STABILIZATION OF EXPANSIVE SOILS USING BIGADIC ZEOLITE (BORON BY-PRODUCT)

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Approval of the thesis:

STABILIZATION OF EXPANSIVE SOILS USING BIGADIC ZEOLITE (BORON BY-PRODUCT)

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ABSTRACT

STABILIZATION OF EXPANSIVE SOILS USING BIGADIC ZEOLITE (BORON BY-PRODUCT)

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Expansive soils are a worldwide problem that poses several challenges for civil engineers. Such soils swell when given an access to water and shrink when they dry out. The most common and economical method for stabilizing these soils is using admixtures that prevent volume changes. In this study the effect of using Bigadic zeolite (boron by-product) in reducing the swelling potential is examined. The expansive soil is prepared in the laboratory by mixturing kaolinite and bentonite. Bigadic zeolite (boron by-product) is added to the soil at 0 to 25 percent by weight. Grain size distribution, Atterberg limits and swell percent and rate of swell of the mixtures are determined. Specimens are cured for 7 and 28 days. As a result of the experimental study, it was seen that addition of Bigadic zeolite (boron by-product) decreased swelling potential and rate of swell of the artificially prepared expansive soil specimen at laboratory conditions. The swell percentage and rate of swell of the stabilized specimens are affected positively by curing.

Key Words: Expansive Soil, Soil Stabilization, Swelling Potential, Bigadic Zeolite, Lime, Sand

ÖZ

ŞİŞEN ZEMİNLERİN BİGADİÇ ZEOLİDİ (BOR YANÜRÜNÜ) KULLANILARAK STABİLİZASYONU

Demirbaş, Güneş

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Erdal Çokça

Haziran 2009, 120 sayfa

Şişen zeminler dünya çapında bir problem olup, inşaat mühendislerine çeşitli sorunlar teşkil etmektedir. Bu tür zeminler suya maruz bırakıldıklarında şişip, kurutulduklarında büzüşürler. Bu zeminlerin stabilizasyonu için en yaygın ve ekonomik metod hacim değişikliklerini önleyici katkılar kullanmaktır. Bu çalışmada Bigadiç zeolidinin (bor yanürünü) şişme potansiyeline etkisi incelenmektedir. Kullanılan şişen zemin numunesi laboratuarda kaolin ve bentonit karıştırılarak hazırlanmıştır. Bigadiç Zeolidi (bor yanürünü) ağırlıkça %0 ila %25 oranında katılmıştır. Örneklerin dane çapı dağılımı, kıvam limitleri, şişme yüzdeleri ve şişme hızı tespit edilmiştir. Ayrıca 7 ve 28 gün kür uygulanmıştır. Yapılan deneysel çalışma sonucunda, Bigadiç zeoliti (bor yanürünü) eklenmesinin laboratuar ortamında yapay olarak hazırlanmış şişen zeminin şişme potansiyelini ve şişme hızını düşürdüğü görülmüştür. Stabilize edilen numunelerin şişme yüzdeleri ve şişme hızları kürden olumlu etkilenmişlerdir.

Anahtar Kelimeler: Şişen Zemin, Zemin Stabilizasyonu, Şişme Potansiyeli, Bigadic Zeolidi, Kireç, Kum

To My Family

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LIST OF ABBREVIATIONS

A: Sample A

ASTM: American Society for Testing and Materials

BZ: Bigadic zeolite

CH: Inorganic clays of high plasticity

CL: Inorganic clays, silty clays, sandy clays of low plasticity

dH: Change in initial height of the specimen

Gs: Specific gravity

H: Initial height of the specimen

L: Lime

LL: Liquid limit

MH: Inorganic silts of high plasticity

ML: Inorganic silts, silty or clayey fine sands, with slight plasticity

PI: Plasticity index

PL: Plastic limit

S: Sand

SI: Shrinkage index

SL: Shrinkage limit

t_{50}: Time to reach fifty percent swell

CHAPTER 1

INTRODUCTION

The design of foundations for sites having expansive soils is one of the great challenges facing geotechnical engineers today. Intolerable heave of foundations on expansive soils often affects critical safety aspects of structures (Chao, 2007). The swell and shrinkage distinctiveness of expansive soil causes significant damage to structures such as buildings and pavements. This damage can be attributed to moisture fluctuations caused by seasonal variations. Volumetric changes weaken the subgrade by inducing cracking which causes damage to the overlying structures. A vast majority of expansive soils are montmorillonite-rich clays, over consolidated clays and shales (Nelson and Miller, 1992; Pillappa, 2005).

In many parts of the world, severe damages have been reported in pavements and buried structures in expansive clay soils due to swelling and shrinkage phenomena when moisture increase and decrease in the clay, respectively. In recent years, many researchers have been devoting increasing attention to study of these phenomena and developing constitutive and computational models applied to the engineering behavior of expansive soils (Hong, 2008).

A number of control methods are extensively used in the field to control heave distress in expansive soils which include treatment with calcium-based stabilizers, noncalcium-based stabilizers, asphalt-stabilization, and geo-synthetic reinforcement (Kota et al., 1996). Soil stabilization is known as an alteration of soil properties to meet particular engineering requirements and among these stabilization methods, calcium-based stabilizers like lime; cement and fly ash are most commonly used (Vasudev, 2007).

Expansive soils, which cause multi-billion dollar losses in property and roadways damage in the United States every year, are usually chemically stabilized to reduce their plasticity and volume change potential, and improve other properties. The typical procedure involves mixing the soils with additives like lime, cement or fly ash, watering and compacting to attain the desired moisture content and density, prior to curing (Rivera, 2000).

Zeolites have been recognized for more than 200 years, but only during the middle of the twentieth century they have attracted the attention of scientists and engineers who demonstrated their technological importance in several fields (Cincotti, Mameli, Locci, Orru, Cao, 2006).

It is known that our country has millions of tons of zeolite reserves. Tuffs containing clinoptilolite are very common in Turkey (Kırsan, 2004). The most important zeolite reserves of Turkey have been found in Balıkesir-Bigadic. Zeolites found in some parts of Turkey can be used for flooring, stuccing, construction materials and different purpose in many sectors.

The basic objective of this research is to investigate the effectiveness of by-product Bigadic zeolite as a soil stabilizing agent. The potential use of by-product Bigadic zeolite as a stabilizing agent was investigated for an artificially prepared expansive soil sample which has high swelling potential in laboratory conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Expansive Soils

Expansive soil is a term used for soils which exhibit moderate to high plasticity, low to moderate strength and high swell and shrinkage characteristics (Holtz and Gibbs, 1956).

Expansive soils swell and shrink with changes in moisture content. This volume change behavior is the reason for the cracking of the structures such as buildings or pavements (Figure 2.1). The reason for this behavior is the presence of certain type of heaving mineral known as montmorillonite that has an expanding lattice. This clay mineral expands when it is exposed to water (Chittoori, 2008). Soil rich with these minerals can be found in many places all over the world especially in the arid and semi-arid regions (Hussein, 2001).

Swelling clays are found in many parts of the world, particularly in semi-arid areas. Expansive soil deposits occur in the arid and semi arid regions of the world and are problematic to engineering structures because of their tendency to heave during wet season and shrink during dry season (Mishra et at. 2008).

During the last few decades damage due to swelling action has been observed clearly in the semi arid regions in the form of cracking and breakup of pavements, roadways, building foundations, slab-on-grade members, and channel and reservoir linings, irrigation systems, water lines, and sewer lines (Çokça, 2001).

The annual cost estimates to repair buildings, roads and other structures built on expansive soils are expected to be more than $10 billion (Steinberg, 1998).

Figure 2.1 Heaving Problem (Manosuthıkıj, 2008)

2.1.1 Clay Mineralogy

One of the soil characteristic that is less understood is the dominating clay mineralogy in a given system (Chittoori, 2008). An overview of the clay mineralogy is made in this section, because it is directly related to the expansive nature of soil. The term clay is used as both a particular size and also to represent a family of minerals (Velde, 1995). As a size term, it refers to all constituents of a soil smaller than a particular size, usually 0.002 mm in engineering classifications. As a mineral type it represents the mineral which have a) small particle size, b) a net electrical negative charge and c) plasticity when mixed with water. Their shape is usually platy or in a few cases needle shaped or tubular (Mitchell and Soga, 2005).

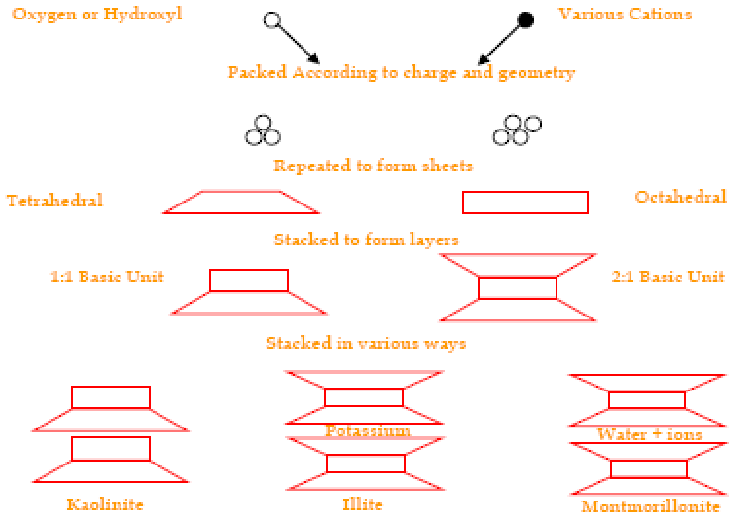

Figure 2.2 Schematic Showing the Clay Mineral Formation (Chittori, 2008)

Kaolinite, illite and montmorillonite are the common clay minerals usually found in the soil (Figure 2.2). Kaolinite is a common phyllasilicate mineral in subgrades; it is most abundant in soils of warm moist climates. Illite is essentially a group name for non-expanding, clay mineral (Chittoori, 2008). Montmorillonite is formed from weathering of volcanic ash under poor drainage conditions or in marine waters (Oweis and Khera, 1998).

Mineral structure of kaolinite, illite and montmorillonite are presented in Figure 2.3, Figure 2.5 and Figure 2.7. SEM photography at kaolinite, illite and montmorillonite are presented in Figure 2.4, Figure 2.6 and Figure 2.8.

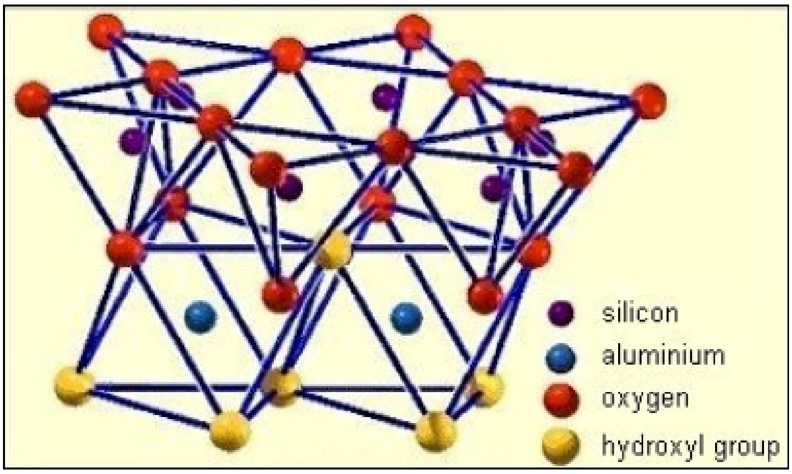

Figure 2.3 Kaolinite Crystal Structure (source: *http://media-2.web.britannica.com/eb-media/76/2676/-004-3893834B.gif*)

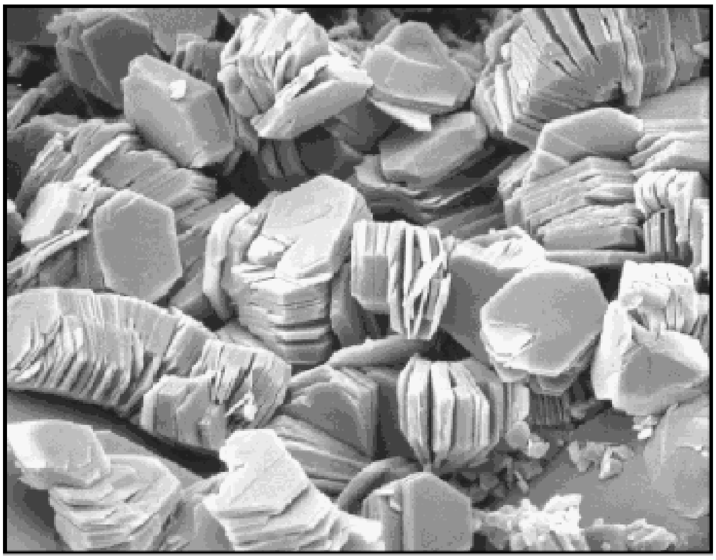

Figure 2.4 SEM Photograph of Kaolinite (source: *http://www.uni-kiel.de/anorg/lagaly/group/jose/Kaolinite.gif*)

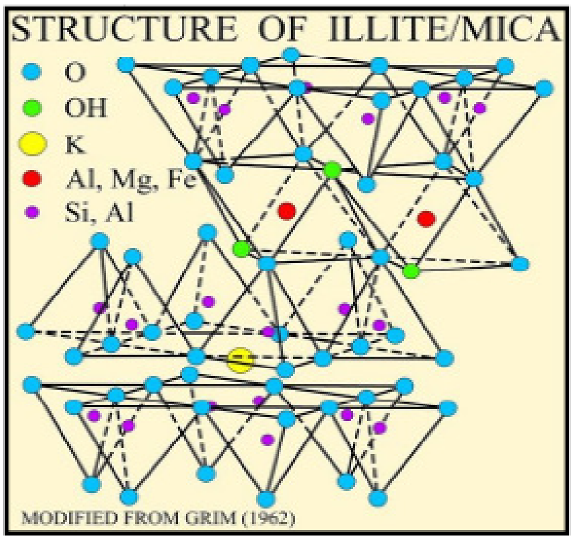

Figure 2.5 Illite Crystal Structure (source: *http://pubs.usgs.gov/of/2001/of01-041/htmldocs/images/illstruc.jpg*)

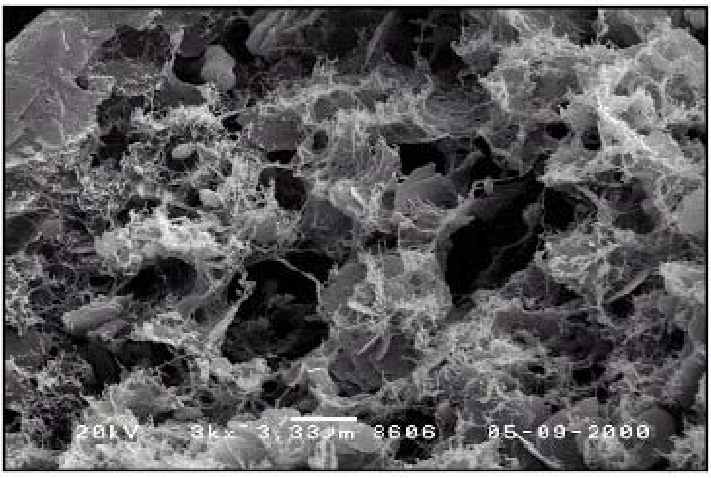

Figure 2.6 SEM Photograph of Illite (source: *http://www.petrotech-assoc.com/images/smectite_Illite_2.jpg*)

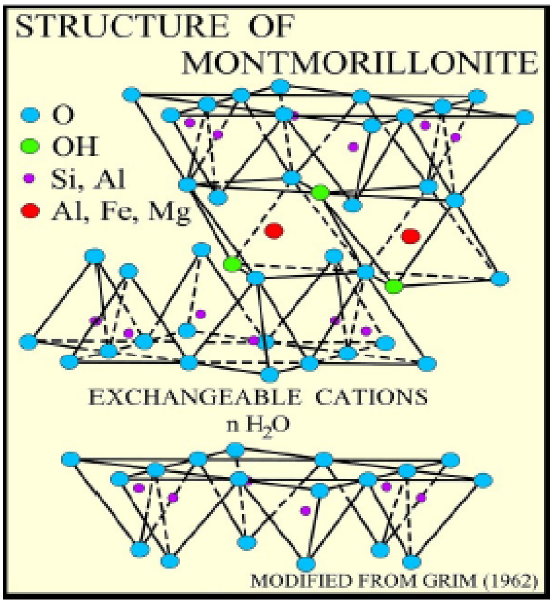

Figure 2.7 Montmorillonite Crystal Structure (source: *http://pubs.usgs.gov/of/2001/of01-041/htmldocs/images/monstru.jpg*)

Figure 2.8 SEM Photograph of Montmorillonite (source: *http://www.webmineral.com/specimens/Smectite.jpg*)

2.1.2 Mechanism of Swelling

Mechanism of swelling of expansive soils is complex. Series of processes take place between water and the clay structure during swelling (Popescu, 1998). There are two fundamental mechanisms for swelling as presented in Figure 2.9 which are interparticle or intercrystalline swelling and intracrystalline swelling.

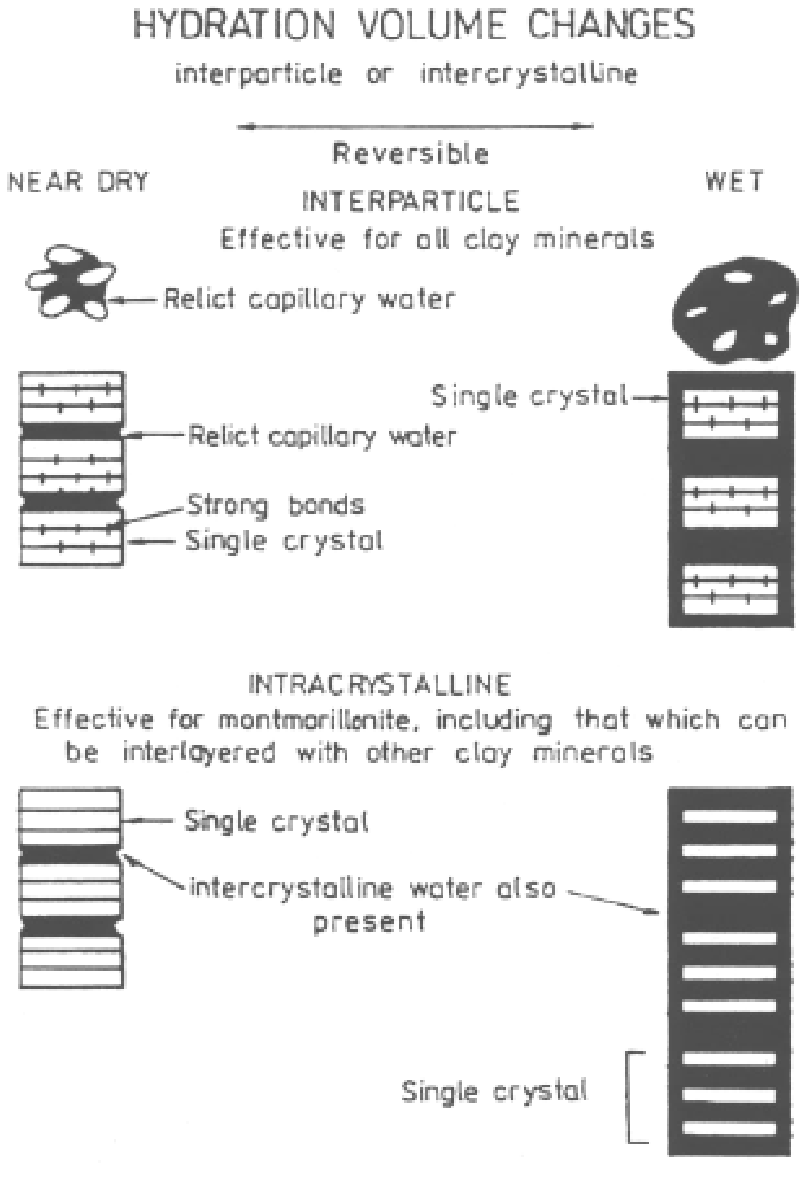

Figure 2.9 Mechanism of Swelling (after Popescu, 1986)

Interparticle or intercrystalline swelling which is effective for all clay minerals. When the clay soil is wetted, the capillary tensions under which the particles are held together by deposit relict water in interconnected pores are relaxed and the clay expands (Gens and Alonso, 1992).

Intracrystalline swelling is effective for expansive clay minerals that are known as montmorillonite group of minerals. The layers are weakly bonded. On wetting, water enters not only into the region between the single crystals but also between the individual layers that make up the crystals (Popescu, 1986).

2.1.3 Factors Affecting Swelling

Three factors play an important role in the heave and swell properties of soils: (i) soil properties such as compaction, natural moisture content variation, dry density and plasticity index; (ii) environmental conditions, which include temperature and humidity and (iii) natural overburden pressure and foundation loading conditions (Nelson and Miller, 1992). All these three factors are presented in Table 2.1, Table 2.2 and Table 2.3.

Table 2.1 Soil Properties Influencing Swell Potential (Nelson and Miller 1992)

FACTOR	DESCRIPTION
Clay Mineralogy	Clay minerals which typically cause soil volume changes are montmorillonites, vermiculates, and some mixed layer minerals. Illites and Kaolinites are frequently inexpansive, but can cause volume changes when particle sizes are extremely fine
Soil Water Chemistry	Swelling is repressed by increased cation concentration and increased cation valence. For example, Mg^{2+} cations in the soil water would result in less swelling than Na^{+} cations
Soil Suction	Soil suction is an independent effective stress variable, represented by the negative pore pressure in unsaturated soils. Soil suction is related to saturation, gravity, pore size and shape, surface tension, and electrical and chemical characteristics of the soil particles and water.
Plasticity	In general, soils that exhibit plastic behaviour over wide ranges of moisture content and that have high liquid limits have greater potential for swelling and shrinkage. Plasticity is an indicator of swell potential
Soil Structure and Fabric	Flocculated clays tend to be more expansive than dispersed clays. Cemented particles reduce swell. Fabric and structure are altered by compaction at high water content or remolding. Kneading compaction has been shown to create dispersed structures with lower swell potential than soils statically compacted at lower water contents
Dry Density	Higher densities usually indicate closer particle spacing, which may mean greater repulsive forces between particles and larger swelling potential

Table 2.2 Environmental Factors Affecting Swell Potential (Nelson and Miller, 1992)

FACTOR	DESCRIPTION
Initial Moisture Content	A desiccated expansive soil will have high affinity for water, or higher suction than the same soil at higher water content, lower suction. Conversely, a wet soil profile will loose water more readily on exposure to drying influences, and shrink more than a relatively dry initial profile. The initial soil suction must be considered in conjunction with the expected range of final suction conditions
Moisture Variations	Changes in moisture in the active zone near the upper part of the profile primarily define heave, it is in those layers that the widest variation in moisture and volume change will occur
Climate	Amount and variation of precipitation and evapotranspiration greatly influence the moisture availability and depth of seasonal moisture fluctuation. Greatest seasonal heave occurs in semiarid climates that have short wet periods
Groundwater	Shallow water tables provide source of moisture and fluctuating water tables contribute to moisture
Drainage	Surface drainage features, such as ponding around a poorly graded house foundation, provide sources of water at the surface; leaky plumbing can give the soil access to water at greater depth
Vegetation	Trees, shrubs, and grasses deplete moisture from the soil through transpiration, and cause the soil to be differentially wetted in areas of varying vegetation
Permeability	Soils with higher permeabilities, particularly due to fissures and cracks in the field soil mass, allow faster migration of water and promote faster rates of swell
Temperature	Increasing temperatures cause moisture to diffuse to cooler areas beneath pavements and buildings

Table 2.3 Stress Conditions Affecting Swell Potential (Nelson and Miller, 1992)

FACTOR	DESCRIPTION
Stress History	An overconsolidated soil is more expansive than the same soil at the same void ratio, but normally consolidated. Swell pressures can increase on aging of compacted clays, but amount of swell under light loading has been shown to be unaffected by aging. Repeated wetting and drying tend to reduce swell in laboratory samples, but after a certain number of wetting-drying cycles, swell is unaffected.
In situ Conditions	The initial stress state in a soil must be estimated in order to evaluate the probable consequences of loading the soil mass and/or altering the moisture environment therein. The initial effective stresses can be roughly determined through sampling and testing in a laboratory, or by making in-situ measurements and observations
Loading	Magnitude of surcharge load determines the amount of volume change that will occur for a given moisture content and density. An externally applied load acts to balance interparticle repulsive forces and reduces swell
Soil Profile	The thickness and location of potentially expansive layers in the profile considerably influence potential movements. Greatest movement will occur in profiles that have expansive clays extending from the surface to depths below the active zone. Less movement will occur if expansive soil is overlain by nonexpansive material or overlies bedrock at shallow depth

2.1.4 Oedometer Methods for Measuring Swell Properties

The most common measurement of stress-strain relationship involves the use the one-dimensional consolidation apparatus or oedometer. A compression curve obtained from an oedometer test for a saturated soil is a relationship between the amount of volume change in the soil and the normal stress (Chao, 2007).

There are three test methods which are Method A, Method B and Method C for swell properties as stated in ASTM D4546-03. Time-swell curve is presented in Figure 2.10.

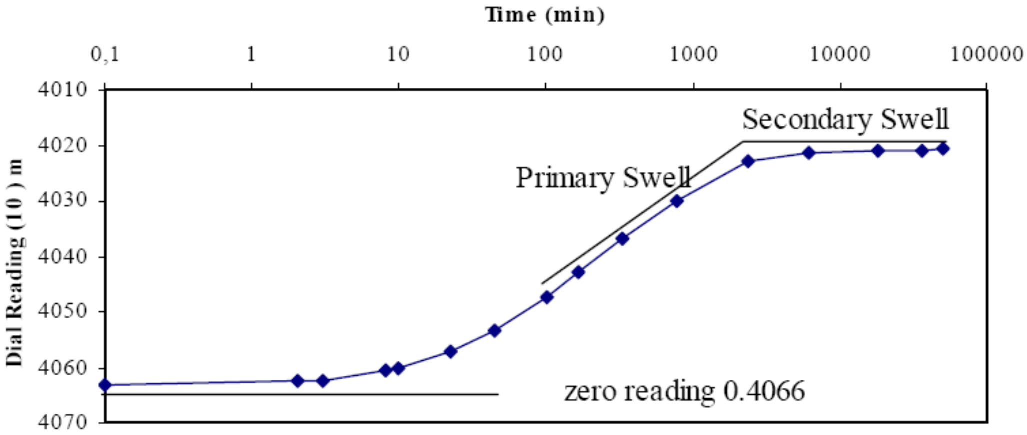

Figure 2.10 Time - Swell Curve (modified from ASTM, 1999)

Swelling percentage can be found by dividing the difference in vertical height ($\Delta H = H_1 - H_O$) to the original height (H_O).

2.1.4.1 Method A

Step 1-3 in Figure 2.11 shows 5 minute period when the deformation is recorded after removal of σ_1, the specimen is inundated. The seating pressure is applied on specimen after taking initial deformation readings. The specimen inundated to swell vertically. During swelling, deformations are recorded. At step 3-4 in Figure

2.11, primary swell is complete. Till the specimen recompresses to its initial void ratio and original height, a vertical pressure is applied (Figure 2.11, step 4-6).

Free swell, percent heave and swell pressure are measured in Method A.

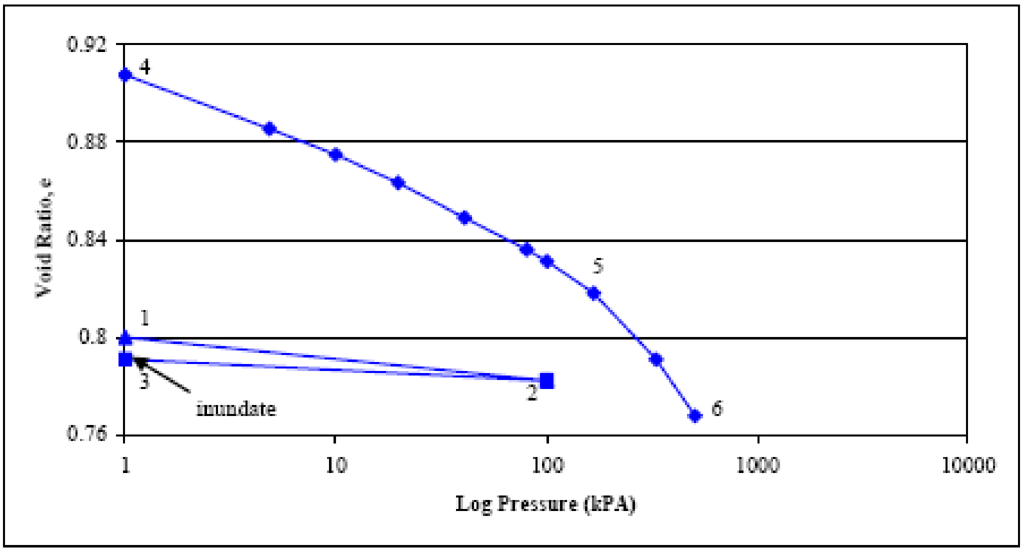

Figure 2.11 Void Ratio – Log Pressure Curve for Method A (Modified from ASTM, 1999)

2.1.4.2 Method B

At step 1-2 in Figure 2.12, deformation is read within 5 minutes of placing vertical pressure after applying a vertical pressure exceeding the seating pressure within 5 minutes of placing the seating pressure. Immediately after deformation is read, the specimen is inundated. Rests of the procedures are similar to Method A.

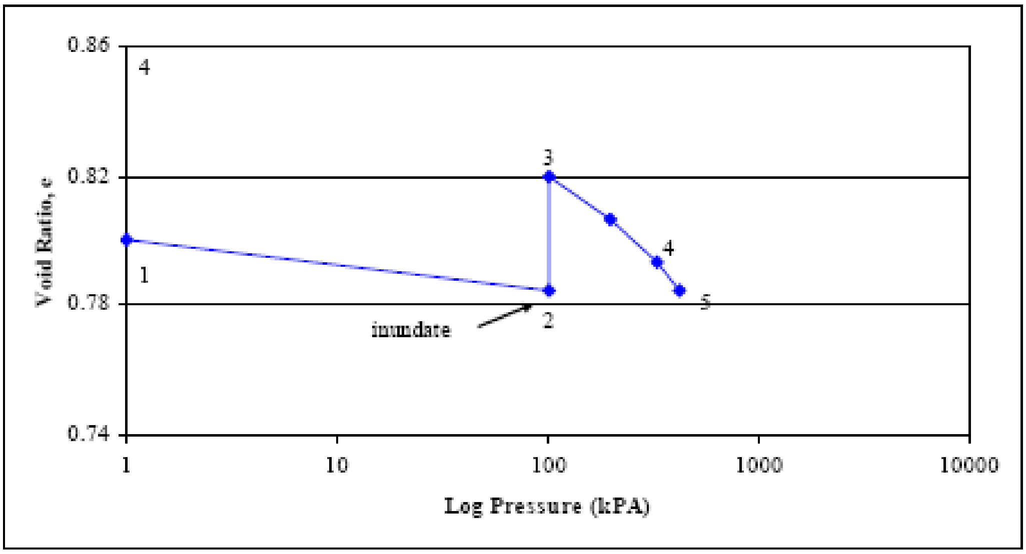

Figure 2.12 Void Ratio – Log Pressure Curve for Method B (Modified from ASTM, 1999)

The swell pressure is measured in Method B.

2.1.4.3 Method C

An initial stress is applied. The deformation within 5 minutes is read after placing initial stress and immediately the specimen is inundated with water as shown at steps 1-2 in Figure 2.13. The specimen is loaded vertically as presented in Method A. After step 7, rebound curve following consolidation is determined.

Swell pressure, preconsolidation pressure and percent heave or settlement within the range of applied vertical pressures are measured in Method C.

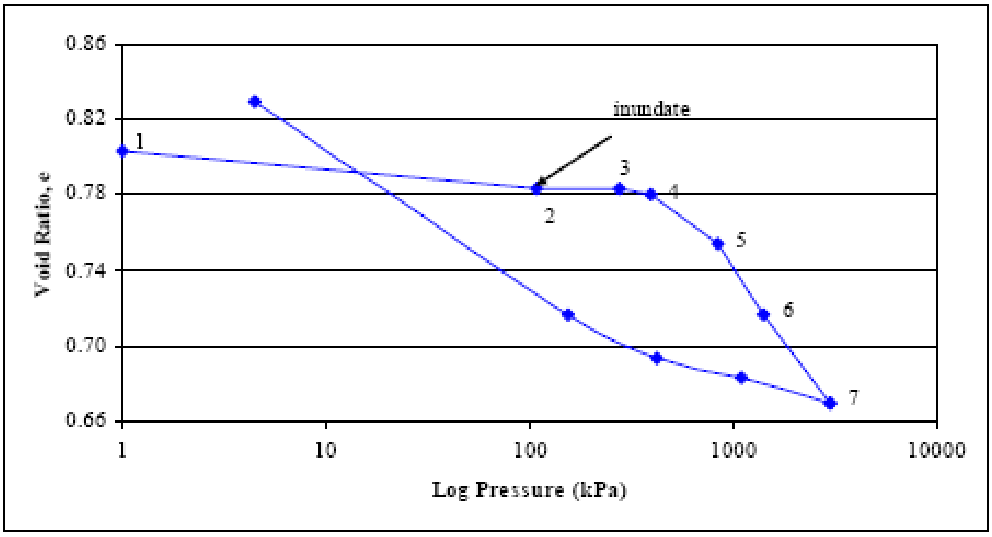

Figure 2.13 Void Ratio – Log Pressure Curve for Method C (Modified from ASTM, 1999)

2.2 Stabilization of Expansive Soils

The term soil stabilization is applied to any process which improves the properties of a soil and which enables it to perform and sustain its intended engineering use (Winterkorn, 1955). The chief objectives of stabilization are to improve soil strength, to decrease permeability and water absorption, and to improve bearing capacity and durability under cyclical conditions such as varying moisture content or repeated applications of stress at amplitudes less than the soils ultimate strength-fatigue life (Gillott, 1987).

There are two commonly used stabilization methods in order to improve the strength and durability of soils which are mechanical and chemical. No attempt is made here to describe the mechanical stabilization.

2.2.1 Lime Stabilization

The strength, bearing capacity and durability of soils can be increased by addition of some chemical materials. One of the commonly used is lime. Lime is formed by the decomposition of limestone at elevated temperatures. When lime is combined with water and the soluble silica and alumina present in clay, a chemical reaction occurs, resulting in the formation of new compounds. When combined with the water, its primary function is alteration at particle structure and increased resistance to shrink swell and moisture susceptibility (Chittoori, 2008).

2.2.1.1 Cation Exchange

Negatively charged clay particles adsorb cations of specific type and amount. The ease of replacement or exchange of cations depends on several factors, primarily the valence of the cation. Higher valance cations (e.g. Ca^{++}) easily replace cations of lower valance (e.g. Na^{+}). For ions of the same valance, size of the hydrated ion becomes important; the larger the ion, the greater the replacement power. If other conditions are equal, trivalent cations are held more tightly than divalent and divalent cations are held more tightly than monovalent cations (Mitchell and Soga, 2005). A typical replaceability series is shown as follows:

$Na^{+} < Li^{+} < K^{+} < Rb^{+} < Cs^{+} < Mg^{2+} < Ca^{2+} < Ba^{2+} < Cu^{2+} < Al^{3+} < Fe^{3+} < Th^{4+}$

Below is an example of the cation exchange (Sivapullaiah, 1996);

$Ca^{2+} + Na^{+}$ - Clay $\rightarrow Ca^{2+}$ Clay + (Na^{+})

The thickness of the diffused double layer decreases as replacing the divalent ions (Ca^{2+}) from stabilizers with monovalent ions (Na^{+}) of clay. Thus, swelling potential decreases (Baser, 2009).

2.2.1.2 Flocculation and Agglomeration

Cation exchange reactions result in the flocculation and agglomeration of the soil particles with consequent reduction in the amount of clay-size materials and hence the soil surface area, which inevitably accounts for the reduction in plasticity (Terzaghi and Peck, 1967). Flocculation and agglomeration change the clay texture from that of a plastic, fine grained material to that of a granular soil (Yazici, 2004).

2.2.1.3 Pozzolanic Reactions

Time depending pozzolanic reactions play a major role in the stabilization of the soil, since they are responsible for the improvement in the various soil properties (Show et al., 2003). Calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) are the two outputs in pozzolanic reactions.

$Ca^{2+} + 2(OH)^{-} + SiO_2$ (Clay Silica) → CSH

$Ca^{2+} + 2(OH)^{-} + Al_2O_3$ (Clay Alumina) → CAH

2.2.2 Stabilization by Bigadic Zeolite

Bigadic zeolite was previously studied in construction sector for some reasons. For instance, Okucu (2006) studied on evaluation of zeolitic tuffs as cement additives and had the positive results. In this study the use of Bigadic zeolite is examined as a soil stabilizing agent to reduce swelling and some positive results were obtained. The major reason for this positive result is the pozzolanic reactions happened because of the CaO content of Bigadic zeolite.

CHAPTER 3

BIGADIC ZEOLITE

3.1 Zeolite

Zeolites have been recognized for more than 200 years, but only during the middle of the twentieth century they have attracted the attention of scientists and engineers who demonstrated their technological importance in several fields (Cincotti, Mameli, Locci, Orru, Cao, 2006).

The history of zeolites began in 1976 when the Swedish mineralogist Cronstedt discovered the first zeolite mineral, stilbite. He recognized zeolites as a new class of minerals consisting of hydrated aluminosilicates of the alkali and alkaline earths (Bekkum, Flanihen, Jansen, 1991).

Zeolites are crystalline aluminosilicates of group IA and group IIA elements such as sodium, potassium, magnesium and calcium. Chemically they are represented by the empirical formula $M_{2/n}O.Al_2O_3.ySiO_2.wH_2O$ where y is 2 to 10, n is the cation valance and w represents the water contained in the voids of the zeolite. Structurally, zeolites are complex, crystalline inorganic polymers based on an infinitely extending three-dimensional, four-connected framework of AlO_4 and SiO_4 tetrahedra linked to each other by the sharing oxygen ions (Bekkum, Flanihen, Jansen, 1991).

