STABILIZATION OF EXPANSIVE CLAYS USING GRANULATED BLAST FURNACE SLAG (GBFS), GBFS-LIME COMBINATIONS AND GBFS CEMENT

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VEYSEL YAZICI

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Prof. Dr. Canan ÖZGEN
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Erdal ÇOKÇA
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Erdal ÇOKÇA
Supervisor

Examining Comittee Members

Prof. Dr. Türker MİRATA

Prof. Dr. Erdal ÇOKÇA

Assist. Prof. Dr. Sadık BAKIR

Assist. Prof. Dr. K. Önder ÇETİN

Dr. Vehbi ÖZAYDIN

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Veysel YAZICI

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ABSTRACT

STABILIZATION OF EXPANSIVE CLAYS USING GRANULATED BLAST FURNACE SLAG (GBFS), GBFS-LIME COMBINATIONS AND GBFS CEMENT

Yazıcı, Veysel
M. Sc., Department of Civil Engineering
Supervisor: Prof. Dr. Erdal Çokça

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Expansive clays undergo a large swell when they are subjected to water. Thus, expansive clay is one of the most abundant problems faced in geotechnical engineering applications. It causes heavy damages in structures, especially in water conveyance canals, lined reservoirs, highways, airport runways etc., unless appropriate measures are taken. In this thesis, Granulated Blast Furnace Slag (GBFS), GBFS - Lime combinations and GBFS Cement (GBFSC) were utilized to overcome or to limit the expansion of an artificially prepared expansive soil sample (Sample A). GBFS and GBFSC were added to Sample A in proportions of 5 to 25 percent. Different GBFS-Lime combinations were added to Sample A by keeping the total addition at 15 percent. Effect of stabilizers on grain size distribution, Atterberg limits, swelling percentage and rate of swell of soil samples were determined. Effect of curing on swelling percentage and rate of swell of soil samples were also determined. Leachate analysis of GBFS, GBFSC and samples stabilized by 25 percent GBFS and GBFSC was performed. Use of stabilizers successfully decreased the amount of swell while increasing the rate of swell. Curing samples for 7 and 28 days resulted in less swell percentages and higher rate of swell.

Key Words: Expansive Soil, Granulated Blast Furnace Slag (GBFS), Granulated Blast Furnace Slag Cement (GBFSC), Leachate Analysis, Soil Stabilization, Swelling Potential.

ÖZ

ŞİŞEN KİLLERİN YÜKSEK FIRIN CÜRUFU, CÜRUF-KİREÇ KARIŞIMLARI VE CÜRUFLU ÇİMENTO İLE İYİLEŞTİRİLMESİ

Yazıcı, Veysel
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Erdal Çokça

Nisan 2004, 100 Sayfa

Şişen killer suya maruz kaldıklarında büyük oranda şişme kapasitesine sahiptirler. Bu nedenle, Geoteknik mühendisliğinde en sık karşılaşılan problemlerden birisi şişen kil problemidir. Şişen killer özellikle su iletim kanallarında, kaplamalı rezervuarlarda, otoyollarda, havaalanı pistlerinde vb, gerekli önlemler alınmadığı takdirde ağır hasarlara neden olmaktadır. Tez çalışmasında yapay bir şişen kil numunesinin (Numune A) iyileştirilmesi için Granüle Yüksek Fırın Cürufu (GYFC), GYFC - Kireç karışımları ve GYFC Çimentosu (GYFCÇ) kullanılmıştır. Şişen zemin numunesinin iyileştirilmesi amacıyla GYFC ve GYFCÇ, %5 ile %25 arasında değişen oranlarda kullanılmıştır. Aynı amaçla GYFC - Kireç karışımları toplam numune ağırlığının %15'ini geçmeyecek şekilde kullanılmıştır. Şişen zemin numunelerinin iyileştirilmesinde kullanılan bu maddelerin ve bunların değişik oranlarının numunelerin dane dağılımı, Atterberg limitleri, şişme yüzdesi ve şişme hızı üzerindeki etkileri incelenmiştir. Kürün şişen zemin numunelerinin şişme yüzdesi ve şişme hızları üzerindeki etkileri de gözlemlenmiştir. GYFC, GYFCÇ ve bunların %25 oranında kullanıldığı numunelerin sızıntı suyu analizleri yapılmıştır. Zemin iyileştirici malzemelerinin (GYFC, GYFC-Kireç karışımları, GYFCÇ) kullanımı, şişen zemin numunelerinin şişme yüzdelerini önemli bir şekilde düşürürken, şişme hızlarını önemli bir şekilde arttırmıştır. 7 ve 28 günlük kürler, şişme yüzdelerini daha da azaltmış, şişme hızlarının daha da artmasını sağlamıştır.

Anahtar Kelimeler: Granüle Yüksek Fırın Cürufu, Granüle Yüksek Fırın Cürufu Çimentosu, Sızıntı Suyu Analizi, Şişen Zemin, Şişme Potansiyeli, Zemin İyileştirilmesi.

To My Wife

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Sample A
ASTM	American Society for Testing and Materials
CH	Inorganic clays of high plasticity
CL	Inorganic clays, silty clays, sandy clays of low plasticity
dH	Change in vertical height of the specimen
GBFS	Granulated blast furnace slag
GBFSC	Granulated blast furnace slag cement
G_s	Specific gravity
H	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
PL	Plastic limit
PI	Plasticity index
SL	Shrinkage limit
t_{50}	Time to reach 50% of total swell

CHAPTER 1

INTRODUCTION

Changes in the moisture content of clay soils are generally accompanied by volume changes. On moisture uptake there is generally a volume increase and moisture loss is accompanied by shrinkage (Gillott, 1968).

Expansion of soils is generally observed in unsaturated clays which are of certain mineralogical structures (eg. Smectites). Such soils have a high capacity of water absorption thus they absorb water meanwhile their volume increase. Expansive soils are generally abundant in the arid or semi-arid regions where the rate of evaporation is much higher than rate of precipitation. In Turkey, climatic conditions of Central Anatolia and Southeastern Anatolia regions may favor the formation of such soils (Birand, 2001).

There are many definitions of expansive soils. Expansive soil is a term generally applied to any soil that has a potential for shrinking and swelling under changing moisture conditions (Nalbantoğlu and Güçbilmez, 2002). An expansive soil will shrink when water (or moisture) content is reduced and will swell when the water content increases.

Expansive soils cause more damage to structures, particularly light buildings and pavements, than any other natural hazard, including earthquakes and floods in USA. Expansive soils are a worldwide problem that poses several challenges for civil engineers. They are considered a potential natural hazard, which can cause extensive damage to structures if not adequately treated (Al-Rawas, 2002).

The movement of swelling may exert enough pressure to crack sideways, driveways, basement floors, pipelines and even foundations. Thus, it is very important that studies be done in order to limit the hazards caused by expansive soils.

1.1. Review on Expansive Soils

As mentioned earlier, expansive soils swell when given access to water and shrink when they dry out. The moisture may come from rain, flooding, leaking water from sewer lines or from reduction in surface evapotranspiration when an area is covered by a building or pavement. Soils containing the clay mineral montmorillonite (a smectite) generally exhibit high swelling properties (Wayne,1984; Komine and Ogata, 1996).

There are many correlations that are useful for identifying potentially expansive soils. It is also possible to identify them visually. Visual indications may be (Wayne, 1984).

1- Wide and deep shrinkage cracks occurring during dry periods,
2- Soil is rock-hard when dry, but very stiff and sticky when wet,
3- Damages on the surrounding structures due to expansion of soil.

The swelling and shrinkage phenomenon depends on several factors, including type and amount of clay minerals and cations, moisture content, dry density, soil structure, and loading conditions (Al-Rawas, 2002).

1.2. Structure of Clay Minerals

It is well known that at least two definitions of clay exist. The geotechnical definition depicts as *clay* those particles that have an effective diameter smaller than 0.002 mm. Mineralogists on the other hand define clay as particles formed by polimeric chains of some specific mineral, while no size restrictions are given. As a consequence, not all the soil particles with a diameter < 0.002 mm are mineralogically clays, nor clay minerals have to be smaller that 0.002 mm (Musso, 2000).

The basic units of which the clays are made are Silica (SiO_2) tetrahedral sheets and Aluminum (Al) or Magnesium (Mg) Oxides octahedral sheets. Sheets can combine in different ways, so as to form layers of different minerals.

In most clay mineral structures, the silica tetrahedra are interconnected in a sheet structure. Three of the four oxygens in each tetrahedron are shared to form a hexagonal net as shown in figure 1.1. The bases of the tetrahedra are all in the same plane, and the tips all point in the same direction. The structure can repeat indefinitely and has the composition $(Si_4O_{10})^{4-}$ (Mitchell, 1993).

