress paths of these soils are linear. In this part of the study, the effect of curing time on the stress paths of the lime treated soils with different sulfate level has been studied and the results are presented below.

Figure 4.52 represents the effect of 365 day curing time on the stress paths for the lime treated soil. As it can be seen in Figure 4.52, the stress paths of the lime treated soils became more and more linear and the roundness decreased due to the rises of curing periods. The figure shows that the lines become linear without any rounded part after 365 days curing periods. The changes in the shape of the stress path of the lime treated soils after 365 days curing time can be explained due to the cementation of the soil particles due to the pozzolanic reactions. As a result of the cementation of the soil particles, the stress paths changed from rounded to linear shape of the stress paths. With increasing curing time, the bonds between the soil particles became very strong and the linearity of the stress path increased.

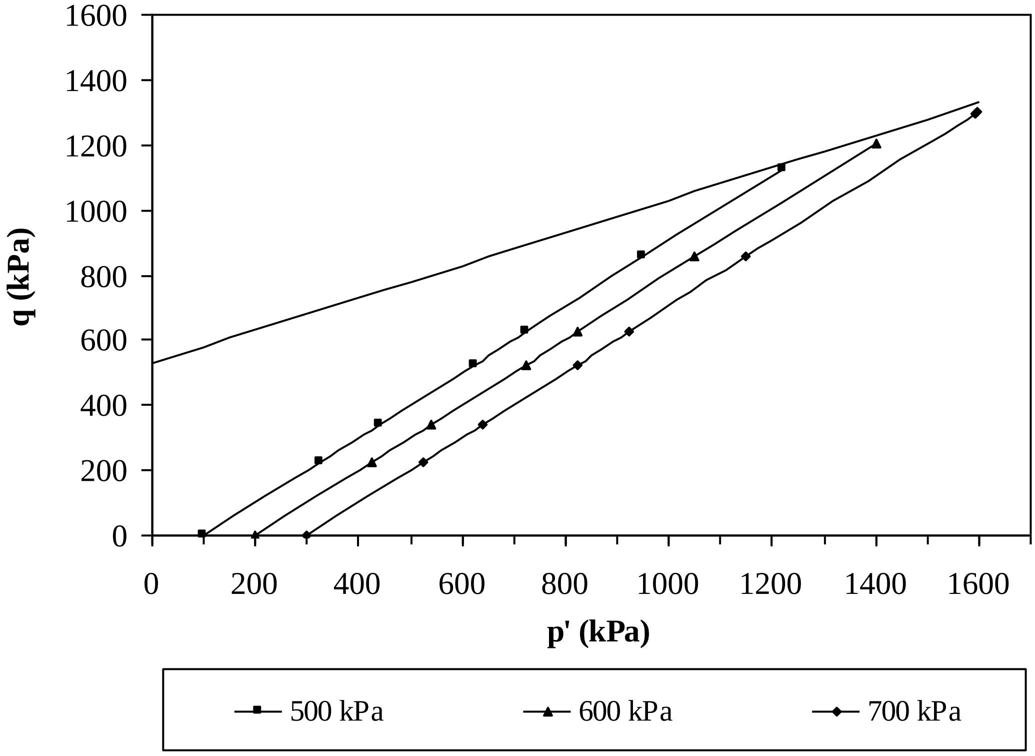


Figure 4.49 Effective stress paths for lime treated soil at 365 days curing periods

Figures 4.50 and 4.51 investigate the curing time effect on the effective stress path for the lime treated soils subjected to 2000 ppm sulfate. The figures indicate that 2000 ppm sulfate level is not high enough to affect the characteristics of the lime treated soils. The ettringite formation was not possible at this sulfate levels. The pozzolanic reactions proceeded successfully with long curing periods in low sulfate levels.

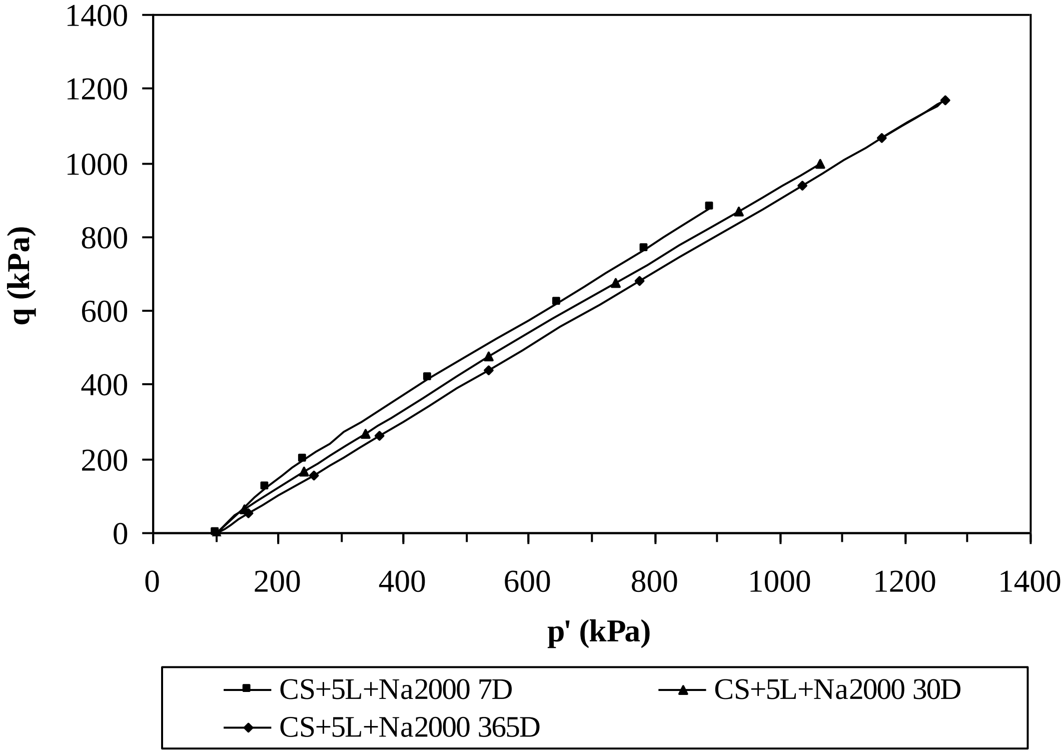


Figure 4.50 Effect of different curing times on the stress paths for lime treated soils subjected to 2000 ppm sulfate

Figures 4.52 and 4.53 shows the effect of curing time on the effective stress paths for the lime treated soils subjected to 5000 ppm sulfate. The figures indicated that the treated soils stress paths were cured at 7, 30 and 365 days. Figure 4.52 indicate that after a long curing period of 365 days, the effective stress paths became curved. That can be explained due to the formation of the ettringite minerals which prevent the pozzalanic reactions and cause the breaking of the cementation bonds. Therefore, at longer curing periods, the stress paths became curved towards the left at 5000 ppm sulfate concentration.

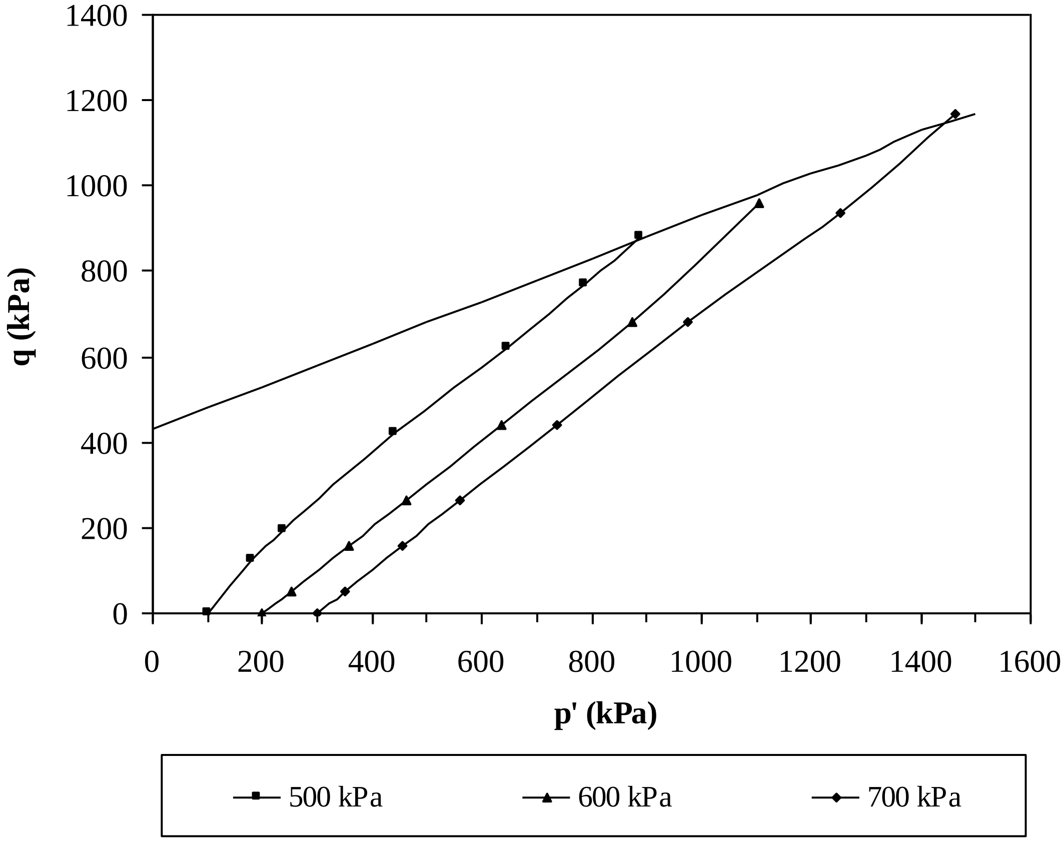


Figure 4.51 Effective stress paths for lime treated soils subjected to 2000 ppm sulfate cured at 365 days