In Turkey, especially in the central Aegean region there are many different types of zeolites. In some sectors and industries zeolites were started to be used in 90's in Turkey. In the Five Years Development Plan in mining report in 2001, State Planning Organization (DPT) states the importance of zeolite and shows its uses in different sectors such as pollution control, wastewater treatment, energy, agriculture, stockbreeding, mining, construction, etc…

Cakicioglu-Ozkan and Ulku (2005) examined water vapor adsorption properties of the clinoptilolite rich zeolite tuff, from Bigadic, and its modified forms. They showed the useful effect of HCl treatment on water vapor adsorption characteristics of clinoptilolite rich natural Bigadic zeolite.

Cincotti, Mameli, Locci, Orru and Cao (2006) presented the extension of their investigation on the practical exploitation of Sardinian natural zeolites as low-cost materials for heavy metal ions removal from aqueous solutions. Therefore it is obviously seen from the academic studies and uses of zeolites in different sectors, zeolites do not have any negative effect to the environment. As a result of this study, if Bigadic zeolite is used as soil stabilizer, it will not pollute the ground water.

3.2 Bigadic Zeolite and Site Information

Bigadic zeolite is excavated in order to reach to the boron mines in Bigadic in Balikesir. There are three boron open mines in the zone of Etimaden in Bigadic which are Simav, Acep and Tulu mines. There is not any facility in Acep mine at the moment, 85% of the total output from these three mines is supplied from Simav mine which is the biggest mine. Also zeolite is taken out from Simav and Tulu mines and stocked separately. Figure 3.1 shows the geological map of the region. Some photographs are given in Figure 3.2 and 3.3 from Simav and Acep mines.

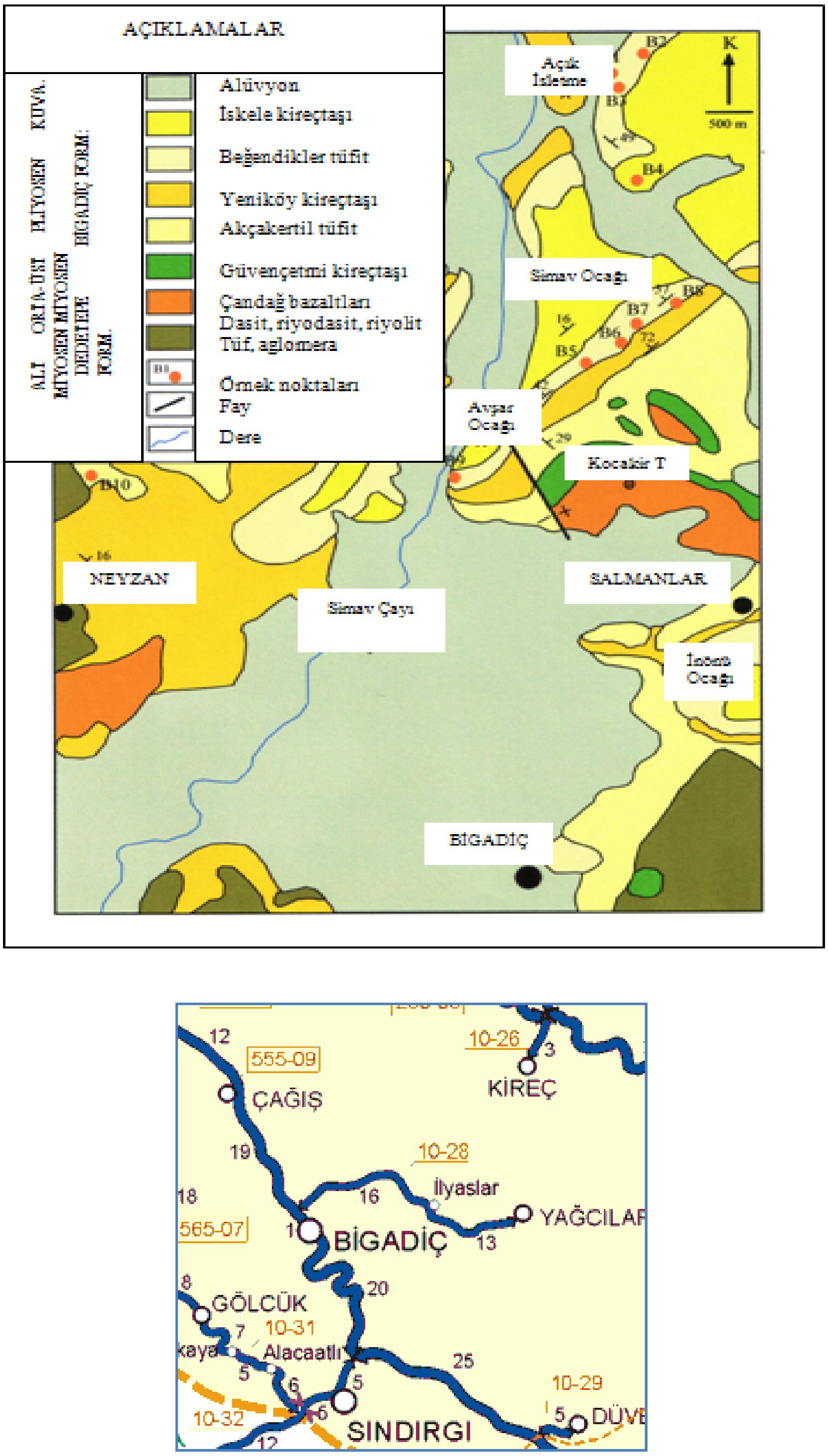

Figure 3.1 Geological Map of Bigadic Boron Basin (General Directorate of Mineral Research and Exploration, Geology Division, 2003)

Figure 3.2 View from Simav Mine

Figure 3.3 View from Acep Mine

Etimaden is the owner of the whole region and it is a governmental establishment. Their aim is to take out 800,000 ton/year boron but this amount is very changeable from year to year according to the weather conditions. Because it is an open mine, rain is the most important factor which affects the works at the site.

In order to obtain 800,000 ton/year boron from Simav mine, 30,000,000 ton/year earth has to be excavated. 1,700,000 ton/year of this amount is Bigadic zeolite. Because of many uses of zeolite are well known, Etimaden stocks it separately from the other wastes. Etimaden tries to market it and also use that by-product zeolite in order to stabilize their roads in the mine. Etimaden started to stock by-product Bigadic zeolite 3 years ago. Estimated quantity stocked for Bigadic zeolite is 4,000,000 ton in Simav mine. Estimated quantity of Bigadic zeolite in Bigadic basin is 5 Billions ton.

Figure 3.4 View from Simav Mine Showing the Terrains

Simav mine is the biggest open mine in the region (Figure 3.4 – 3.8). The lowest part is leveled as +20m and the highest part is leveled as +250m. In each 10m, new terrains are prepared. Etimaden's aim is to reach -90m level in the coming years. Terrains are easily seen from Figure 3.4.

Figure 3.5 Bigadic Zeolite Stock Areas in Simav Mine.

General Directorate of Mineral Research and Exploration (MTA) goes on drilling in the region in order to direct Etimaden for the boron reserves. During these drillings, zeolite is also detected around the mines. Figure 3.9 shows one of the drillings around Tulu mine.

Figure 3.6 View from Simav Mine.

Figure 3.7 View from Zeolite Stock Area in Simav Mine

Figure 3.8 View from Zeolite Stock Area in Simav Mine

Bigadic zeolite is stocked separately than the other wastes. In Figure 3.8, right top part in the figure shows the stock area of wastes excavated and bottom part shows the stock area for zeolite.

Figure 3.9 View from Drilling of MTA nearby Tulu Mine

3.3 Bigadic Zeolite in the Market

There is only one private company in Bigadic which operates raw zeolite and markets it. Its sale for domestic market was 5,000 ton/year and for foreign market was 1,200 ton/year in 2008.

There are two types of products. One occurs only from the particles whose diameters are between 1mm and 3mm. This product is generally used for agricultural purposes. The other product occur very fine particles whose diameters are less than 100 micron. This product is mainly used for chemical treatment, fishing and additive to animal food. It is calculated that the cost for the first product is around 90 TL/ton and for the second one is around 185 TL/ton. The raw zeolite is supplied from Etimaden with a very low price and after the grinding process it is packed. Figure 3.10 and 3.11 show the processes and the warehouse.

Figure 3.10 View from the Warehouse

Figure 3.11 View from the grinding machine

In this study before performing experiments, zeolite was supplied from Bigadic was in rock size. It was ground in METU Civil Engineering Department Material Laboratory and a material was obtained which can pass through sieve number 40.

CHAPTER 4

EXPERIMENTAL WORK

4.1 Purpose

The purpose of this experimental study is to investigate the effects of the addition of Bigadic zeolite on Atterberg limits, grain size distribution, swell percentage and rate of swell of an expansive soil sample; and also, to investigate the effect of curing on swell percentage and rate of swell of an expansive soil stabilized with Bigadic zeolite.

4.2 Material

Materials used in this study are Bigadic zeolite, kaolinite, bentonite, lime and sand. Bigadic zeolite is the by-product of the boron mine in Bigadic Boron Work in rock size. Bigadic zeolite was ground into fine grains at METU Civil Engineering Department Material Laboratory (Figure 4.1). By-product Bigadic zeolite was passed through number 40 sieve before usage. Specific gravity of Bigadic zeolite is 2.31.

Bentonite is the product of Karakaya Bentonite Factory in the form of fine sized grains. Kaolinite is the product of Esan Industrial Minerals Company of Eczacıbaşı. During sample preparation there was no need to sieve bentonite because of its fine sized particles. Kaolinite was sieved through number 40 sieve.

Figure 4.1 View from Bigadic Zeolite

X-ray diffraction patterns were analyzed at Department of Mineral Analysis and Technology in General Directorate of Mineral Research (MTA). Mineral composition and chemical analysis of the Bigadic zeolite were determined and presented at Figure 4.2 and Figure 4.3.

Zeolites are used in the purification of waste water (Kırşan, 2004). Although there are some hazardous materials in Bigadic zeolite, the contents of such materials are very small therefore Bigadic zeolite is not expected to affect the ground water in a negative way.

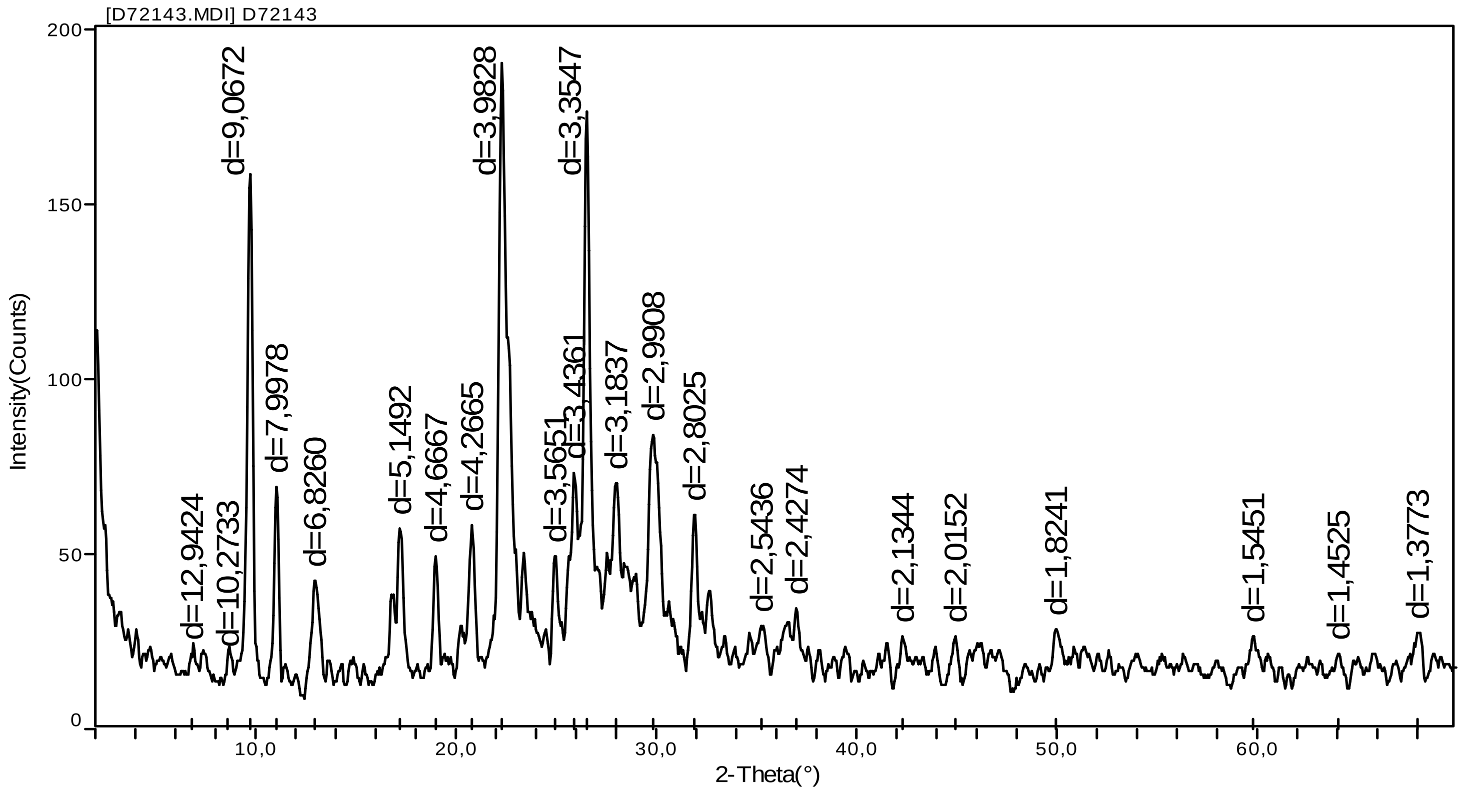

Figure 4.2 X-Ray Diffraction Patterns for Bigadic Zeolite Sample

Sample No: B3					
A.Z	pH	Na_2O	MgO	Al_2O_3	SiO_2
%		%	%	%	%
9.65	8.54	0.40	0.80	11.50	70.60
P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3
%	%	%	%	%	%
K0.1	3.00	3.90	0.10	K0.1	0.90
d	F	Sc	V	Cr	Co
gr/cm3	Ppm	ppm	Ppm	ppm	Ppm
1.98	K1500	K20	13	K60	K50
Ni	Cu	Zn	Rb	Sr	Ce
Ppm	Ppm	ppm	Ppm	ppm	Ppm
K30	K30	31	198	96	K500
Y	Zr	Nb	Ba	La	Pb
Ppm	Ppm	ppm	Ppm	ppm	Ppm
17	99	K20	150	K40	65
Nd	Yb	Th	U	SO_3	Cl
Ppm	Ppm	ppm	Ppm	%	Ppm
38	K10	38	K10	0.02	0.03
Klinoptilolit, Amorf material, Illit					

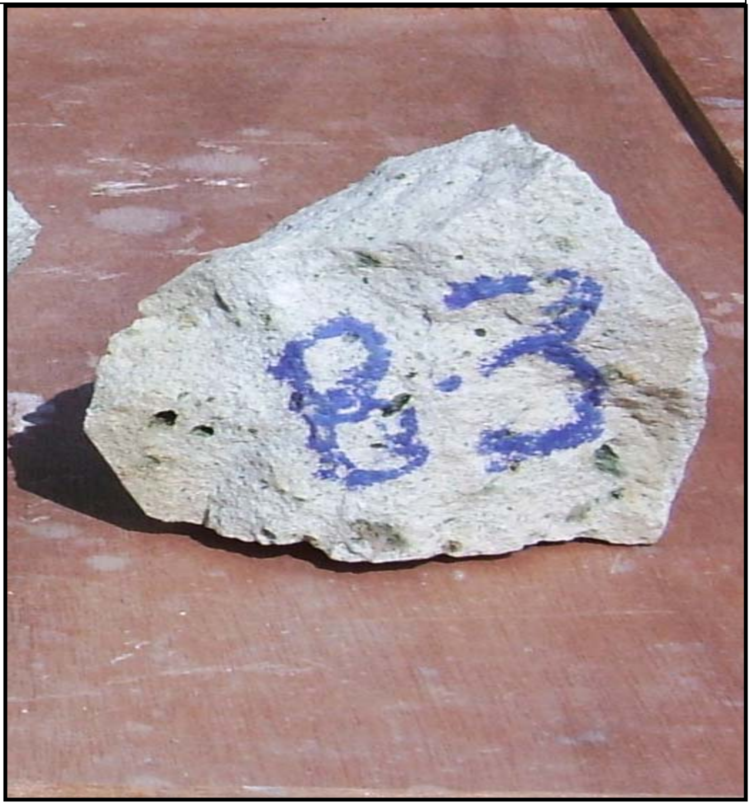

Figure 4.3 Chemical Analyses and Mineral Composition of the Bigadic Zeolite Sample

4.3 Preparation of Specimens and their Basic Properties

Sample A was prepared as an artificial expansive soil, by mixing kaolinite and bentonite (Figure 4.4). 130 g sample was prepared each time for free swell tests. Expansive soil sample was prepared by mixing 85% kaolinite and 15% bentonite. At the beginning of the study, 20% Bigadic zeolite was added to Sample A to see the effect of stabilizer. After the free swell test, it was seen that Bigadic zeolite was an effective stabilizer. Then from 5% to 25% Bigadic zeolite was added to Sample A and experiments were performed. Furthermore in order to show the effect of Bigadic zeolite as stabilizer, an inert material which is sand was added to Sample A and tests were performed in order to find the differences (Figure 4.4). Moreover only lime from 1% to 5% and Bigadic zeolite and lime together (totally 15%) were analyzed (Figure 4.4). Totally 18 different samples were analyzed in this study (Figure 4.4 and Table 4.1).

Before mixing all different materials, all of them were sieved through number 40 sieve. After mixing different materials by trowel, samples were sieved two times through number 30 sieve. Then 10% water (around 13 g) was added to the samples and mixed by trowel.

Hydrometer test, Atterberg test and specific gravity tests were performed according to ASTM D 2435. Clay and silt percentages were found by grain size distribution curves from hydrometer test and sieve analyses. Grain size distribution curves for each sample which is Bigadic zeolite, sand, lime, Bigadic zeolite + lime added samples are given in Appendix A.

Specific gravity (G_s) values for each sample were determined. G_s values were determined also for 100% Bigadic zeolite, sand and lime separately. Specific gravity values of the samples are given in Figure 4.5.

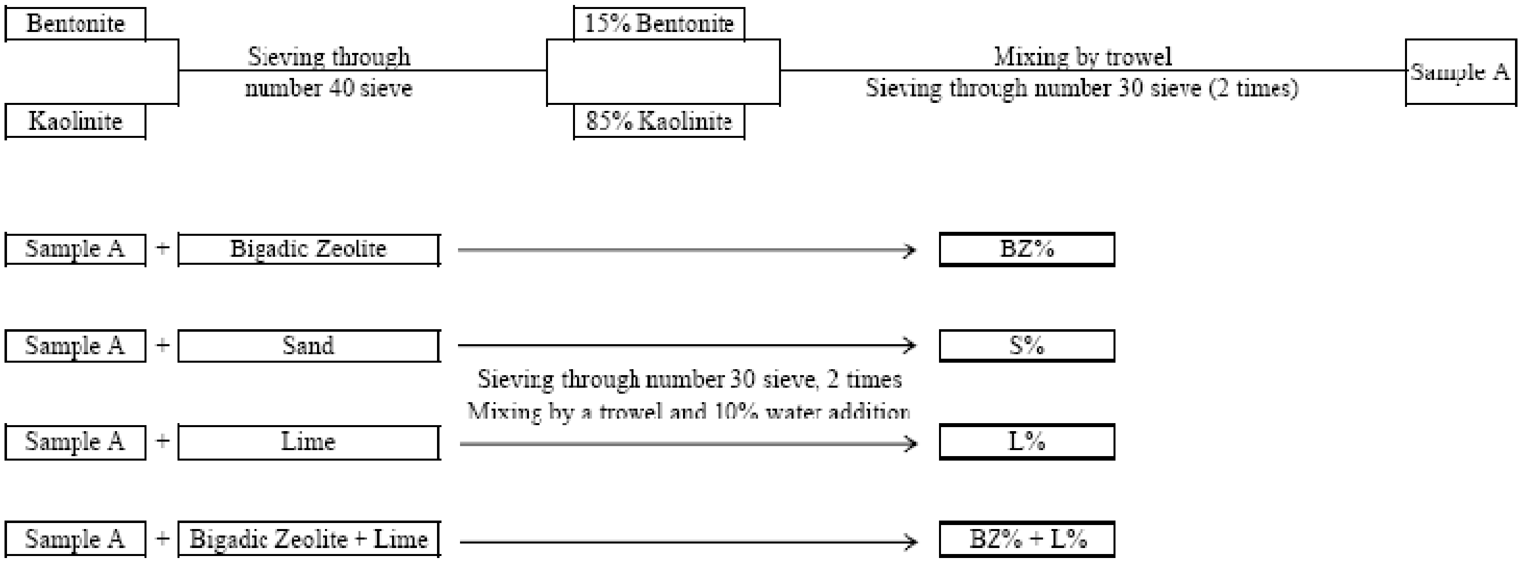

Figure 4.4 Preparations of Samples

Table 4.1 Specimens Used

Sample	**Expansive Soil (%)**	**Bigadic Zeolite (%)**	**Sand (%)**	**Lime (%)**
Sample A	100	0	0	0
BZ 5%	95	5	0	0
BZ 10%	90	10	0	0
BZ 15%	85	15	0	0
BZ 20%	80	20	0	0
BZ 25%	75	25	0	0
BZ 100%	0	100	0	0
L 1% + BZ 14%	85	14	0	1
L 3% + BZ 12%	85	12	0	3
L 5% + BZ 10%	85	10	0	5
S 5%	95	0	5	0
S 10%	90	0	10	0
S 15%	85	0	15	0
S 20%	80	0	20	0
S 25%	75	0	25	0
L 1%	99	0	0	1
L 3%	97	0	0	3
L 5%	95	0	0	5

Liquid limit, plastic limit, plasticity index, shrinkage limit and shrinkage index were determined for samples and shown in Figure 4.6, Figure 4.7, Figure 4.8, Figure 4.9 and Figure 4.10.

The results of sieve analysis, hydrometer test, Atterberg Limit tests and specific gravity test are given in Table 4.2. Soil classification was done according to Unified Soil Classification System (USCS) by plotting test results on plasticity chart as shown in Figure 4.11.

Swelling potential of each specimen was calculated according to the PI values and clay percentages listed on Table 4.2 and presented on Figure 4.12. Activity in Figure 4.12 is calculated by dividing plasticity index to clay percentage.

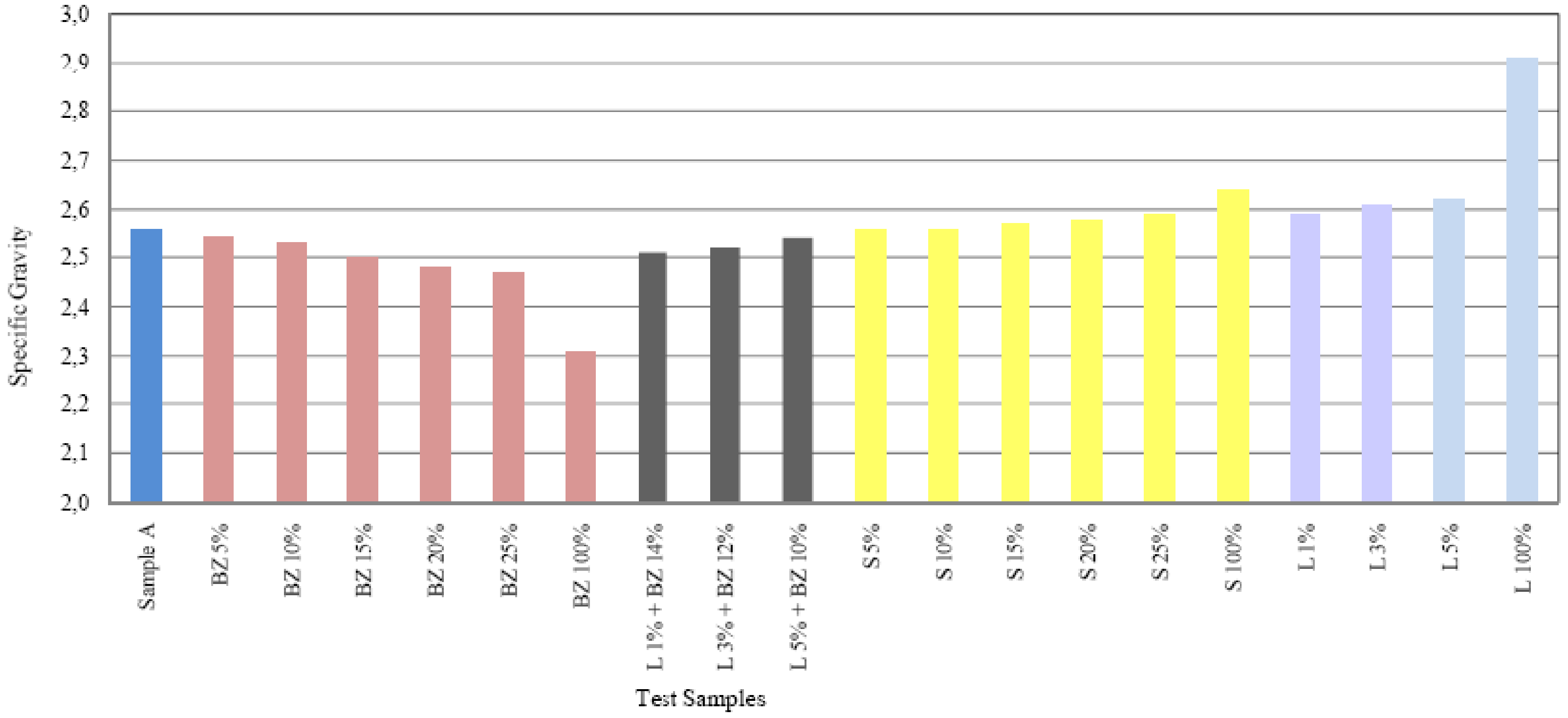

Figure 4.5 Effect of Addition of Additives on Specific Gravity (Gs) of the Samples

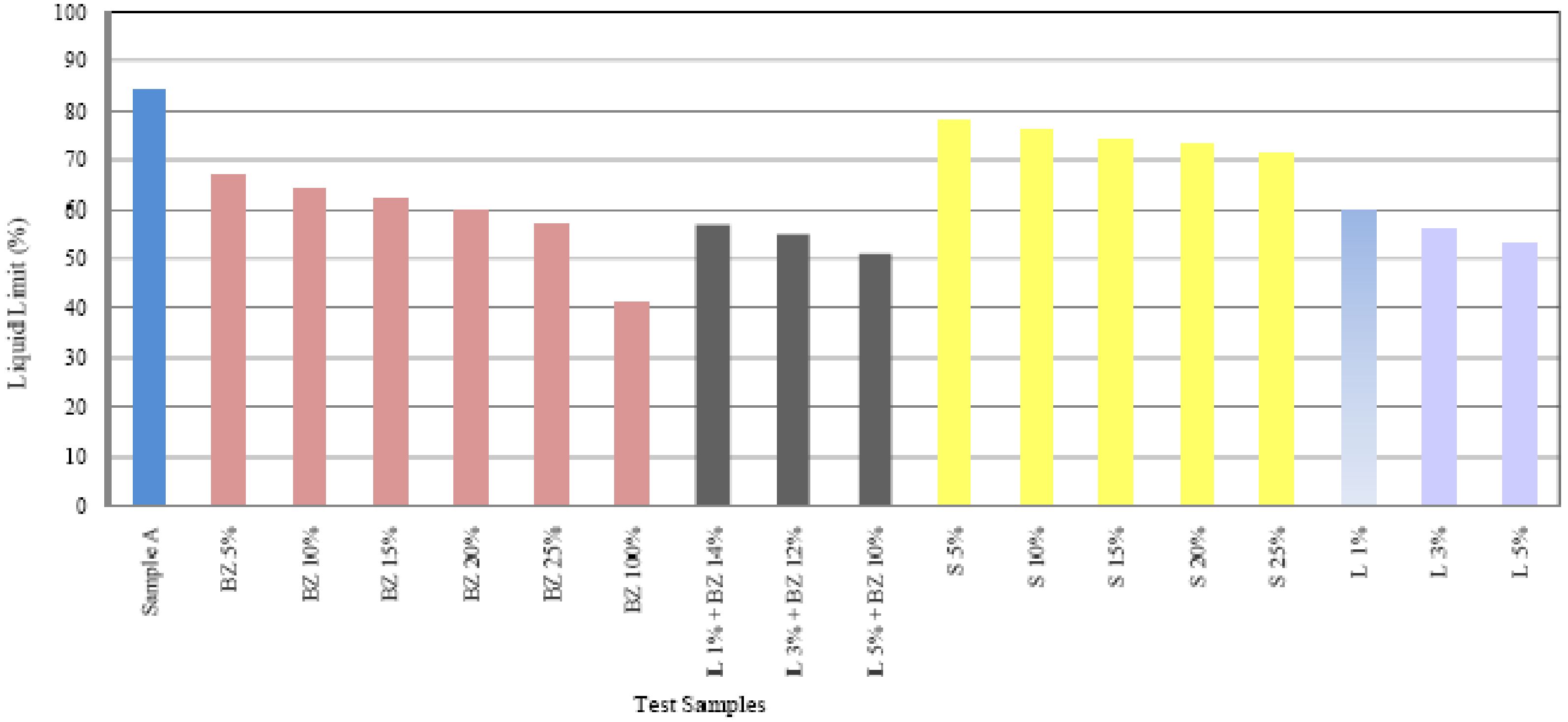

Figure 4.6 Effect of Addition of Additives on Liquid Limit (LL) of the Samples

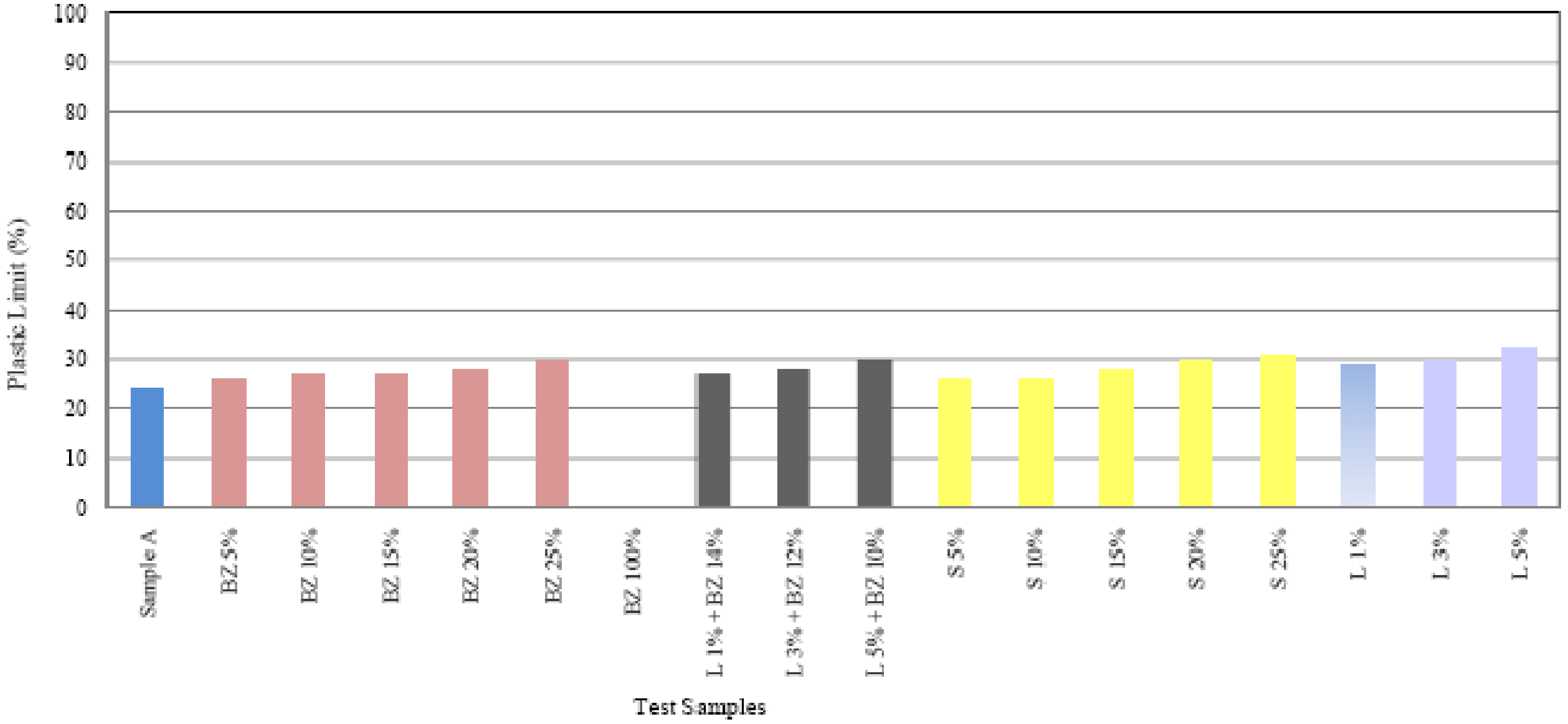

Figure 4.7 Effect of Addition of Additives on Plastic Limit (PL) of the Samples

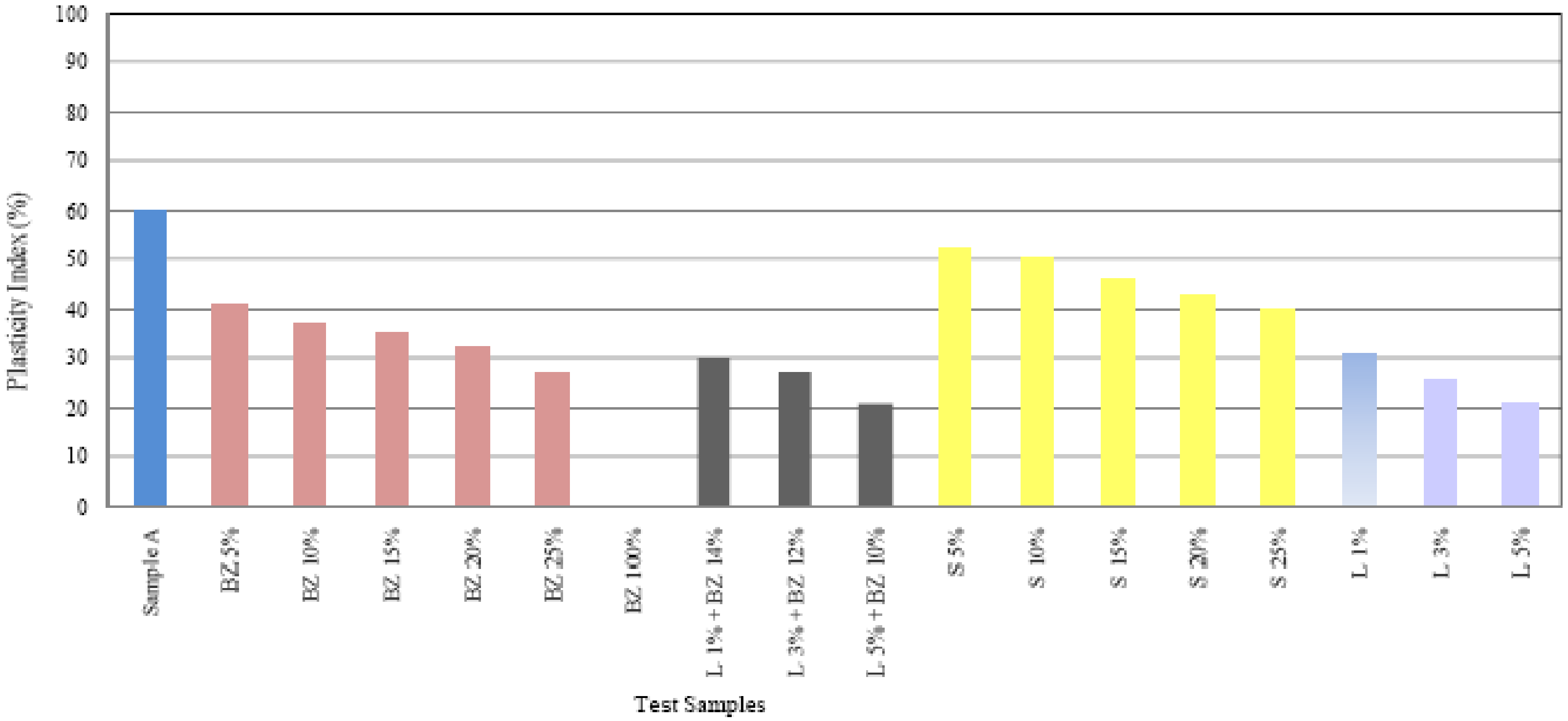

Figure 4.8 Effect of Addition of Additives on Plasticity Index (PI) of the Samples