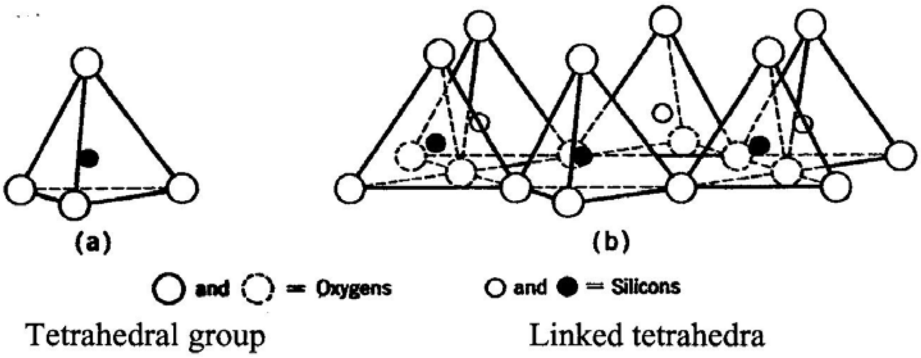

Figure 1.1. Silica Tetrahedron and Layer (after Grim, 1953)

In a sharp notation, useful for schematic representation of mineral layers, the silica sheet is identified as:

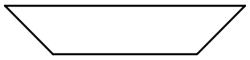

Figure 1.2. Scheme for the Silica sheet (after Craig, 1992)

The octahedral sheet is composed of magnesium or aluminum coordinated octahedrally with oxygens and hydroxyls. The coordination of Aluminum or Magnesium atoms with oxygens or hydroxils gives rise to structural units with an octahedral shape. Octahedrons, as for tetrahedrons, have the capacity to join in sheets. Depending on the charge of the main cation (Al^{3+}, Mg^{2+}) the distinction between dioctahedrals and trioctahedrals structures is made (Mitchell, 1993).

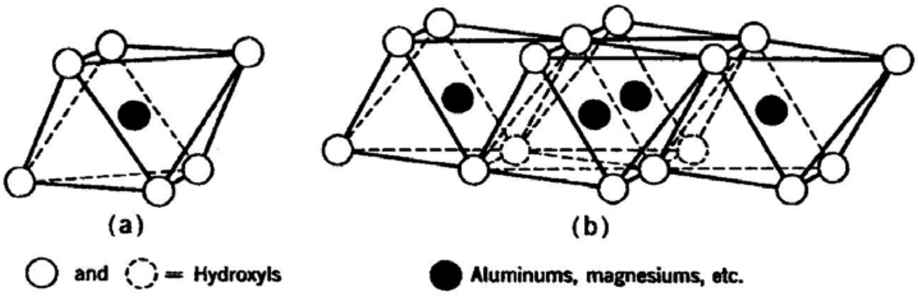

Figure 1.3. Octahedron and Octahedral Sheet (after Grim, 1953)

Those cations have to balance the negative electrical charge of the octahedral arrangement of oxygens and hydroxyls, equal to two electrons per unit. Therefore while the Magnesium ion needs to be present in every unit, the Aluminum ion will be required just in two cells over three.

The mineralogical name for the Aluminum sheet is Gibbsite, the one for Magnesium is Brucite. Schematic representations are shown in figure 1.4.

G B

Figure 1.4. Schemes for Gibbsite and Brucite (after Craig, 1992)

The various clay minerals are formed by the stacking combinations of basic sheet structures with different forms of bonding between the combined sheet. The main clay minerals are;

1. Kaolinite
2. Illite
3. Montmorillonite.

1.2.1. Kaolinite

Kaolinite consists of a structure based on a single sheet of silica tetrahedrons combined with a single sheet of alumina octahedrons as shown in figure 1.5. The combined silica-alumina sheets are held together fairly tightly by hydrogen bonding, thus a kaolinite particle may consist of over one hundred stacks.

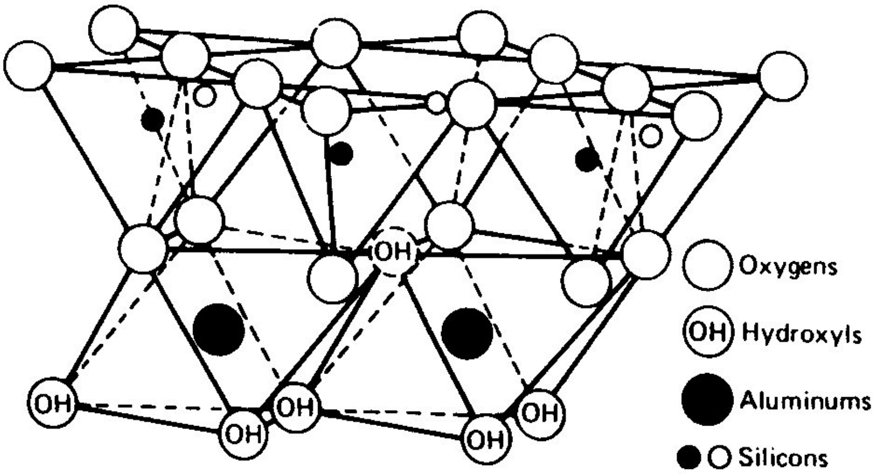

Figure 1.5. Diagrammatic Sketch of the Structure of Kaolinite. (after Grim,1953)

1.2.2. Illite

Illite has a basic structure consisting of a sheet of alumina octahedrons between and combined with two sheets of silica tetrahedrons as shown in figure 1.6. The combined sheets are linked together by fairly weak bonding due to (non-exchangeable) potassium ions held between them.

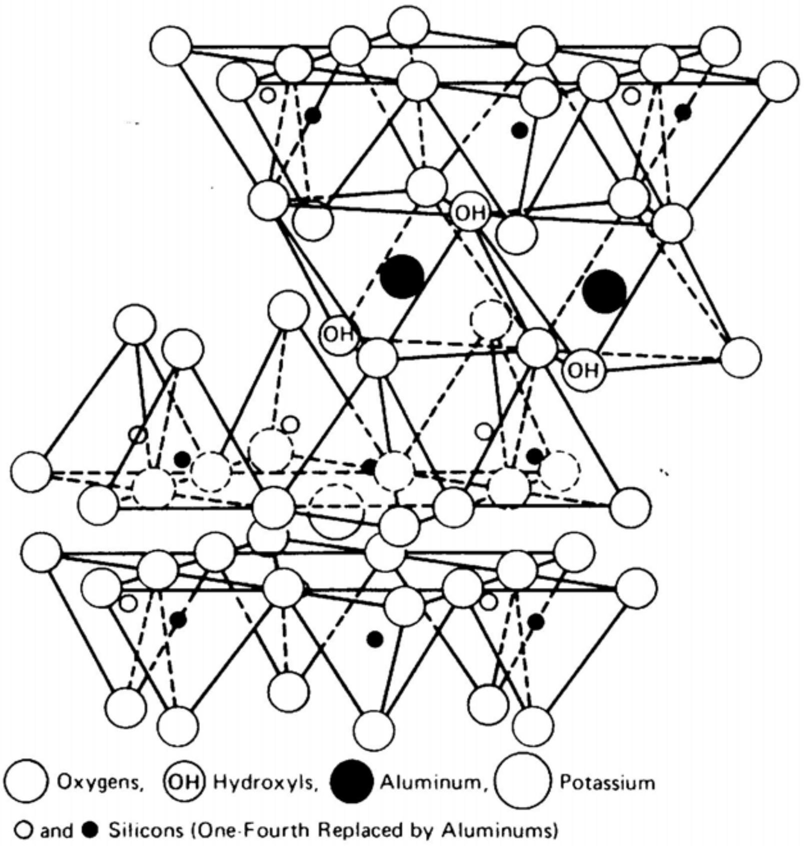

Figure 1.6. Diagrammatic Sketch of the Structure of Illite. (after Grim, 1953)

1.2.3. Montmorillonite

Montmorillonite has the same basic structure as illite as shown in figure 1.7. In the octahedral sheet there is partial substitution of aluminum by magnesium. The space between the combined sheets is occupied by water molecules and (exchangeable) cations other than potassium. There is a very weak bond between the combined sheets due to these ions. Considerable swelling of montmorillonite can occur due to additional water being absorbed between the combined sheets.

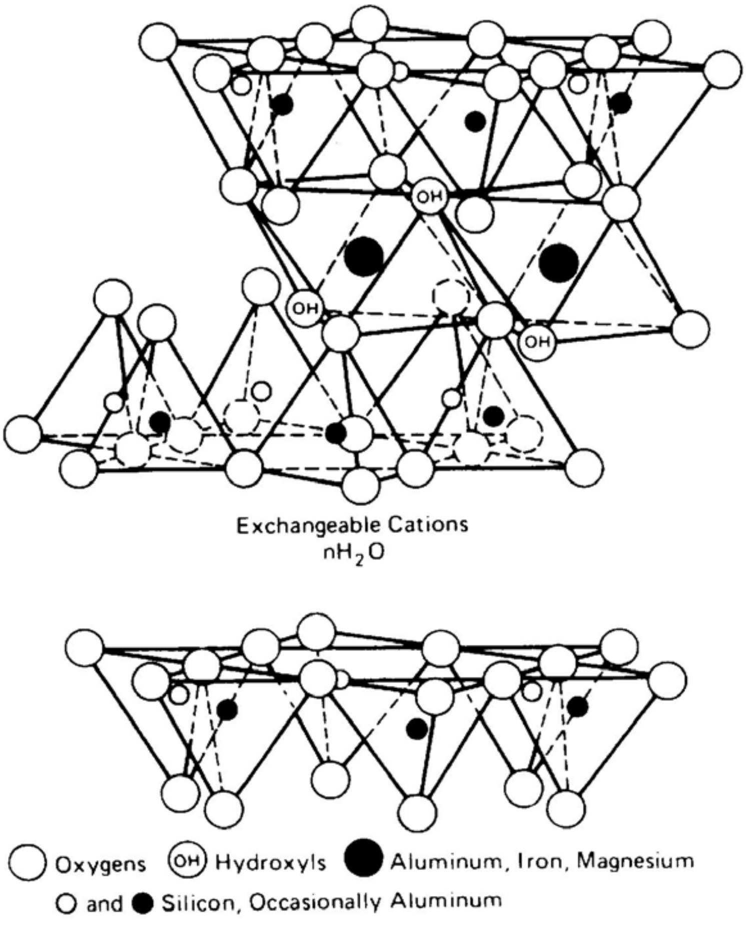

Figure 1.7. Structure of Montmorillonite (after Grim, 1953)

Schemes for the basic clay minerals are shown on figure 1.8.