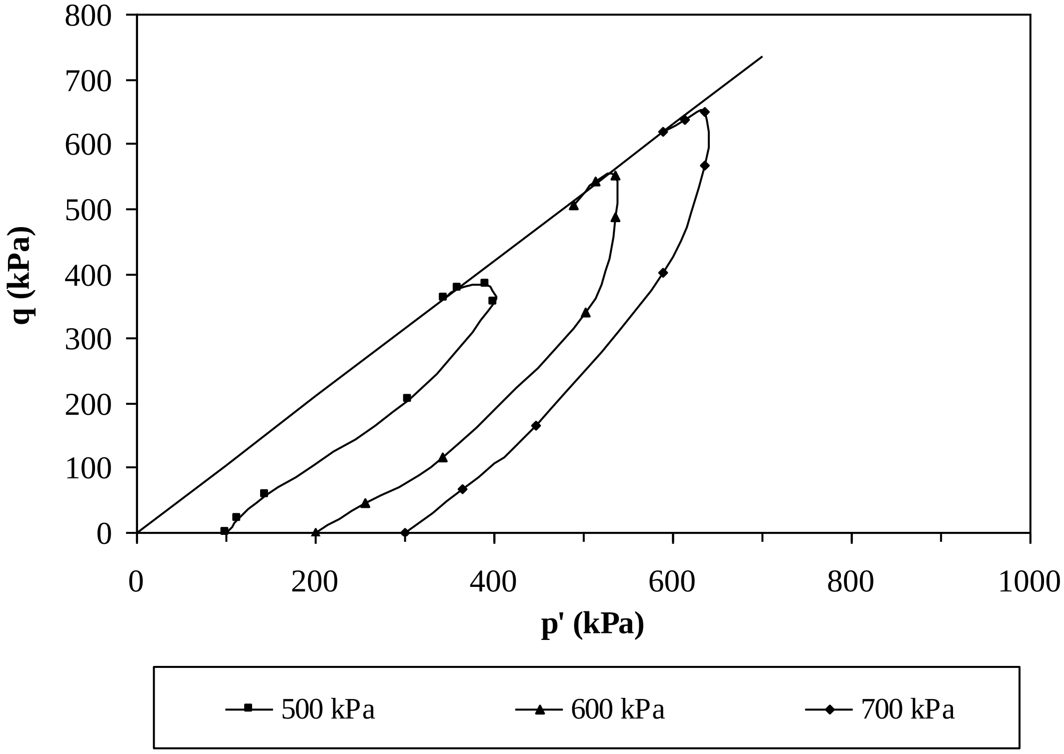


Figure 4.52 Effective stress paths for lime treated soils subjected to 5000 ppm sulfate cured at 365 days

Different curing times for the lime treated soils subjected to 5000 ppm sulfate are shown in Figure 4.53. The variation of effective stress paths curves for long term and short term curing periods are shown in Figure 4.53. After a long term of curing period, the curves become more and more rounded as displayed in Figure 4.53.

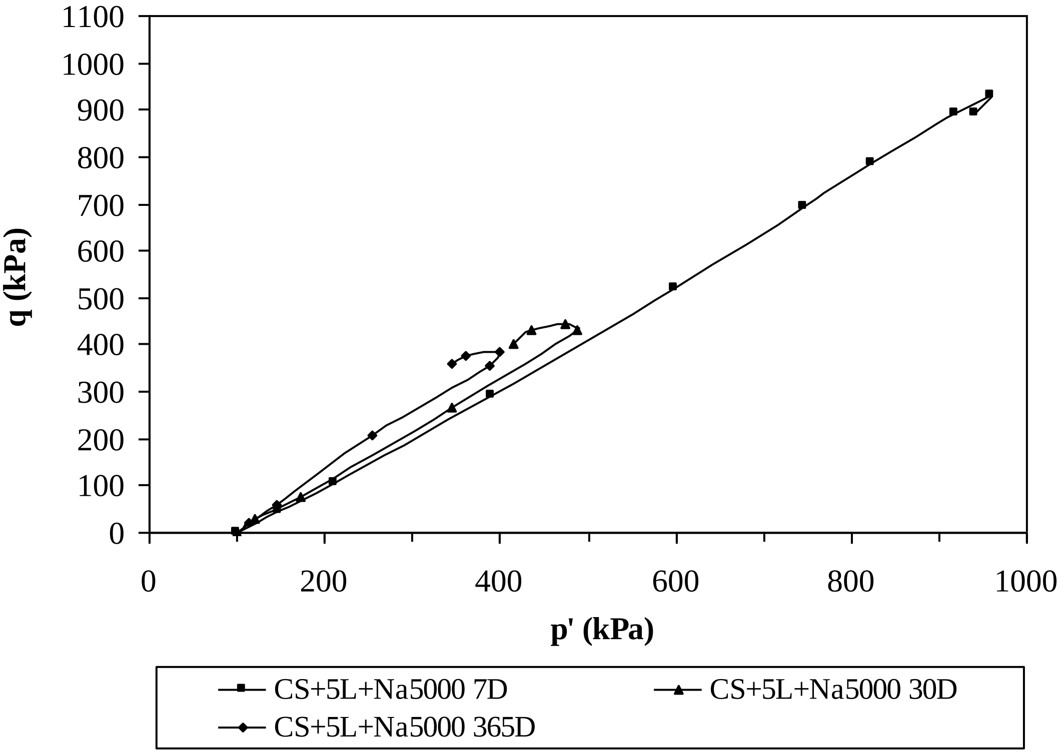
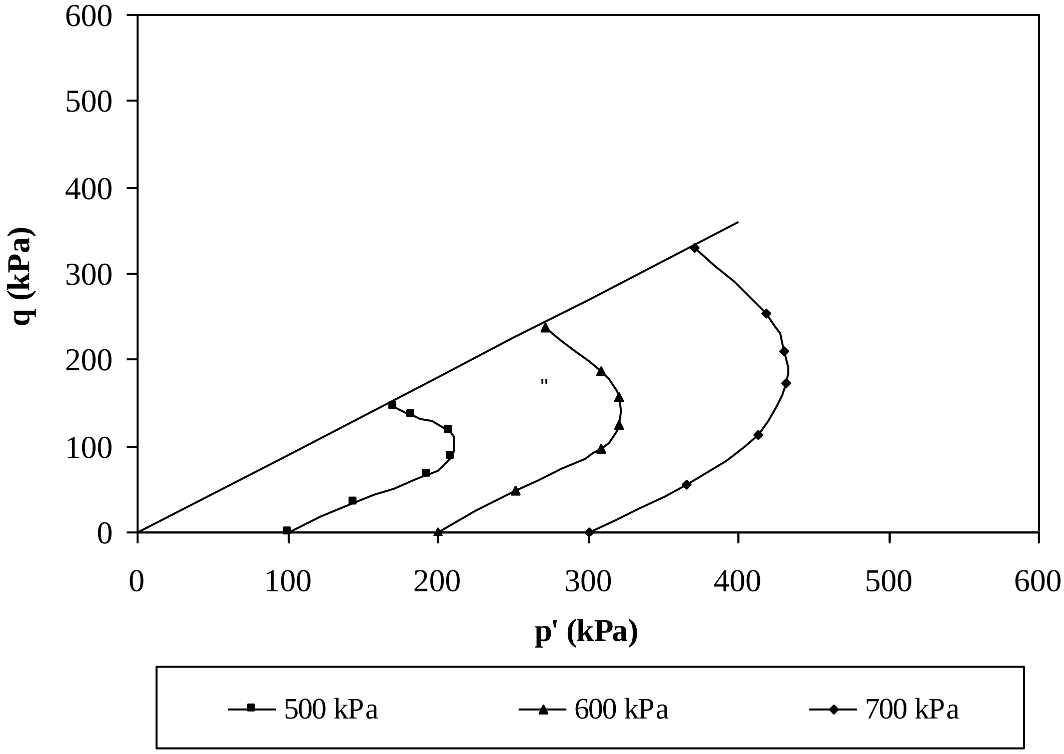


Figure 4.53 Effect of different curing times on stress paths for lime treated soils subjected to 5000 ppm sulfate

The effective stress paths of lime treated soils subjected to 10000 ppm sulfate at different curing periods and different cell pressures are given in Figures 4.54 and 4.55. Figure 4.54 clearly shows that after long curing periods, the effective stress path curves become similar to normally consolidated clays. The figure indicates that the cell pressure values also affect the curve's roundness. Effective stress path curved roundness increase by the increase in the cell pressure.