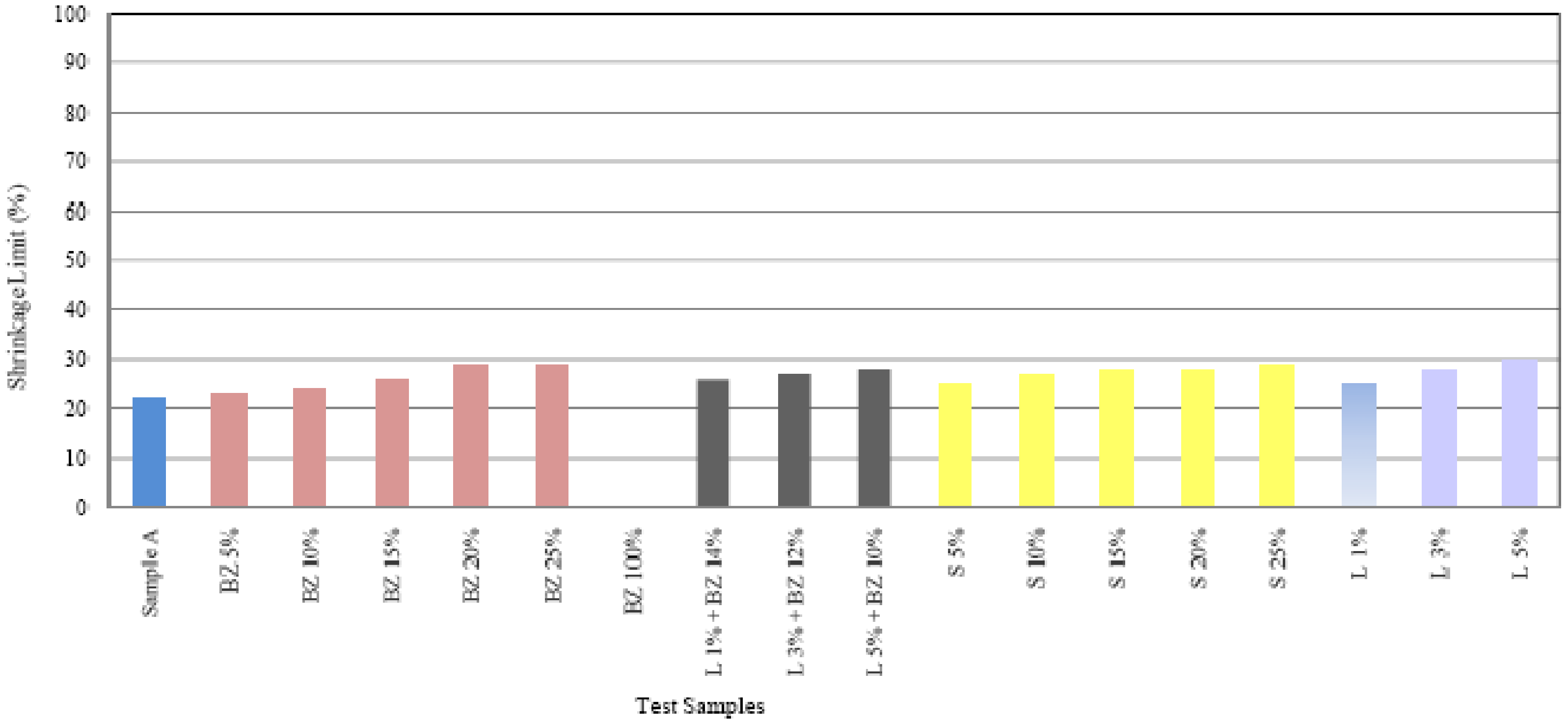

Figure 4.9 Effect of Addition of Additives on Shrinkage Limit (SL) of the Samples

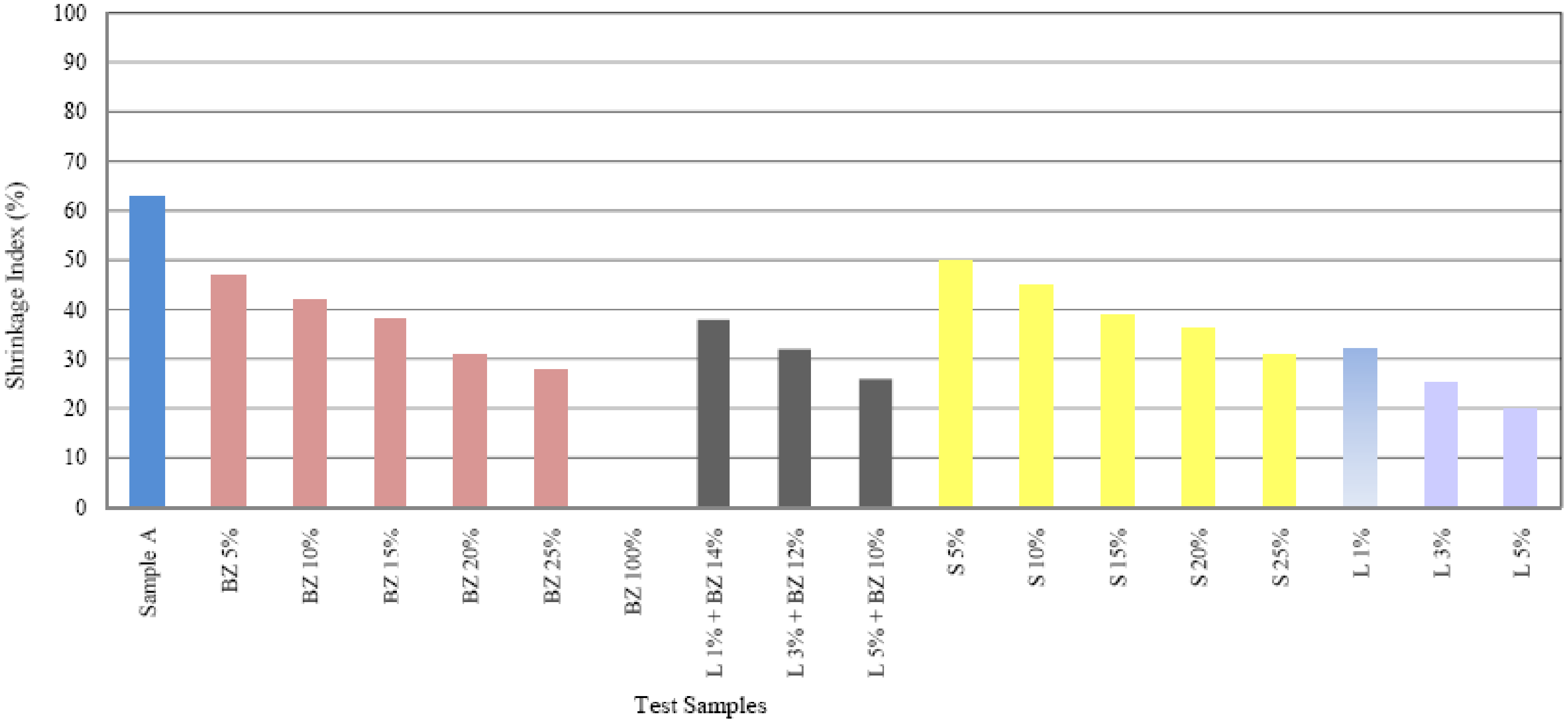

Figure 4.10 Effect of Addition of Additives on Shrinkage Index (SI) of the Samples

Table 4.2 Properties of the Samples

Sample	Clay (%)	Silt (%)	G_s	LL (%)	PL (%)	PI (%)	SL (%)	SI (%)	USCS	Activity	Swelling Potential
Sample A	47.1	52.9	2.56	84	24	60	22	63	CH	1.27	Very High
BZ 5%	46.3	53.7	2.54	67	26	41	23	47	CH	0.89	High
BZ 10%	44.7	55.3	2.53	64	27	37	24	42	CH	0.83	Medium
BZ 15%	42.3	57.7	2.50	62	27	35	26	38	CH	0.83	Medium
BZ 20%	39.8	60.2	2.48	60	28	32	29	31	CH	0.80	Medium
BZ 25%	37.1	62.9	2.47	57	30	27	29	28	CH	0.73	Low
BZ 100%	19.1	80.9	2.31	41	NP	NP	*	*	*	*	*
L 1% + BZ 14%	42.4	57.6	2.51	57	27	30	26	38	CH	0.71	Medium
L 3% + BZ 12%	41.8	58.2	2.52	55	28	27	27	32	CH	0.65	Low
L 5% + BZ 10%	39.1	60.9	2.54	51	30	21	28	26	ML or OL	0.54	Low
S 5%	46.2	53.8	2.56	78	26	52	25	50	CH	1.13	High
S 10%	45.1	54.9	2.56	76	26	50	27	45	CH	1.11	High
S 15%	42.8	57.2	2.57	74	28	46	28	39	CH	1.07	High
S 20%	39.9	60.1	2.58	73	30	43	28	36	CH	1.08	High
S 25%	37.5	62.5	2.59	71	31	40	29	31	CH	1.07	High
L 1%	43.2	56.8	2.59	60	29	31	25	32	CH	0.72	Medium
L 3%	41.5	58.5	2.61	56	30	26	28	25	CH	0.63	Low
L 5%	36.7	63.3	2.62	53	32	21	30	20	MH or OH	0.57	Low

NP: Non-plastic
* Could not be determined

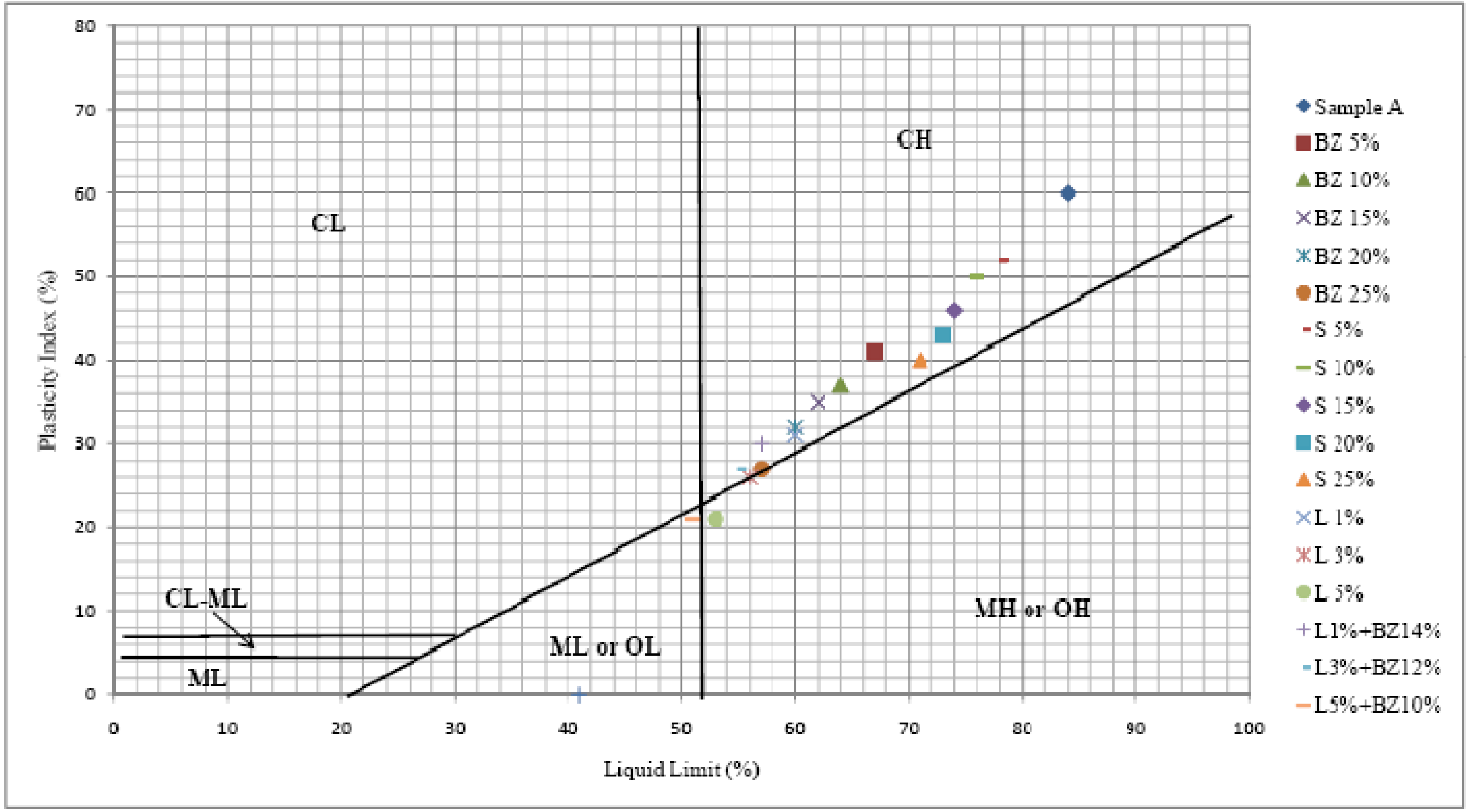

Figure 4.11 Plasticity Chart: Unified System

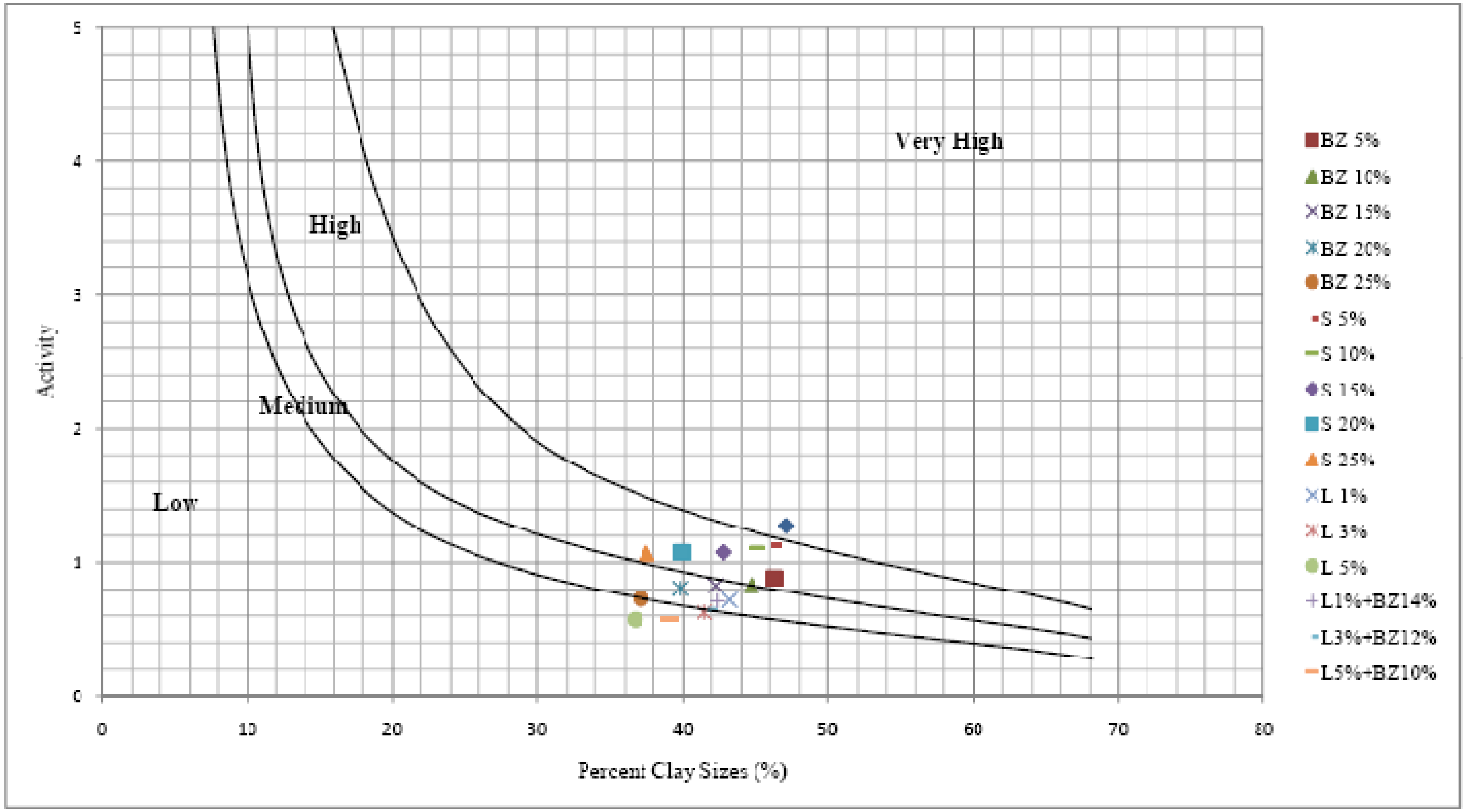

Figure 4.12 Swell Potential Classifications with Clay Fraction and Activity (After Seed, et al., 1962)

4.4 Free Lime Content Test

One of the reasons in using Bigadic zeolite is its pozzolanic activity because of its lime content. In order to determine lime content of test samples ASTM C 25 (Standard Test Methods for Chemical Analysis of Limestone, Quicklime and Hydrated Lime) was used. These experiments were performed at METU Chemistry Department, Chemistry Laboratory.

First of all, 40g sugar is dissolved in 100ml carbon dioxide free water, several drops of 4% phenolphthalein indicator were put and 0.1N NaOH is added to this mixture in order to have neutralized sugar solution. Afterwards, 2.8g of specimen is put into 40ml of carbon dioxide free water and 100ml of neutralized sugar solution is added to this mixture. Then 15min. waited for reactions and at each 5min, solution is swirled. After 15min the solution is titrated with HCl until the first disappearance of the pink color.

$L = (N \times V \times 3.704) / W$

Where,

L: available lime, %
N: 1, normality of acid solution
V: standard HCl (1N), ml
W: weight of sample, g

By means of free lime content test on stabilizers, it is detected that there is some lime content in Bigadic zeolite which decreases swell potential with an average available lime content of 3%.

4.5 Free Swell Ratio Test

Sridharan and Prakash proposed free swell ratio test and the following formula in order to detect the swell property of soils (Sridharan and Prakash, 2004).

FSR = Vd / Vk

Where,

FSR: free swell ratio, %
Vd: sediment volume of 10g oven dried soil passing a 425 µm sieve in distilled water
Vk: sediment volume of 10g oven dried soil passing a 425 µm sieve in carbon tetra chloride or kerosene.

Samples were prepared without adding water. 10g of each sample was added to 100ml of water in a graduated jar and to 100ml of kerosene in a graduated jar separately. Sediment volumes of samples were measured after 24 hours. Then free swell ratios of samples were calculated according to the measured values. Soil classification according to the free swell ratios are presented by Sridharan and Prakash in Table 4.3

Table 4.3 Soil Classification Based on Free Swell Ratio (Sridharan and Prakash, 2004)

Free Swell Ratio	Soil Expansivity	Clay Type	Dominant Clay Mineral Type
< 1.0	Negligible	Non-swelling	Kaolinitic
1.0 - 1.5	Low	Non-swelling and swelling	Kaolinitic and Montmorillonitic
1.5 - 2.0	Moderate	Swelling	Montmorillonitic
2.0 - 4.0	High	Swelling	Montmorillonitic
> 4.0	Very High	Swelling	Montmorillonitic

The free swell ratio values of the samples are given in Figure 4.13.

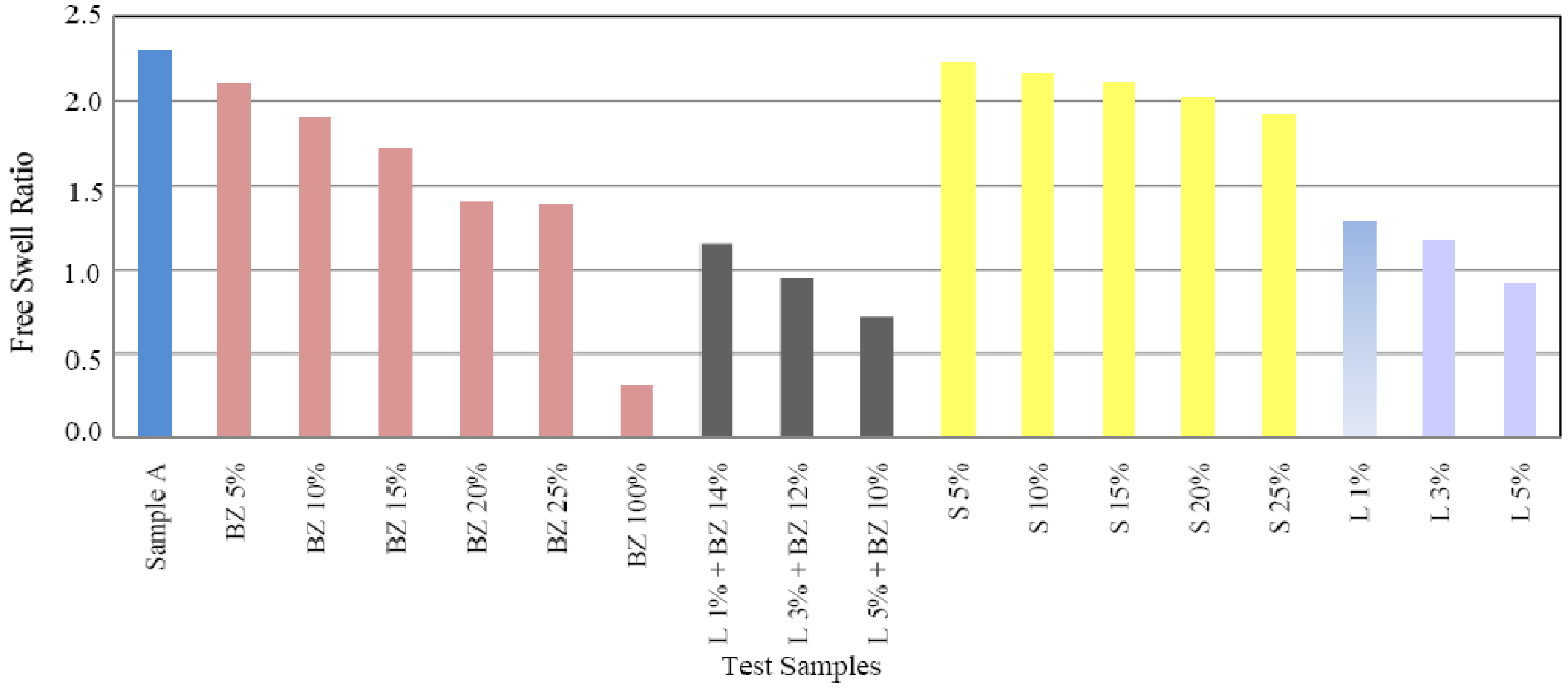

Figure 4.13 Effect of Addition of Stabilizers on Free Swell Ratio

4.6 Free Swell Test

After performing free lime content test and free swell ratio test; it was seen that Bigadic zeolite can be used for the stabilization of expansive soils and free swell tests were done. Effect of cure on free swell and rate of swell were analyzed.

After preparing samples as stated in section 4.3, samples were compacted into guide ring obtaining a bulk density of 1.80 g/cm^3 and a dry density of 1.64 g/cm^3. Compaction was done in three layers and by means of hydraulic jag. After compaction of a layer, a threaded surface was prepared by screwdriver. This prevents the deformation of specimen during transferring it from guide ring to consolidation ring (Figure 4.14).

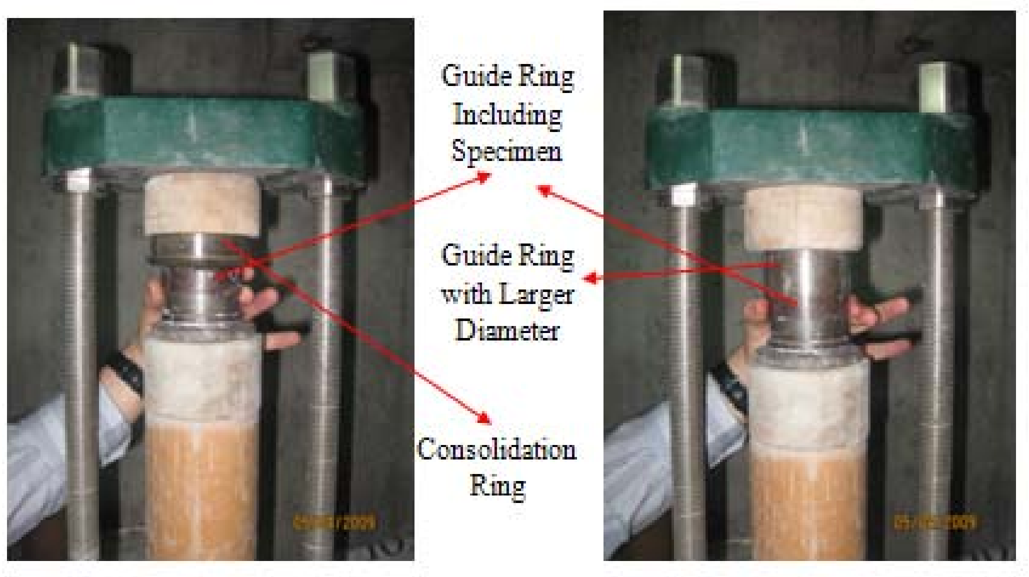

Figure 4.14 Compaction Set Up and Transfer of Specimens

After compaction, specimen was transferred from guide ring into consolidation ring as shown in Figure 4.14 at left side. For free swell tests with 7 days and 28 days cures, transfer was done from guide ring into another guide ring with a slightly larger diameter in order to prevent damaging of the specimens as shown in Figure 4.14 at right side.

Before performing free swell tests of the cured specimens, they were cured at 22ºC and 70% relative humidity in the dessicator for 7 and 28 days.

Swelling was determined by means of the free swell test set up as shown in Figure 4.15. The test specimen is in the form of a disc, held inside of a consolidation ring and lying between two porous stones and the upper porous stone, which can move inside the ring with a small clearance, is fixed below a metal loading cap through which pressure can be applied to the specimen (Craig, 1986).

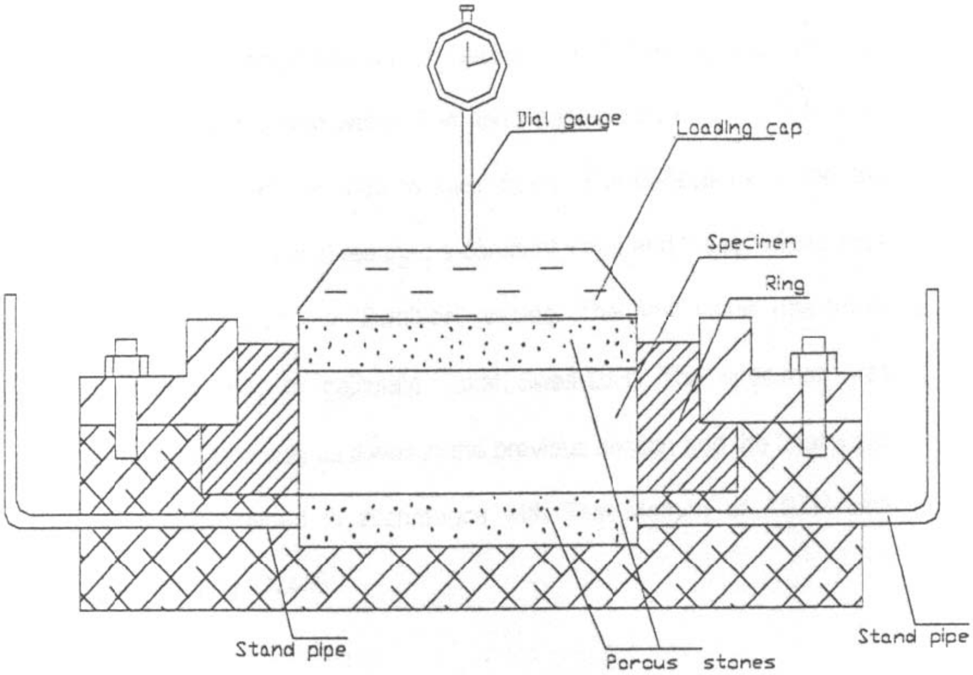

Figure 4.15 Free Swell Test Set Up (Craig, 1986)

A dial gage was mounted to the top part of the free swell test set up in order to measure the vertical deflection. At the beginning of the test, dial gage was set to zero. Then water was poured from stand pipes and directly from the top of the set up. Deflection values were read in different period of times till the sample had no tendency to swell more. Free swell is expressed by the following formula:

Free Swell = $(\Delta h / h) \times 100$

Where,

Δh: change in height
h: initial height of the specimen (around 19mm)

4.7 Test Results

Free swell tests were performed and shown in Appendix B for different specimens without cure, 7 days cure and 28 days cure.

Free swell values are given in Figure 4.16, Figure 4.17 and Figure 4.18 for the specimens without cure, with 7 days cure and with 28 days cure. Figure 4.19 shows the effect of cure in free swell values. Normalized swelling percentages of the specimens are given in Figure 4.20.

Rate of swell cannot be measured with a specific method. Therefore, for the evaluations of the results of this experimental study the rate of swell is defined as the time to reach 50 percent swell, t_{50}, i.e., the time elapsed to half the full swell (Basma and Tuncer, 1990). Time to reach 50% swell in seconds against percent stabilizer added are presented in Figure 4.21, Figure 4.22, Figure 4.23 separately and in Figure 4.24 the effect of cure on t_{50} values of the specimens are given together (without cure, with 7 days cure, with 28 days cure).

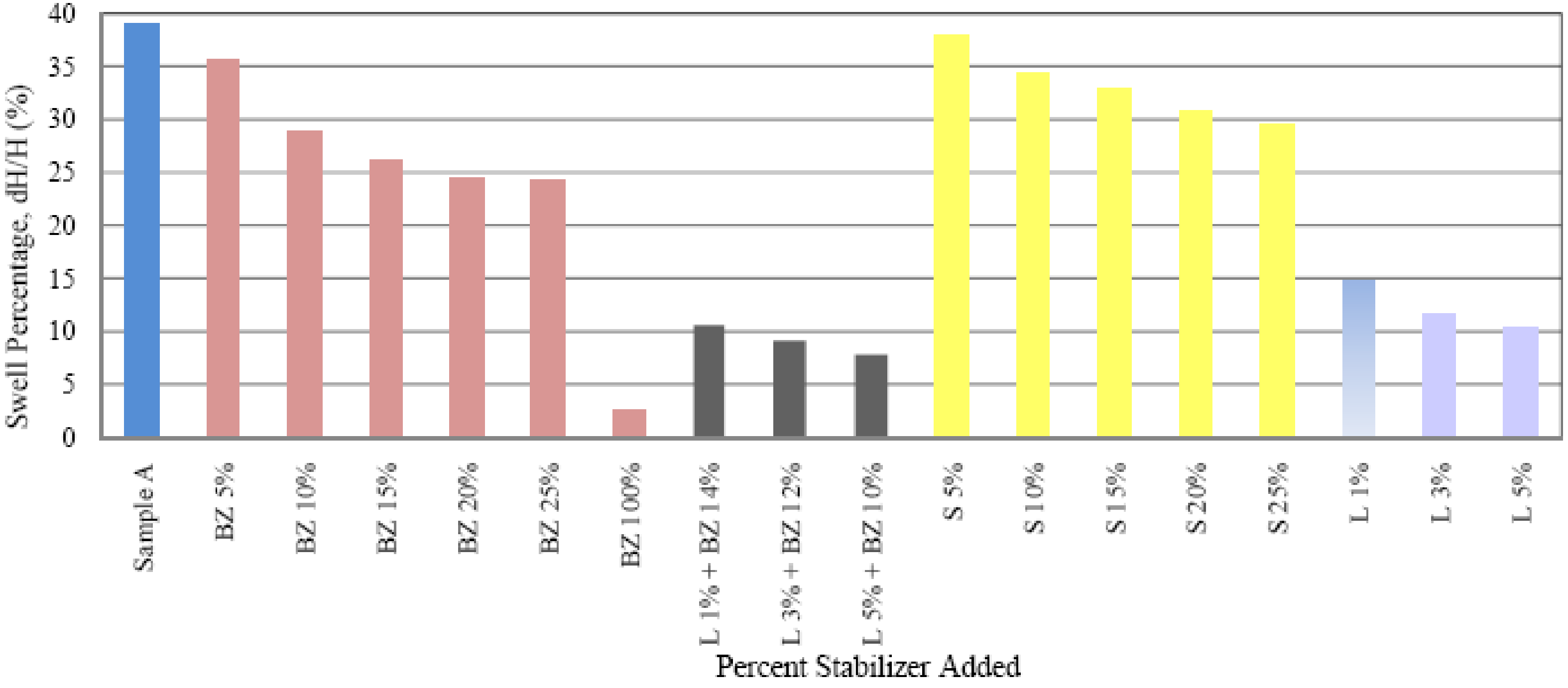

Figure 4.16 Variation of Swell Percentage according to the Type and Amount of Stabilizer Added

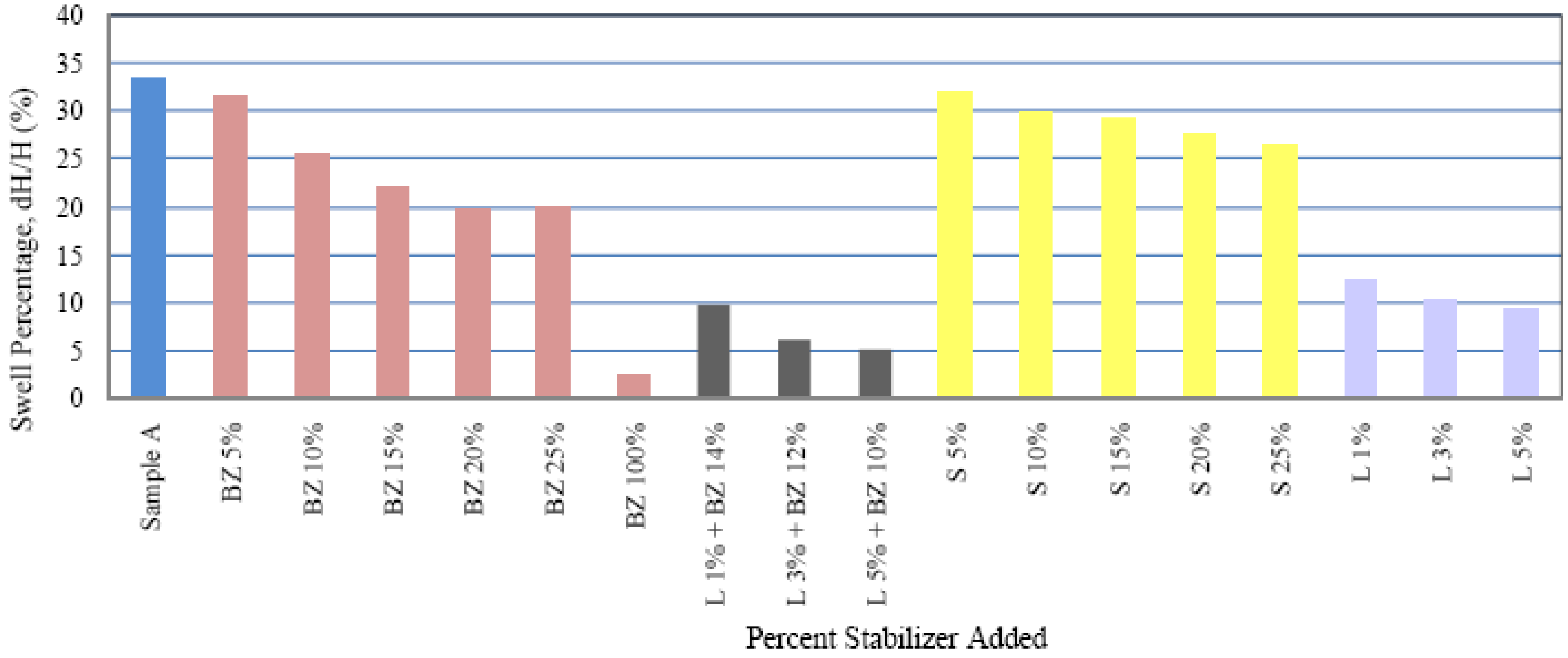

Figure 4.17 Variation of Swell Percentage according to the Type and Amount of Stabilizer Added, 7 Days Cured

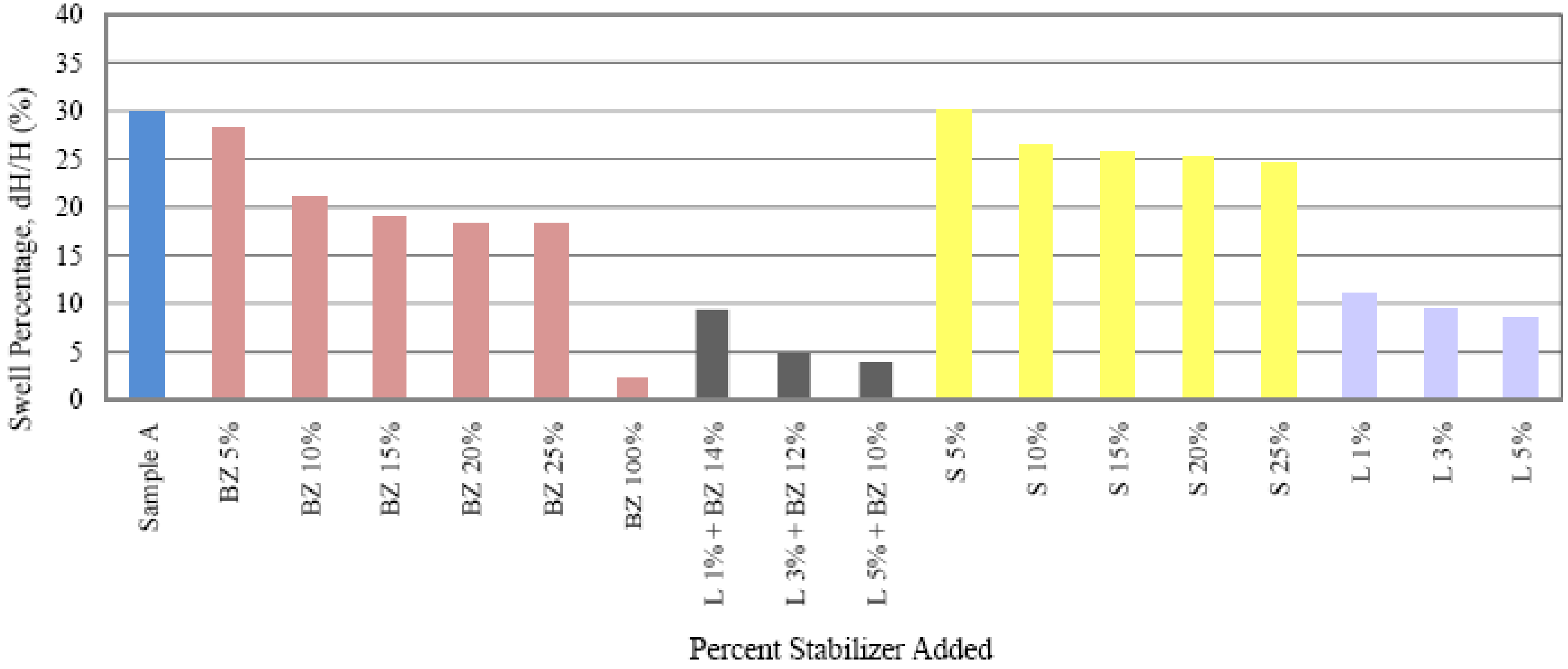

Figure 4.18 Variation of Swell Percentage according to the Type and Amount of Stabilizer Added, 28 Days Cured