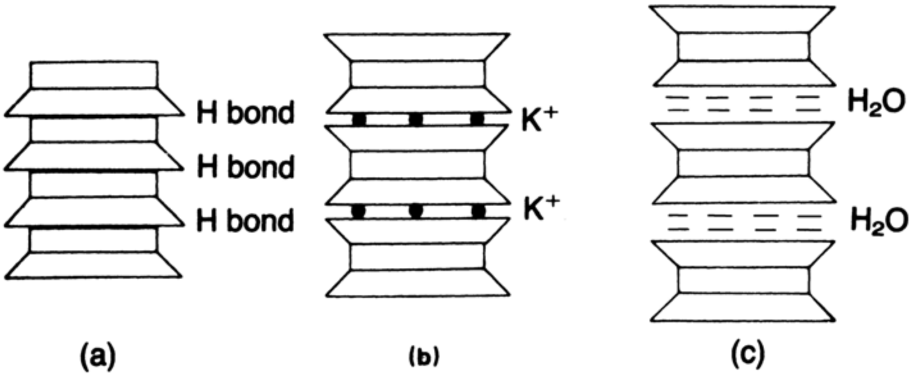

Figure 1.8. Schemes for a) Kaolinite b) Illite c) Montmorillonite (after Craig, 1992)

1.3. Mechanism of Swelling

The following 7 paragraphs have been summarized from (Attewell, 1976).

The clay minerals have the property of sorbing certain anions and cations and retaining them in an exchangeable state. The exchangeable ions are held around the outside of the silica-alumina clay mineral structural unit.

Compositional variation through ionic or isomorphous substitution within the clay mineral crystal lattice can leave the structural unit with a net negative charge. Substitution also reduces the crystal size and alters its shape. Exposed hydroxyl groups and broken surface bonds can also lead to a net negative charge on the structural unit. The presence of this net negative charge means that soluble cations can be attracted or adsorbed on to the surface of the clay mineral structural units without altering the basic structure of the clay mineral. The ability of a clay to hold cations is termed its ***cation exchange capacity.*** The most common soluble cations are Na^+, K^+, Ca^{2+}, Mg^{2+}, H^+, and NH_4^+. Cation exchange capacity (C.E.C.) has major significance in determining clay mineral properties, particularly the facility with which they adsorb water.

Cation exchange capacity (C.E.C.) measures two of the fundamental properties of clays: the surface area and the charge on this surface area. The surface of a clay can be of two sorts, external and internal (Figure 1.9). The external exchange capacity measures nothing more than the average crystalline size. The surface capacity of adsorption is largely dependent upon broken bonds and surface growth defects.

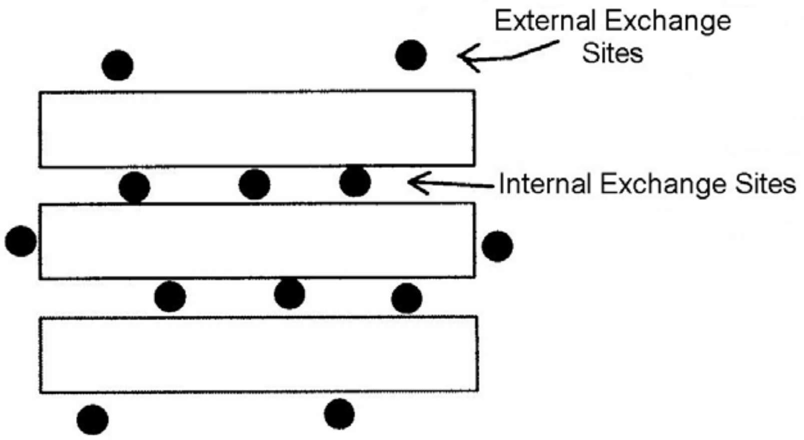

Figure 1.9. Different Types of Exchange Sites on Clay Particles, Surface and Absorbed Ion Interlayer Sites.

The internal exchange capacity is much more interesting in that it reflects the overall charge imbalance on the layer structure and the absorption capacity of the clays. The exchange capacity is an estimate of both the number of ions adsorbed between the layers of a clay structure and of those adsorbed on the outer surfaces.

C.E.C., measured in terms of milliequivalent of the atomic weight of solvent/100 gram of the dry solid, varies widely for various types of clay minerals (Table 1.1).

Table 1.1. Cation Exchange Capacity (C.E.C.) of Main Clay Minerals (Grim, 1953)

Clay Mineral	CEC (meq/100 g)
Kaolinite	3-15
Illite	10-40
Montmorillonite	80-150

The exchange capacity is almost always measured as a function of the number of cations (positively charged) which can be measured on the clay surface once it is washed free of exchange salt solution. The operation is performed by immersing a quantity of clay in an aqueous solution containing a salt, usually chloride or ammonium hydroxide.

The soluble ions adsorbed with the water onto the interlayer structure can affect the adsorbed water arrangement in several ways. Principally, they act as a bond of varying strength holding the structural layer together and controlling the thickness of adsorbed water. Their effectiveness will depend on the size and charge. Thus Na^+, K^+ will tend to be weak and a clay-water system containing these ions will be capable of adsorbing large amounts of water. Ca^{2+}, Mg^{2+}, on the other hand, will have stronger links and a clay-water system containing them will possess substantially lower water content. Inclusion of Fe^{3+} or Al^{3+} would reduce the water content and plasticity and this is in fact the basis of the electrochemical or electro-osmotic method of clay stabilization.

1.4. Factors Affecting Swelling of Soils

Factors affecting the swelling of soils can be considered in three main groups;

- Soil characteristics (Table 1.2)
- Environmental factors (Table 1.3)
- The state of stress (Table 1.4)

Table 1.2. Soil Properties Influencing Swelling Potential of Soils (Nelson and Miller, 1992)

FACTOR	DESCRIPTION
Clay Content and Mineralogy	Clay minerals which typically cause soil volume changes are montmorillonites, vermiculates, and some mixed layer clay minerals. Swelling potential increases with the increasing amount of such clay minerals.
Soil Water Chemistry	Swelling is repressed by increased cation concentration and increased cation valance. For example, Mg^{+2} cations in the soil water would result in less swelling than Na^{+} cations.
Soil Structure and Fabric	Flocculated clays tend to be more expansive than dispersed clays. Cemented particles reduce swell.
Initial Dry Density	Higher densities indicate closer particle spacings which mean greater repulsive forces between particles and larger swelling potential.
Initial Water Content	As the initial water content increases, the initial degree of saturation will also increase and the affinity of soil to absorb water will decrease, so the amount of swelling will decrease.
Fine Grained Fraction	As the amount of fine particles increase, the amount of swelling will increase due to the larger surface area.
Plasticity Index	In general, soils that exhibit plastic behavior over wide ranges of moisture content and that have high liquid limits have greater potential for swelling. Plasticity index is an indicator of swelling potential.

Table 1.3. Environmental Conditions Influencing the Swelling Potential of Soils (Nelson and Miller, 1992)

FACTOR	DESCRIPTION
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 a source of moisture and fluctuating water tables contribute to moisture content of soils.
Drainage	Poor surface drainage leads to moisture accumulations or ponding.
Vegetation	Vegetation (trees, shrubs, grasses, etc.) 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 1.4. Stress Conditions Influencing the Swelling Potential of Soils (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.
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 movement.

1.5. Oedometer Methods to Measure Swelling Properties

Generally, the easiest way of measurement of swelling properties of clays are the Oedometer Test Methods.

Three different methods are described in ASTM Standards with designation number D 4546-90, namely, Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils. It is essential that the terminology in these methods is clearly understood.

Swell: The increase in elevation or dilation of soil column following sorption of water.

Percent Swell: 100dH/H, where dH is the increase or decrease of vertical height of soil column, and H is the original height of soil column.

Primary Swell: The short term swell that ends at the point of intersection of the tangent of reverse curvature to the curve of a dimensional change vs. logarithm of time plot with the tangent to the straight-line portion representing long-term of, or secondary swell (Figure1.10).

Secondary Swell: starts at the intersection point of the tangents and ends at the point of completion of the total swell. It is also defined as long-term swell (Figure1.10).

As it can be seen on Figure 1.10, there is a slight difference in the amount between the primary and the total swell. In most cases this difference is negligible. Thus, in this study, the term "Swell" refers to "Total Swell" for which the vertical height of the specimen no longer increases with time.