. Figure 4.54 Effective stress paths for lime treated soils subjected to 10000 ppm sulfate cured at 365 days

Figure 4.55 indicates the long and short curing time effects on the effective stress paths for the lime treated soils subjected to 10000 ppm sulfate. The figure indicates that after 7 days of curing period, effective stress path curves become curved towards the left side. The roundness of the curves increase with the increase in curing periods. This can be explained due to the formation of the new ettringite minerals and the broken bonds of the cementations. The figure indicates that after a long curing period, the effective stress path curves became similar to the characteristic of a normally consolidated clay.

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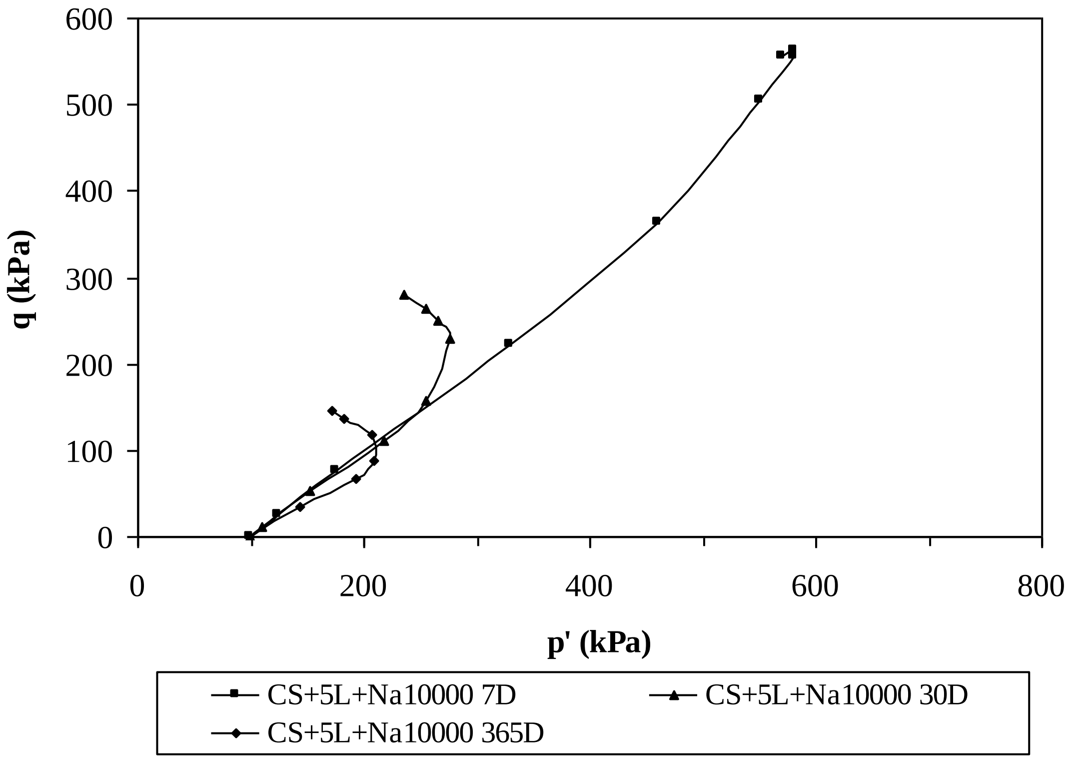

Figure 4.55 Effect of different curing times on the stress paths for the lime treated soils subjected to 10000 ppm sulfate

4.6.4 Shear strength parameters

The effective strength parameters c´ and ø´ were obtained from the Mohr's circles plots. Figures 4.56, 4.57 and 4.58 show the Mohr's circles of the control soil, lime treated soils and lime treated soils with 10000 ppm sulfate concentration, respectively. The obtained effective strength parameters for the control soil CS, the lime treated soil and the lime treated soil with different sulfate concentrations were shown in Table 4.4. The effective cohesion and the effective friction angle of the control soil were obtained to be 0 and 28^0, respectively. Test results represents that the addition of lime into the control soil created remarkable increase in the effective shear strength parameters due to the flocculation and cementation of the soil particles.