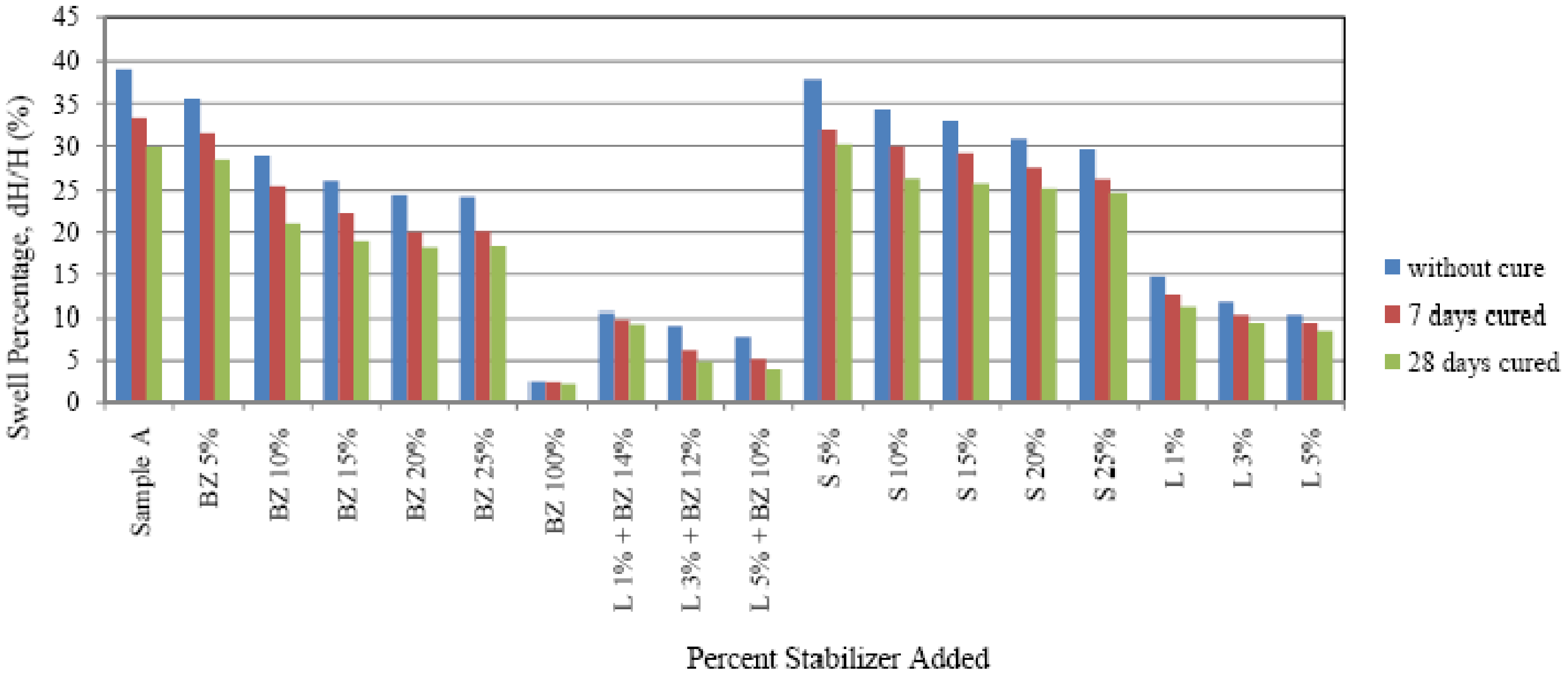

Figure 4.19 Effect of Cure on Swelling Percentage of the Specimens

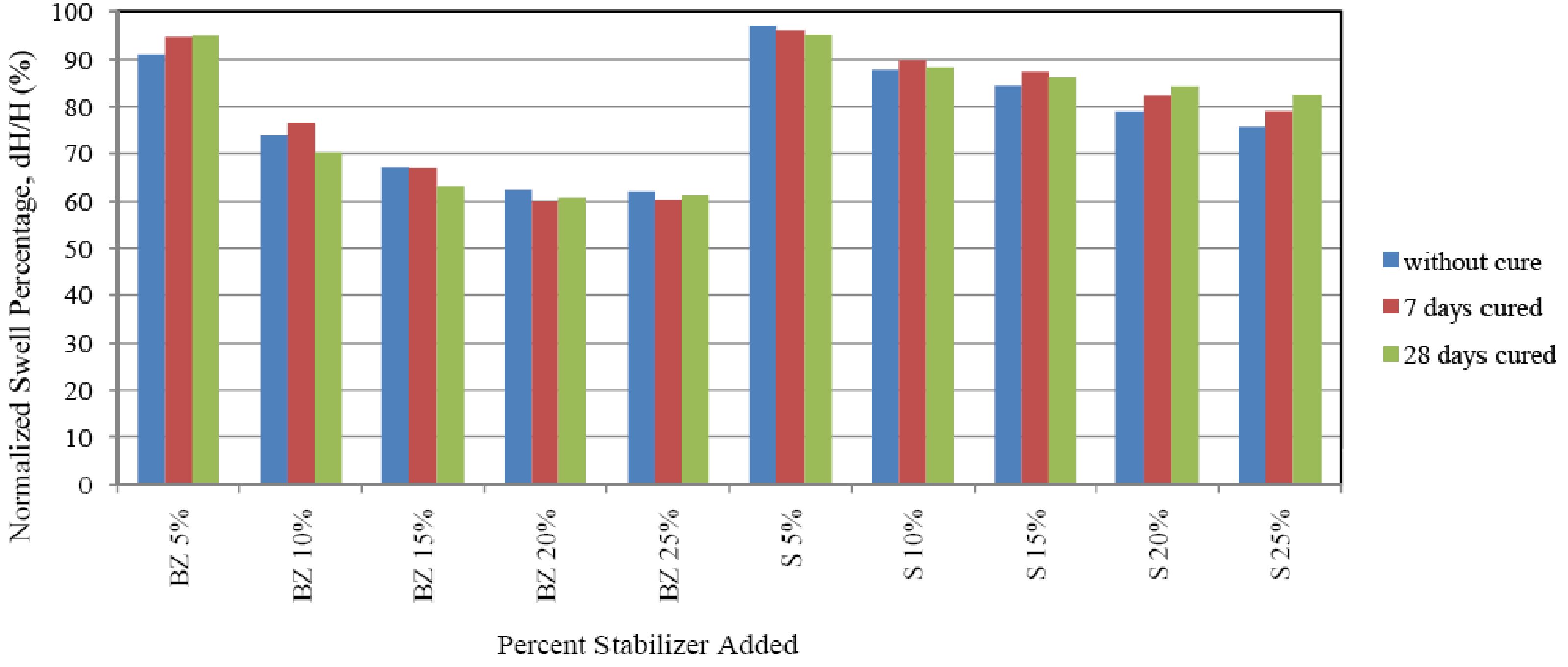

Figure 4.20 Normalized Swelling Percentage of the Specimens

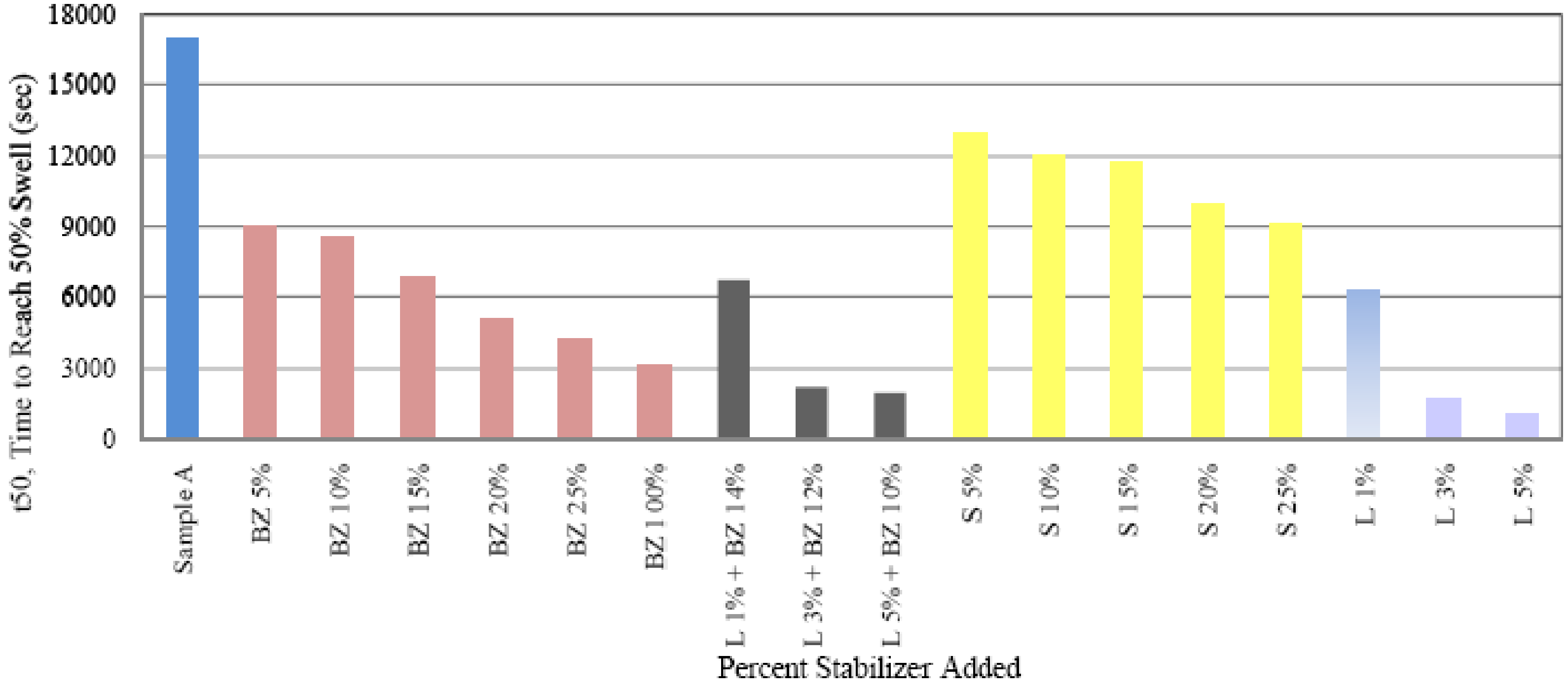

Figure 4.21 Variation of t_{50} with Type and Amount of Stabilizer Added without Curing

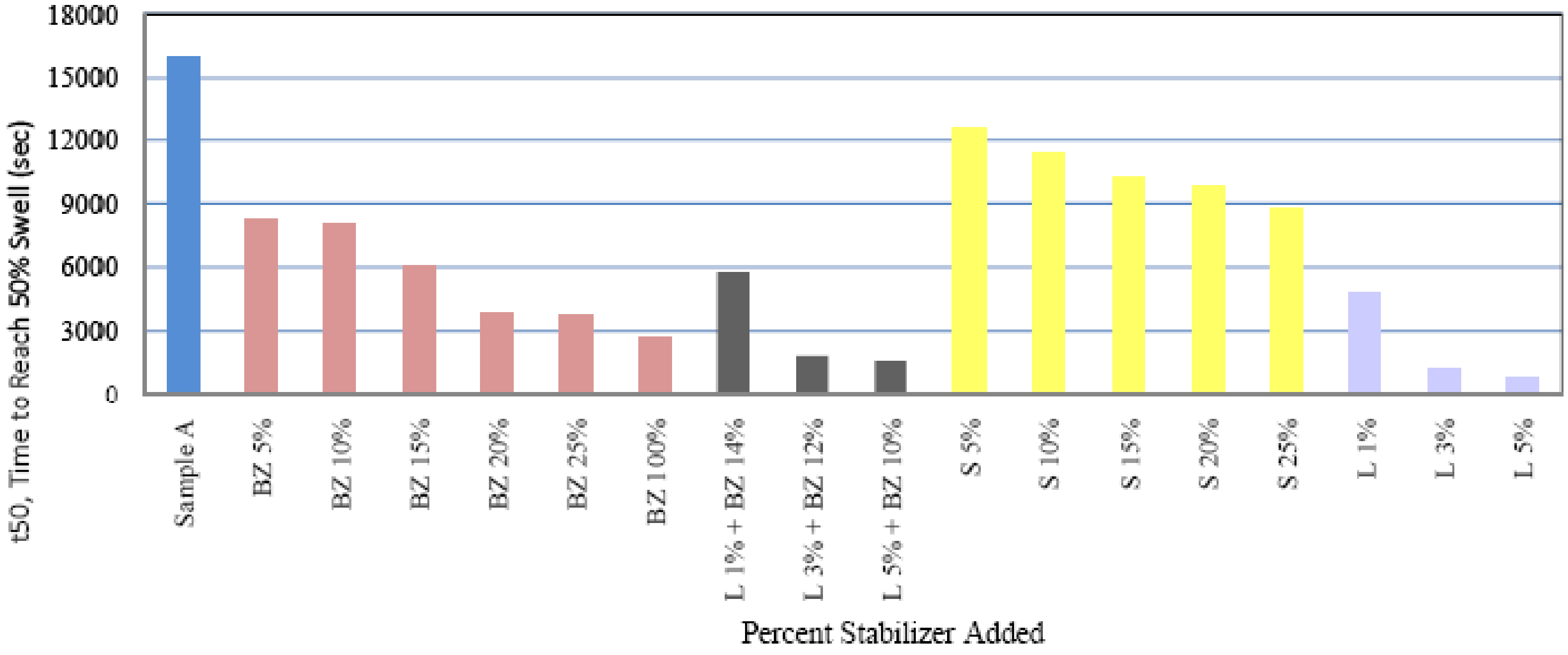

Figure 4.22 Variation of t_{50} with Type and Amount of Stabilizer Added after 7 Days Curing

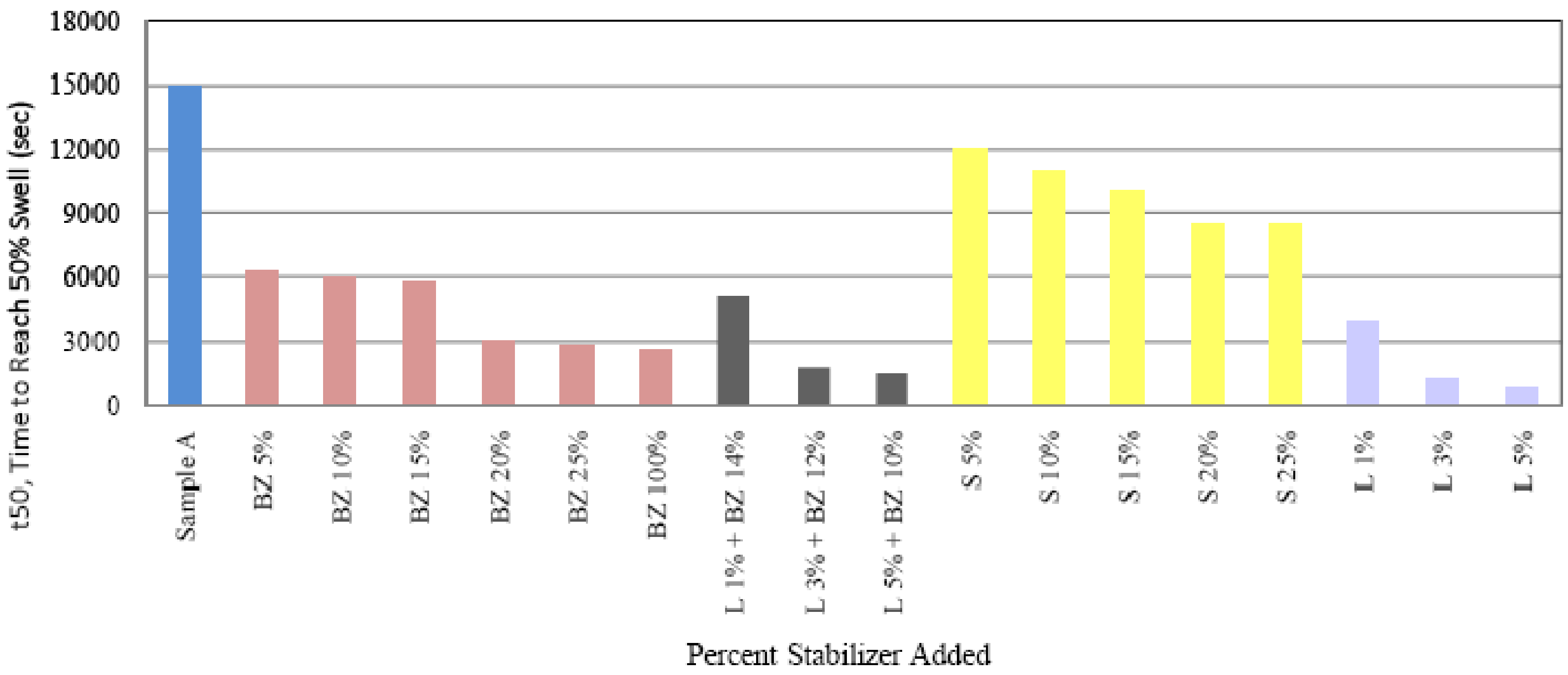

Figure 4.23 Variation of t_{50} with Type and Amount of Stabilizer Added after 28 Days Curing

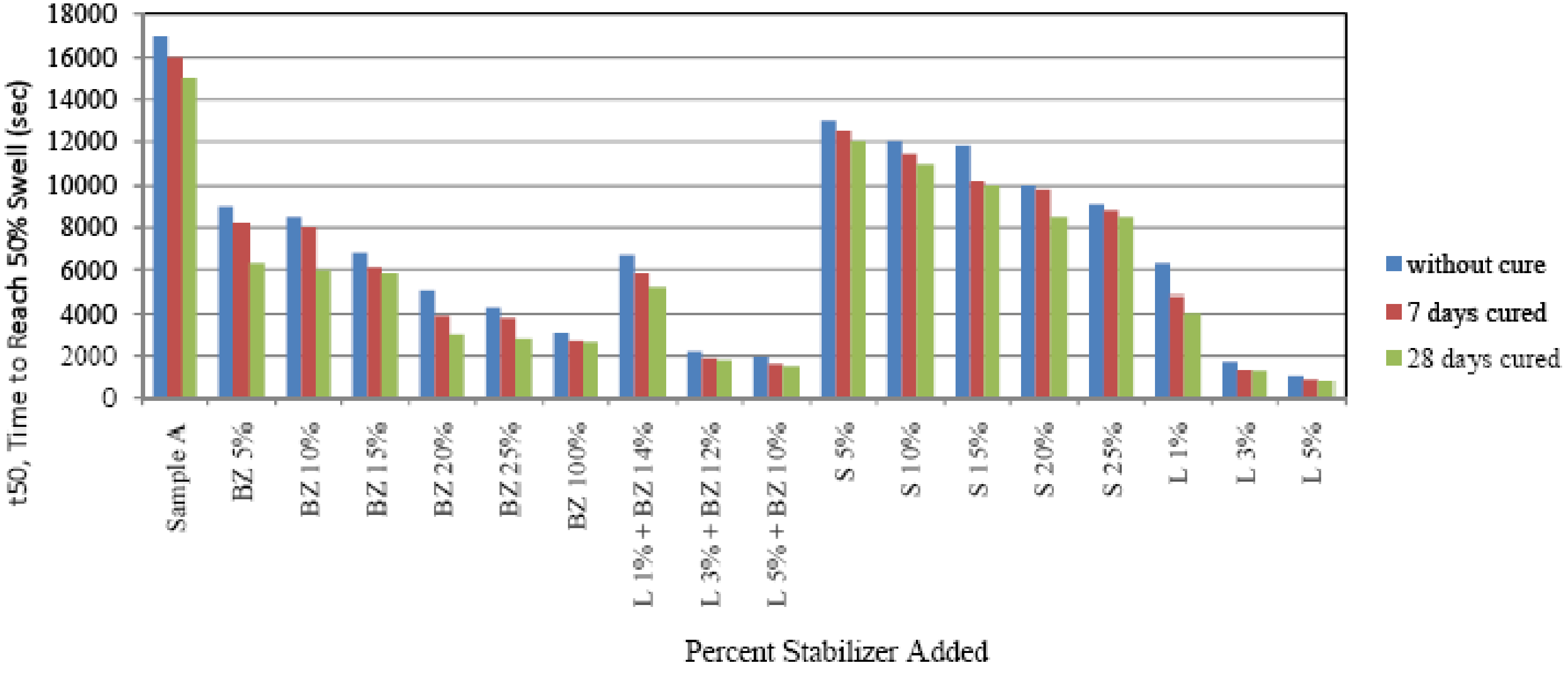

Figure 4.24 Effect of Cure on t_{50} of the Specimens

4.8 Calculations for Estimation of Swell Percentage

There is an approach in order to estimate swell percentage by means of the swelling percentage versus time graphs prepared after free swell tests. By using the same data another graph is prepared which is time/free swell versus time graph. In time/free swell versus time graphs after some time elapsed, a straight-line relationship is apparent (Sivapullaiah, 1996). Swell percentage can be estimated from the slope of straight-line part of time/free swell versus time.

Following relationship was proposed by Dakshanamurthy (1978);

$S = t / (m * t + c)$

Where,

S: swell percentage
t: the time at which swelling is required
c: constant
m: slope of time/free swell versus time graph
$S = \lim_{t \to \infty} (t / (m * t + c)) = \lim_{t \to \infty} (t / (t * (m + c / t))) = 1 / m$

Time / free swell versus time graphs for the specimens in 4 categories; "Bigadic zeolite, sand, lime, Bigadic zeolite plus lime with the three situations which are without cure; 7 days cure and 28 days cure are presented in Appendix C. Estimated and measured free swell percentages are shown in Figure 4.27, Figure 4.28 and Figure 4.29. Comparison of estimated values with measured values is given in Table 4.4.

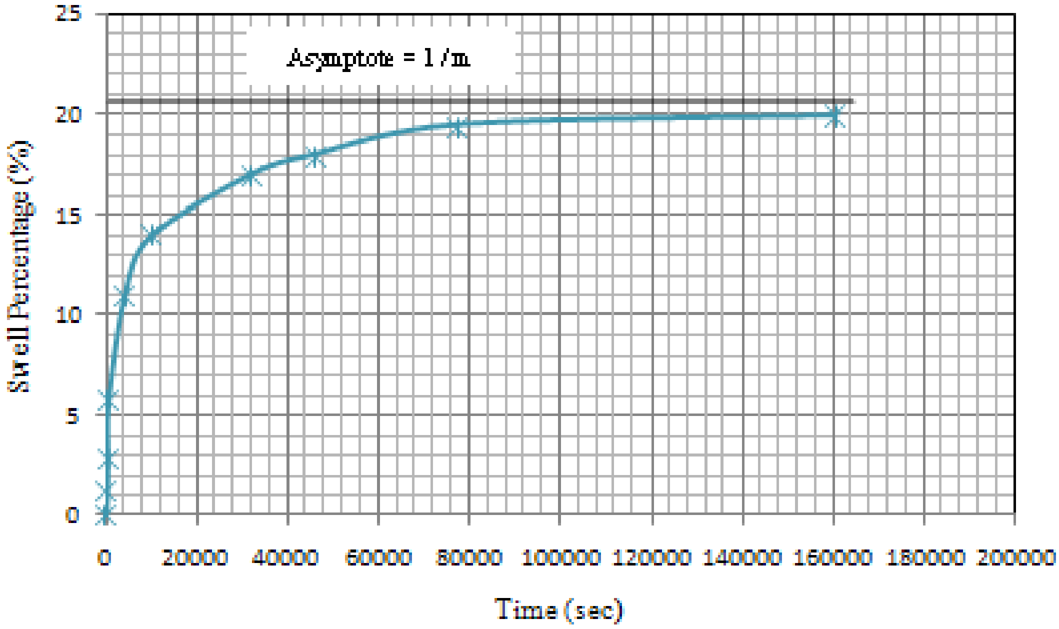

Figure 4.25 Swell Percentage vs. Time Graph of 7 Days Cured 20% BZ Specimen

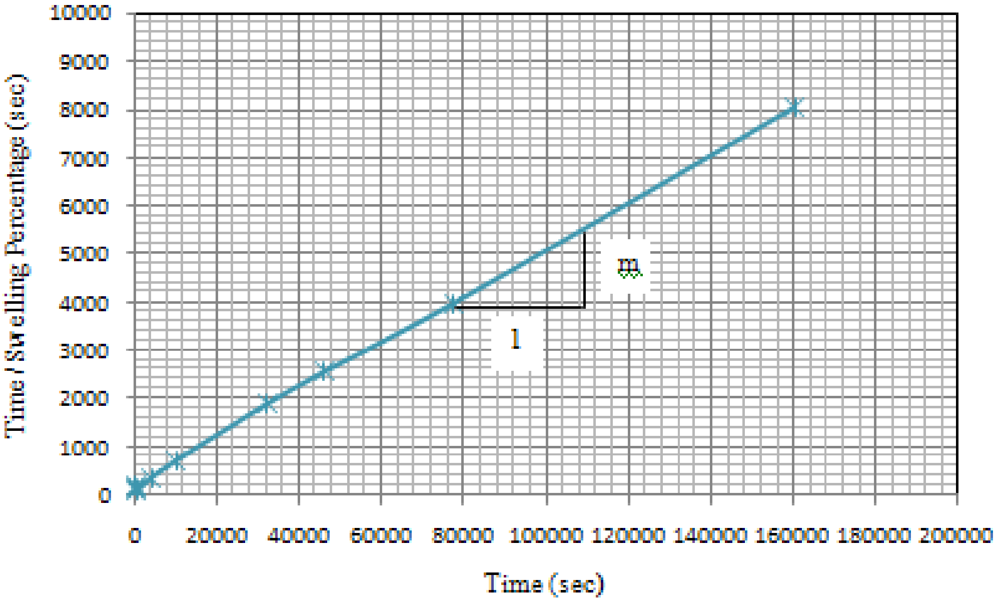

Figure 4.26 Time / Swell Percentage vs. Time Graph of 7 Days Cured 20% BZ Specimen

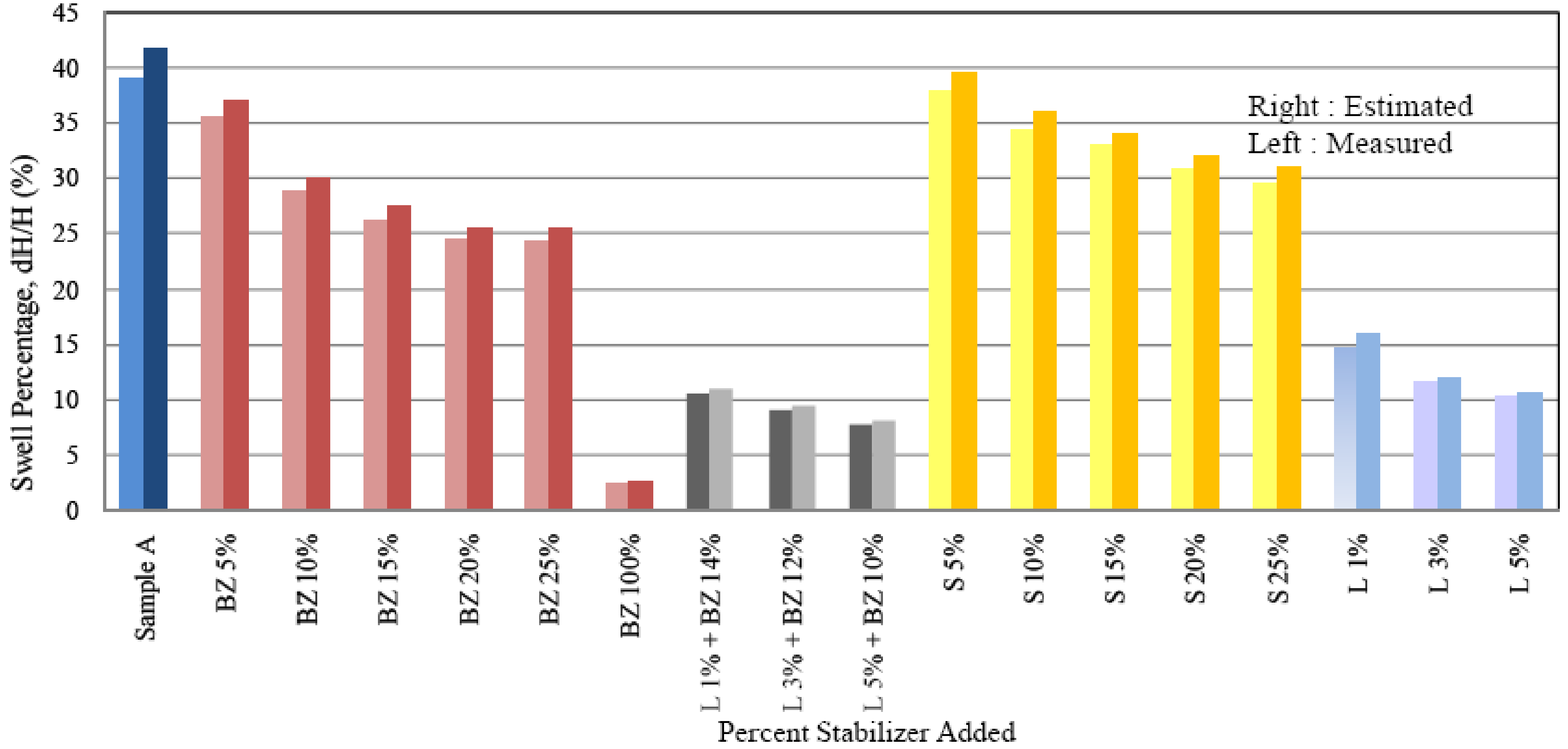

Figure 4.27 Measured and Estimated Swelling Percentage Graph for Test Specimens

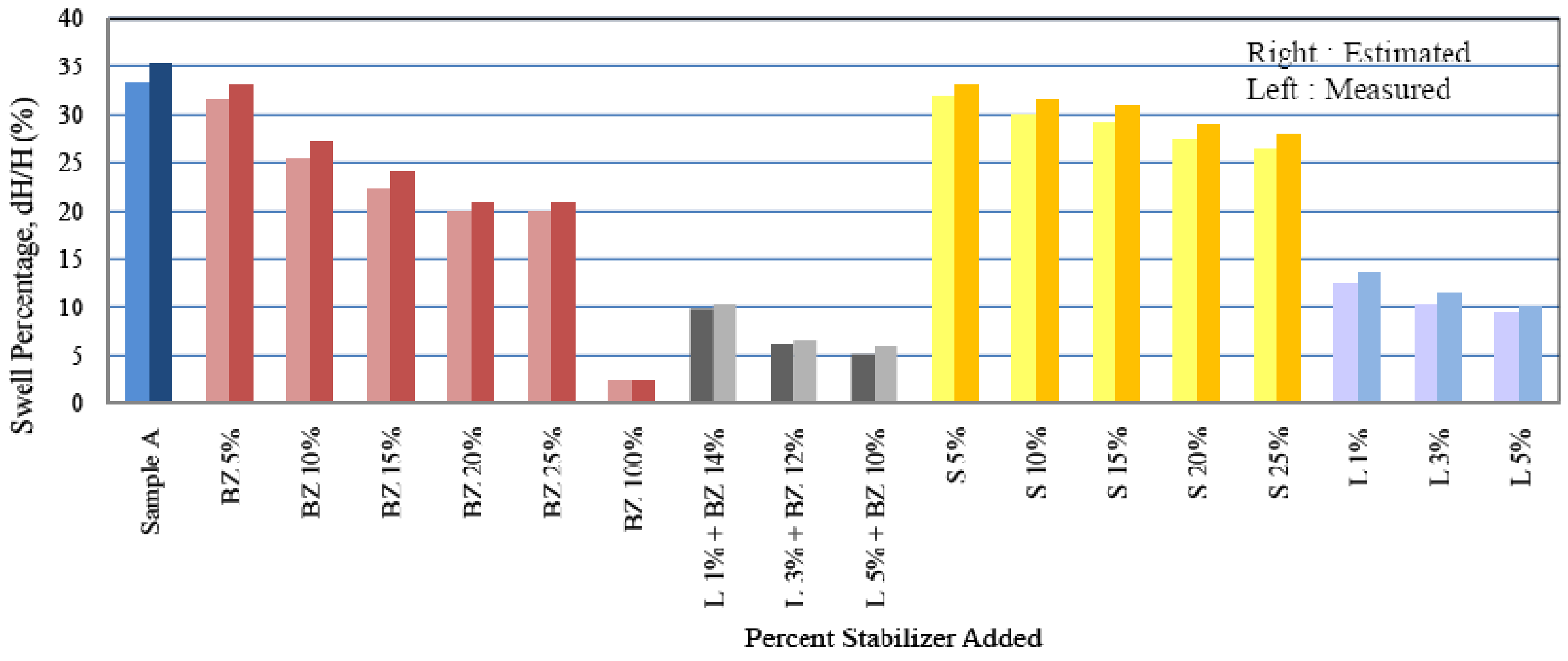

Figure 4.28 Measured and Estimated Swelling Percentage Graph for 7 Days Cured Test Specimens

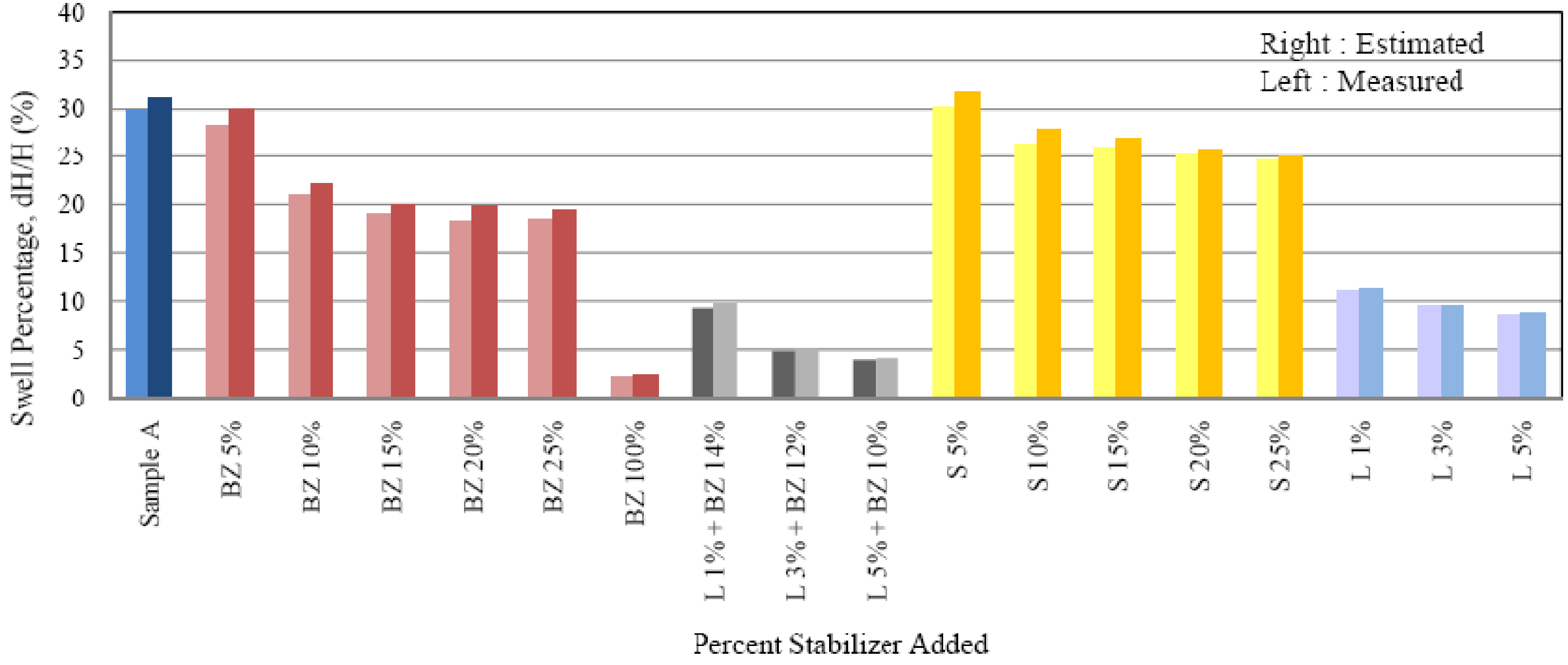

Figure 4.29 Measured and Estimated Swelling Percentage Graph for 28 Days Cured Test Specimens

Table 4.4 Estimated and Measured Swell Values

Sample	Without Cure			7 Days Cure			28 Days Cure		
	Measured (%)	Estimated (%)	Difference (%)	Measured (%)	Estimated (%)	Difference (%)	Measured (%)	Estimated (%)	Difference (%)
Sample A	39,0	41,7	2,7	33,3	35,2	1,9	29,8	31,2	1,4
BZ 5%	35,5	37,0	1,5	31,5	33,0	1,5	28,3	30	1,7
BZ 10%	28,8	30,0	1,2	25,4	27,0	1,6	20,9	22	1,1
BZ 15%	26,1	27,5	1,4	22,2	24,0	1,8	18,9	20	1,1
BZ 20%	24,4	25,5	1,1	19,9	21,0	1,1	18,2	19,7	1,5
BZ 25%	24,2	25,4	1,2	20,1	21,0	0,9	18,3	19,3	1,0
BZ 100%	2,5	2,6	0,1	2,4	2,5	0,1	2,2	2,3	0,1
L 1% + BZ 14%	10,6	11,0	0,4	9,8	10,4	0,6	9,3	9,8	0,5
L 3% + BZ 12%	9,1	9,5	0,4	6,2	6,6	0,4	4,8	5,1	0,3
L 5% + BZ 10%	7,8	8,1	0,3	5,2	6,0	0,8	3,9	4,1	0,2
S 5%	37,8	39,5	1,7	31,9	33,0	1,1	30,1	31,7	1,6
S 10%	34,3	36,0	1,7	29,9	31,5	1,6	26,4	27,9	1,5
S 15%	32,9	34,0	1,1	29,1	31,0	1,9	25,7	27	1,3
S 20%	30,8	32,0	1,2	27,4	29,0	1,6	25,2	25,5	0,3
S 25%	29,5	31,0	1,5	26,3	28,0	1,7	24,6	25	0,4
L 1%	14,7	16,0	1,3	12,5	13,6	1,1	11,1	11,3	0,2
L 3%	11,7	12,0	0,3	10,4	11,5	1,1	9,4	9,5	0,1
L 5%	10,4	10,7	0,3	9,4	10,0	0,6	8,5	8,8	0,3
Mean of Differences			1,1			1,2			0,8

CHAPTER 5

DISCUSSION OF TEST RESULTS

5.1 Effects of Stabilizers on the Grain Size Distribution

Grain size distribution curve of Sample A shifted after adding all of the stabilizers (Appendix A). The direction of all shifts for all stabilizers was to the coarser side.