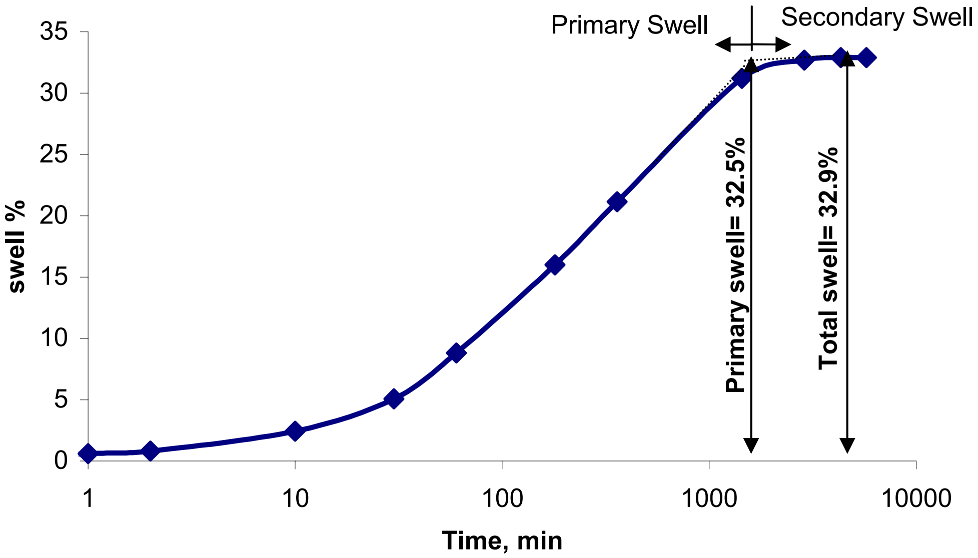

Figure1.10. A Typical Time-Swell Curve

The Test Methods in ASTM D4546-90 require that a soil specimen be restrained laterally and loaded axially (vertically) in a consolidometer (oedometer) with access to free water. These methods are summarized as follows.

1.5.1. Method A

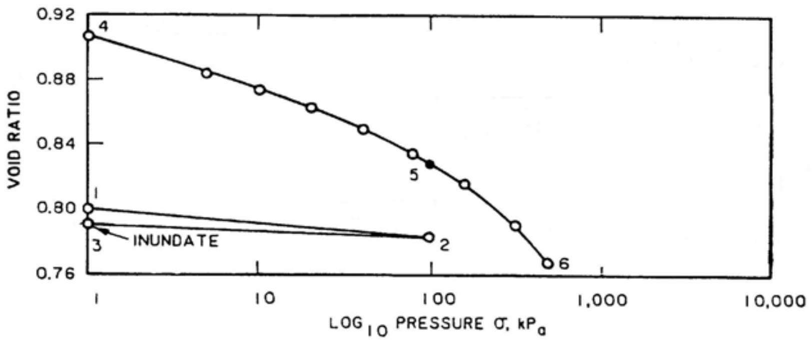

Figure 1.11. An Example Void Ratio-Log Pressure Curve for Method A. (ASTM D 4546-90, 1993)

The specimen is inundated and allowed to swell vertically at the seating pressure (pressure of at least 1 kPa applied by the weight of the top porous stone and load plate) until the primary swell is complete (Figure 1.11, Step 3-4). The specimen is loaded vertically after primary swell has occurred until its initial void ratio/height is obtained (Figure 1.11, Step 4-6)..

This method measures (a) the free swell, (b) percent heave for vertical confining pressures up to the swell pressure, and (c) the swell pressure.

1.5.2. Method B

A vertical pressure exceeding the seating pressure is applied to the specimen before placement of free water into the consolidometer (Figure 1.12, Step 1-2). The specimen is then given access to free water. This may result in swell, swell then contraction, contraction, or contraction then swell. The amount of swell or settlement is measured at the applied pressure after movement is negligible (Figure 1.12, Step 2-3).

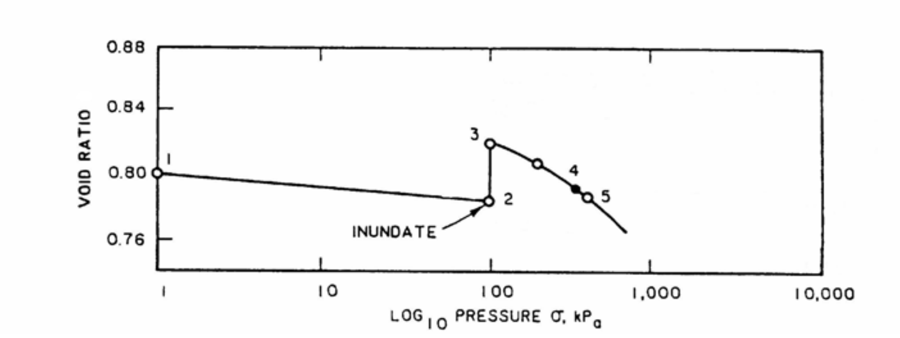

Figure 1.12. An Example Void Ratio-Log Pressure Curve for Method B. (ASTM D 4546-90, 1993)

This method measures (a) the percent heave or settlement for a vertical pressure usually equivalent to the estimated in situ vertical overburden and other vertical pressure up to the swell pressure, and (b) the swell pressure if the specimen is loaded vertically until the initial void ratio or height is obtained (Figure 1.12, Step 3-5)..

1.5.3. Method C

An initial vertical pressure which is equivalent to the estimated vertical in situ pressure or swell pressure is applied after placement of the seating pressure (Figure 1.13, Step 1-2), and the specimen is inundated with water. The specimen is maintained at constant height by adjustments in vertical pressure after the specimen is inundated in free water to obtain swell pressure. (Figure 1.13, Step 2-3). A consolidation test is subsequently performed in accordance with Test Method ASTM D 2435 (Figure 1.13, Step 3-7). Rebound data is used to estimate potential heave.

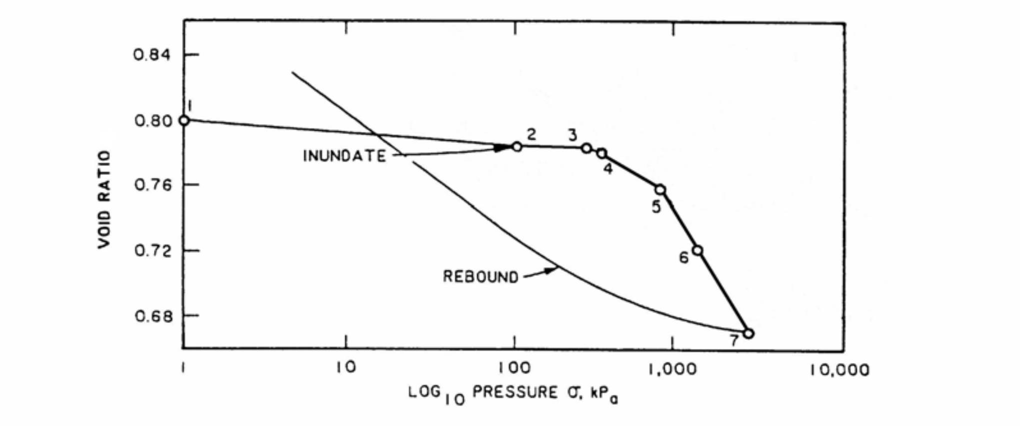

Figure 1.13. An Example Void Ratio-Log Pressure Curve for Method C. (ASTM D 4546-90, 1993)

This method measures (a) the swell pressure, (b) preconsolidation pressure, and (c) the percent heave or settlement within the range of applied pressures.

CHAPTER 2

STABILIZATION OF EXPANSIVE SOILS

Soil stabilization is a procedure where natural or manufactured additives or binders are used to improve the properties of soils.

There are several methods that have been used to minimize or eliminate the effect of expansive soils on structures. These methods include chemical stabilization, soil replacement with compaction control, prewetting, moisture control, surcharge loading, and use of geosynthetics.

Chemical additives, such as lime, cement, fly ash, and other chemical compounds have been used in expansive soil stabilization for many years with various degrees of success (Al-Rawas, 2002).

2.1. Nature of Soil Stabilization

All the chemical additives used to stabilize expansive soils have cementitious property. Cementitious materials stabilize soils and modify their properties through cation exchange, flocculation and agglomeration, and pozzolanic reactions. Additionally, cement provides hydration products, which increase the strength of the base materials as well as enhance the performance of the treatment (Wang, 2002).

2.1.1. Cation Exchange

In a dry clay, adsorbed cations are tightly held by the negatively charged clay particles. Under a given set of environmental conditions (temperature, pressure, pH, chemical and biological composition of the water), a clay will adsorb cations of specific type and amount. The total amount adsorbed will balance the charge deficiency of the solid particles. Exchange reactions can occur in response to changes in the environmental conditions. These reactions involve replacement of a part or all of the adsorbed ions of one type by ions of another type (Figure 2.1). Although the exchange reactions do not ordinarily affect the structure of the clay particles themselves, important changes in the physical and physicochemical properties of the soil may result.