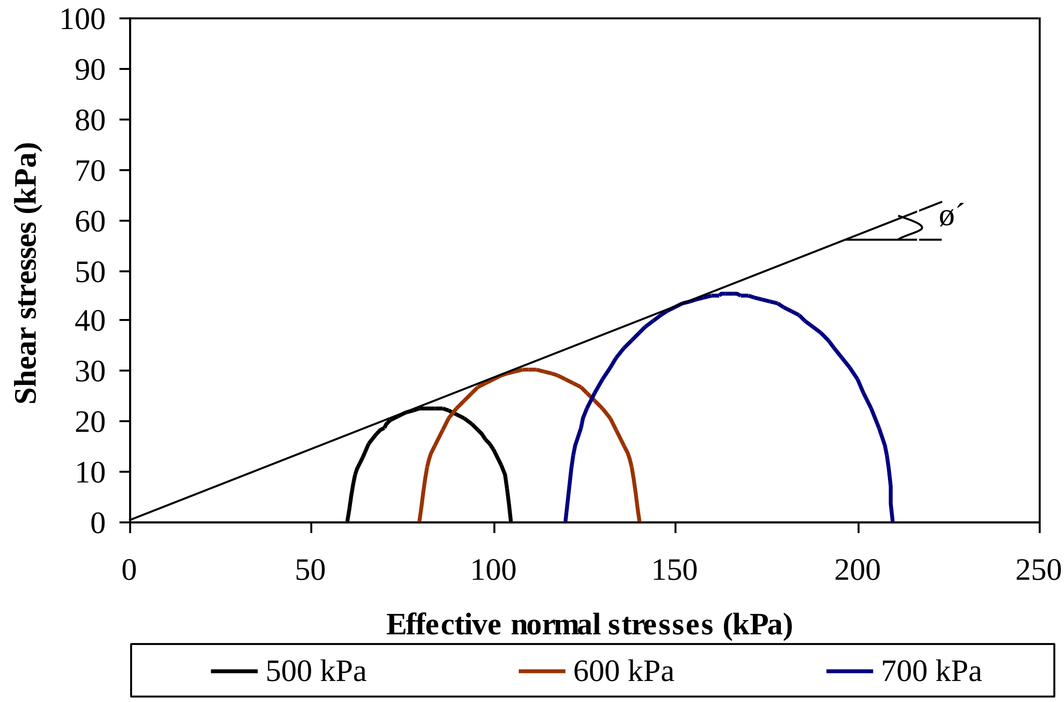

Figure 4.56 Mohr's circles of control soil

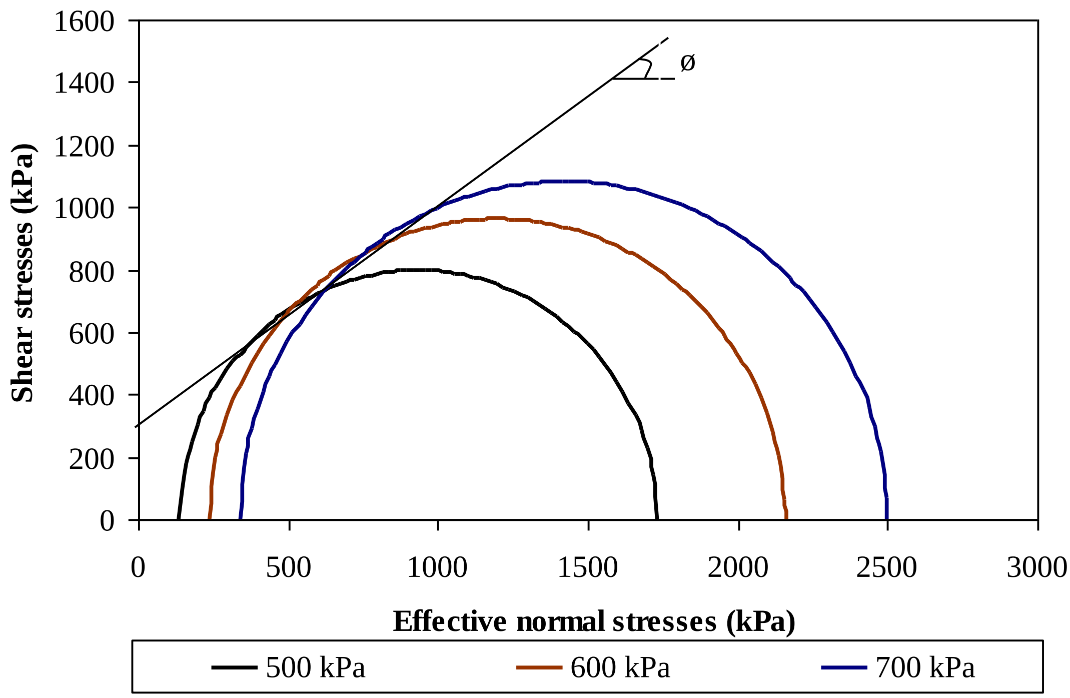

Figure 4.57 Mohr's Circles of lime treated soils

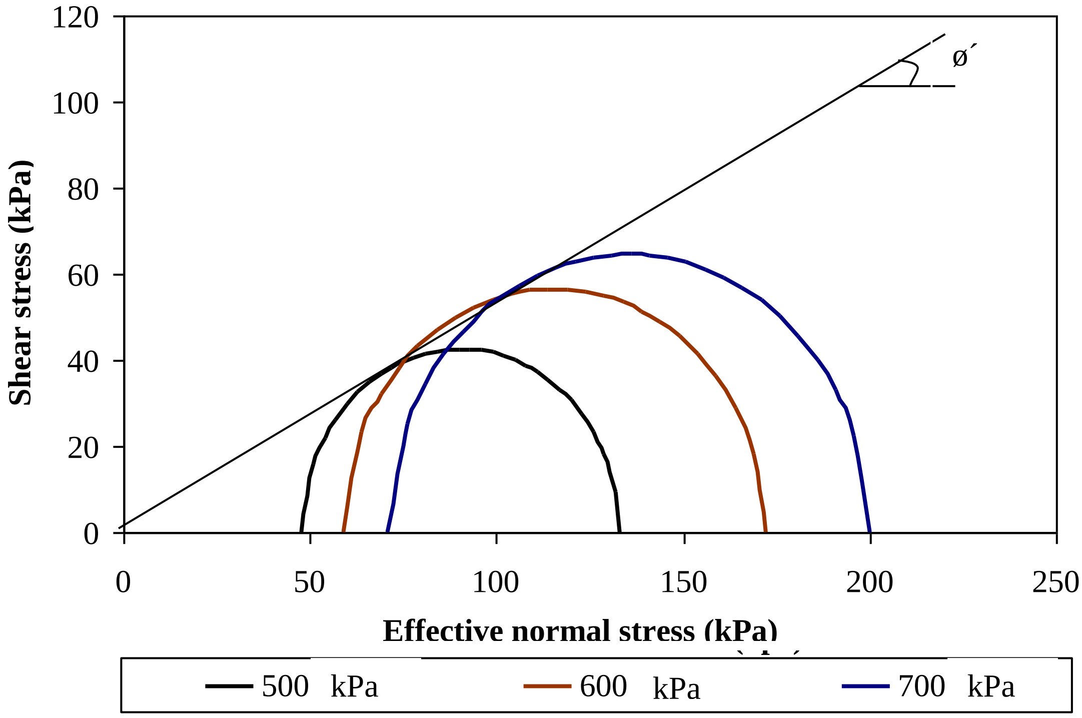

Figure 4.58 Mohr's Circles of lime treated soils with 10000 ppm sulfate concentration at 365 days curing period

Table 4.4 Shear strength parameters for CS, CS+5L and CS+5L subjected to different sulfate concentrations at different curing time

	Curing time (days)	c´ (kpa)	ø´ (^{0})
Control Soil	0	0	29
CS+5L	7	120	54
	30	285	54
	365	296	53
CS+5L+Na2000	7	108	54
	30	275	55
	365	282	55
CS+5L+Na5000	7	97	54
	30	205	48
	365	215	49
CS+5L+Na10000	7	93	52
	30	24	49
	365	0	48

The values in Table 4.4 show that treatment of the soil with lime increased the effective cohesion and the friction angle. The effective shear strength parameters continued to increase with the increase in curing time. The pozzolanic reaction increased the cementation of the soil particles and that resulted in an increase in the shear strength parameters. Test results in Table 4.4 indicated that at higher concentration of sulfate: 5000 and 10000 ppm, the effective shear strength parameters of the lime treated soils decreased. Especially, the shear strength parameter, c' of the lime treated soil at 10000 ppm sulfate concentration decreased dramatically with the increase in curing time and became 0 at 365 days. That is because of the formation of the highly expansive ettringite minerals which prevented the cementation process and caused reduction in the shear strength parameters. These findings are in good agreement with the earlier investigators (Sivapullaiah 2000). The shear strength test results indicated that the behavior of the lime treated soils with high sulfate concentration are very similar to that of a normally consolidated clay. Test results indicated that, in the absence of sulfate, the effective stress paths of the lime treated soil are similar to that of an overconsolidated soil (cemented soil). However, the presence of sulfate in the lime treated soils destroys the cementing effect of lime and prevents the formation of the cementitious compounds. Thus, the stress-strain behavior effective stress paths of the lime treated soil with 10000 ppm sulfate became similar to that of a normally consolidated soil rather than the cemented soil (Sivapullaiah 2000).

4.7 Cyclic Swell –Shrink Test Results

Cyclic swell-shrink tests were performed for control soil, lime stabilized soil and lime stabilized soil subjected to different sulfate concentrations with and without slag. Cyclic swell-shrink tests were performed by using the modified one-dimensional oedometer test apparatus. The schematic diagram of the modified test setup was given in Figure 3.7. For the drying part of the cyclic tests, samples were heated up to 40^0C temperature.

The vertical deformation of the samples represented as a $\Delta H/H_i$, where ΔH is the change in height of the sample after the swelling or shrinking and H_i is the initial height of the sample at the beginning of the first cycle. The swell-shrink curves of the control soil and the lime treated soils subjected to cyclic swell-shrink tests are given in Figure 4.59. For the control soil, swell values increased after the increasing number of cycles. The figure indicated that after the fourth cycle, the deformation of the control soil reached the equilibrium state. Addition of lime to the control soil gradually reduced the swelling and shrinking of the lime treated soil at the first swell-shrink cycle. The reduction of the swell and shrink at the first swell-shrink cycle was due to the short term stabilization that was due to the flocculation and aggregation of the soil particles. The figure indicates that after the first cycle, the swell-shrink values started to increase. The result of increasing swell-shrink values can be explained due to the broken bonds which enabled the water to enter into the soil pores and caused an increase in the deformation of the soil. The figure indicates that after the fourth cycle, the lime treated soils deformations had reached equilibrium state. The deformation of the control soil was 11.91% and 4.46% for the lime stabilized soil at the equilibrium state.

Figures 4.60 and 4.61 indicate the vertical deformation of the lime treated soils subjected to different sulfate concentrations of 2000, 5000 and 10000 ppm. For the lime treated soil subjected to 2000 ppm sulfate, the swell-shrink values were not very much affected with the addition of 2000 ppm sulfate as shown in Figures 4.60 and 4.61. The vertical deformation was almost the same as the lime treated soil. The figures indicate that after the fourth cycle, the vertical deformation of the soil subjected to 2000 ppm sulfate, reached the equilibrium state. The results show that 2000 ppm sulfate level was not effective to change the characteristics of the lime treated soils.