When Bigadic zeolite added to Sample A, the grain size distribution curve shifted to the coarser side significantly. In order to find the reason for this shift whether from the addition of silt sized particles to Sample A or because of the pozzolanic reactions, Figure A-5 (Appendices) was plotted. Grain size distribution curves of Sample A, calculated 25% Bigadic zeolite, 25% Bigadic zeolite and 100% Bigadic zeolite were plotted on this figure. Calculated 25% Bigadic zeolite was obtained by considering 25% Bigadic zeolite and 75% Sample A on the mass basis. This figure showed that calculated value is on finer side and concluded that it is mainly because of the addition of silt sized particles and there are also some pozzolanic reactions which cause the flocculation of clay particles.

5.2 Effects of Stabilizers on the Liquid Limit

With the addition of stabilizers, liquid limit of Sample A decreased and as the stabilizer percentage increased liquid limit of Sample A decreased more. The maximum decrease occured by 5% lime + 10% Bigadic zeolite stabilizers by an amount of 39.3%. The minimum decreased occured by 5% sand by an amount of 7.1% (Table 5.1).

Table 5.1 Percentage Changes in Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), Shrinkage Limit (SL), Shrinkage Index (SI) and Activity

Samples	Change in LL (%)	Change in PL (%)	Change in PI (%)	Change in SL (%)	Change in SI (%)	Change in Activity (%)
Sample A	0.0	0.0	0.0	0.0	0.0	0.0
BZ 5%	-20.2	8.3	-31.7	4.5	-25.4	-29.9
BZ 10%	-23.8	12.5	-38.3	9.1	-33.3	-34.6
BZ 15%	-26.2	12.5	-41.7	18.2	-39.7	-34.6
BZ 20%	-28.6	16.7	-46.7	31.8	-50.8	-37.0
BZ 25%	-32.1	25.0	-55.0	31.8	-55.6	-42.5
L 1% + BZ 14%	-32.1	12.5	-50.0	18.2	-39.7	-44.1
L 3% + BZ 12%	-34.5	16.7	-55.0	22.7	-49.2	-48.8
L 5% + BZ 10%	-39.3	25.0	-65.0	27.3	-58.7	-57.5
S 5%	-7.1	8.3	-13.3	13.6	-20.6	-11.0
S 10%	-9.5	8.3	-16.7	22.7	-28.6	-12.6
S 15%	-11.9	16.7	-23.3	27.3	-38.1	-15.7
S 20%	-13.1	25.0	-28.3	27.3	-42.9	-15.0
S 25%	-15.5	29.2	-33.3	31.8	-50.8	-15.7
L 1%	-28.6	20.8	-48.3	13.6	-49.2	-43.3
L 3%	-33.3	25.0	-56.7	27.3	-60.3	-50.4
L 5%	-36.9	33.3	-65.0	36.4	-68.3	-55.1

“-“ means decrease; “+” means increase

5.3 Effects of Stabilizers on Plastic Limit

Addition of the stabilizers increased the plastic limit of Sample A. Plastic limit of Sample A increased as the stabilizer percentage increased. The max increase occured in 5% Lime addition as 33.3%. On the other hand, the minimum increase occured was 8.3% for three stabilizers which are 5% Bigadic zeolite, 5% sand and 10% sand (Table 5.1).

5.4 Effects of Stabilizers on Plasticity Index

Effects of stabilizers on plasticity index are tabulated in Table 5.1. Plasticity index of Sample A decreased dramatically by addition of stabilizers and also when the percentage of stabilizer increased, plasticity of Sample A decreased more. The maximum change occured was 65%. Addition of Bigadic zeolite with a percentage of 25% decreased plasticity index of Sample A to 55%.

5.5 Effects of Stabilizers on Shrinkage Limit

Shrinkage limit of Sample A increased with addition of stabilizers. Shrinkage limit of Sample A increased as the stabilizer percentage increased (Table 5.1). The maximum increase on shrinkage limit occured with the addition of 5% lime with a percentage of 36.4%. Addition of 25% Bigadic zeolite increased shrinkage limit of Sample A with a percentage of 31.8. Any difference on shrinkage limit between 25% and 20% Bigadic zeolite did not occur.

5.6 Effects of Stabilizers on Shrinkage Index

With addition of stabilizers, shrinkage index of Sample A decreased dramatically. As the stabilizer percentage increased, shrinkage index increased. The maximum reduction is 68.3% for 5% lime. Addition of 25% Bigadic zeolite decreased the shrinkage index of Sample A with a percentage of 55.6 (Table 5.1).

5.7 Effects of Stabilizers on the Specific Gravity

Addition of Bigadic zeolite (G_s = 2.31) decreased the specific gravity of Sample A (G_s = 2.56). On the other hand, addition of sand and lime increased the specific gravity of Sample A. Table 4.1 shows specific gravity value of each sample.

5.8 Effects of Stabilizers on the Activity

Addition of stabilizers were resulted in reduction of activity of Sample A (Table 5.1). The maximum reduction of activity and swelling potential occured in (5% lime + 10% Bigadic zeolite) sample.

5.9 Effects of Stabilizers on Free Swell Ratio

Free swell ratio of Sample A was 2.3 and classified as high swelling and dominant clay mineral type was montmorillonite (Fig 4.13). The inert material sand as stabilizer showed a slight decrease in free swell ratio. Bigadic zeolite and lime additions showed significant decrease. The most effective stabilizer for decreasing free swell ratio was the combination of Bigadic zeolite and lime. For 5% Lime and 10% Bigadic Zeolite sample, free swell ratio decreased to 0.73. There is no big difference in free swell ratio of 20% Bigadic zeolite and 25% Bigadic zeolite added samples.

5.10 Effects of Stabilizers on the Swell Percentage

Addition of stabilizers decreased swell percentages of specimens as tabulated in Table 5.2. The reason for that is adding non-expansive material into potentially expansive soils.

Addition of Bigadic zeolite decreased the swell percentage of Sample A up to a level of 37.9% for without cure case. There is not much difference between 25% and 20% Bigadic zeolite stabilizers.

Addition of 5% lime decreased the swell percencentage of Sample A by 73.4% for without cure case. Mixture of Bigadic zeolite and lime was the most effective stabilizer to decrease the swell percentage.

Lime is more effective to decrease swell percentage than Bigadic zeolite.

Table 5.2 Percentage Changes in Swelling Percentage (%) for Specimens without Cure, 7 Days Cured and 28 Days Cured

Specimen	Without Cure	7 Days Cured	28 Days Cured
	Change in Swell Percentage (%)	**Change in Swell Percentage (%)**	**Change in Swell Percentage (%)**
Sample A	0.0	0.0	0.0
BZ 5%	-8.9	-5.1	-48.8
BZ 10%	-26.2	-29.8	-50.0
BZ 15%	-33.1	-36.7	-61.9
BZ 20%	-37.5	-39.2	-75.6
BZ 25%	-37.9	-38.6	-76.3
L 1% + BZ 14%	-72.9	-68.8	-63.8
L 3% + BZ 12%	-76.7	-83.8	-88.4
L 5% + BZ 10%	-80.0	-86.8	-90.0
S 5%	-3.0	-0.9	-21.9
S 10%	-12.1	-11.6	-28.8
S 15%	-15.5	-13.8	-36.3
S 20%	-21.1	-15.7	-38.8
S 25%	-24.3	-17.5	-45.0
L 1%	-62.3	-62.8	-70.0
L 3%	-70.0	-68.4	-91.9
L 5%	-73.4	-71.6	-94.7

“-“ means decrease

5.11 Effects of Stabilizers on the Rate of Swell

As it is shown in Table 5.3, addition of stabilizers decrease t_{50}, the time necessary for 50% swell of total swell. Rate of swell of specimens decrease as the stabilizer percentage increases. The maximum reduction in rate of swell was 84.5% for 5%

lime + 10% Bigadic zeolite. For 25% Bigadic zeolite decrease in rate of swell was 39.7%.

Table 5.3 Percentage Changes in t_{50} (min) for Specimens without Cure, 7 Days Cured and 28 Days Cured

Specimen	**Without Cure**	**7 Days Cured**	**28 Days Cured**
	Change in t_{50} (%)	**Change in t_{50} (%)**	**Change in t_{50} (%)**
Sample A	0.0	0.0	0.0
BZ 5%	-5.4	-47.1	-58.0
BZ 10%	-23.6	-50.0	-60.3
BZ 15%	-33.2	-60.0	-61.3
BZ 20%	-40.0	-70.6	-80.0
BZ 25%	-39.7	-74.7	-81.3
L 1% + BZ 14%	-70.6	-60.6	-65.7
L 3% + BZ 12%	-81.3	-87.1	-88.1
L 5% + BZ 10%	-84.5	-88.5	-90.0
S 5%	-4.1	-23.5	-20.0
S 10%	-10.1	-29.4	-26.7
S 15%	-12.5	-30.6	-33.3
S 20%	-17.6	-41.2	-43.3
S 25%	-21.0	-46.5	-43.3
L 1%	-62.3	-62.9	-73.3
L 3%	-68.7	-90.0	-91.5
L 5%	-71.7	-94.1	-94.8

“-“ means decrease

5.12 Effect of Cure on Swell Percentage

Because of pozzolanic reactions during the period of cure, generally swelling percentage decreases more for 7 days and 28 days cured cases relative to the without cure cases (Table 5.2).

$$(\Delta H/H)_{\text{without cure}} > (\Delta H/H)_{\text{7 day cured}} > (\Delta H/H)_{\text{28 days cured}}$$

The maximum decrease in swell percentage is 94.7% for 28 days cured 5% lime added specimen. For 28 days cured 25% Bigadic zeolite added specimen, the reduction occured is 76.3%.

5.13 Effect of Cure on Rate of Swell

Rate of swell decreased for each of the specimens with addition of stabilizer (Table 5.3). But curing had some effects for decreasing the rate of swell.

$$(t_{50})_{\text{without cure}} > (t_{50})_{\text{7 day cured}} > (t_{50})_{\text{28 days cured}}$$

For 28 days cured 5% lime added specimen the maximum decrease in t_{50} occurred with an amount of 94.8%. For 28 days cured, 25% Bigadic zeolite added specimen, the maximum reduction in t_{50} was 81.3%.

5.14. General Discussion on Test Results

The addition of lime, lime + Bigadic zeolite and Bigadic zeolite alone to the expansive clay; (a) reduces the clay content and a corresponding increase in the percentage of coarse particles; (b) reduces liquid limit (LL), (c) raises the shrinkage limit (SL) and (d) reduces the plasticity index (PI) of soil, and hence swelling potential. In one process, a base exchange occurs with the calcium ions of Bigadic zeolite replacing sodium on the surface of the expansive clay particle. The net result is a low base exchange capacity for the particle with a resulting lower swelling potential. Addition of Bigadic zeolite resulted in the formation of aggregations which reduced the swelling potential of the soil (i.e. particle size distribution).

Addition of Bigadic zeolite is more effective in reducing swell potential and rate of swell than addition of the same amount of sand. Therefore addition of Bigadic zeolite can not be considered as non-expansive (inert) material addition.

Since lime addition and Bigadic zeolite addition give similar results, similar reactions can be expected.

Generally swell potential and rate of swell of the specimens decreased by curing. The reason for this is assumed to be the pozzolanic reactions during the period of cure.

CHAPTER 6

CONCLUSION

In this study, the effect of Bigadic zeolite (by-product) was investigated as a soil stabilizing agent to decrease the swelling potential of an expansive soil (i.e. Sample A). In the laboratory conditions an artificial expansive soil sample (Sample A), which has high swelling potential, was prepared. Bigadic zeolite was added to the Sample A up to a maximum of 25 percent. In order to compare the effectiveness of Bigadic zeolite in reducing the swelling potential of Sample A, lime was added to Sample A up to 5 percent, sand was added up to 25 percent and different percentages of Bigadic zeolite + lime (maximum 15% in total) were added.

The aim of this study was to decrease the volume change of the expansive soil (Sample A) by adding Bigadic zeolite. According to the test results, the following conclusions can be drawn:

1. Addition of Bigadic zeolite shifted the grain size distribution curve of the samples and with increasing amount of Bigadic zeolite, soil became coarser. The reason for this shift can be concluded as the addition of silt sized particles and some pozzolanic reactions.

2. Liquid limit, plasticity index and shrinkage index decreased after addition of Bigadic zeolite, whereas plastic limit and shrinkage limit increased.

3. Addition of Bigadic zeolite decreased the activity of samples. Small amount of lime is more effective than Bigadic zeolite in reducing the activity of samples.

4. The swelling percentage of the specimens decreased by addition of Bigadic zeolite. 10 percent Bigadic zeolite + 5 percent lime was the most effective stabilizer in decreasing the swelling potential of the expansive soil A.

5. Rate of swell of the specimens decreased by addition of Bigadic zeolite to Sample A.

6. Curing decreases the swelling percentage and rate of swell of Bigadic zeolite added specimens.

7. There is not much difference in swelling potential and rate of swell for 20 and 25 percent Bigadic zeolite added specimens. Therefore the maximum amount for Bigadic zeolite addition can be thought as 20 percent.

8. The Bigadic zeolite (boron by-product) can be used for the stabilization of the expansive soils near to the boron mines in Bigadic.

Recommendations for Future Research

In this study, Bigadic zeolite was examined as a stabilizing agent for expansive soils and swell potential tests were performed. Although performed swell tests are reliable, additional tests can be done to examine the microfabric and mineralogical characteristics of the specimens in order to reach to the full scale characterization of the specimens.

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APPENDIX A

GRAIN SIZE DISTRIBUTION CURVES

Grain size distribution curves for Bigadic zeolite, sand, lime and Bigadic zeolite and lime together added samples are presented in Appendix A. Grain size distribution curves of 100%, 25%, and calculated 25% of Bigadic zeolite are presented.

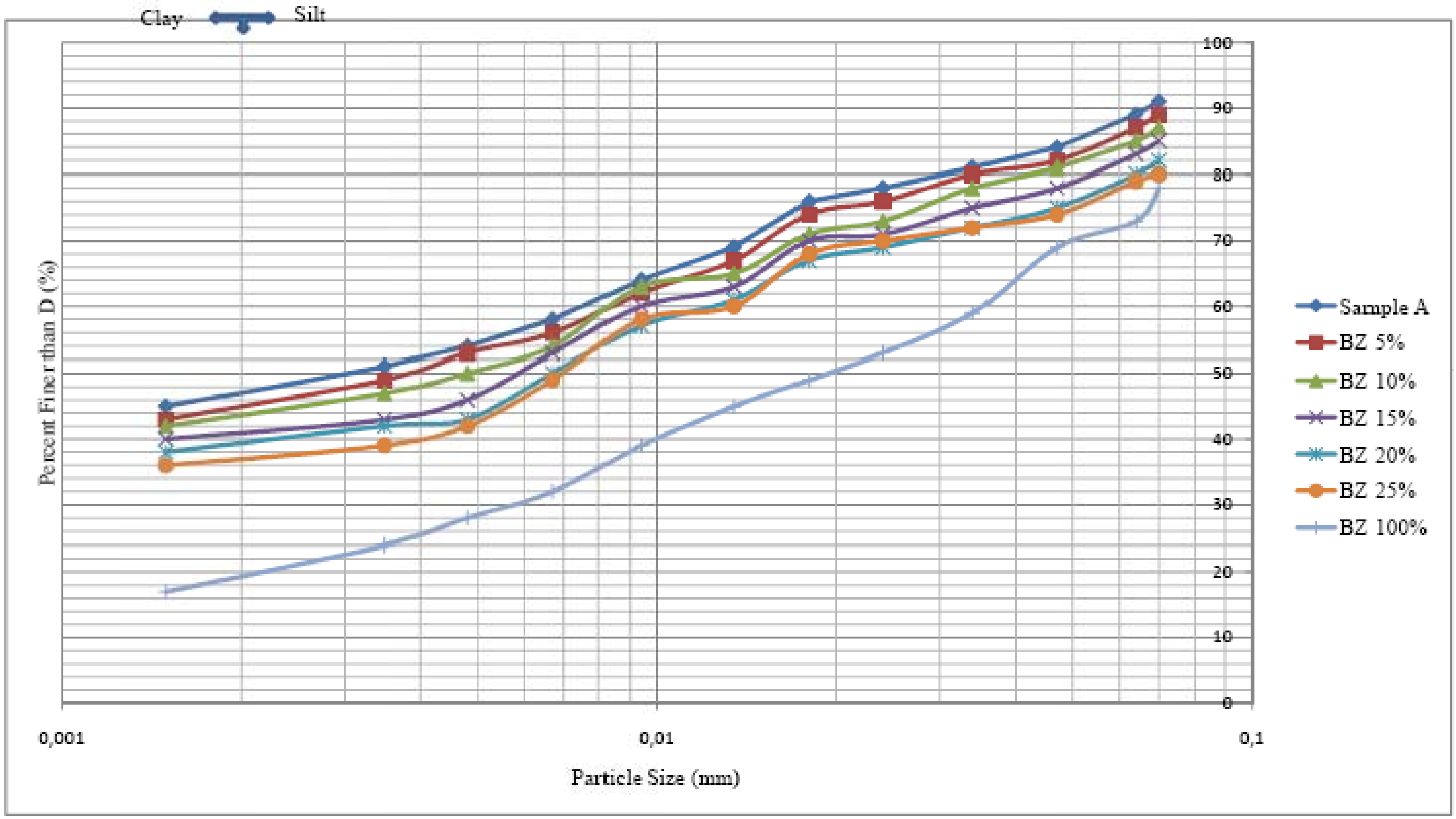


Figure A.1 Grain Size Distribution Curves of Bigadic Zeolite Added Samples

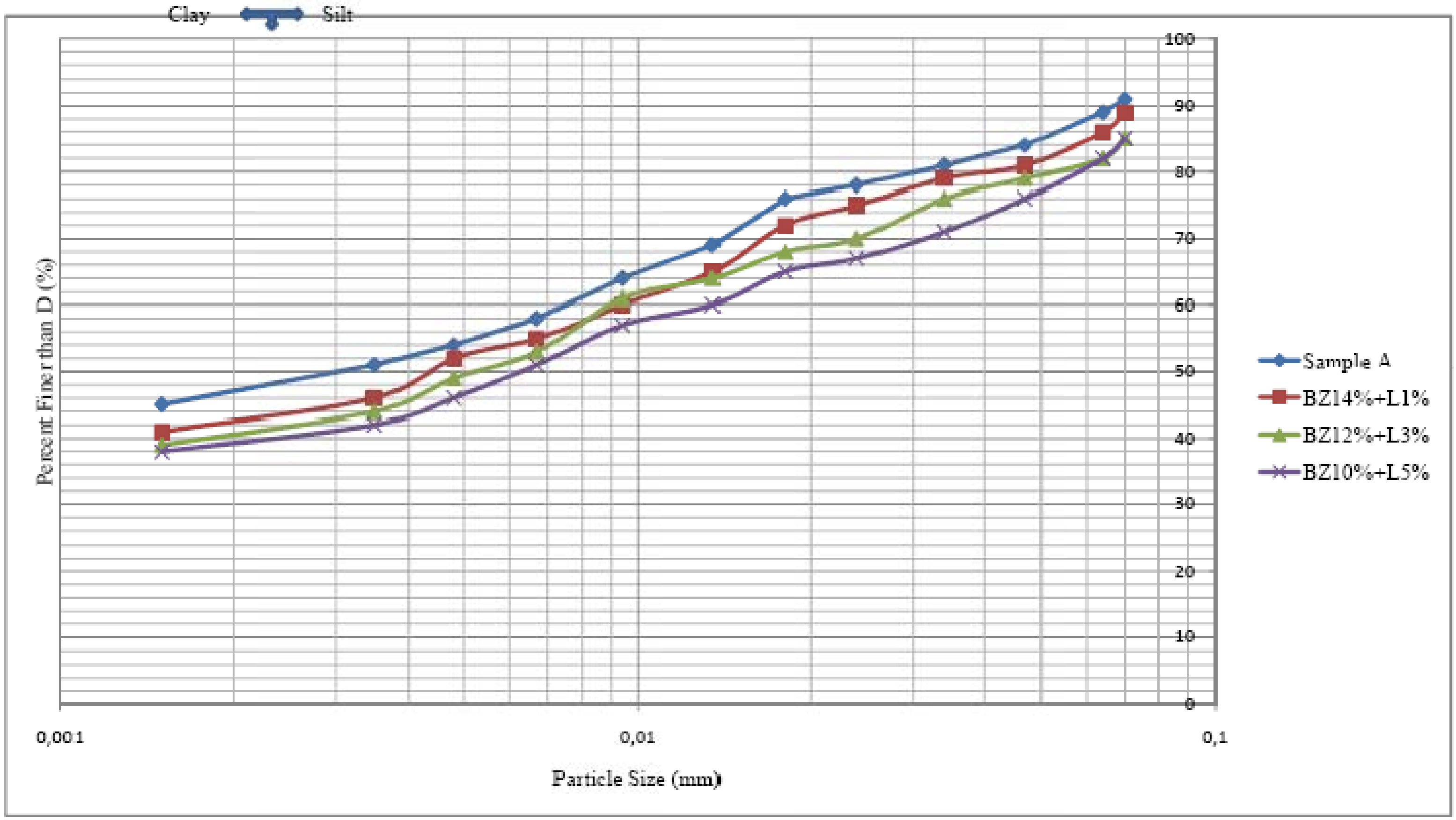


Figure A.2 Grain Size Distribution Curves of Bigadic Zeolite and Lime Added Samples

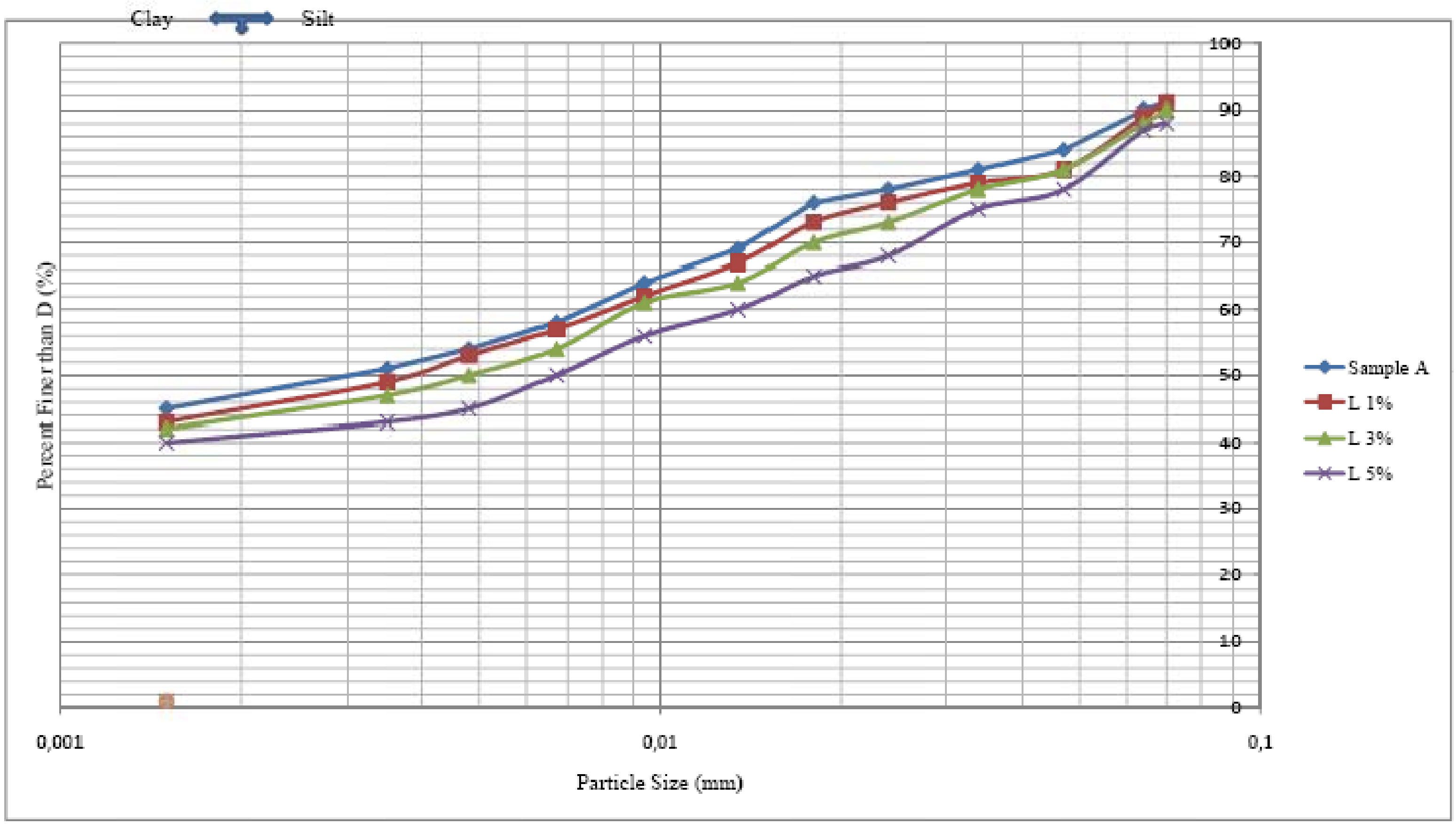


Figure A.3 Grain Size Distribution Curves of Lime Added Samples

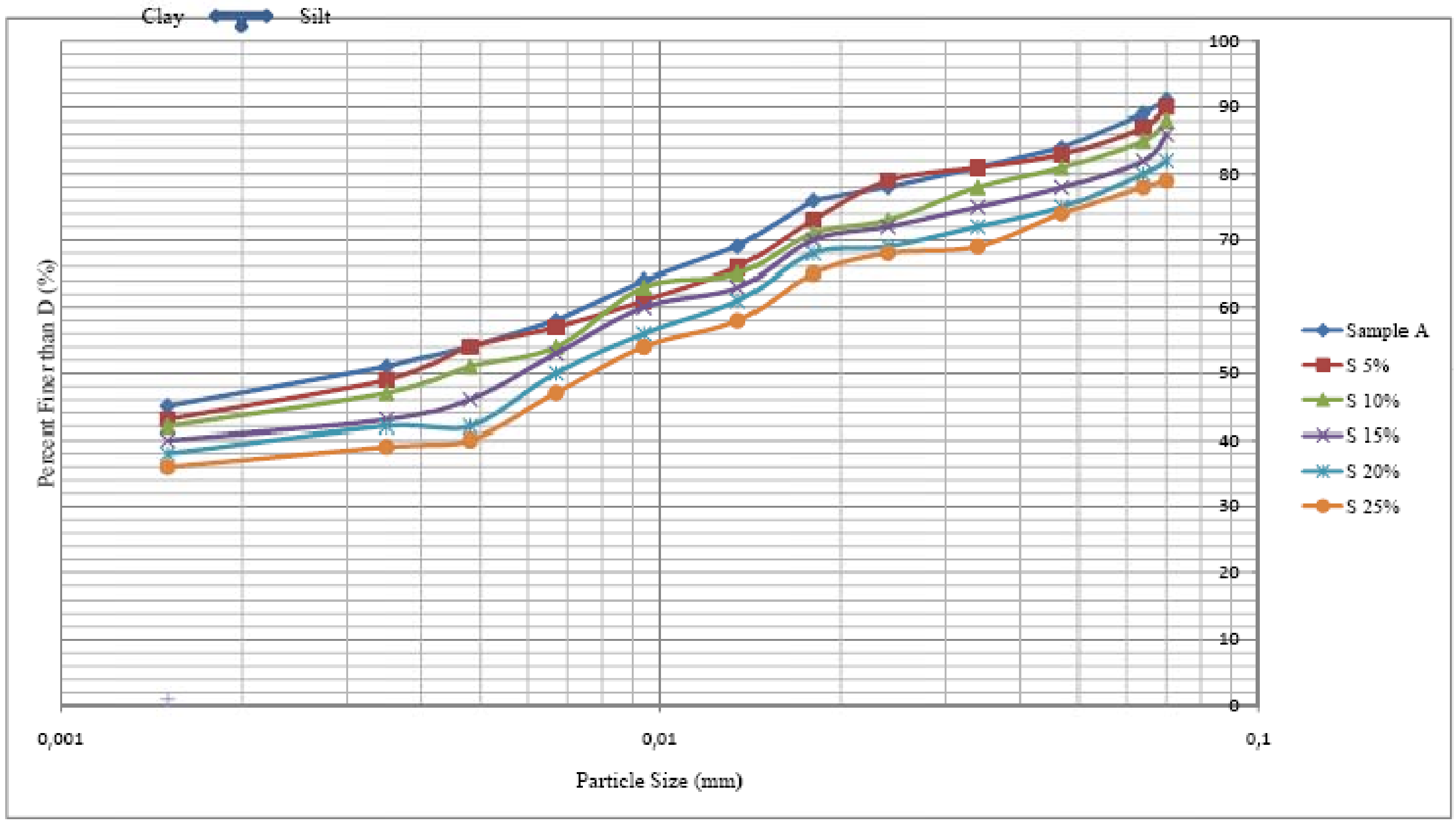


Figure A.4 Grain Size Distribution Curves of Sand Added Samples

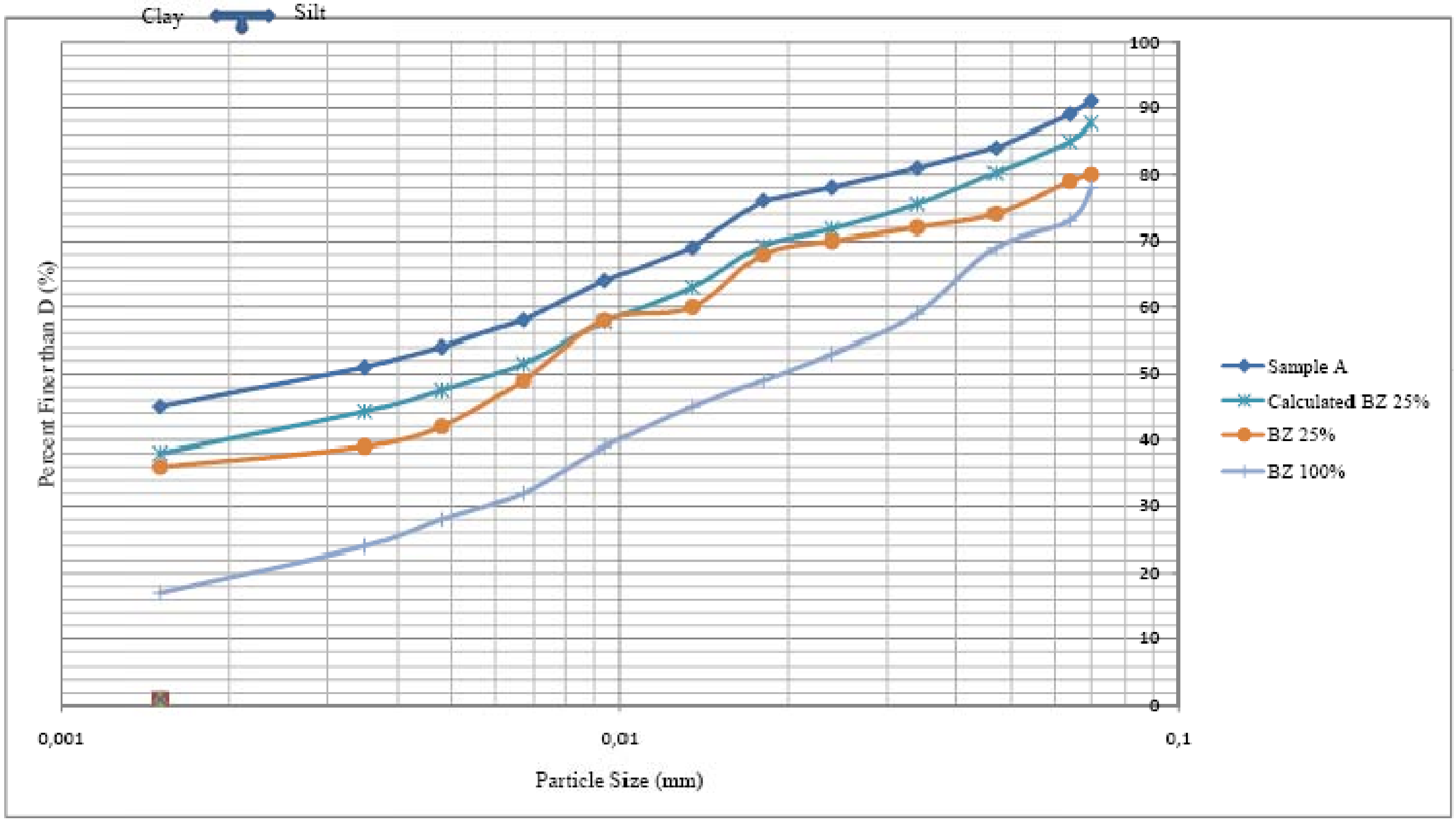


Figure A.5 Grain Size Distribution Curves of Sample A, 25% BZ calculated 25% BZ, 100%BZ

APPENDIX B

SWELL PERCENTAGE VERSUS TIME GRAPHS

Swell percentage versus time graphs for Bigadic zeolite, sand, lime and Bigadic zeolite and lime together added specimens without cure, 7 days cured and 28 days cured are presented in Appendix B.