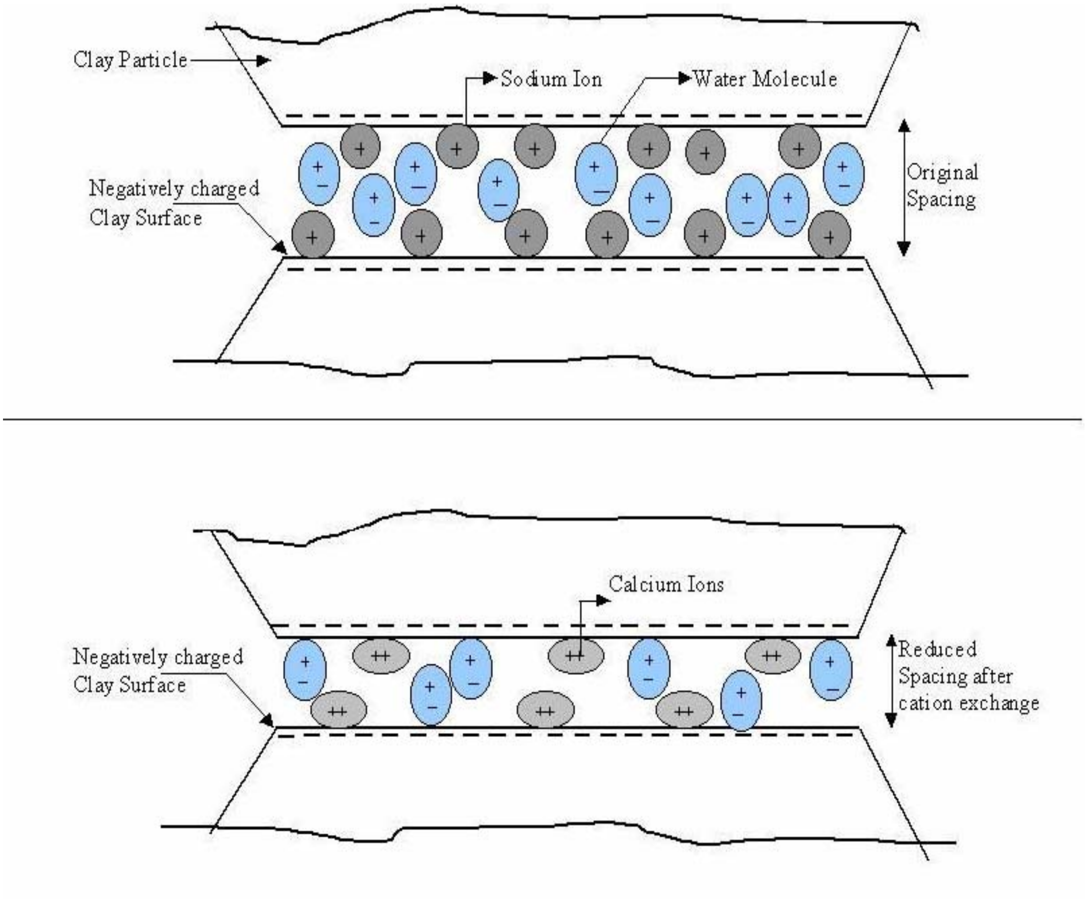

Figure 2.1. Cation Exchange

Ions between clay layers may be replaced by ions of another type. The ease of replacement depends mainly on the valence, relative abundance of the different ion types, and ion size. If other conditions are equal, trivalent cations are held more tightly than divalent, and divalent cations are held more tightly than monovalent. Ordinarily, small cations tend to displace large cations. A typical replaceability series is; $Na^+ < Li^+ < K^+ < Rb^+ < Cs^+ < Mg^{2+} < Ca^{2+} < Ba^{2+} < Cu^{2+} < Al^{3+} < Fe^{3+} < Th^{4+}$ (Mitchell, 1993).

These cations may be present naturally in the water surrounding the clay particles, or supplied artificially with different stabilizers such as lime or other pozzolanic or cementitious materials for soil stabilization applications.

Cation exchange initiates the stabilization process very quickly, and is followed by flocculation and agglomeration.

2.1.2. Flocculation and Agglomeration

Flocculation and agglomeration change the clay texture from that of a plastic, fine grained material to that of a granular soil. Flocculation is the process of clay particles altering their structure from a flat, parallel structure to a more random orientation. Agglomeration is thought to occur as the flocculated clay particles begin to form weak bonds at the edge-surface interfaces of the clay particles, because of the deposition of cementitious material at the clay particle interfaces.

2.1.3. Pozzolanic Reaction

Pozzolanic reaction is a secondary process of soil stabilization. One prerequisite for the formation of additional cementing materials is the solution of silica and alumina from clay components. The high pH environment of a soil cement system increases the solubility and reactivity of the silica and alumina present in clay particles. The degree of the crystallinity of the minerals and particle size distribution are some factors influencing solubility. It is postulated that calcium ions combine with silica and alumina dissolved from the clay lattice to form additional cementitious material (C-S-H and C-A-H), where C=CaO, S=SiO_2 , H=H_2O , A= Al_2O_3 (Tasong, 1999).

2.1.4. Cementitious Hydration

Cement hydration produces cementitious material, C-S-H and C-A-H (see section 2.1.3), form a network and serve as the "glue" that provides structure and strength in a cement treated soil. The most rapid strength increases occur between one day and one month; smaller gains in strength (due to continued hydration and formation of cementitious material) continue to occur for years (Wang, 2002; Wild,1998).

In this study, Granulated Blast Furnace Slag (GBFS), Granulated Blast Furnace Slag-Lime Blends (GBFS-Lime), and Granulated Blast Furnace Slag Cement (GBFSC) will be utilized as cementitious materials while trying to stabilize the expansive soil sample.

2.2. Blast Furnace Slag

With rapid growth of industrialization, there is pressure all over the world on available land, not only for housing and industrial complexes, but for land-filling as means of disposing huge quantities of waste generated from industrial and mining-mineral processing operations. The problem of waste disposal has reached a stage where it occupies large tracts of land for storage of wastes, which can be much larger than that of industry. These problems suggest that there should be some broad-base action to use waste materials for production of value-added products (Rai, 2002).

In the production of iron, iron ore, iron scrap, and fluxes (limestone and/or dolomite) are charged into a blast furnace along with coke for fuel. The coke is combusted to produce carbon monoxide, which reduces the iron ore to a molten iron product. This molten iron product can be cast into iron products, but is most often used as a feedstock for steel production.

Blast Furnace Slag is a nonmetallic coproduct produced in the process. It consists primarily of silicates, aluminosilicates, and calcium aluminosilicates (Seggiani, 2003). The molten slag, which absorbs much of the sulfur from the charge, comprises about 20 percent by mass of iron production (Monshi, 1999). Figure 2.2 presents a general schematic, which depicts the blast furnace feedstocks and the production of blast furnace coproducts (iron and slag).

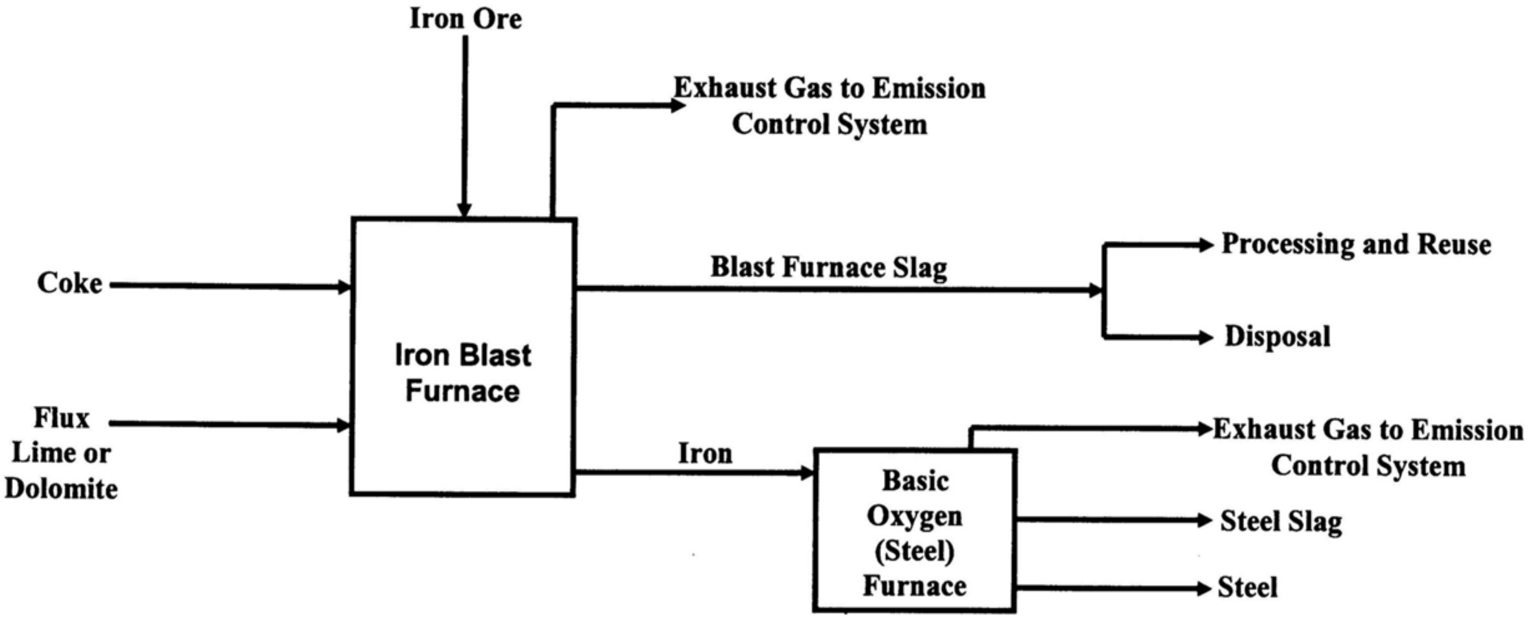

Figure 2.2. General Schematic of Blast Furnace Operation and Blast Furnace Slag Production (TFHRC, 2004)

Different forms of slag product are produced depending on the method used to cool the molten slag. These products include air-cooled blast furnace slag, expanded or foamed slag, pelletized slag, and granulated blast furnace slag (TFHRC, 2004).