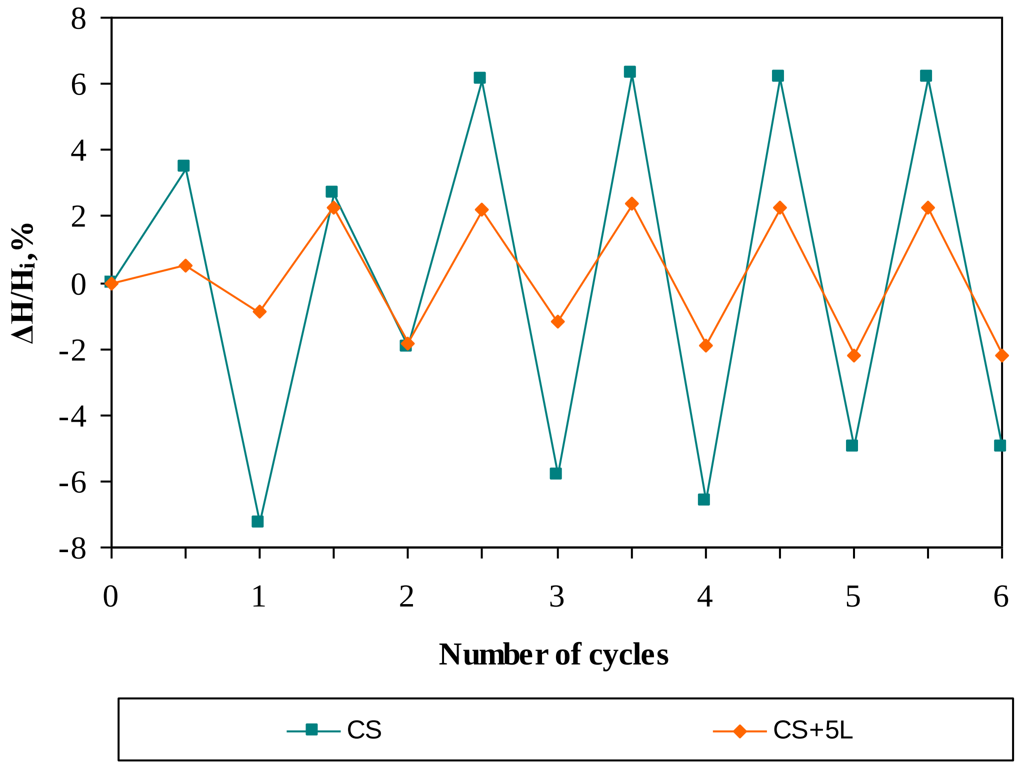

Figure 4.59 Vertical deformations of the CS and CS+5L

However, Figure 4.60 indicated that the lime treated soil subjected to 5000 ppm sulfate did not behave in the same way as the soil with 2000 ppm sulfate. At the first cycle, the swell-shrink values were low, but after the repeated wetting/drying cycles, the swell values increased as shown in Figure 4.60. The increases in the deformation values were due to the formation of the ettringite minerals in the soils.

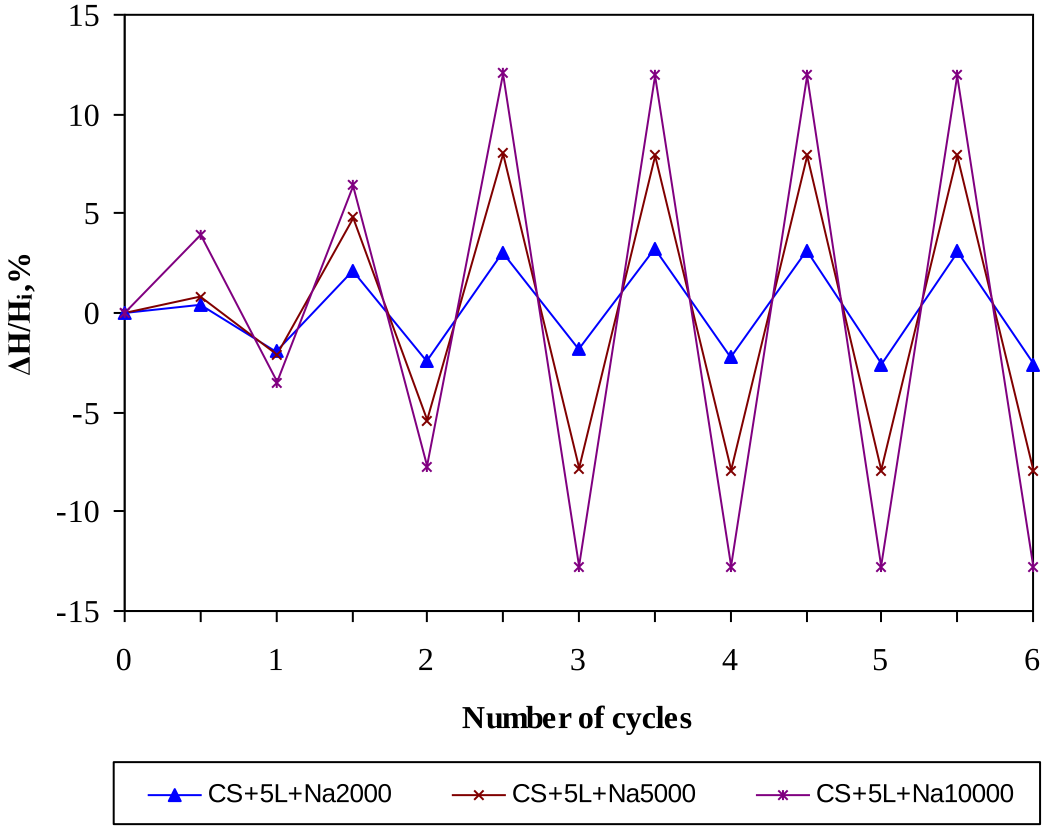

Figure 4.60 Vertical deformations of the lime treated soils subjected to different sulfate concentrations

The swell-shrink cycles of the lime treated soils subjected to 10000 ppm sulfate in Figure 4.60 showed that after the second cycle there was a dramatic increase in the swell values of this soil. It was observed that when the sulfate level of the soil was increased, the change in the deformation of the soil was also increased due to the formation of the ettringite minerals in the soils. The sulfate, which is present in the soils, suppressed the formation of the cementitious compounds and facilitated the formation of the ettringite minerals in the soil. Because of these highly expansive clay minerals, the swell potential of this soil increased while increasing the sulfate concentration in the soils. The vertical deformation variation of the lime treated soils subjected to different sulfate concentration was 5.8%, 16.0% and 24.8% at 2000, 5000 and 10000 ppm sulfate concentrations, respectively.

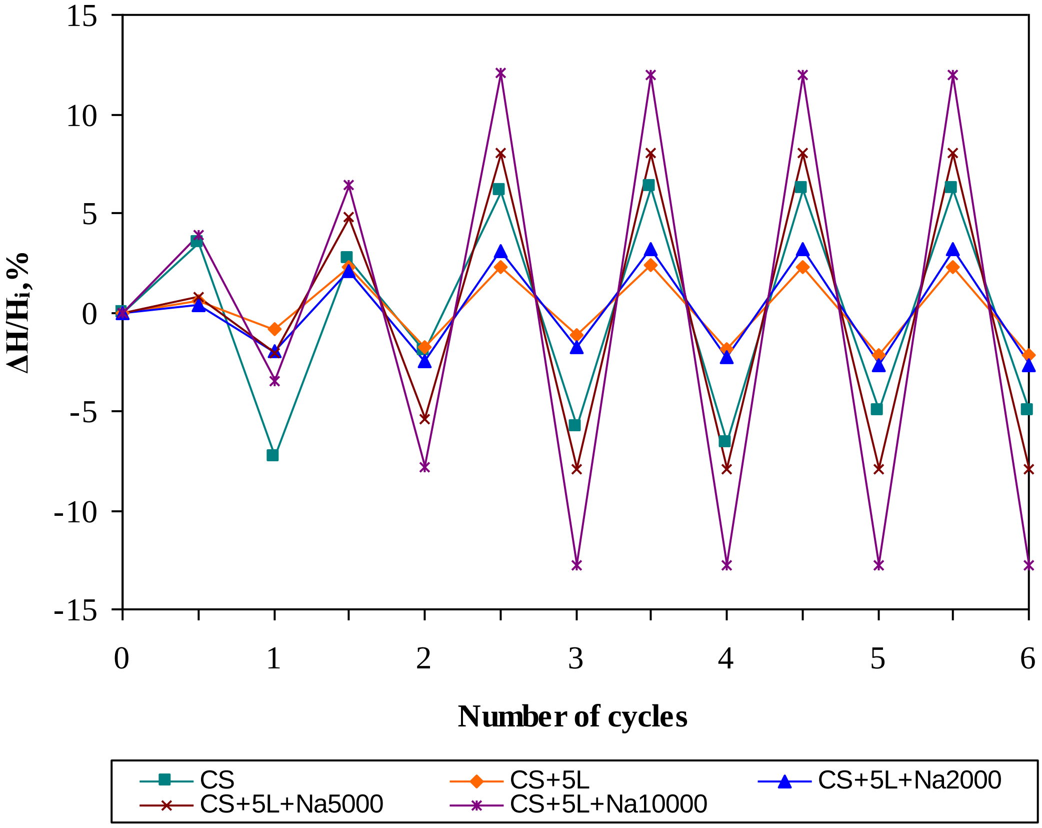

Figure 4.61 Comparisons of vertical deformations for CS, lime treated soil and lime treated soils subjected to different sulfate concentrations

Test results in the Figure 4.61 indicated that the presence of sulfate in the lime treated soils caused problems and increased the deformation of the soil resulting in and causing higher swell-shrink values. In this study, in order to eliminate the effect of sulfate on the lime treated soils, slag was introduced into the soil so that the formations of the ettringite minerals were prevented. The effect of slag on the vertical deformations of the lime treated soils subjected to different sulfate concentrations are shown in Figures 4.62 and 4.63. The figures indicate that the deformation of the lime treated soils with different sulfate concentrations increased slightly after the first cycle with the presence of slag in the soil, and then reached equilibrium after the fourth cycles. Figure 4.63 shows that the vertical deformation of the lime treated soils, even with higher sulfate levels, resulted in lower vertical deformation values compared to the lime treated soils without slag. The results obtained in the soils with slag were almost the same as the values obtained in the lime treated soils without slag. The vertical deformations of the lime treated soils subjected to 2000, 5000 and 10000 ppm sulfate concentrations, together with 6% slag were 2.44%, 2.43% and 4.20%, respectively. The results in Figures 4.62 and 4.63 showed that addition of slag into the soil eliminated the harmful effect of the sulfate in the lime treated soils.