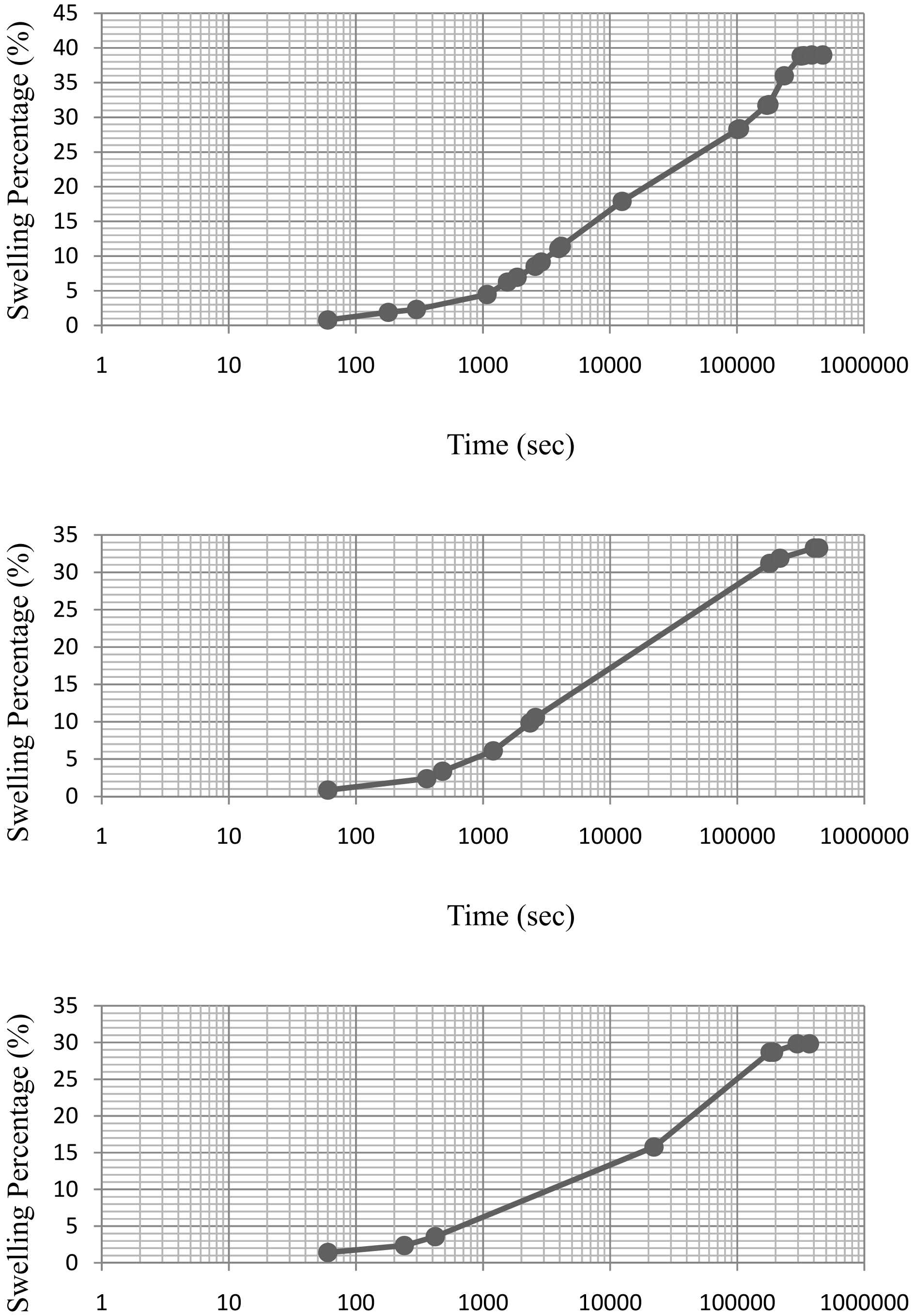


Figure B.1 Swell Percentage versus Time Relationship for Sample A; Without Cure, 7 Days Cured and 28 Days Cured respectively

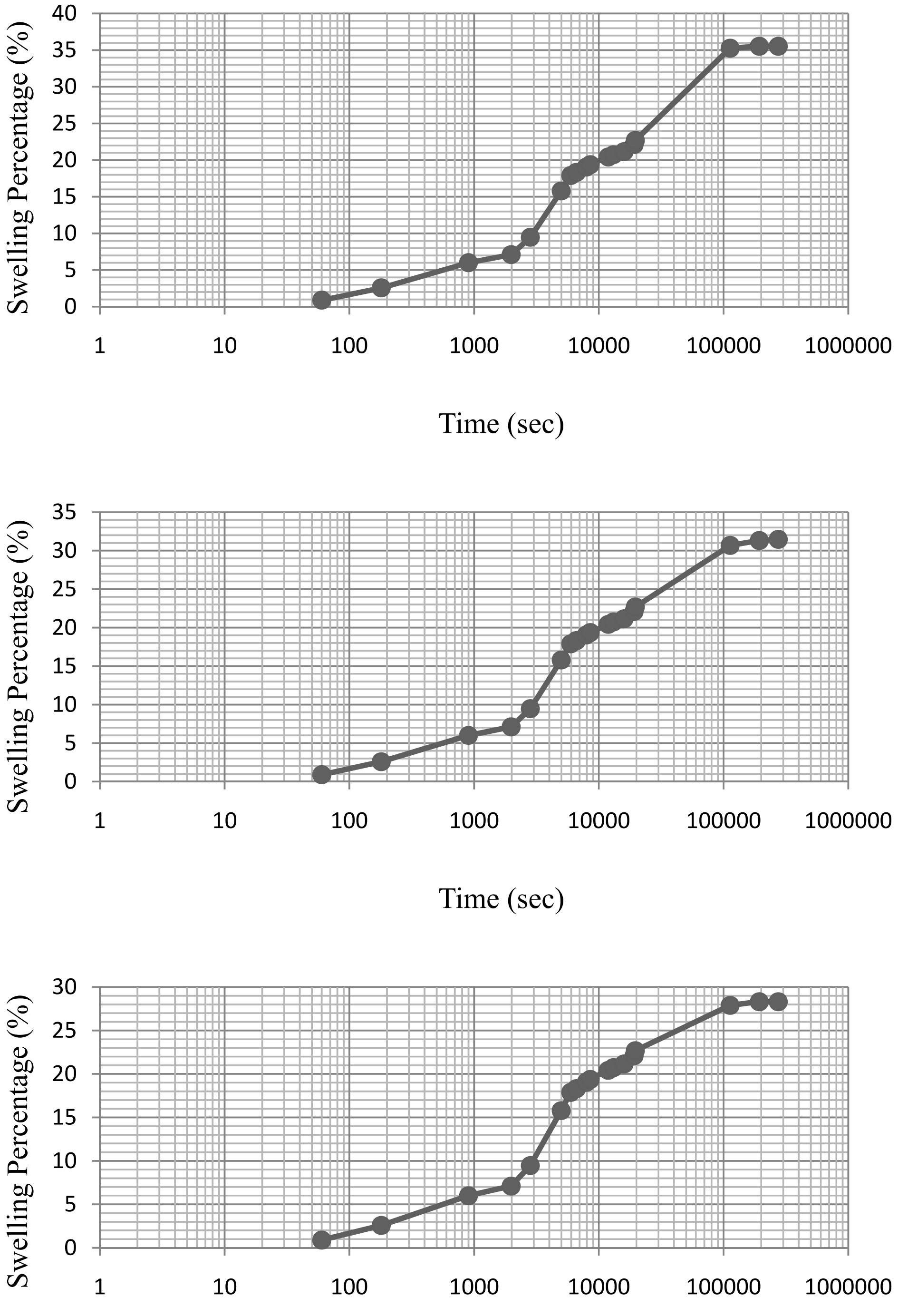
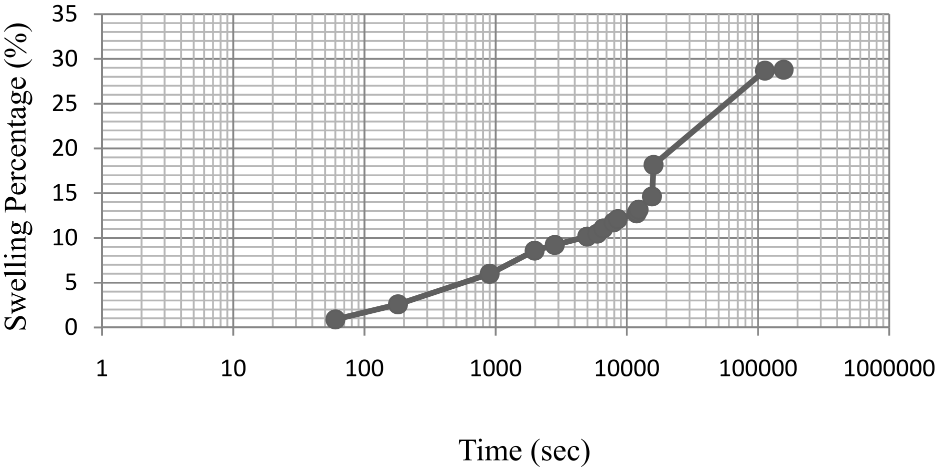
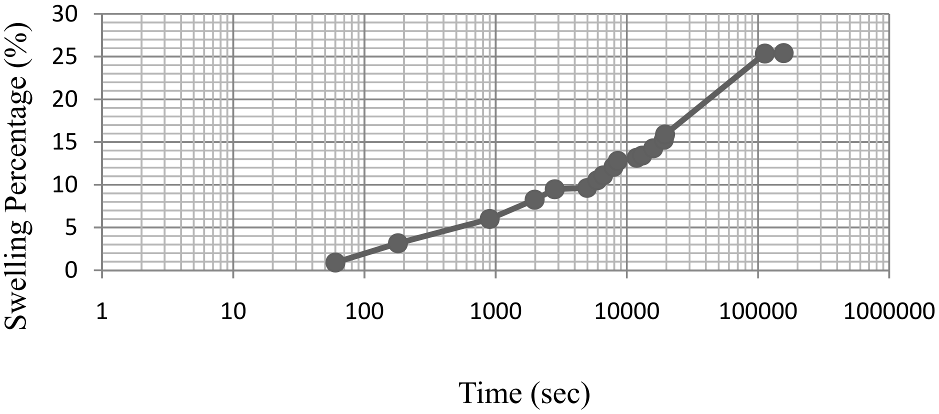


Figure B.2 Swell Percentage versus Time Relationship for BZ 5%; Without Cure, 7 Days Cured and 28 Days Cured respectively





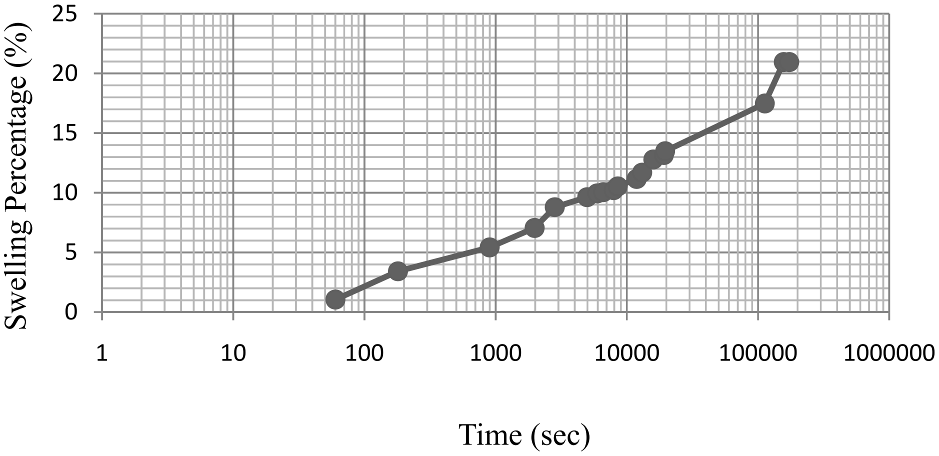


Figure B.3 Swell Percentage versus Time Relationship for BZ 10%; Without Cure, 7 Days Cured and 28 Days Cured respectively

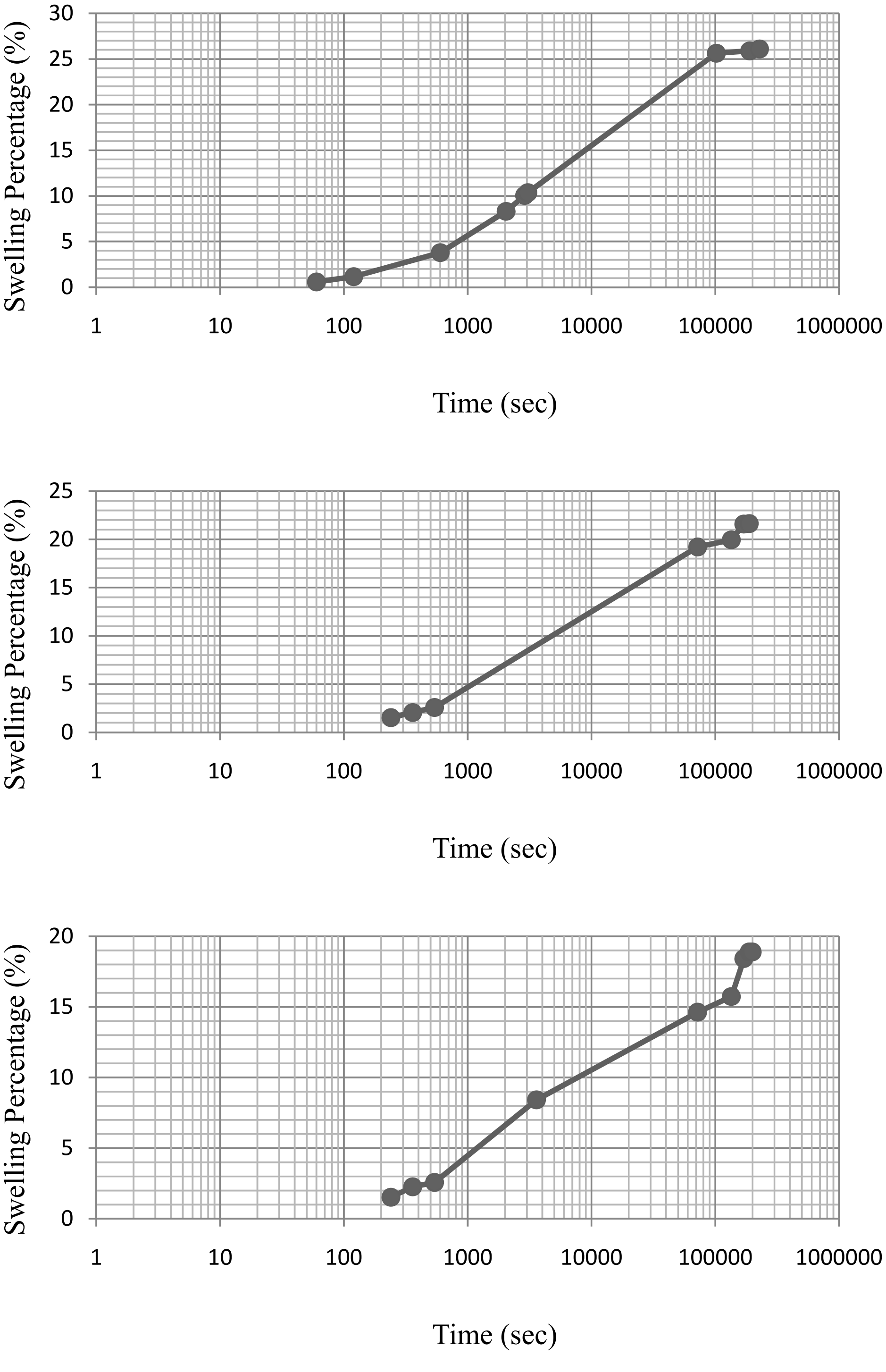


Figure B.4 Swell Percentage versus Time Relationship for BZ 15%; Without Cure, 7 Days Cured and 28 Days Cured respectively

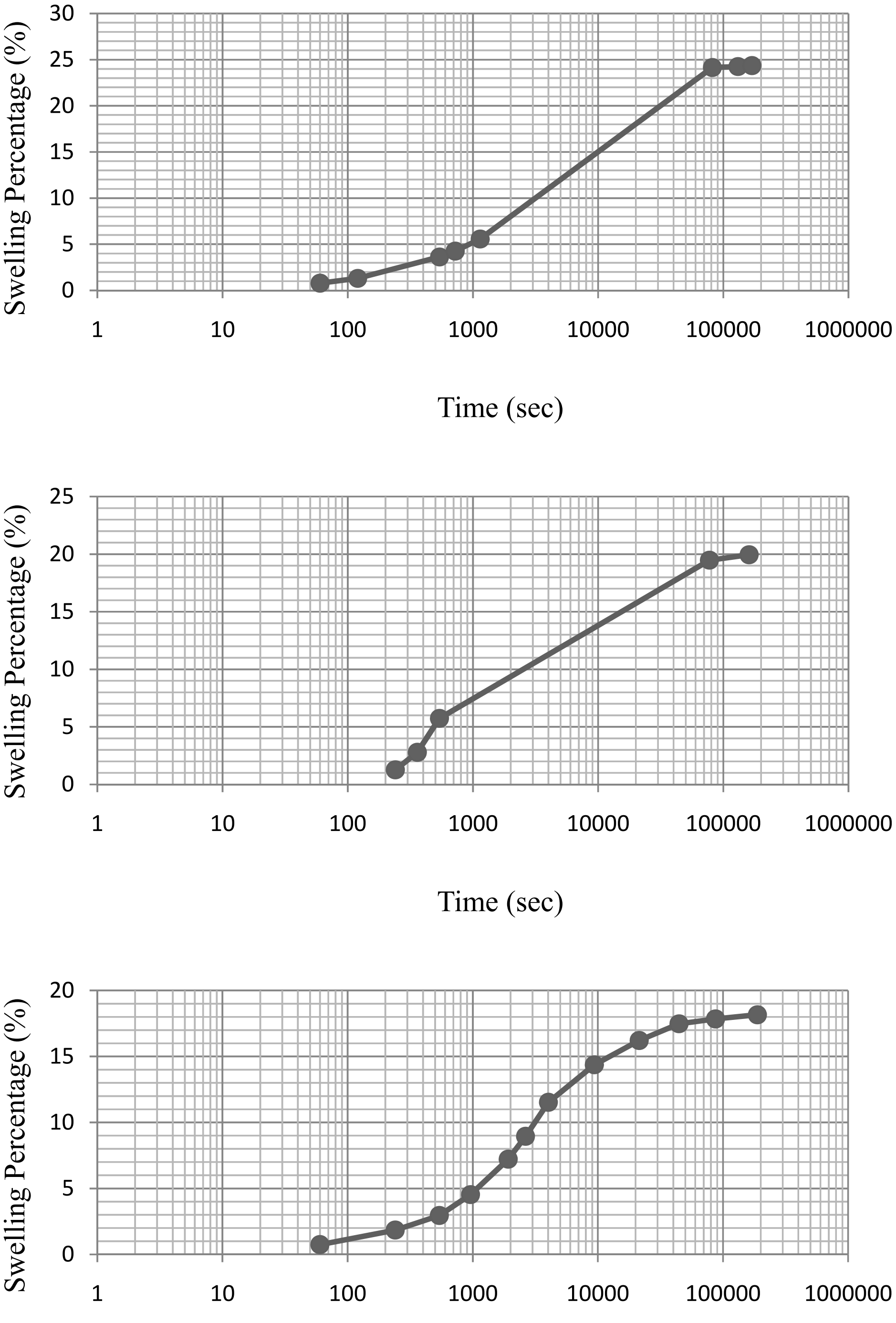
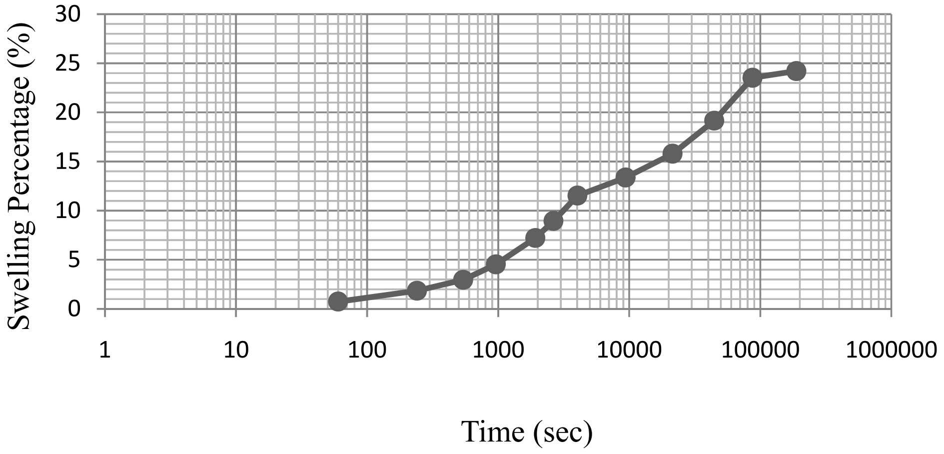
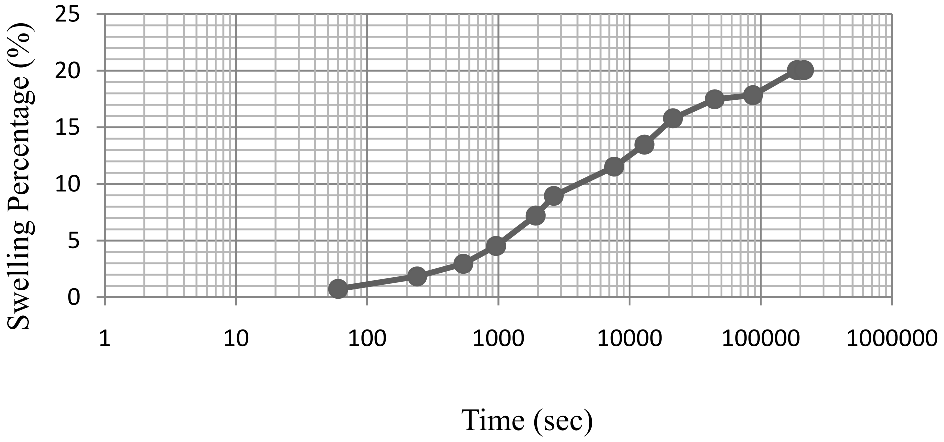


Figure B.5 Swell Percentage versus Time Relationship for BZ 20%; Without Cure, 7 Days Cured and 28 Days Cured respectively





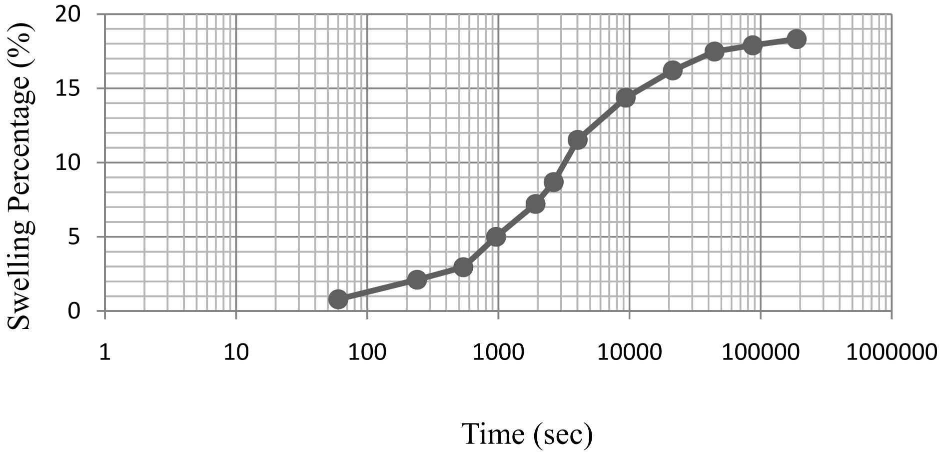


Figure B.6 Swell Percentage versus Time Relationship for BZ 25%; Without Cure, 7 Days Cured and 28 Days Cured respectively

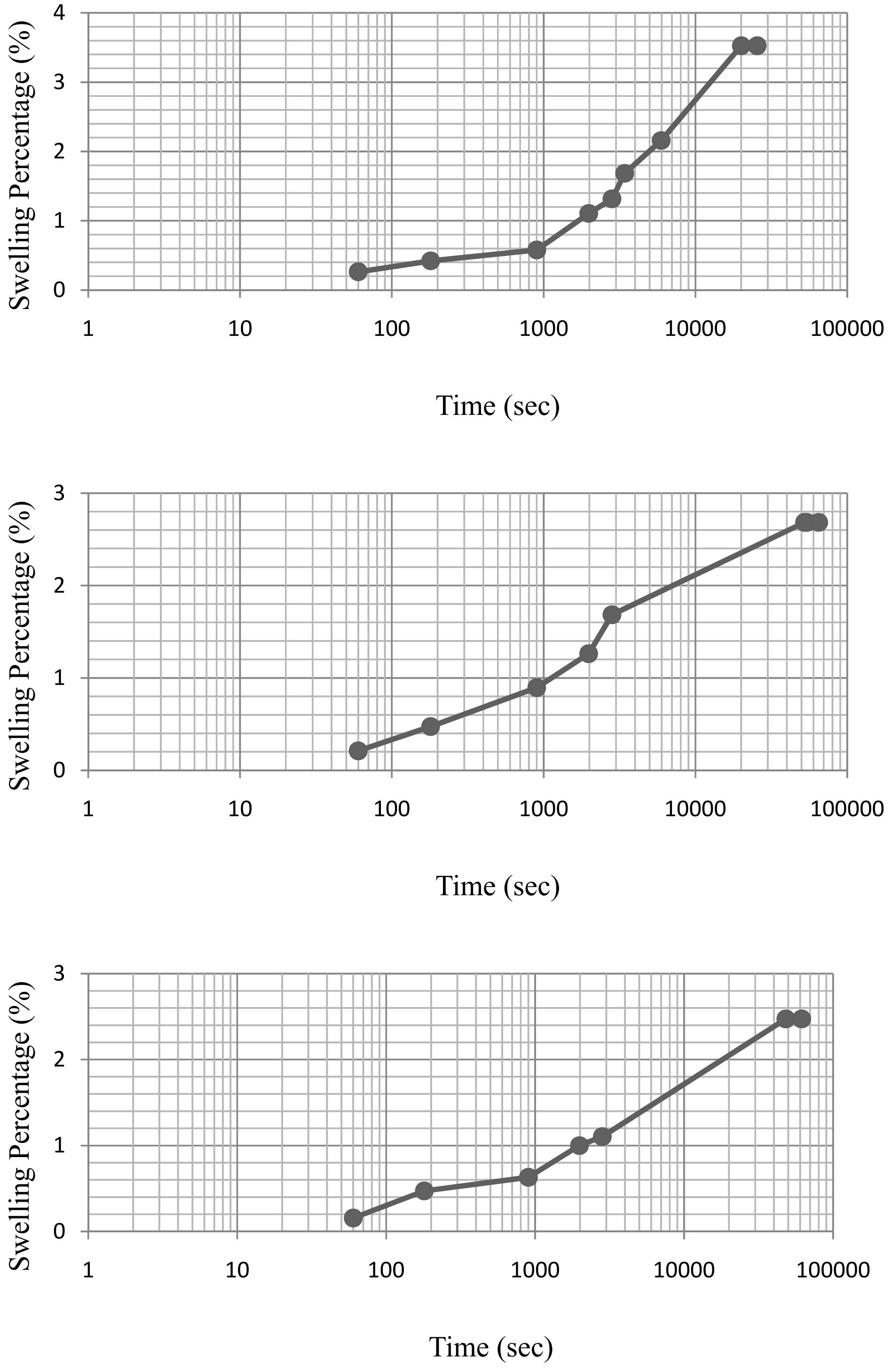
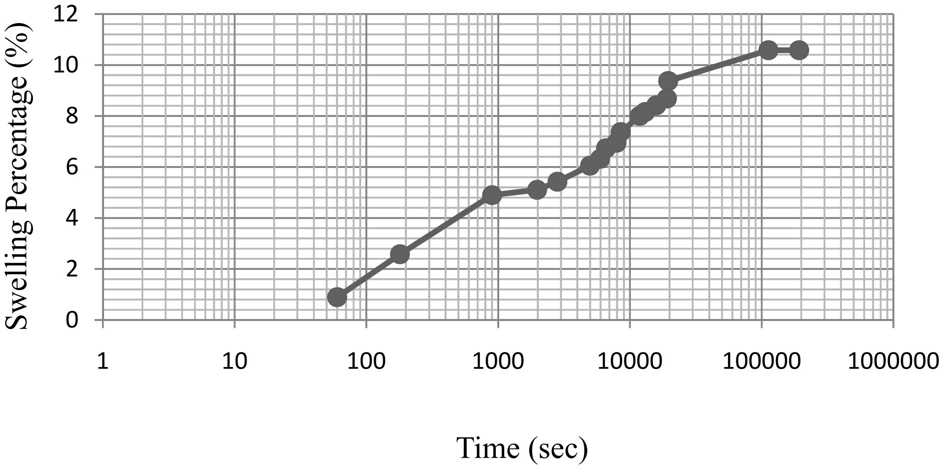
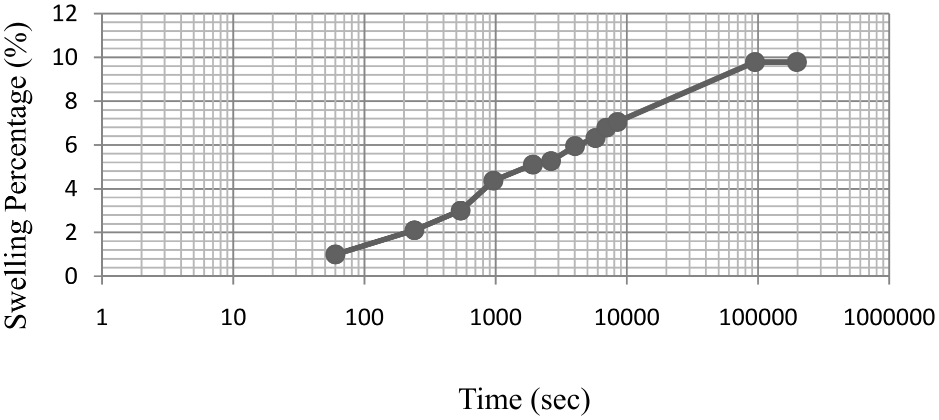


Figure B.7 Swell Percentage versus Time Relationship for BZ 100%; Without Cure, 7 Days Cured and 28 Days Cured respectively





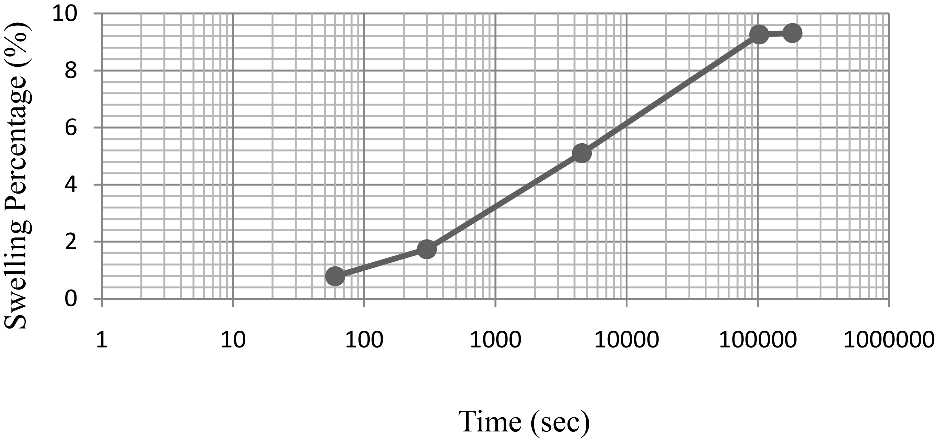


Figure B.8 Swell Percentage versus Time Relationship for BZ 14% + L 1%; Without Cure, 7 Days Cured and 28 Days Cured respectively

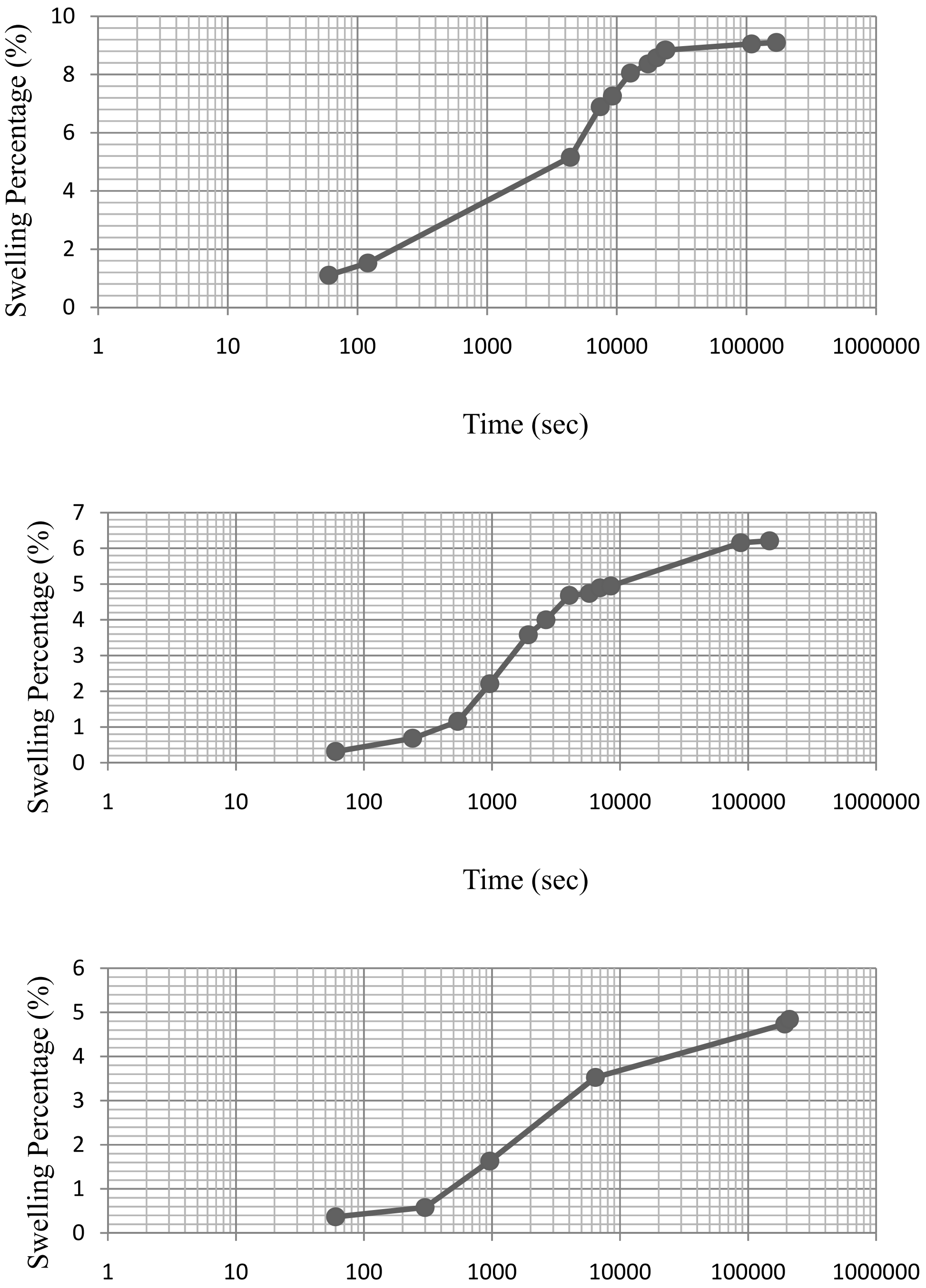


Figure B.9 Swell Percentage versus Time Relationship for BZ 12% + L 3%; Without Cure, 7 Days Cured and 28 Days Cured respectively

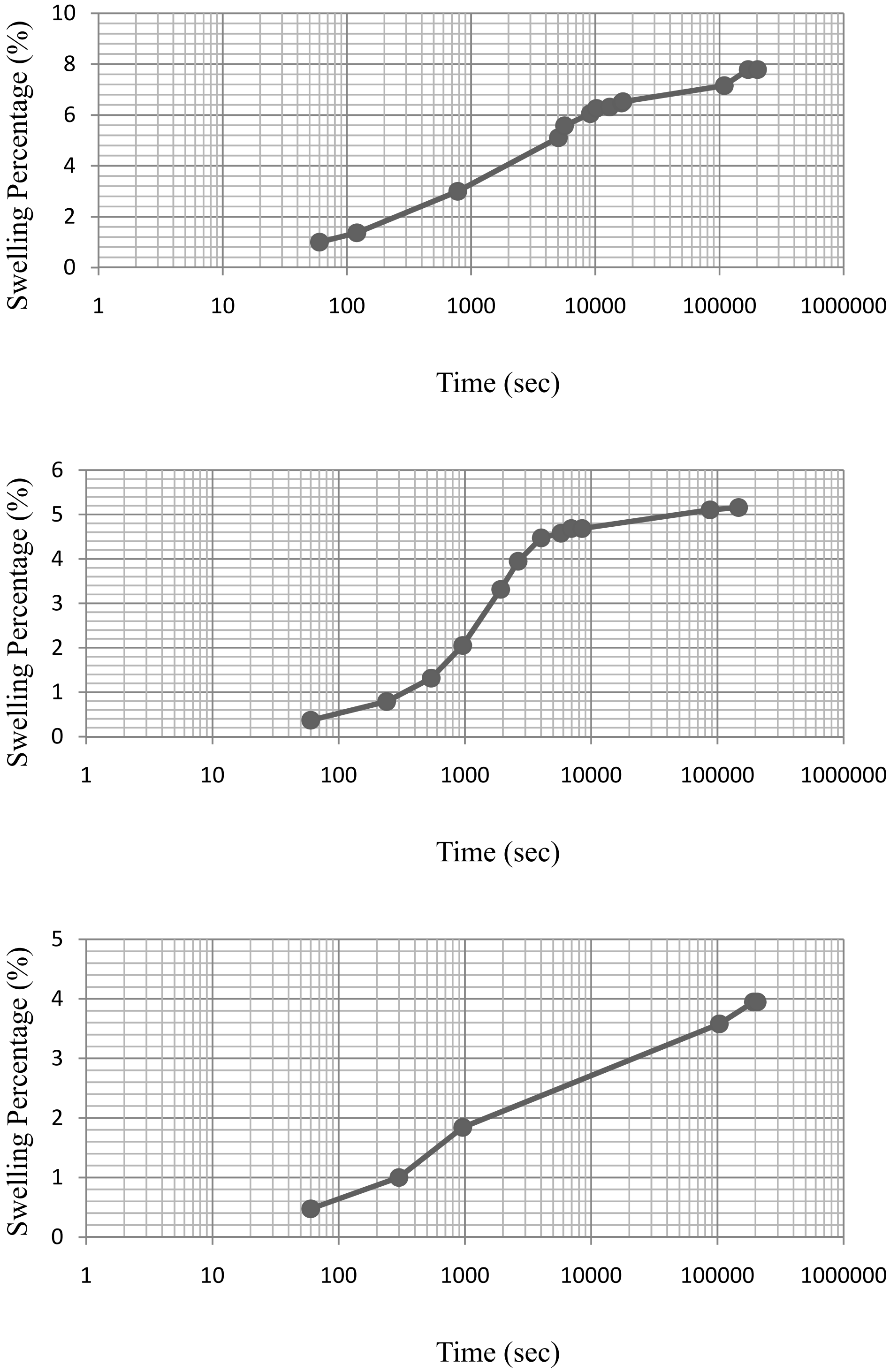
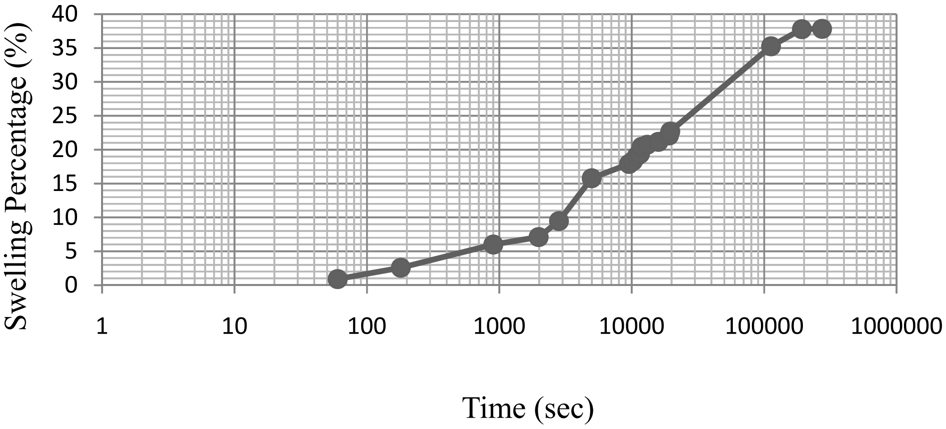
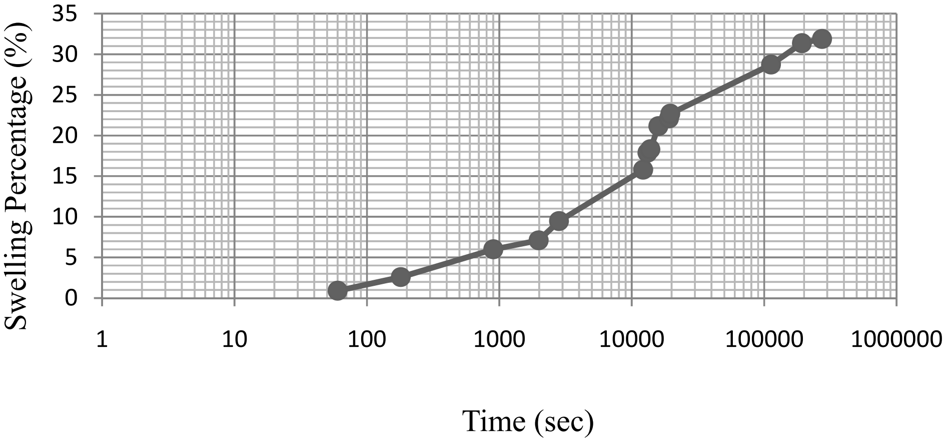