2.2.1. Air-Cooled Blast Furnace Slag

If the liquid slag is poured into beds and slowly cooled under ambient conditions, a crystalline structure is formed, and a hard, lump slag is produced, which can subsequently be crushed and screened.

2.2.2. Expanded or Foamed Blast Furnace Slag

If the molten slag is cooled and solidified by adding controlled quantities of water, air, or steam, the process of cooling and solidification can be accelerated, increasing the cellular nature of the slag and producing a lightweight expanded or foamed product. Foamed slag is distinguishable from air-cooled blast furnace slag by its relatively high porosity and low bulk density.

2.2.3. Pelletized Blast Furnace Slag

If the molten slag is cooled and solidified with water and air in a spinning drum, pellets, rather than a solid mass, can be produced. By controlling the process, the pellets can be made more crystalline, which is beneficial for aggregate use, or more vitrified (glassy), which is more desirable in cementitious applications. More rapid quenching results in greater vitrification and less crystallization.

2.2.4. Granulated Blast Furnace Slag (GBFS)

If the molten slag is cooled and solidified by rapid water quenching to a glassy state, little or no crystallization occurs. This process results in the formation of sand size (or frit-like) fragments, usually with some friable clinkerlike material. The physical structure and gradation of granulated slag depend on the chemical composition of the slag, its temperature at the time of water quenching, and the method of production.

When crushed or milled to very fine cement-sized particles, granulated blast furnace slag (GBFS) has cementitious properties, which make a suitable partial replacement for or additive to Portland cement (Wild, 1998; Rai,2002).

2.3. Granulated Blast Furnace Slag-Lime Blends (GBFS-Lime)

As stated in section 2.2.4, GBFS itself is a cementitious material. It reacts more slowly with water than Portland cement, but it can be activated chemically. Activators can be either alkaline activators such as lime, or sulfate activators such as calcium sulfate. They will lead to the formation of C-S-H gels (see section 2.1.3) , which is known as the main cementing agent (Wang, L, 2002).

In this study, different proportions of GBFS and Lime blends are used to stabilize an expansive soil sample (Sample A).

2.4. Granulated Blast Furnace Slag Cement (GBFSC)

Since the first discovery of cementitious properties of granulated blast furnace slag (GBFS) by Emil Langen in 1862 and particularly after the oil crisis in 1970s, manufacture of GBFSC has substantially increased due to greater emphasis on energy conservation, utilization of waste materials and certain technical advantages over ordinary Portland cement (PC), such as higher resistance to agressive conditions. Today, GBFSC accounts for nearly 15% of all cement used in Western Europe.

Blast Furnace Slag has been widely used as a successful replacement material for Portland Cement, improving some properties and bringing economic benefits. In the recent years, the production of pig iron has increased progressively in the world. Approximately 300 kg of slag is generated per ton of iron (Escalante, 2001).

Turkey is one of the leading manufacturers of cement and steel in Europe, producing around 35 million tons of cement and 13 million tons of crude steel annually. However, the manufacture of GBFSC was about 0.75% and 2.2% of the total Turkish cement production in 1996 and 1998, respectively; this production is now increasing fast with installation of new slag grinding mills around the country (Öner, 2000).

Portland cement is a powdered material that results from intergrinding clinker and gypsum. The manufacturing of clinker is a pyro-process and includes a series of complex chemical reactions which take place in a special kiln. The clinker is a heterogeneous material composed of four major oxide phases: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). According to nomenclature used in cement chemistry $C = CaO$, $S = SiO_2$, $A = Al_2O_3$, $F = Fe_2O_3$, $H = H_2O$, $\hat{S} = SO_3$. The reactions between cement and water can be described as follows:

$$2C_3S + 6H \longrightarrow C\text{-}S\text{-}H + 3Ca(OH)_2 \qquad (1)$$

$$2C_2S + 4H \longrightarrow C\text{-}S\text{-}H + Ca(OH)_2 \qquad (2)$$

$$2C_3A + 27H \longrightarrow C_4AH_{19} + C_2AH_8 \qquad (3)$$

$$C_3A + 3CSH_2 + 26H \longrightarrow C_6A\,\hat{S}_3H_{32} \text{ (ettringite)} \qquad (4)$$

$$C_3A\,\hat{S}_3H_{32} + 3C_3A + 4H \longrightarrow 3C_4A\hat{S}H_{12} \text{ (monosulfate)} \qquad (5)$$

With regard to soil stabilization, the first two calcium silicate phases are the most important. Upon hydration, these two phases produce calcium hydroxide which provides available calcium for cation exchange, flocculation and agglomeration, and stabilizes the clayey soil. These two phases also provide calcium silicate hydrate (C-S-H), which produce strength and cemented structure in the soil matrix. The reaction of cement hydration is much more complex than the equations given earlier, especially in soil cement system. When mixed with water, cement hydration is initiated and calcium concentration in the soils builds up quite rapidly, and the solution becomes immediately saturated with calcium hydroxide. As calcium ions (Ca^{2+}) are released in solution, they are available for stabilization. Initial absorption of calcium by clay is rapid and then is slow as it becomes increasingly diffusion dependent. Hydration can continue at an ever-slowing pace over many years, and therefore calcium hydroxide is produced during this time. This helps maintain the high pH level. Maintaining a high pH in a soil cement system is also important because high pH is necessary for long-term pozzolanic reactions to occur (Wang, L, 2002).

If GBFS is finely ground and blended with ordinary Portland cement, it reacts with $Ca(OH)_2$ to form additional C-S-H gels, which is the main cementing product of hydration of cements (Erdoğan, 1995).

Although Granulated Blast Furnace Slag Cements are known as produced by grinding Granulated Blast Furnace Slag together with Portland Cement Clinker and a small amount of Gypsum Rock, recent studies on separate grinding concluded that separate grinding should be preferred in view of lower specific energy consumption, ease of manufacture, higher addition of slag (i.e., less environmental hazards) on top of higher flexibility in product quality arrangement according to market requirements (Öner, 2001).

The proportions of GBFS and clinker+gypsum rock may vary depending on the need of application. Generally GBFS is not less than 20% of the total blend. The amount of GBFS may be raised up to 80% if a more economical Granulated Blast Furnace Slag Cement is desired.

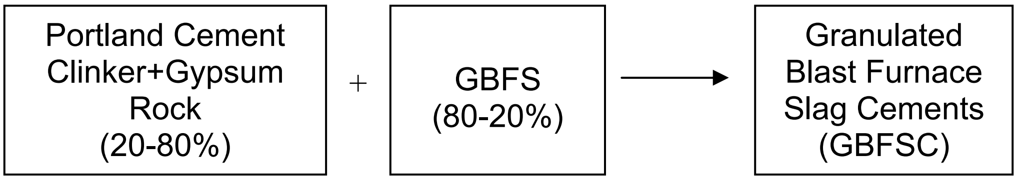

Figure 2.3. Typical Blending Proportions for GBFSC (after Erdoğan, 1995)

Granulated Blast Furnace Slag Cements have certain advantages on Ordinary Portland Cements, which may be summarized as follows.

a) Lower Heat of Hydration,
b) More resistant to aggressive conditions (e.g., sulphate attack),
c) Lower alkali-silica reactions,
d) High ultimate strength,
e) More workability,
f) Lower costs of manufacture and energy (Öner, 2001).

In this study, GBFSC is manufactured by blending ordinary Portland cement and GBFS in proportions of 20% and 80% respectively. Both Portland Cement and GBFS were samples taken from OYSA-İskenderun cement grinding plant.

CHAPTER 3

EXPERIMENTAL STUDY

3.1. Purpose

The purpose of this experimental study is first to determine the effects of Granulated Blast Furnace Slag (GBFS), GBFS-Lime blends, and Granulated Blast Furnace Slag Cement (GBFSC) on an expansive soil sample, Sample A, on grain size distribution, Atterberg Limits, swelling potential, and rate of swell without curing, and secondly to determine the effects of curing on swelling potential, and rate of swell. The possible chemical effects of using GBFS and GBFSC in expansive soil stabilization are also investigated.

3.2. Material

Bentonite (Na-Montmorillonite): Bentonite was the product of Karakaya Bentonite Factory.

Kaolinite: Kaolinite was the product of ESAN Industrial Minerals Company of Eczacıbaşı.

Lime: It was a commercially available hydrated lime with a specific gravity of 2.76.

Granulated Blast Furnace Slag (GBFS): GBFS was obtained from İskenderun-OYSA Cement Grinding Plant. Its specific gravity is 2.88.

Granulated Blast Furnace Slag Cement (GBFSC): GBFSC was produced in the Soil Mechanics laboratory of DSİ by blending 20% of ordinary Portland Cement and 80% of ground GBFS in mass, both obtained from İskenderun-OYSA Cement Grinding Plant. It is very difficult to find GBFSC in the market because Cement Grinding Plants generally produce such cements upon large demands. The specific gravity of produced GBFSC is 2.89.