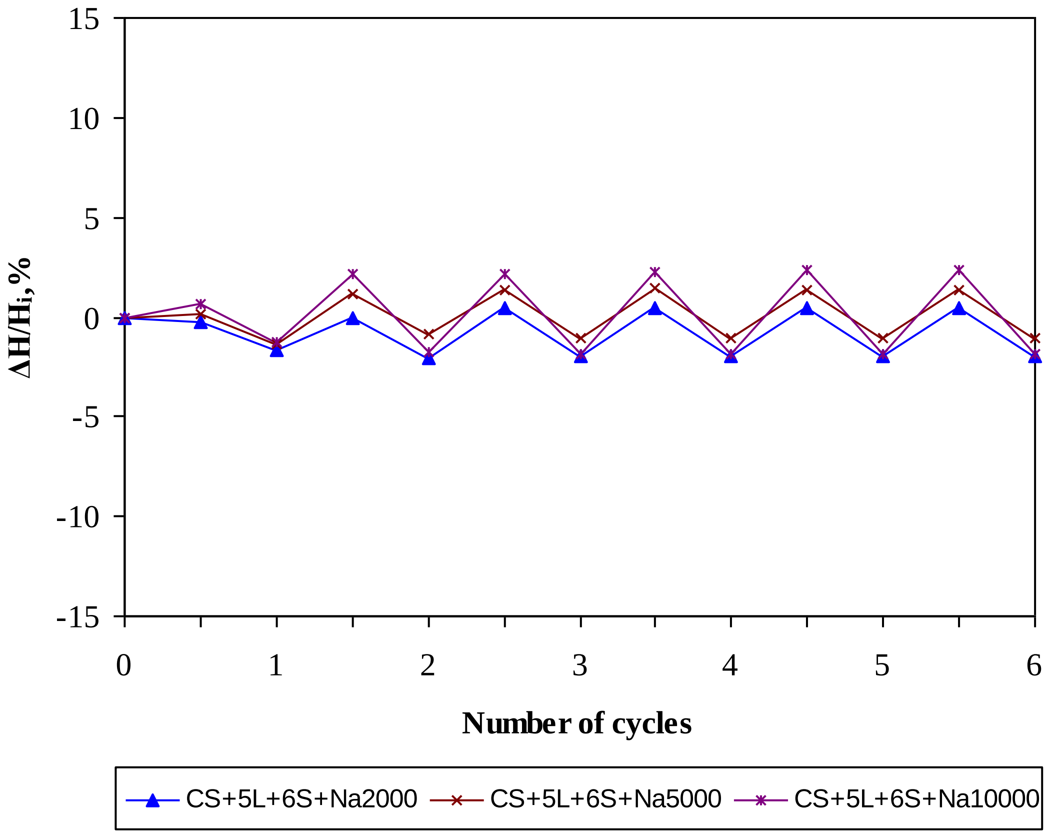

Figure 4.62 Effect of slag on the vertical deformation of the lime treated soils subjected to different sulfate concentrations

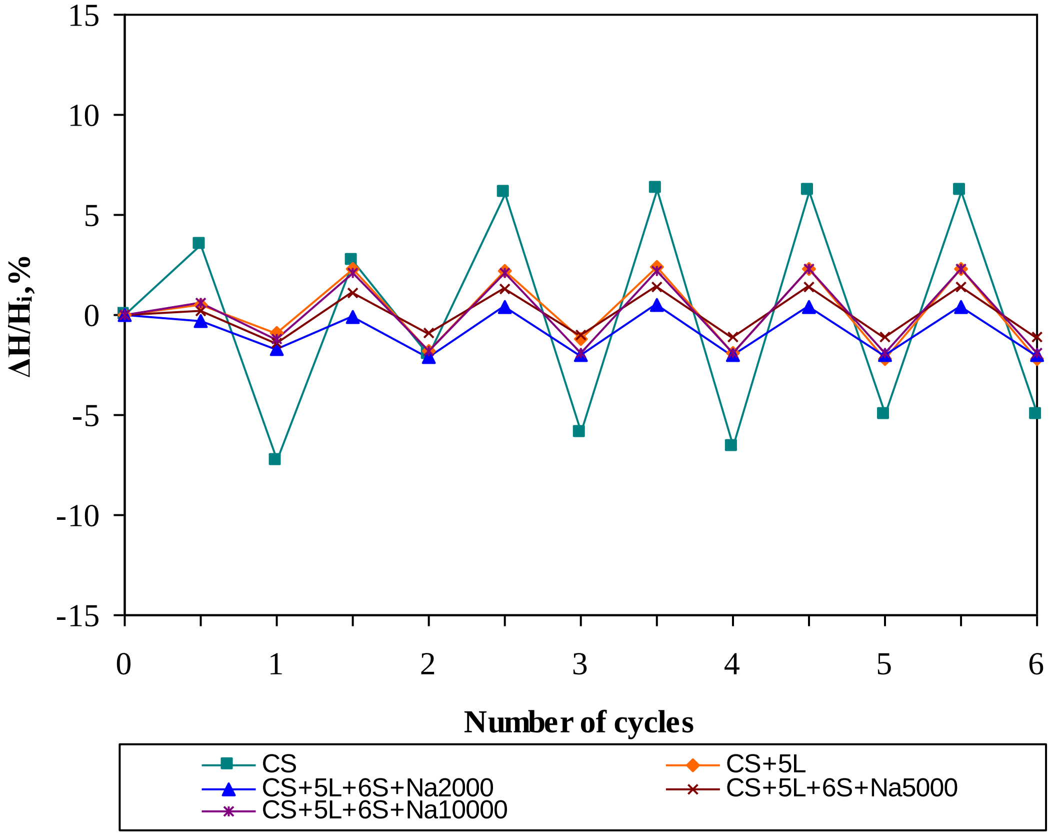

Figure 4.63 Comparisons of the vertical deformations for CS, lime treated soil and lime treated soils subjected to different sulfate concentrations with slag

4.8 Mineralogical Analyses

4.8.1 X-Ray Diffraction Analysis

The X-Ray diffraction analysis was conducted for control soil and lime treated soils with 10000 ppm sulfate. Figure 4.64 and 4.65 shows the X-Ray diffraction analysis results for the control soil and the lime treated soils with 10000 ppm sulfate concentrations. Figure 4.65 shows the formation of the ettringite minerals in lime treated soils with 10000 ppm sulfate concentrations.