Figure B.10 Swell Percentage versus Time Relationship for BZ 10% + L 5%; Without Cure, 7 Days Cured and 28 Days Cured respectively





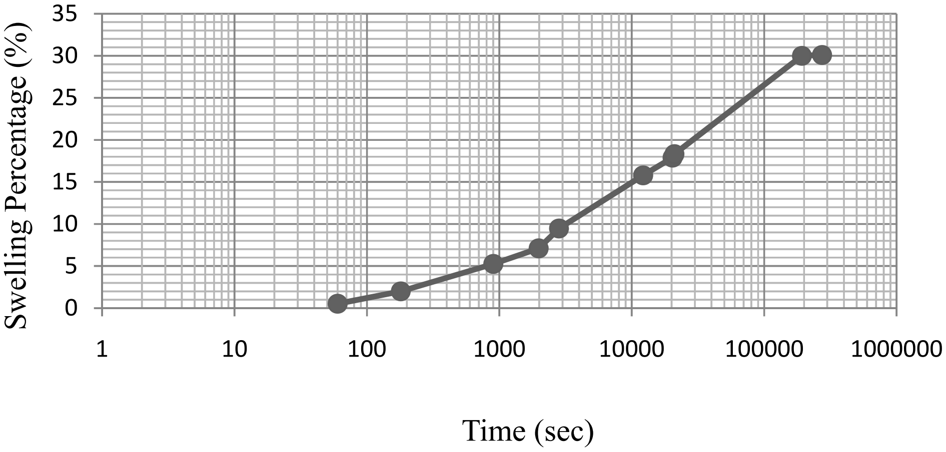


Figure B.11 Swell Percentage versus Time Relationship for S 5%; Without Cure, 7 Days Cured and 28 Days Cured respectively

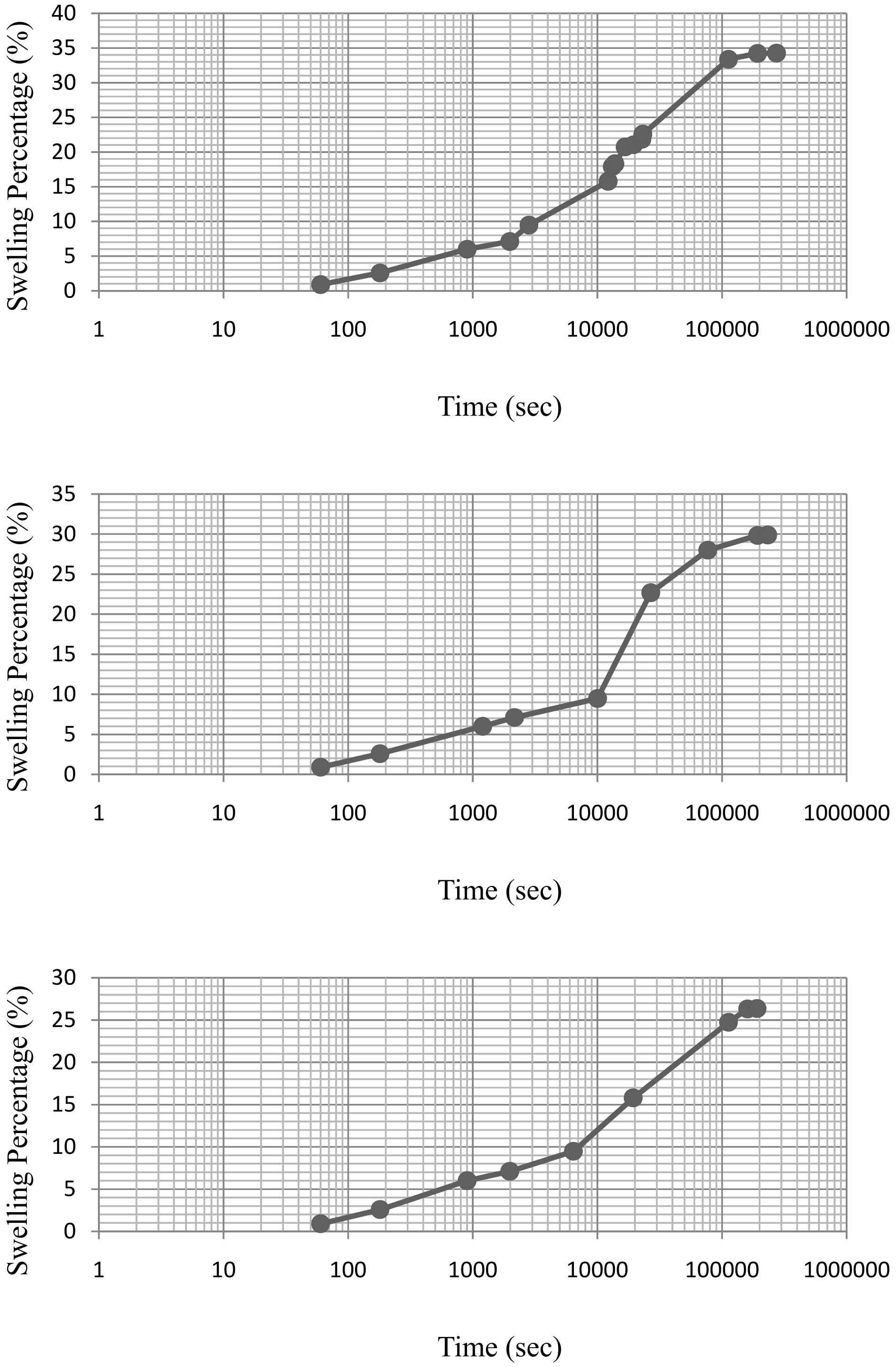


Figure B.12 Swell Percentage versus Time Relationship for S 10%; Without Cure, 7 Days Cured and 28 Days Cured respectively

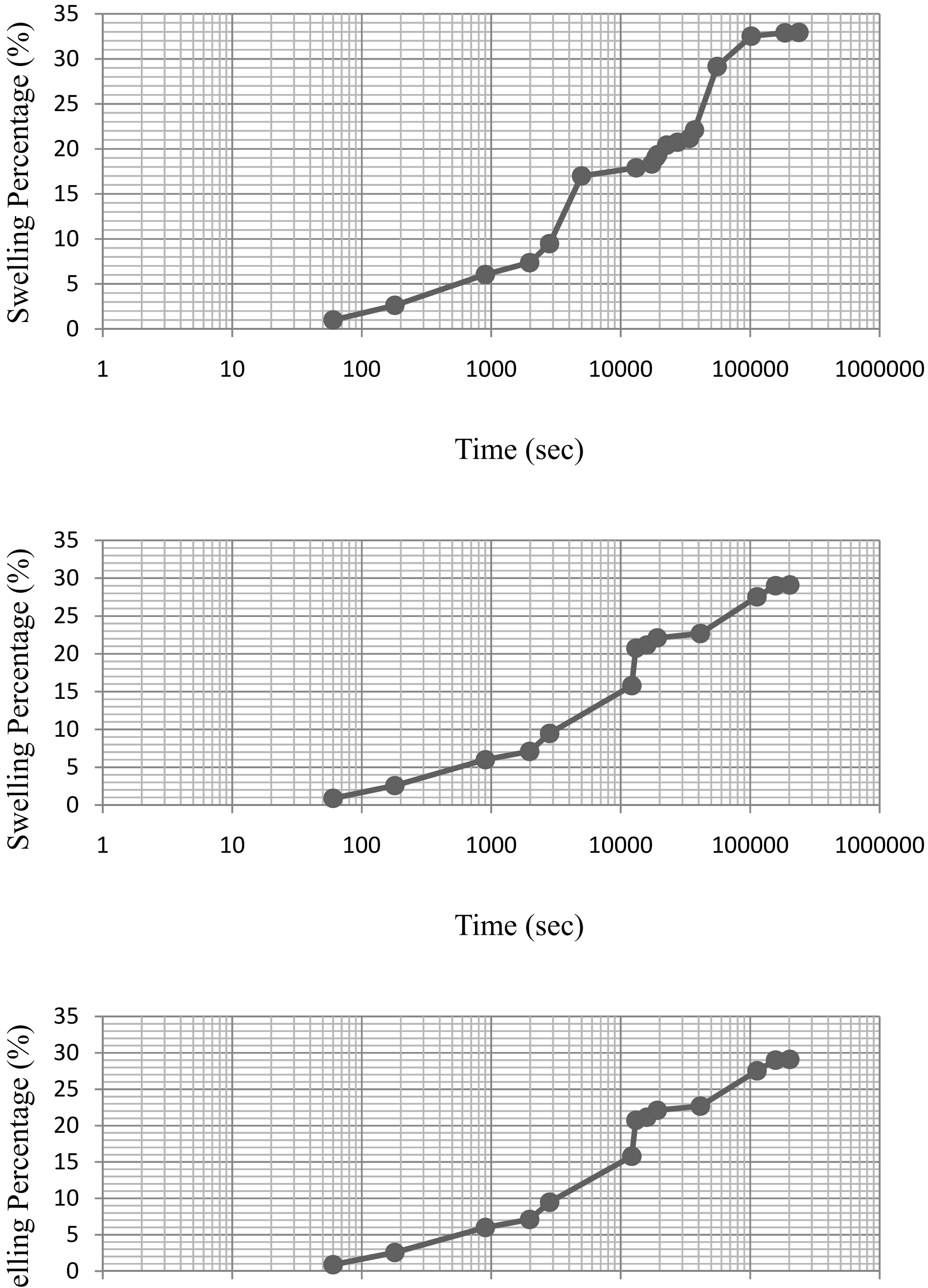


Figure B.13 Swell Percentage versus Time Relationship for S 15%; Without Cure, 7 Days Cured and 28 Days Cured respectively

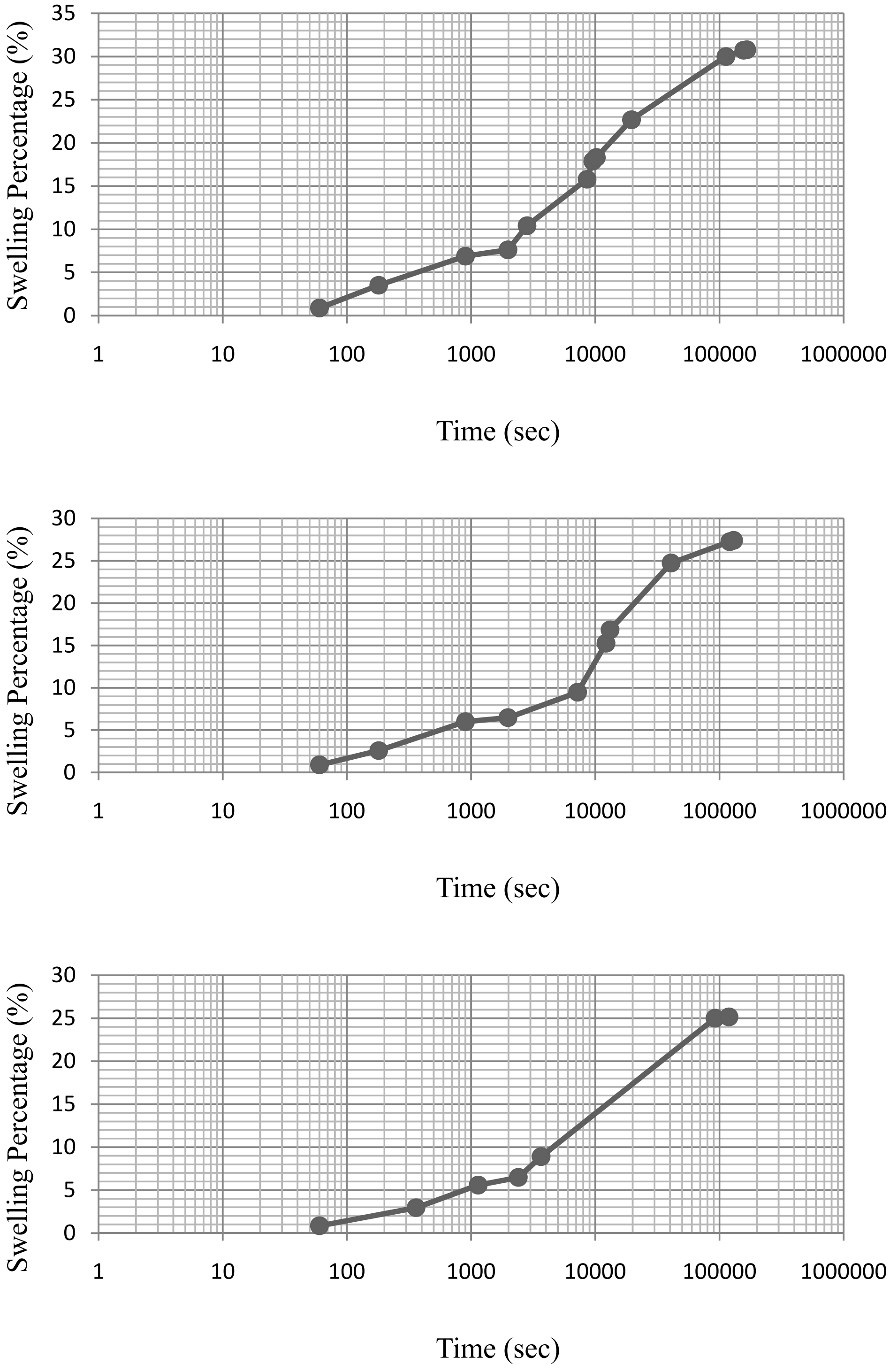


Figure B.14 Swell Percentage versus Time Relationship for S 20%; Without Cure, 7 Days Cured and 28 Days Cured respectively

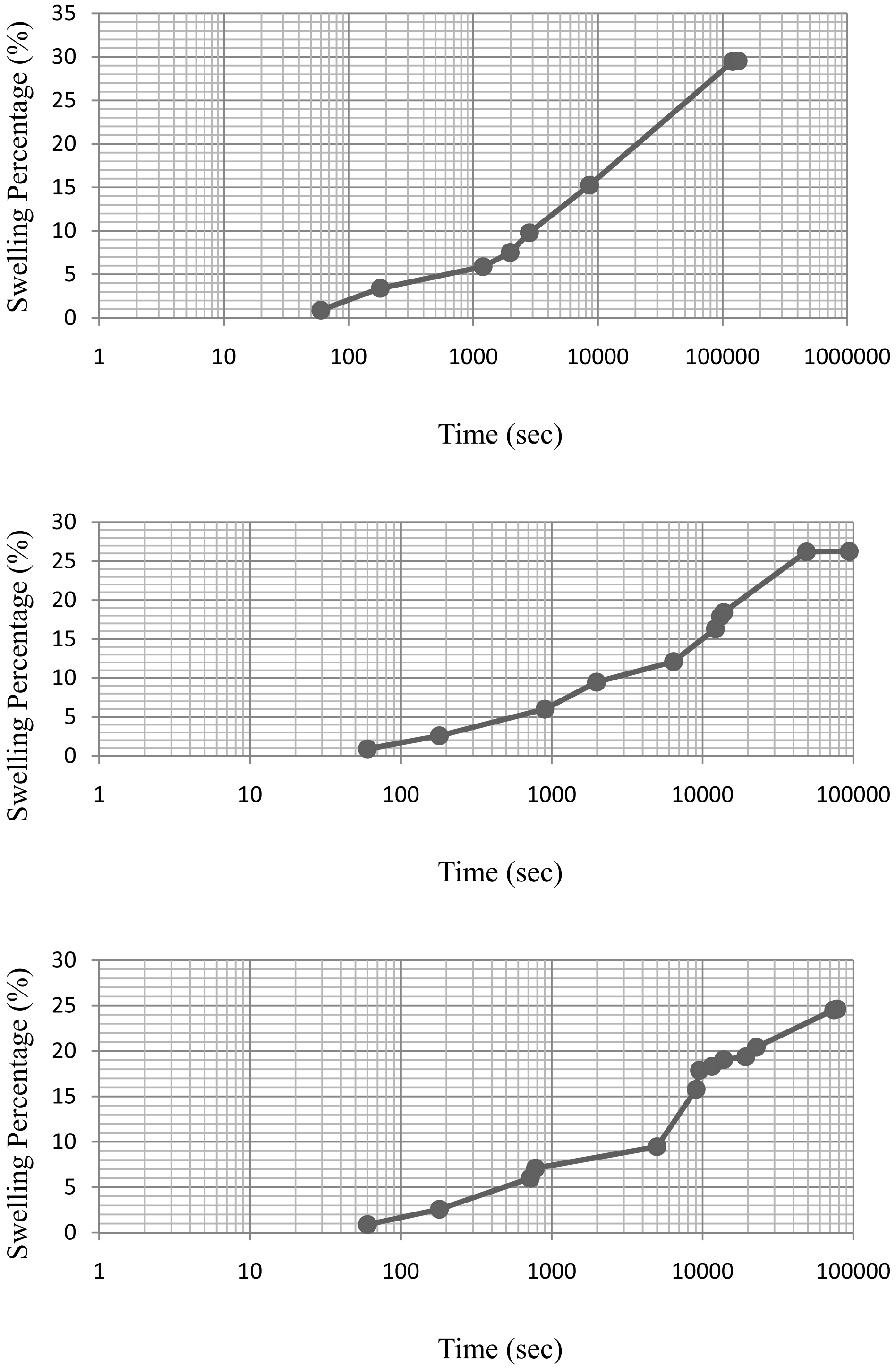


Figure B.15 Swell Percentage versus Time Relationship for S 25%; Without Cure, 7 Days Cured and 28 Days Cured respectively

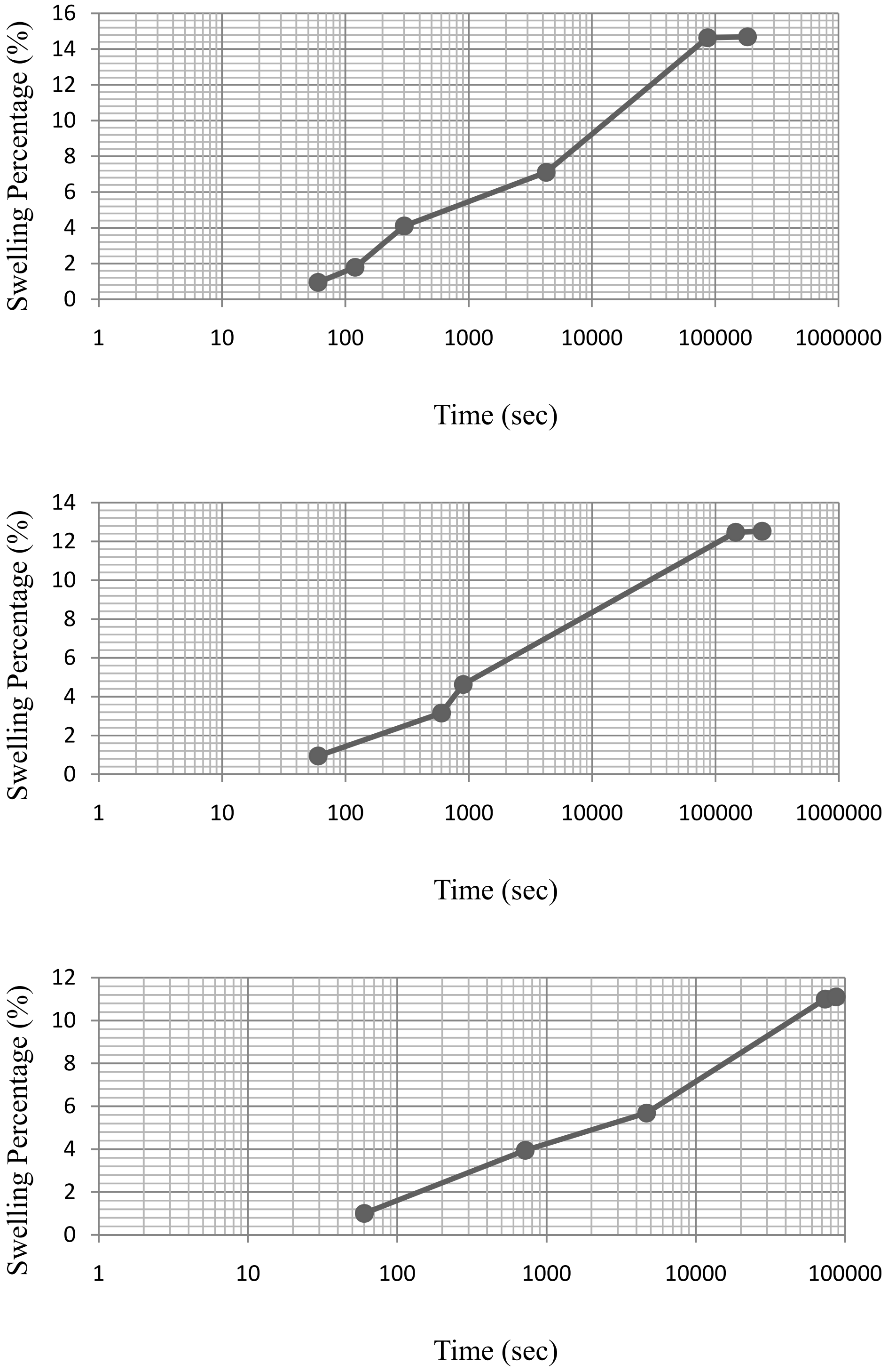


Figure B.16 Swell Percentage versus Time Relationship for L 1%; Without Cure, 7 Days Cured and 28 Days Cured respectively

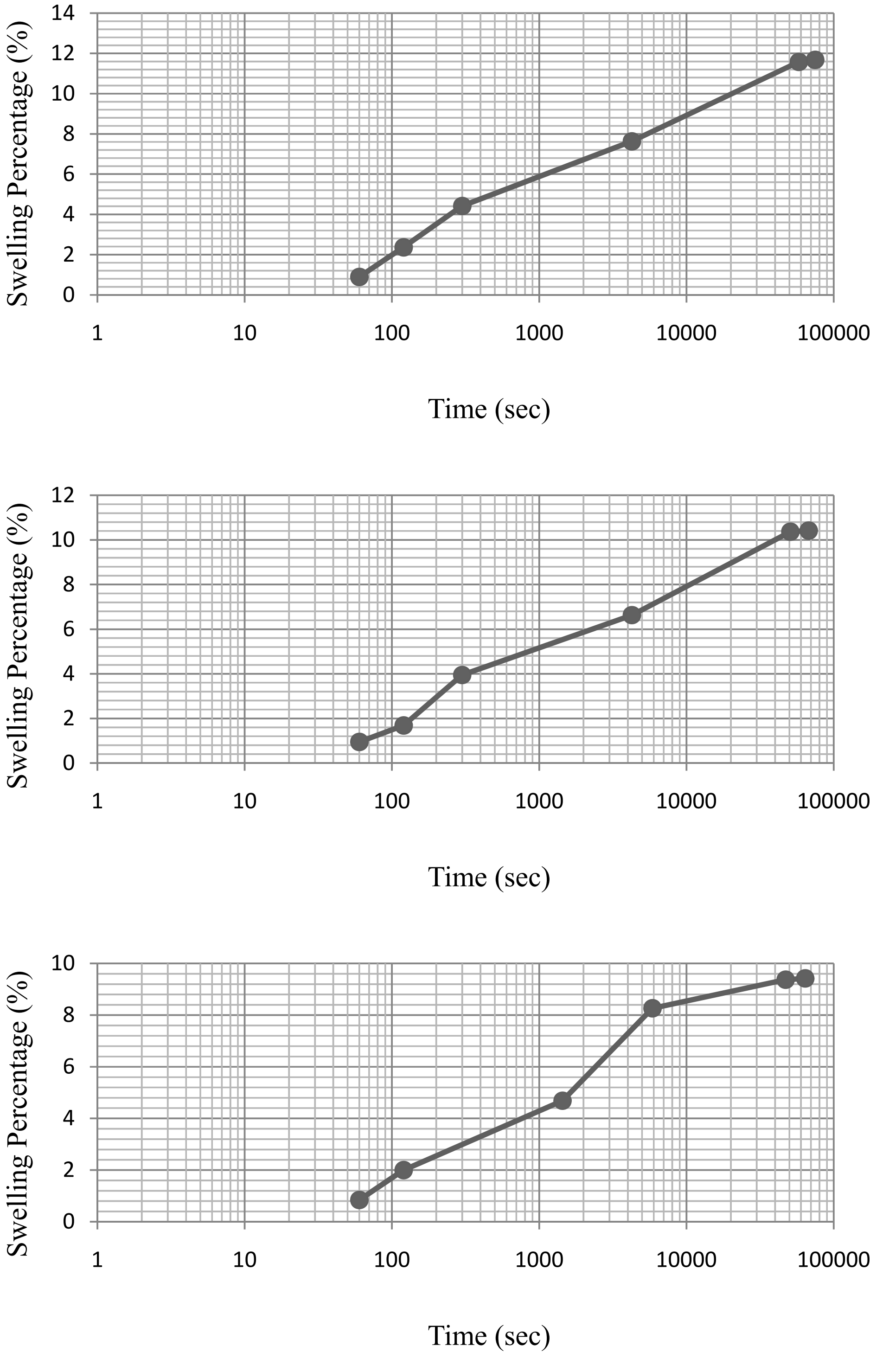
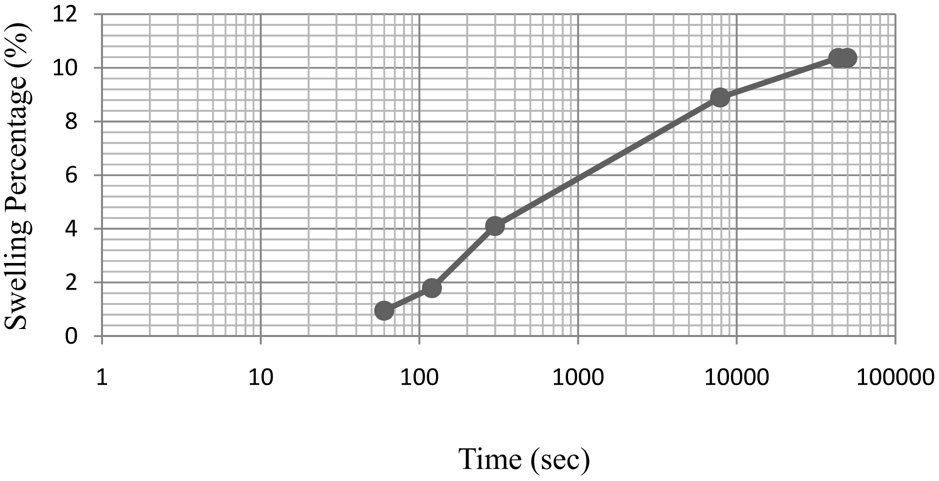
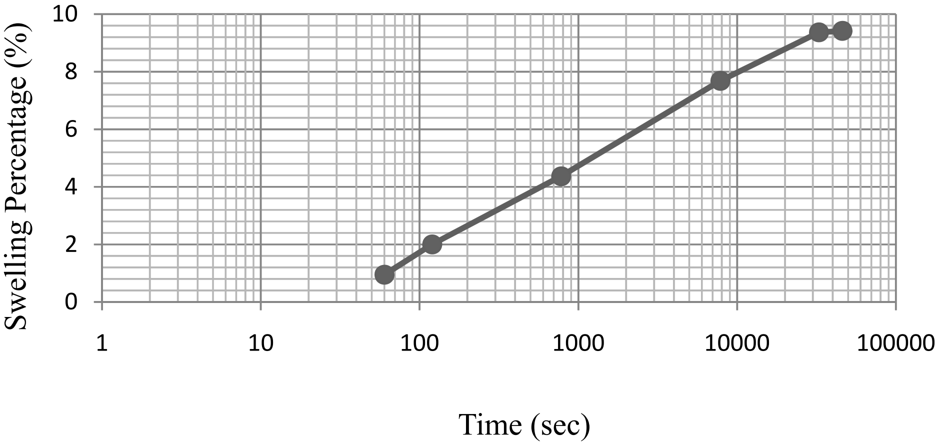


Figure B.17 Swell Percentage versus Time Relationship for L 3%; Without Cure, 7 Days Cured and 28 Days Cured respectively





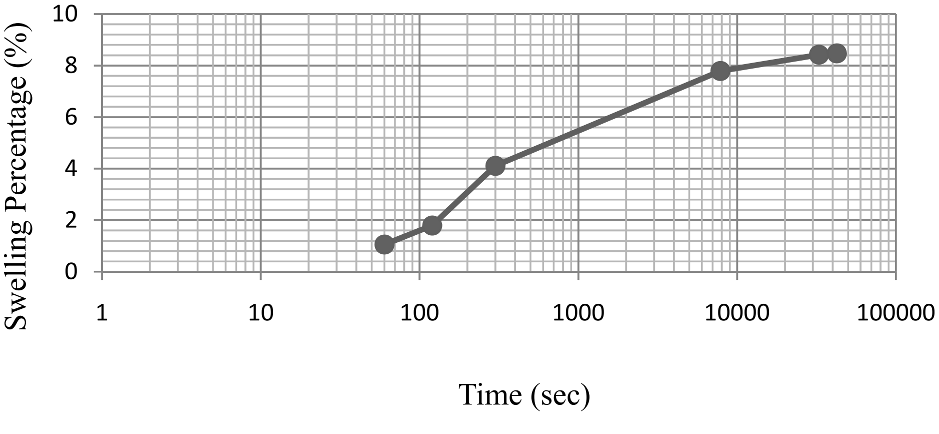


Figure B.18 Swell Percentage versus Time Relationship for L 3%; Without Cure, 7 Days Cured and 28 Days Cured respectively

APPENDIX C

TIME / SWELLING PERCENTAGE VERSUS TIME GRAPHS

Time / swelling percentage versus time graphs for Bigadic zeolite, sand, lime and lime and Bigadic zeolite together added specimens are presented in Appendix C for without cure. 7 days cured and 28 days cured options.

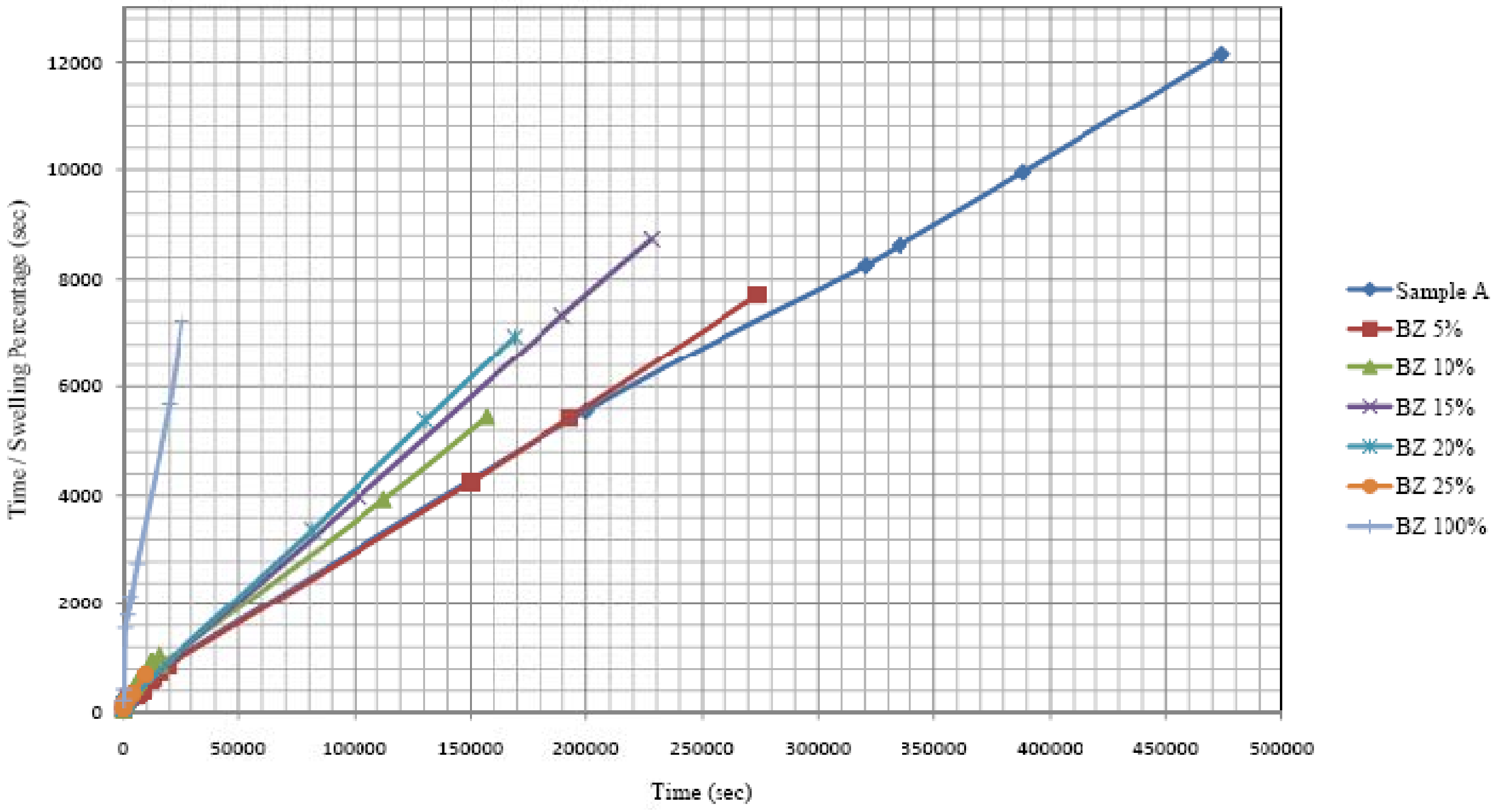


Figure C.1 Time / Swelling Percentage versus Time Graph for BZ Added Specimens

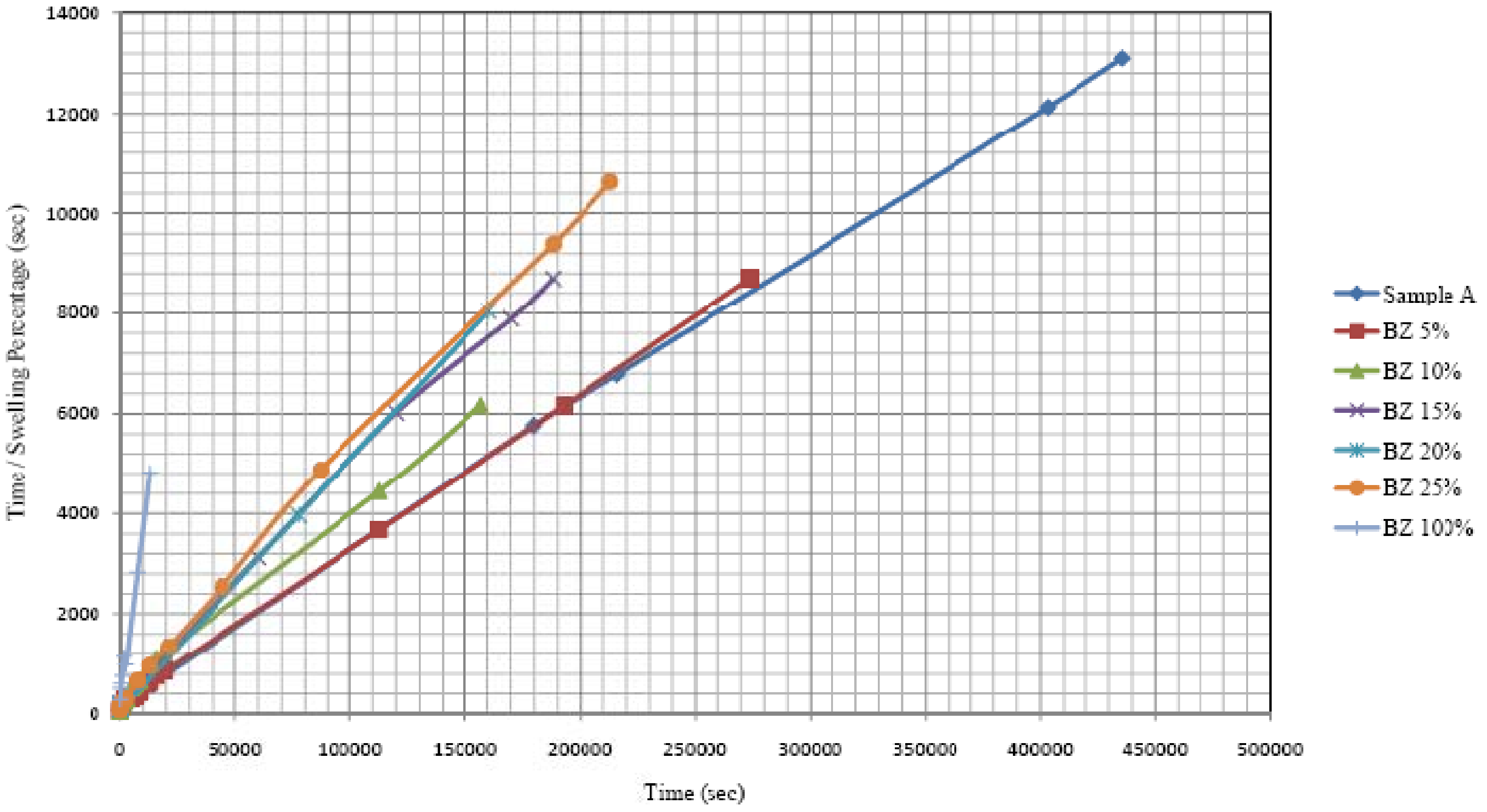


Figure C.2 Time / Swelling Percentage versus Time Graph for BZ Added Specimens, 7 Days Cured