3.3. Chemical Properties of the Materials Used

Chemical analyses of the constituents of each material were done by “Cement Producers Association of Turkey” and the results are given in Table 3.1.

Table 3.1. Results of the Chemical Analysis of the Materials Used

Chemical composition, (%) in mass	**Type of Materials Used**					
	Kaolinite	**Bentonite**	**Lime**	**Portland Cement**	**GBFS**	**GBFSC (calculated)**
SiO_2	49.89	56.19	1.54	20.50	42.29	37.93
Al_2O_3	33.03	14.98	-	5.66	10.56	9.58
Fe_2O_3	1.78	9.45	0.03	3.87	0.32	1.03
CaO	0.42	2.25	67.08	64.99	37.35	42.88
MgO	0.03	1.28	1.26	2.43	6.71	5.85
K_2O	1.69	1.19	0.05	0.83	0.94	0.92
TiO_2	1.33	1.11	0.32	0.29	0.45	0.42
Mn_2O_3	-	-	-	0.06	1.67	1.35
P_2O_5	-	-	-	0.09	0.011	0.03
Cr_2O_3	-	-	-	0.023	0.012	0.01
Na_2O	0.08	2.41	0.02	0.04	0.18	0.15
Loss of Ignition	11.10	1.10	28.50	0.5	0.55	0.54
Insoluble material	-	-	-	-	-	-
SO_3	0.13	0.33	1.09	-	-	-

3.4. Preparation of Specimens

There are many expansive soil sites in nature, but to take samples from any site may result in disturbance of soil samples which may lead to test results that may not represent the actual soil properties. To avoid such errors, an artificial, potentially expansive soil, Sample A, was prepared by mixing Kaolinite and Bentonite as follows.

Sample A consisted of 85% Kaolinite and 15% Bentonite by dry mass. After weighing the constituents, Bentonite and Kaolinite were mixed using a trowel. Then the mixture was sieved together through No.30 (0.600 mm) sieve to obtain a more homogeneous blend (ASTM D 422-90, 1990). A preliminary swell test on Sample A resulted in 32.90% of swell, showing that the sample can be accepted as a highly expansive soil. To overcome the swelling, ground Granulated Blast Furnace Slag (GBFS), a by-product of the steel industry, which is known as a pozzolanic material and used as additive in Portland Cement, was first added in amounts ranging from 5% to 25% of Sample A in dry mass. In the second step, different amounts of lime were used to activate the GBFS. In this stage, the use of additives (GBFS-Lime blends) were limited as follows: in total mass of the samples, Sample A was always 85% of the sample, and GBFS plus lime were 15% of the total mass. In the third step, a Granulated Blast Furnace Slag Cement (GBFSC) was prepared by blending 80% of ground GBFS and 20% of Ordinary Portland Cement by mass. GBFSC was added in amounts ranging from 5% to 25% of the sample to overcome swelling of Sample A.

All the constituents were oven dried for 24 hours, and ground to pass through No.40 (0.425 mm) sieve (ASTM D 422-90, 1990). GBFS was ground to 4000 cm^2/g fineness by a crusher in the Materials of Construction Laboratory of Middle East Technical University. GBFS and

Ordinary Portland Cement were obtained from İskenderun-Oysa Cement Grinding Plant.

Each sample was prepared 60 g in dry mass and to ease compaction into the consolidation ring of the oedometer apparatus, 6 mL of water was added to the sample to obtain 10% water content. The diameter of the consolidation ring was 50.8 mm, minimum diameter specified in ASTM D 2435-70. To obtain 1.8 g/cm^3 bulk density in 34.5 cm^3 of specimen volume, 62.1 g of the prepared sample was weighed and compacted directly into the consolidation ring to a thickness of 17 mm, using a manual compaction piston. In this way, disturbance caused by using guide rings while preparing the specimen and then transferring it to the consolidation ring was avoided.

Samples other than Sample A were prepared by mixing a pre-calculated amount of stabilizer and Sample A at a moisture content of 10%. The samples were all mixed in the same way (Figure 3.1).

The soil mechanics tests were done in the Soil Mechanics Laboratory of DSİ.

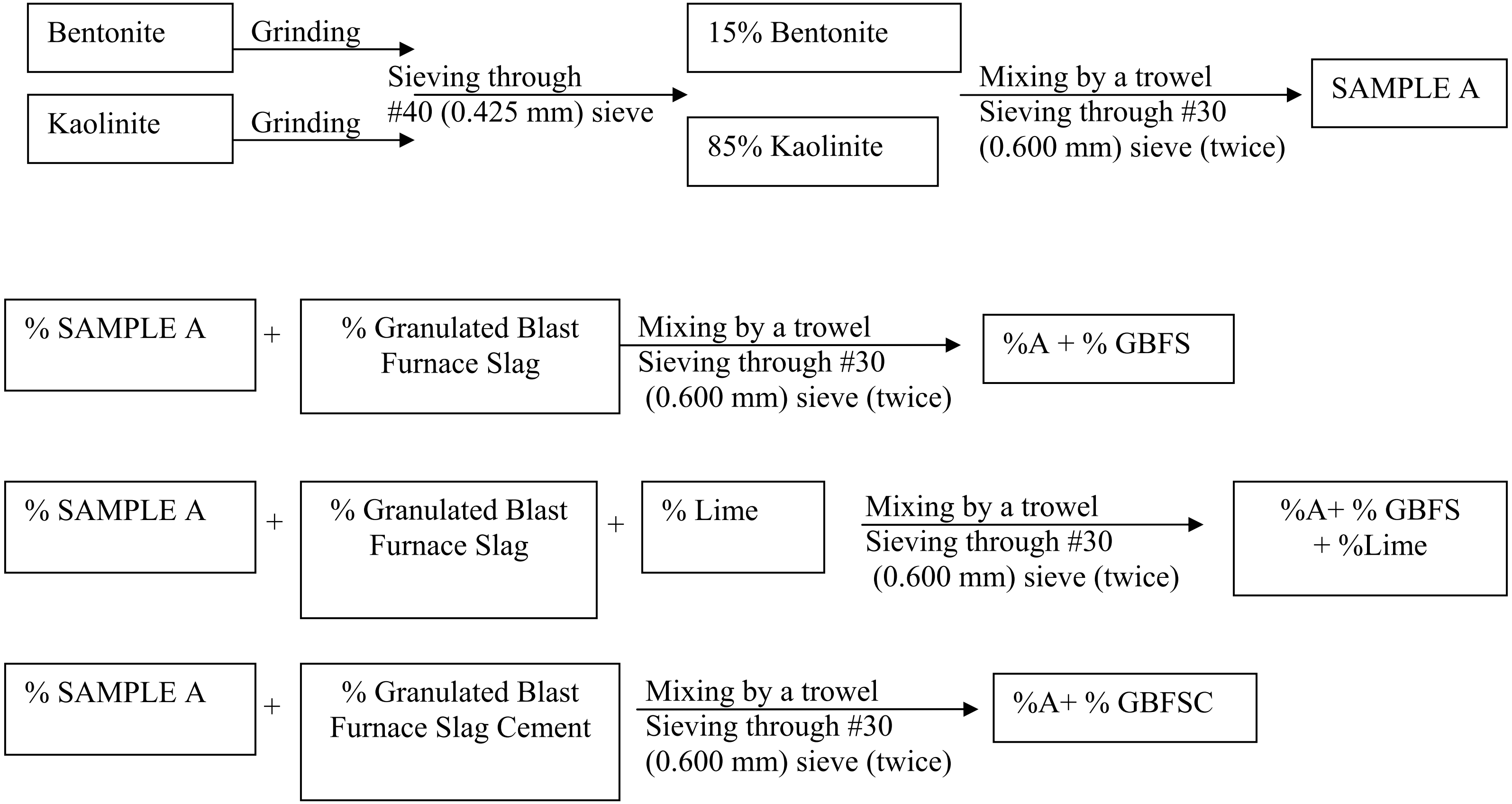

Figure 3.1. Preparation of Samples

For cured samples, the Sample A - Stabilizer blends were compacted directly into consolidation ring at 10% moisture content and sealed to prevent loss of moisture. Sealing was done by covering the surface of the sample by stretch film. Samples were left to cure at 22^{o} C and 70% relative humidity for 7 and 28 days.

3.5. Sample Properties

Hydrometer tests were applied to determine particle size distribution (Figures 3.4 to 3.6). The liquid limits, plastic limits, plasticity indexes, shrinkage limits, and specific gravity of the samples were determined.

All the samples were classified according to the Unified Soil Classification System by plotting test results on a plasticity chart (Figure 3.2, and the sample properties are given in Table 3.2.

The swelling potential of each sample was calculated using activity (PI/ clay fraction) given in Table 3.2 and plotted in Figure 3.3.