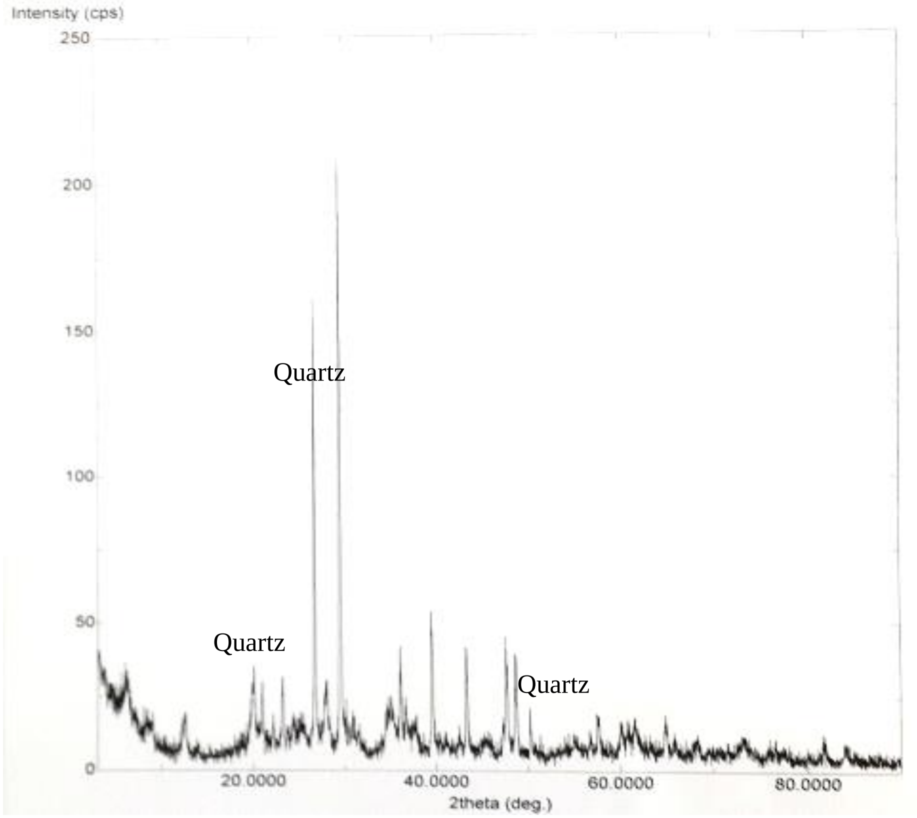

Figure 4.64 XRD of CS

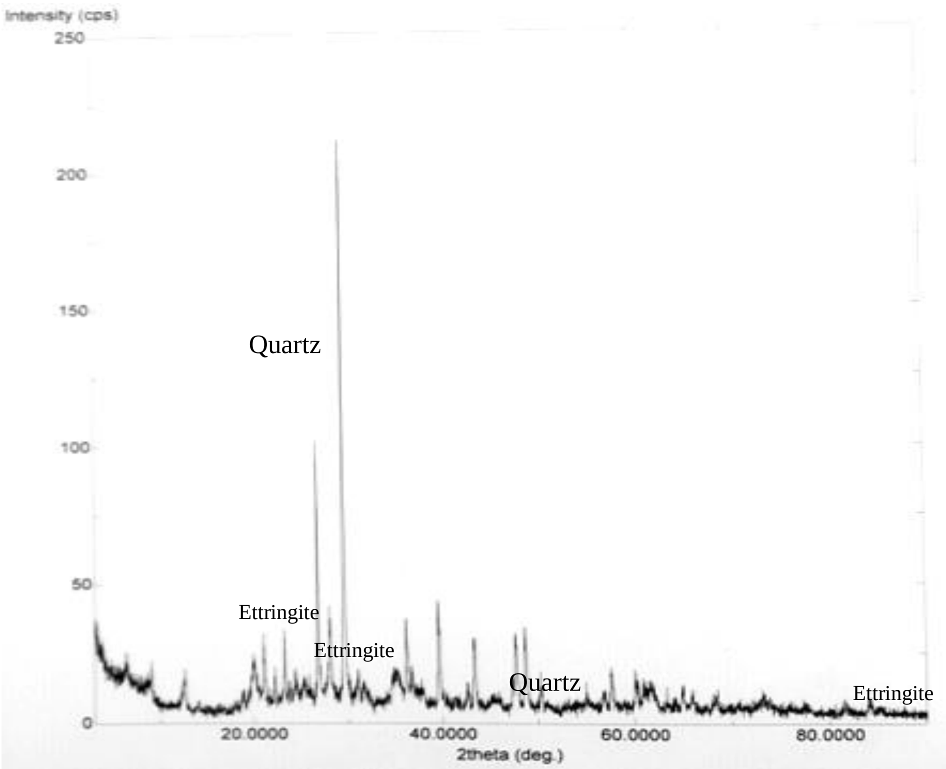

Figure 4.65 XRD of lime treated soils with 10000 ppm sulfate concentration

4.8.2 Scanning Electron Microscopy (SEM)

The scanning electron microscopy (SEM) test was used to dentify the microstructural changes in the lime treated soils with 10000ppm sulfate.

Figures 4.66 and 4.67 represent the results of SEM studies which indicate the changes in the microstructure of the control soil. Figure 4.66 shows the scanning electron micrographs for the control soil and Figure 4.67give the SEM of the 5% lime treated soil with 10000 ppm sulfate concentration.

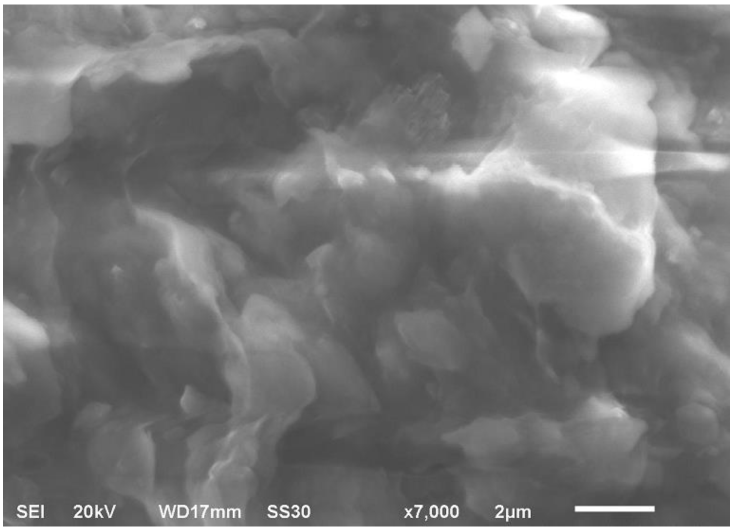

Figure 4.66   SEM pictures for CS

Figure 4.66 shows the clay mineral flakes. Figure 4.67 shows the scanning electron micrograph for lime-treated soil subjected to 10000 ppm sulfate concentration. In this figure, it can be seen that, in the presence of sulfate, some needle-like minerals are formed in the soil. These needle-like minerals are a good indication of the formation of the ettringite minerals which result in abnormal swelling in the lime-treated sulfate bearing soils.

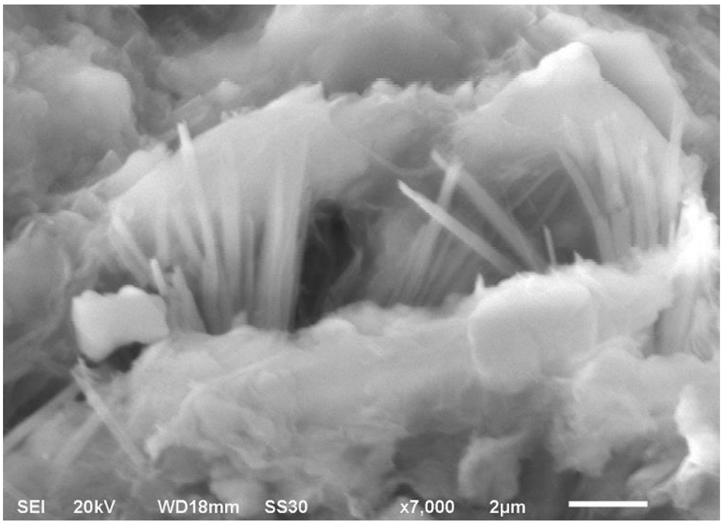

Figure 4.67 SEM pictures for the lime treated soils subjected to 10000ppm sulfate

4.9 Statistical Analyses: Analysis of Variance (ANOVA)

4.9.1 Introduction

In this study, test results were statistically analyzed by using the statistical program: Analysis of Variance (ANOVA). The purpose of using this program was to check statistically if the effect of each variable is significant. The test results obtained for control soil, lime treated soil and lime treated soils subjected to different concentration of sulfate with or without slag were analyzed by using statistical analysis program of ANOVA.

4.9.2 Analysis of Experimental Results

The analysis of variance (ANOVA) tests was used to compare the control and lime treated soils subjected to different sulfate concentration with or without slag. Statistical Pakage for the Social Sciences (*SPSS) 16.0 for windows* program was used to analyze the tests results. Two-way ANOVA test was used for two or more group of experimental data affected by two experimental factors. Two-way ANOVA tests assume that all the experimental data have normally distributed populations with equal variance. The results of swell, linear shrinkage, plasticity index and consolidated undrained triaxial tests were analyzed to determine the cause of variation of lime treated soils with or without slag at different curing and mellowing times. The reason of choosing these tests was to verify the effectiveness of the lime treatment on the control soil. The traditional probability factor of the analysis is 0.05. After the analysis, if the obtained probability is less than 0.05, it means that the lime treated soils data are significantly different from the control soils data.

Two-way ANOVA test was performed to check the effect of sulfate concentration and slag on the variation of plasticity index, linear shrinkage and swell values as shown in Table 4.5. Table 4.5 indicated that the effect of sulfate and slag on plasticity is both statistically significant, because of *p*-value being less than 0.05. The variation in linear shrinkage values due to the variations in different sulfate concentrations and slag content was statistically significant, *p*-value less than 0.05. Also the variation of swell values due to the variations of sulfate concentration and slag content was statistically significant due to the probability values less than 0.05. All the results obtained from the ANOVA analysis substantiated the previous findings that different sulfate concentrations and slag contents significantly affect the plasticity, the linear shrinkage and the swell values.