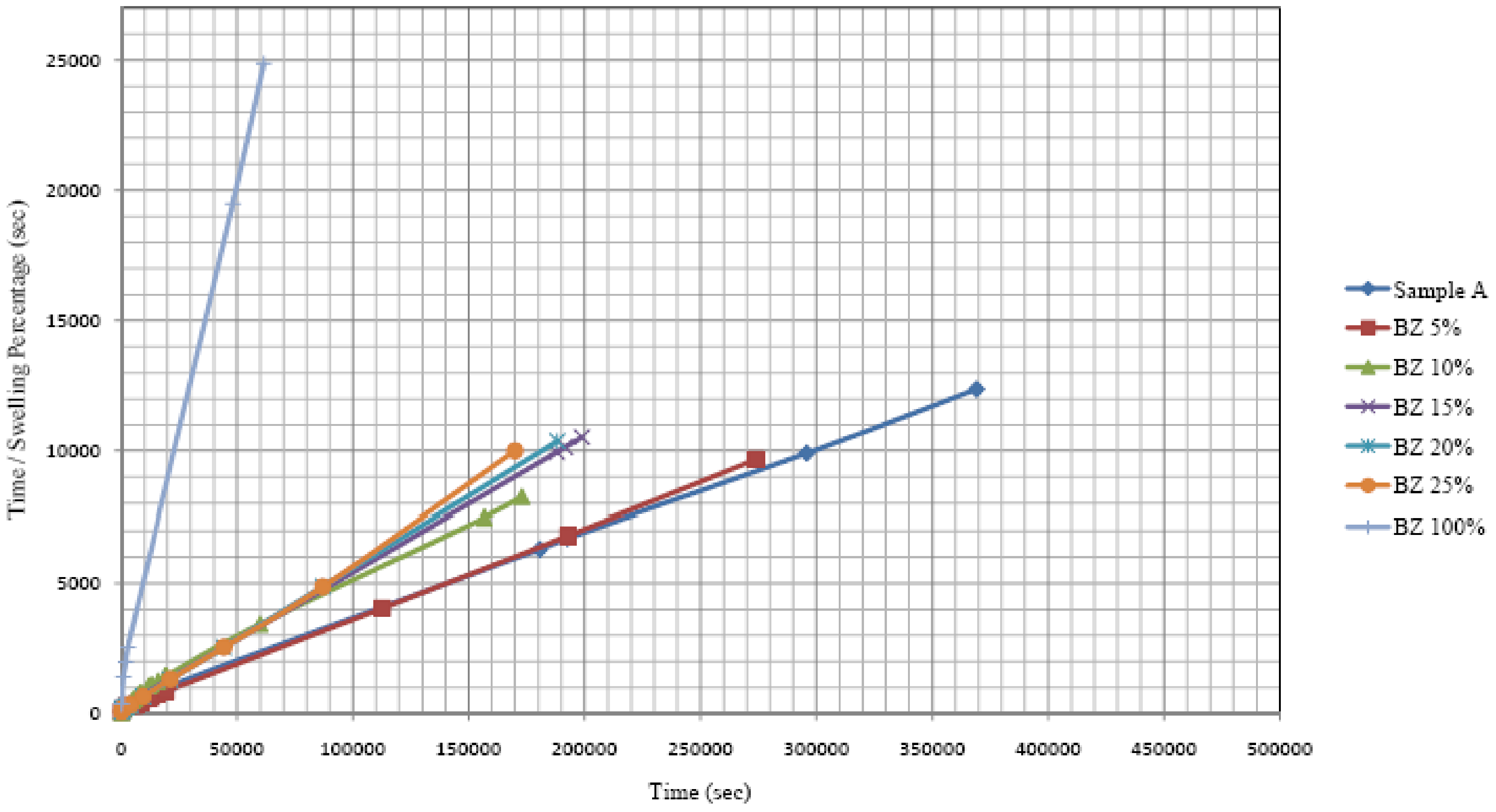


Figure C.3 Time / Swelling Percentage versus Time Graph for BZ Added Specimens, 28 Days Cured

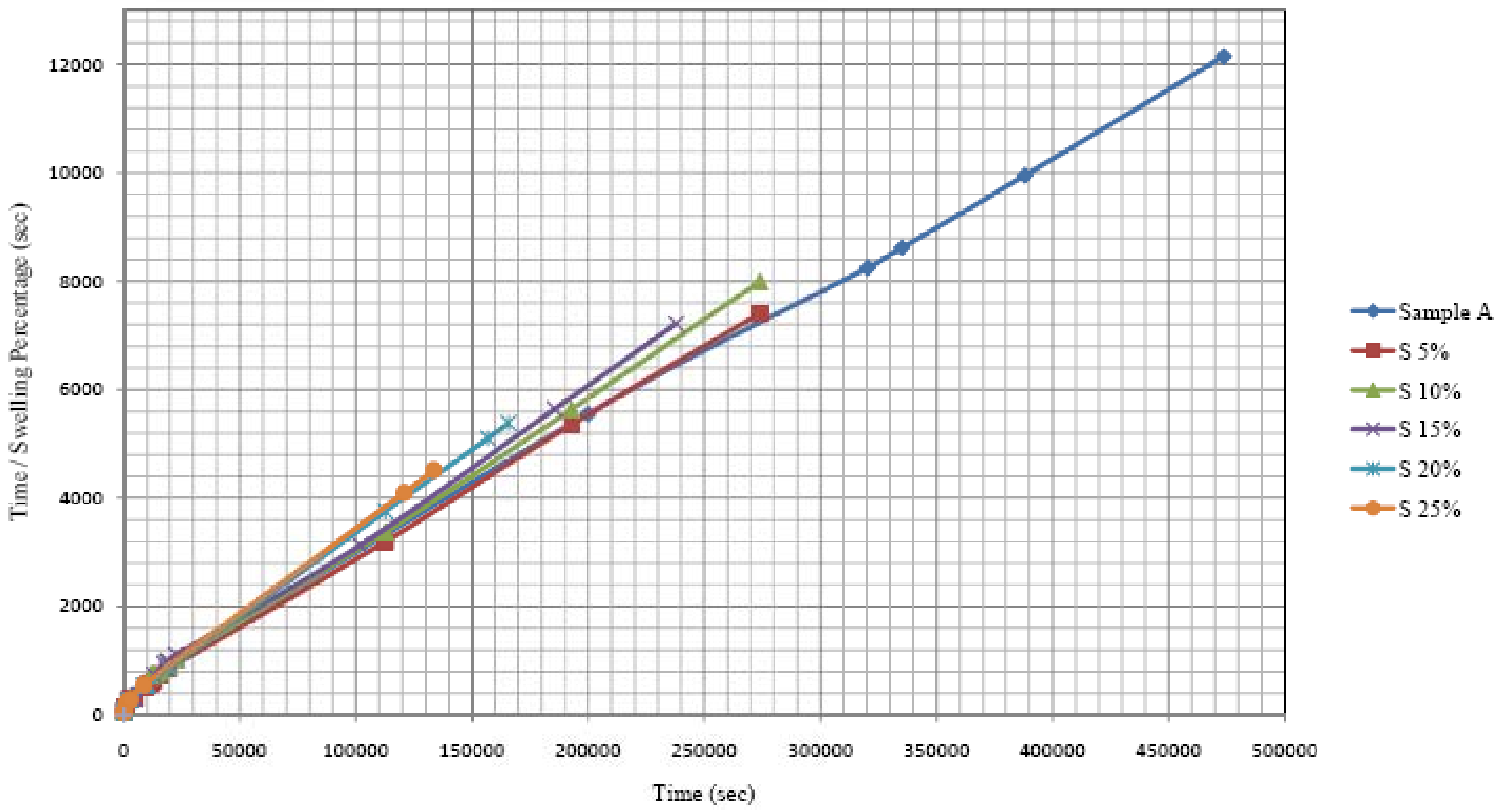


Figure C.4 Time / Swelling Percentage versus Time Graph for S Added Specimens

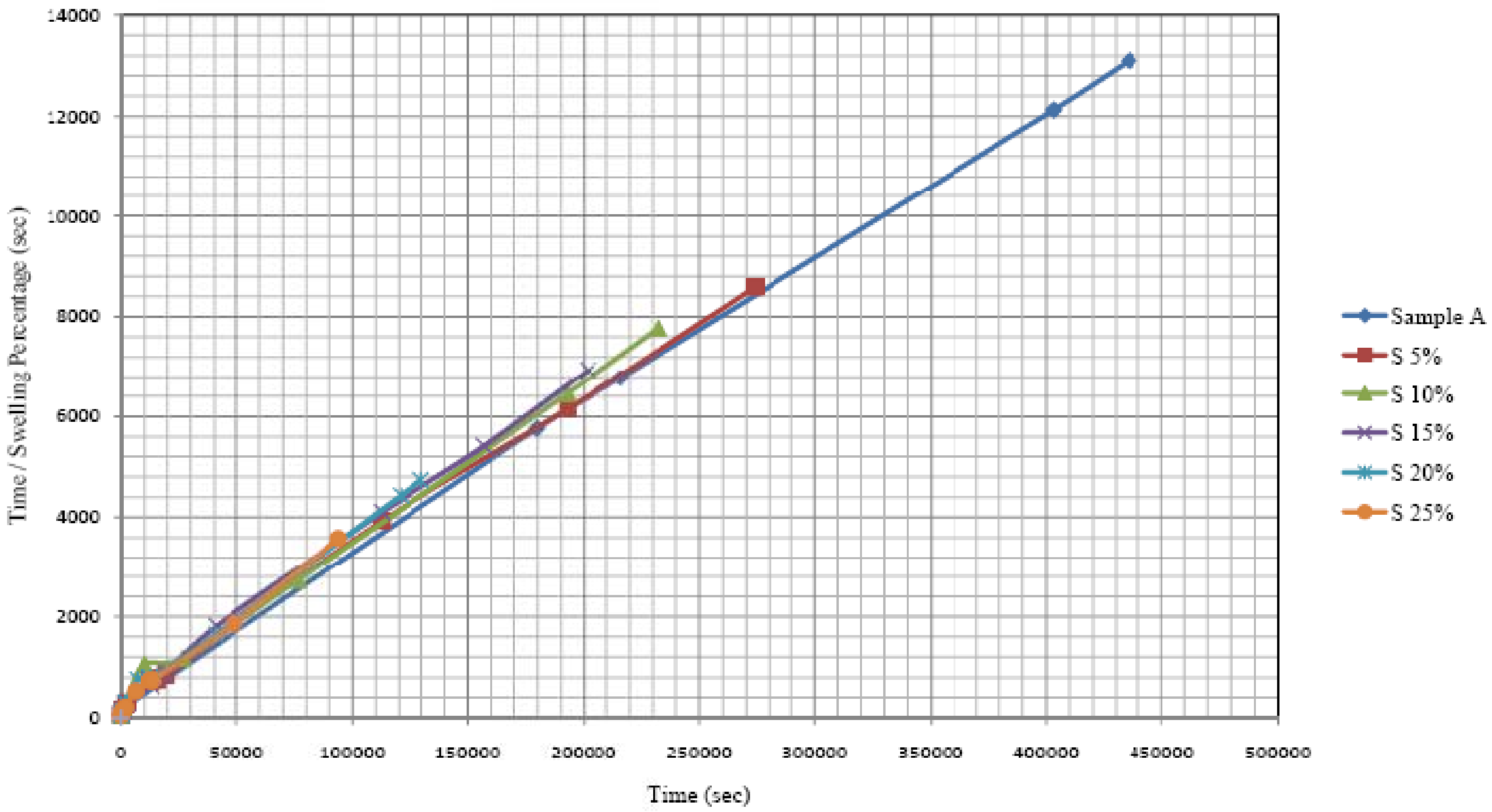


Figure C.5 Time / Swelling Percentage versus Time Graph for S Added Specimens, 7 Days Cured

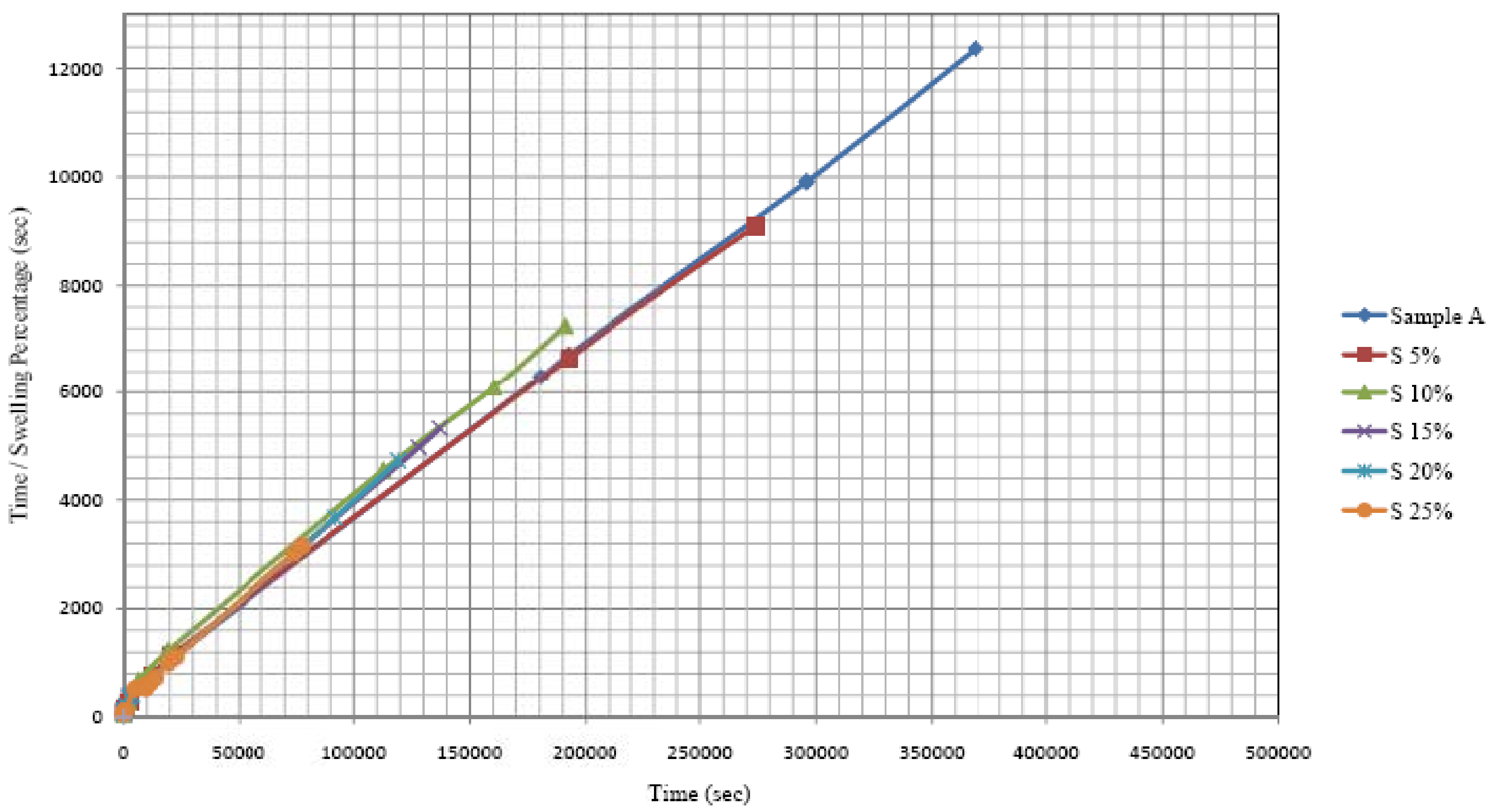


Figure C.6 Time / Swelling Percentage versus Time Graph for S Added Specimens, 28 Days Cured

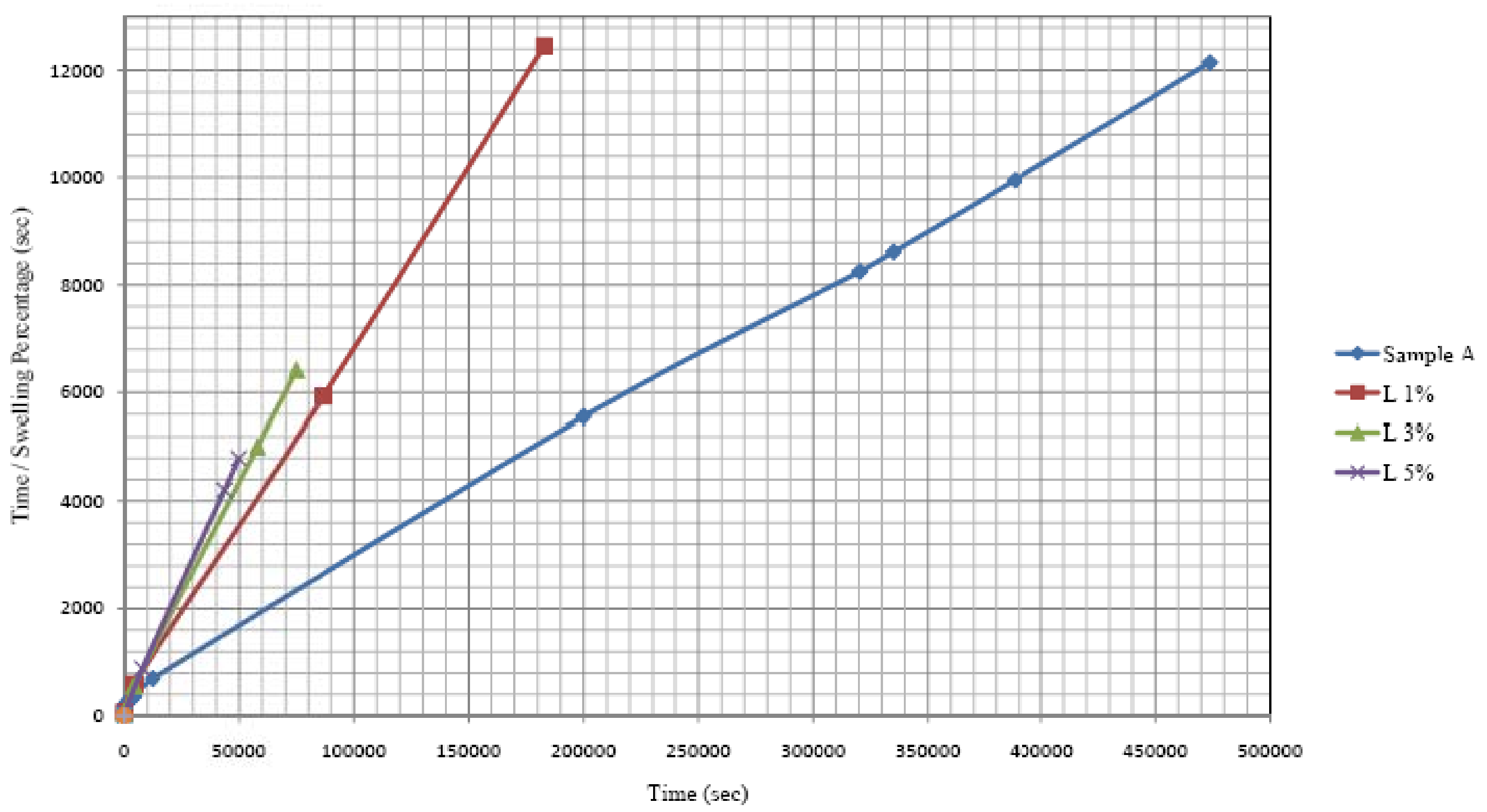


Figure C.7 Time / Swelling Percentage versus Time Graph for L Added Specimens

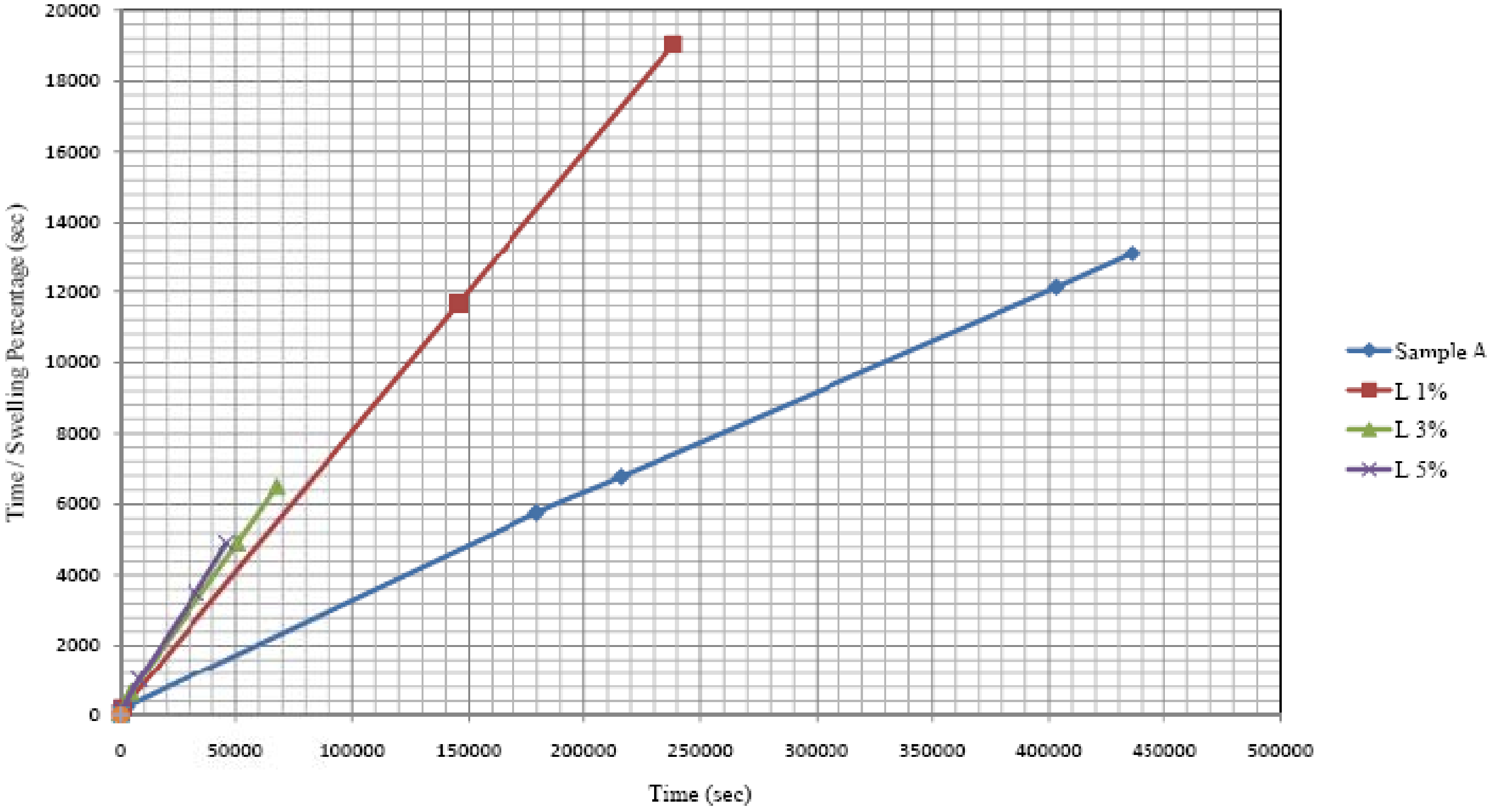


Figure C.8 Time / Swelling Percentage versus Time Graph for L Added Specimens, 7 Days Cured

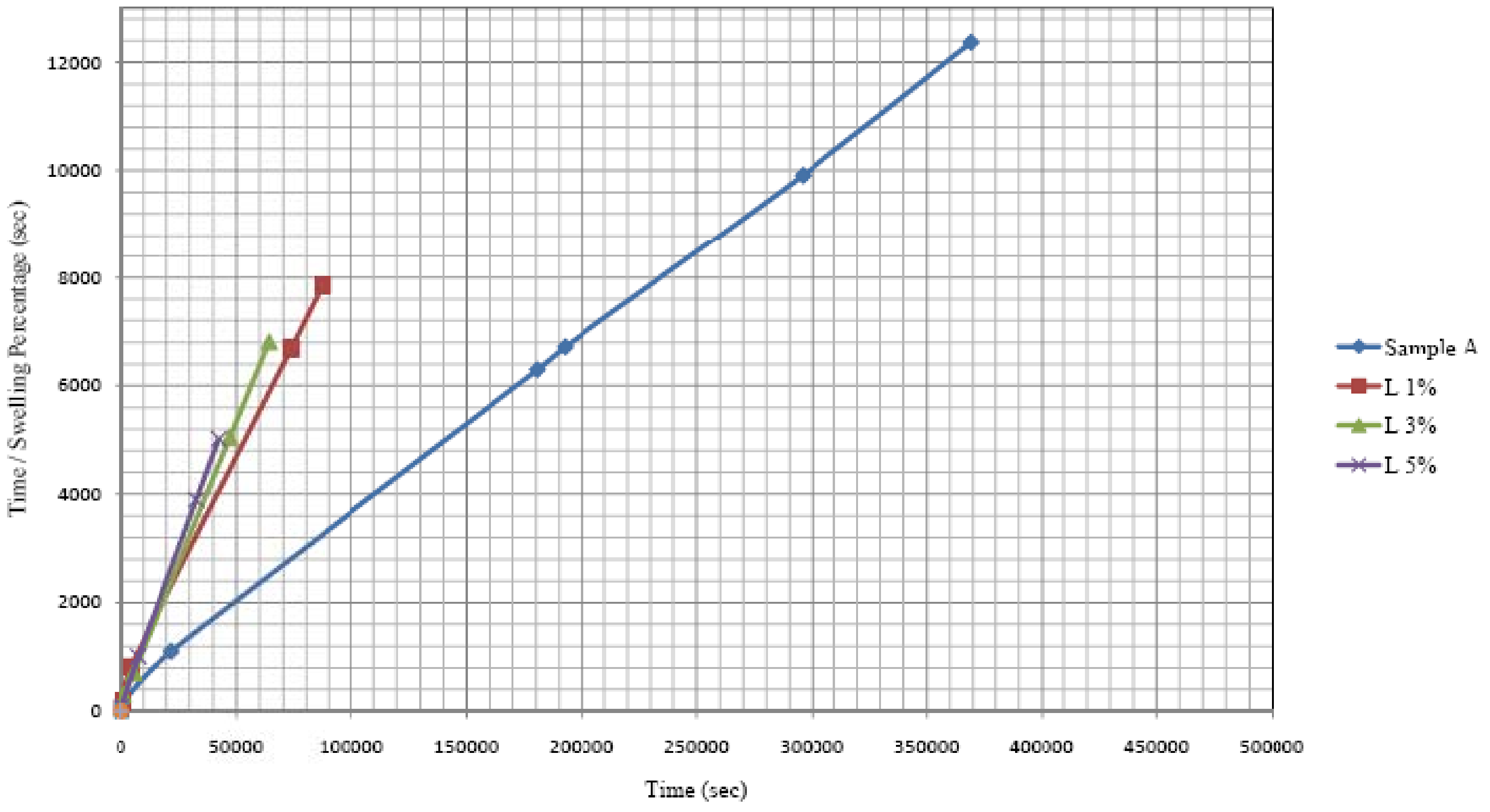


Figure C.9 Time / Swelling Percentage versus Time Graph for L Added Specimens, 28 Days Cured

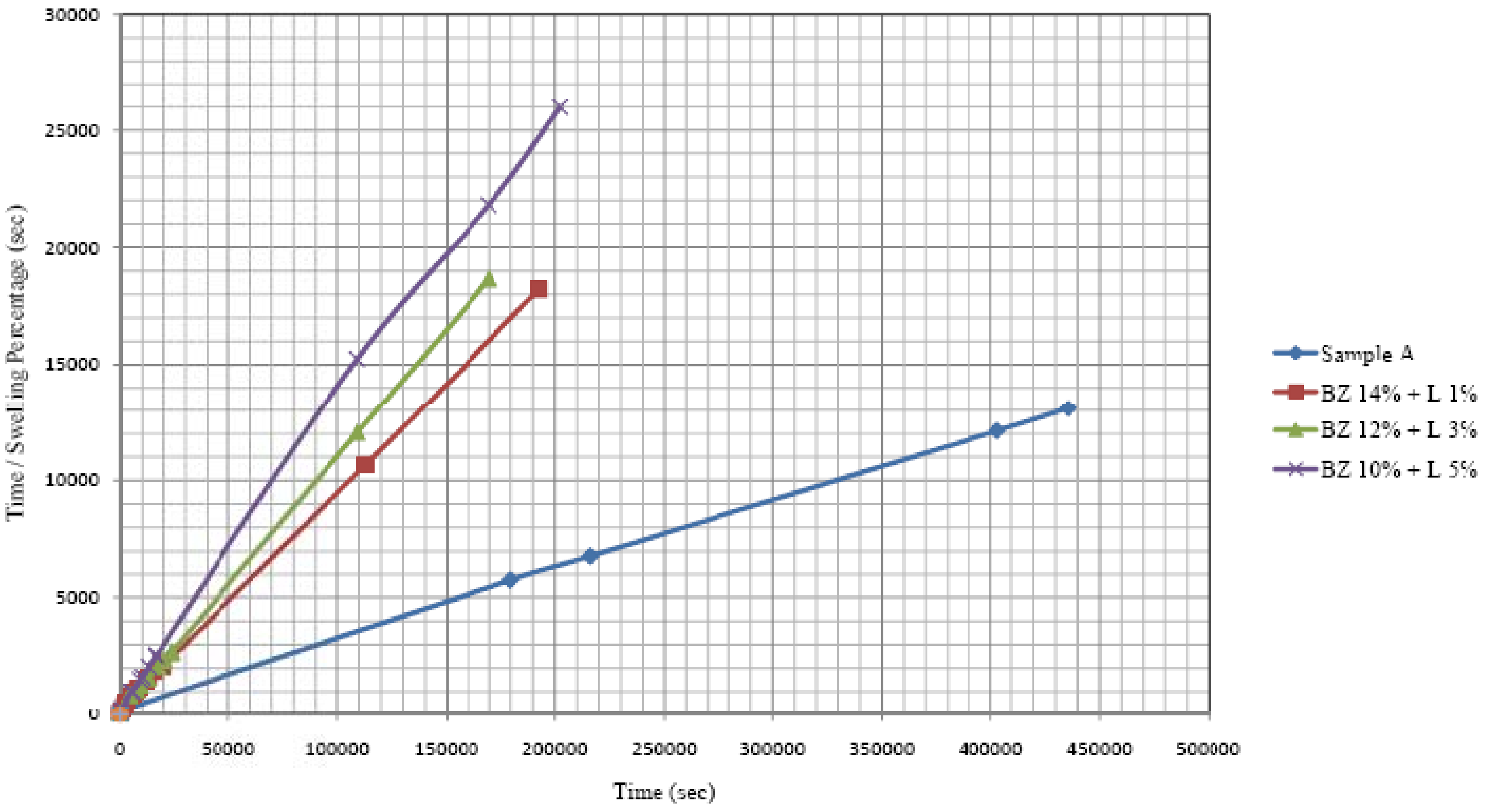


Figure C.10 Time / Swelling Percentage versus Time Graph for BZ and L Added Specimens

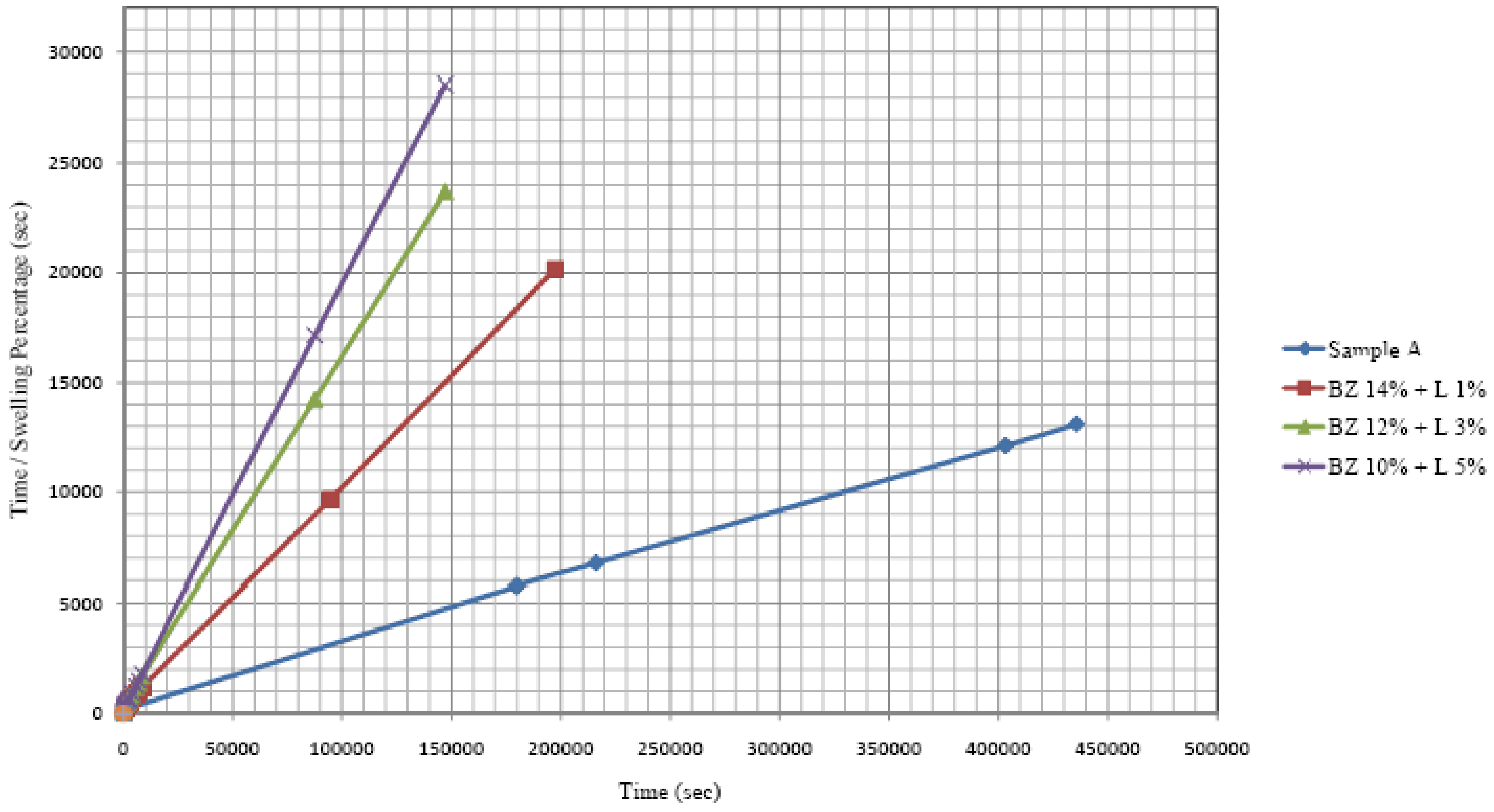


Figure C.11 Time / Swelling Percentage versus Time Graph for BZ and L Added Specimens, 7 Days Cured

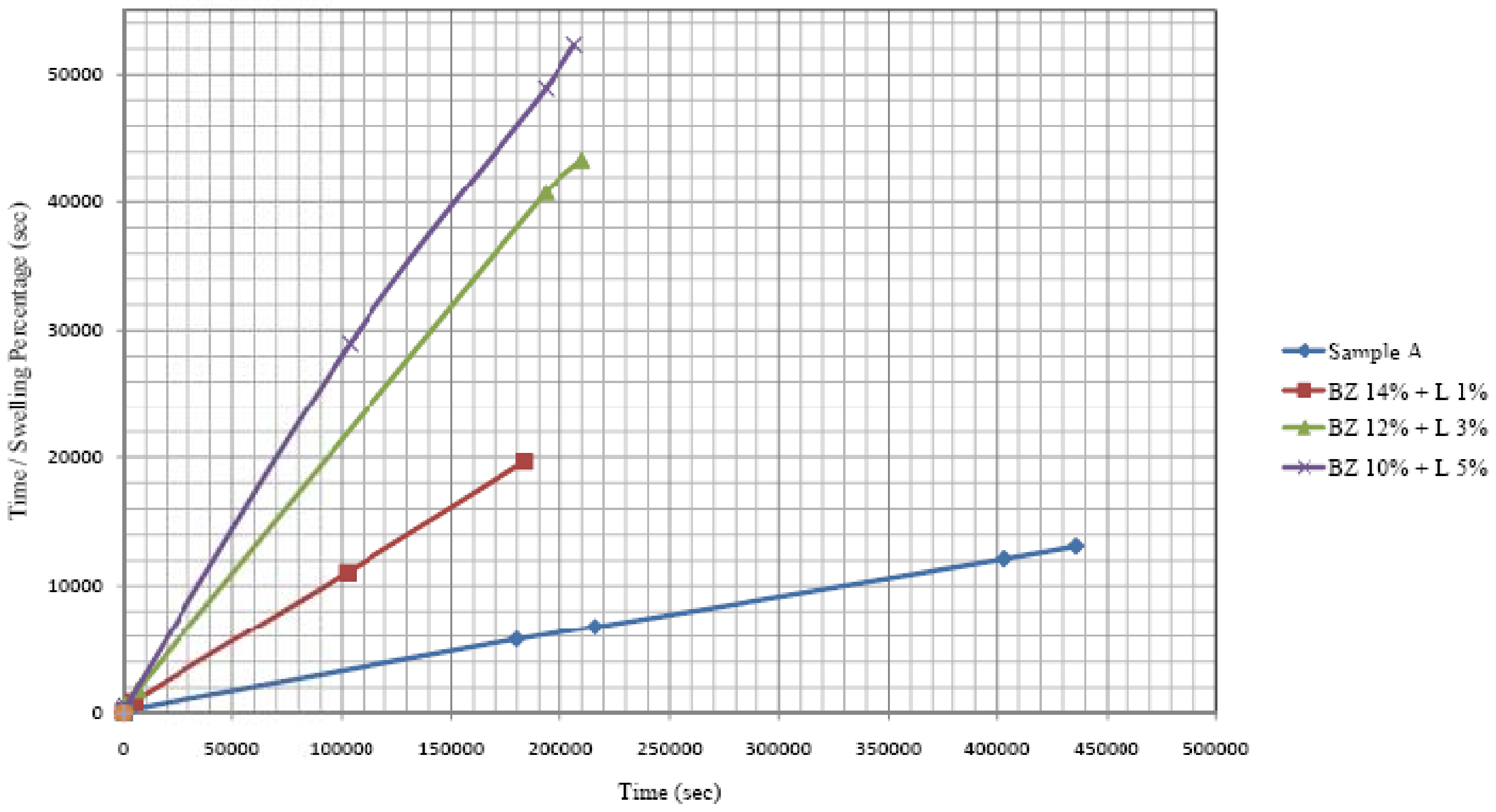


Figure C.12 Time / Swelling Percentage versus Time Graph for BZ and L Added Specimens 28 Days Cured