Table 4.5 ANOVA analyses on the sulfate and slag treated soils: PI, LS and Swell values

Type of test	Source of variation	Probability (P)	Statistically significant or not
Plasticity Index (PI)	Sulfate	0.0040	√
	Slag	0.0001	√
	Sulfate & Slag	0.0040	√
Linear Shrinkage (LS)	Sulfate	0.0010	√
	Slag	0.0001	√
	Sulfate & Slag	0.0150	√
Swell	Sulfate	0.0010	√
	Slag	0.0001	√
	Sulfate & Slag	0.0010	√

ANOVA analysis was also applied to the Consolidated Undrained triaxial tests results by using two-way analysis. Two-way ANOVA analysis was performed in order to check the effect of sulfate concentrations, cell pressures and slag contents on the variation of shear strength of the soils, as shown in Table 4.6. Table 4.6 showed that the sulfate concentrations and the cell pressures at zero curing time did not have any statistically significant effect on the shear strength of the soils. But the results of the analysis indicated that when the curing time increased, the sulfate concentrations and the cell pressures had statistically significant effect on the shear strength.

Table 4.6 ANOVA analyses: Effect of sulfate concentrations and the cell pressures on the shear strength at 0, 7, 30 and 365 days curing time

Curing times (days)	Source of variation	Probability(P)	Statistically significant or not
0	Sulfate	0.415	**x**
	Cell pressure	0.971	**x**
	Sulfate & Cell pressure	0.992	**x**
7	Sulfate	0.0070	√
	Cell pressure	0.0050	√
	Sulfate & Cell pressure	0.0040	√
30	Sulfate	0.0010	√
	Cell pressure	0.0050	√
	Sulfate & Cell pressure	0.0035	√
365	Sulfate	0.0001	√
	Cell pressure	0.0130	√
	Sulfate & Cell pressure	0.0020	√

Table 4.7 indicated that the variation in swell potential due to the variations in the sulfate concentration and the curing periods are statistically significant: *p*-values being less than the 0.05. Table 4.8 shows the effect of compaction delays (mellowing time) on the swell potential values of the lime treated soils subjected to sulfates. The table indicated that the effect of compaction delay and the sulfate concentrations on the swell potentials is statistically significant.

Table 4.7 ANOVA analyses: Effect of curing time and the sulfate concentrations on the swell potentials at 7, 30 and 365 curing times

Curing times (days)	Source of variation	Probability(P)	Statistically significant or not
7	Sulfate	0.0010	√
	Curing period	0.0001	√
	Sulfate & Curing period	0.0130	√
30	Sulfate	0,0080	√
	Curing period	0,0030	√
	Sulfate & Curing period	0,0075	√
90	Sulfate	0,0060	√
	Curing period	0,0045	√
	Sulfate & Curing period	0,0063	√

Table 4.8 ANOVA analyses: Effect of compaction delays and the sulfate concentrations on the swell potentials at 1, 2 and 3 days mellowing time

Mellowing Time (days)	Source of variation	Probability(P)	Statistically significant or not
1	Sulfate	0.0010	√
	Mellowing time	0.0001	√
	Sulfate & Mellowing time	0.0050	√
2	Sulfate	0.0003	√
	Mellowing time	0.0001	√
	Sulfate & Mellowing time	0.0075	√
3	Sulfate	0.0001	√
	Mellowing time	0.0008	√
	Sulfate & Mellowing time	0.0025	√

Chapter 5

CONCLUSIONS

5.1 Introduction

This section reviews the results obtained from the laboratory tests and the statistical analysis of the test results. The recommendation section provides information for further studies on this subject.

5.2 Conclusions

This section lists some of the major conclusions derived from the research results presented in this study:

- Test results revealed that lime was very effective in reducing the plasticity and the swell potential of the fine grained expansive soil. An increase in the strength of the lime treated soil was obtained with only 5% lime-treatment. Test results show that the presence of sulfate in the lime treated soils had an opposite effect on the plasticity and the swell potential of the soils presence of sulfate. The presence of sulfate caused an increase in the plasticity and the swell potential of the soils. Test results indicated that 2000 ppm sulfate concentration in the lime-treated soils was not effective to cause an increase in the plasticity and the swell potential of the soils. However, 5000 and 10000 ppm sulfate concentration in the lime-treated soils caused the plasticity and the swell potentials to increase abnormally and eliminated the remedial effect of lime in expansive soil. The swell potential of the lime-treated soil with

10000 ppm sulfate concentration became three times higher than the control soils swell potential and increased from 3% to approximately 8%.

- Mellowing time (compaction delay) has significant effect on the swell potential of the sulfate bearing soils. Test results indicated that increasing mellowing time, decreased the swell potential of the lime treated soils subjected to different sulfate concentration. The most effective reduction was obtained in 3 days mellowing period for the lime-treated soil subjected to 5000 ppm sulfate concentration. But the swell potential of this soil was still greater than the swell potential of the control soil. The same behaviour in the swell potential of the soil with 10000 ppm sulfate concentration was also observed. The results of the statistical ANOVA analysis substantiated the previous findings and indicated that the effect of compaction delay and the sulfate concentrations on the swell potential is statistically significant. Therefore, in all construction applications, the effect of mellowing time on the lime treated soil properties should be carefully examined and the design should be carried out according to the results obtained test results.

- Temperature has also a significant effect on the soil properties of the lime treated soils. Therefore, the swell tests were performed at two different temperature values: 25^0C and 40^0C. The results showed that at 40^0C temperature, the clay-lime reaction of the lime treated soils subjected to high sulfate concentration was accelerated and consequently, the new ettringite minerals were produced. As a result of this, swell potential of the soils increased. Test results indicated that the weather condition is also a determining factor of the soil-lime reactions.

- Test results revealed that the compressibility of the lime treated soils subjected to different sulfate concentration increased with the increase in sulfate concentration. The compressibility of the soils increased and exceeded the compressibility of the control soil. The formation of the ettringite minerals filled the pore spaces and caused a reduction in the permeability of the treated soils.

- Consolidated undrained triaxial, CU tests, on the control soil and the lime treated soils subjected to different sulfate concentrations were performed and the test results indicated that in the absence of sulfate, lime was very effective in increasing the shear strength of the lime treated soil. However, test results revealed that the shear strength of the lime-treated soils subjected to different sulfate concentrations decreased with the increase in curing time. Dramatic decrease in the shear strength was obtained in the lime treated soil subjected to 10000 ppm sulfate at 365 days curing period. The formation of the ettringite minerals with high plasticity caused reduction in the soil friction and resulted in a decrease in the shear strength of the soil with high sulfate concentration.

- In the absence of sulfate, the effective stress path of the lime treated soil followed the same trend as an overconsolidated soil. However, in the presence of sulfate, the effective stress path of the lime treated soil with

10000 ppm sulfate concentration became similar to that of a normally consolidated soil. Decrease in the shear strength of the lime treated soil with high sulfate concentration and curing time was due to the reduction in the cohesion rather than the internal friction angle (Sivapullaiah, et. al. 2000).

- The results of the statistical ANOVA analysis showed that the sulfate concentrations and the cell pressures at zero curing time did not have any statistically significant effect on the shear strength of the soils. However, ANOVA analysis results also indicated that when the curing time increased, the sulfate concentrations and the cell pressures had a statistically significant effect on the shear strength.

- Test results indicated that the detrimental effect of sulfate in the lime treated soils was eliminated by adding slag into the soil-lime environment. The addition of 6% slag into the lime treated soils prevented the formation of the ettringite minerals and thus, improved the plasticity and the swell potential of the soils. In the presence of 6% slag, the swell potential of the lime-treated soil with 10000 ppm sulfate concentration decreased from 8% to 1% whereas the lime-treated soil with 5000 ppm sulfate concentration showed no swelling.

- Treatment mechanisms were also verified by using the SEM results. The micrographs obtained from the electron microscope revealed the formation of the ettringite minerals which caused an increase in the plasticity and a swell in the presence of sulfate. In the SEM of the lime treated soil subjected to

10000 ppm sulfate solutions, the growth of the ettringite minerals was easily observed.

From the results of this study, it can be concluded that the treatment of sulfate bearing soils with lime may not always be an ideal solution to the volume change problems. The use of lime as a soil stabilizer in sulfate bearing soils should be approached with great care. Test results indicated that the sulfate level of the existing soils should be predetermined before the lime treatment and some preliminary laboratory tests should be performed before field applications.

5.3 Recommendations

For further research some recommendations are mentioned below:

- Narrow sulfate levels such as 3000, 4000 and 7000 ppm should be chosen so that the understanding of the sulfate level effects on lime-induced heave could be better understood.

- For eliminating the harmful effect of sulfate in lime treated soils, other additives (other than slag) could be selected used in the study.

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