Table 3.2. Sample Properties

SAMPLES	Clay (%)	Silt (%)	G_s	LL (%)	PL (%)	PI (%)	Soil Class.	Activity	Swelling Potential
A	49	51	2.65	104.50	29.10	75.40	CH	1.54	Very High
95%A +5%GBFS	42	58	2.68	81.80	28.80	53.00	CH	1.26	High
90%A +10% GBFS	38	62	2.69	81.00	28.60	52.40	CH	1.38	High
85%A +15% GBFS	39	61	2.70	78.50	26.90	51.60	CH	1.32	High
80%A +20% GBFS	35	65	2.72	77.40	26.10	51.30	CH	1.47	High
75%A +25%GBFS	35	65	2.73	75.60	25.10	50.50	CH	1.44	High
85%A +14% GBFS +1%Lime	38	62	2.66	107.40	26.10	81.30	CH	2.14	Very High
85%A +12% GBFS +3%Lime	46	54	2.67	103.10	27.80	75.30	CH	1.64	Very High
85%A +10% GBFS +5%Lime	47	53	2.70	76.90	33.20	43.70	CH	0.93	High
85%A +8% GBFS +7%Lime	43	57	2.71	77.20	35.30	41.90	CH	0.97	High
95%A +5% GBFSC	45	55	2.70	106.70	34.60	72.10	CH	1.60	Very High
90%A +10% GBFSC	47	53	2.71	83.40	36.80	46.60	CH	0.99	High
85%A +15% GBFSC	46	54	2.73	69.10	39.10	30.00	MH	0.65	High
80%A +20% GBFSC	43	57	2.75	68.80	39.30	29.50	MH	0.69	High
75%A +25% GBFSC	42	58	2.77	65.50	40.30	25.20	MH	0.60	Medium

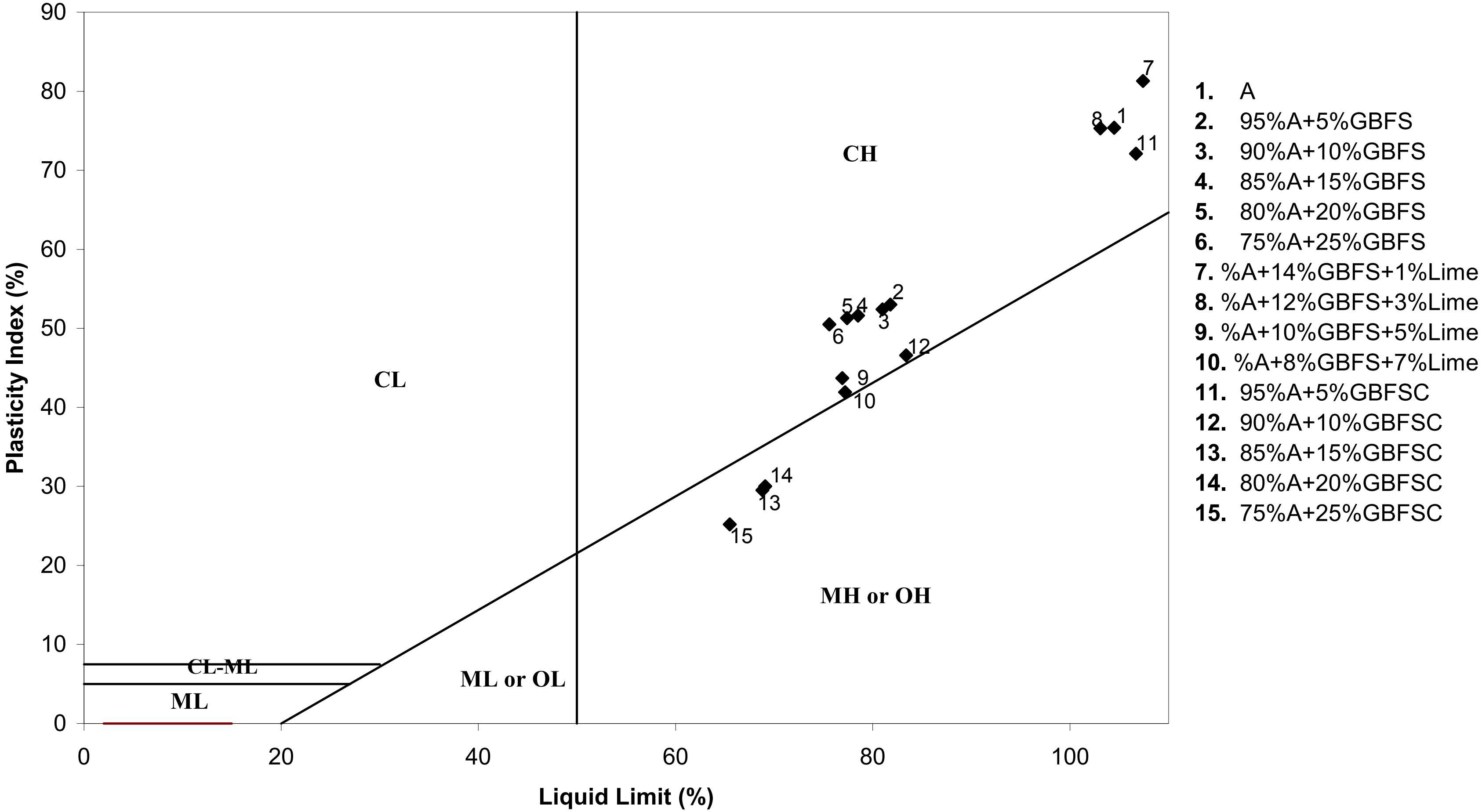

Figure 3.2. Plasticity Chart: Unified System

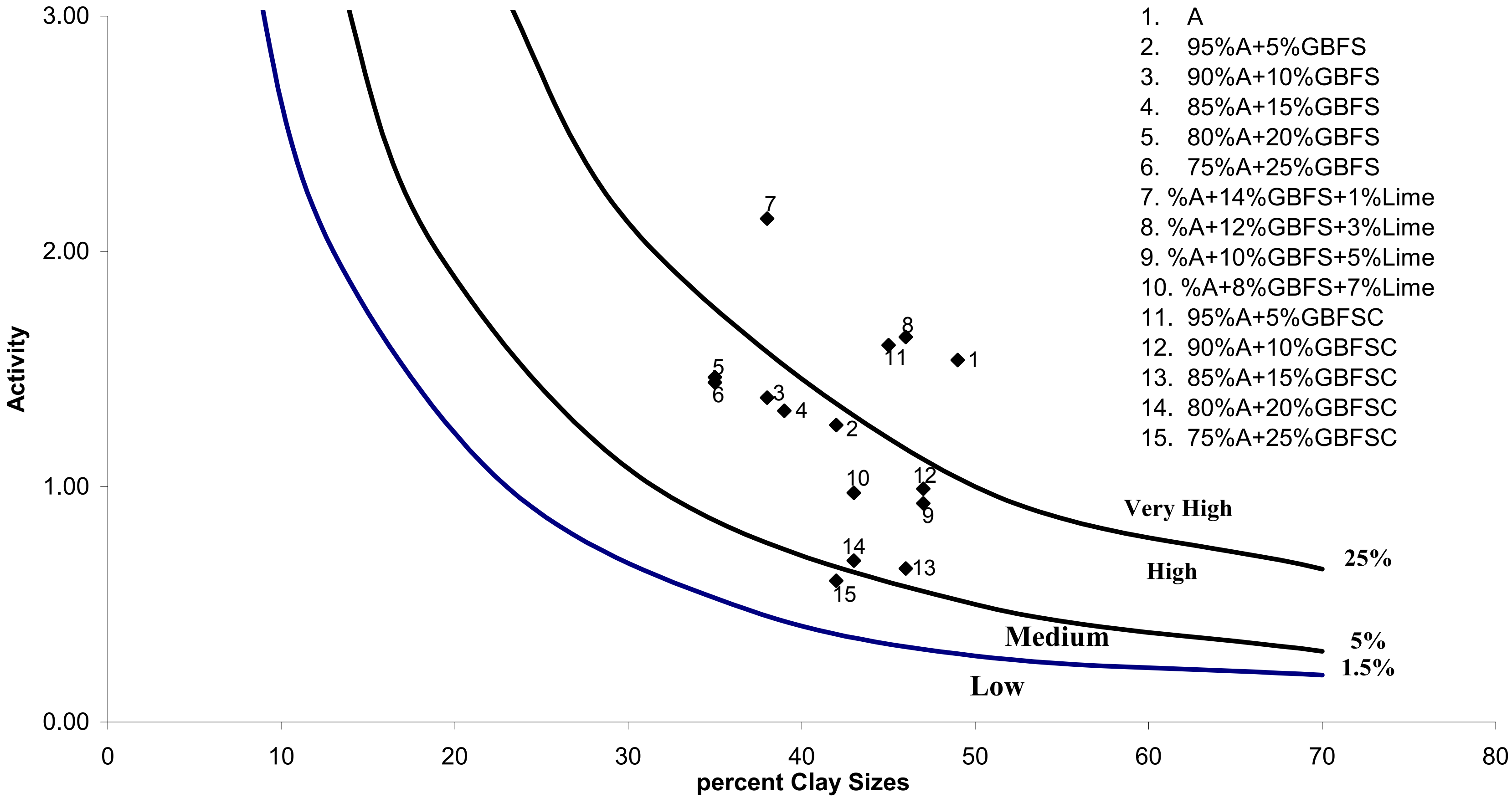

Figure 3.3. Swell Potential Classification according to Clay Fraction and Activity

Grain size distribution curves are plotted according to the groups of GBFS, GBFS-Lime, and GBFSC added samples; the grain size distribution of Sample A and 100% stabilizer are also plotted to see how the grain size distribution changed with the addition of stabilizers (Figures 3.4, to 3.6).

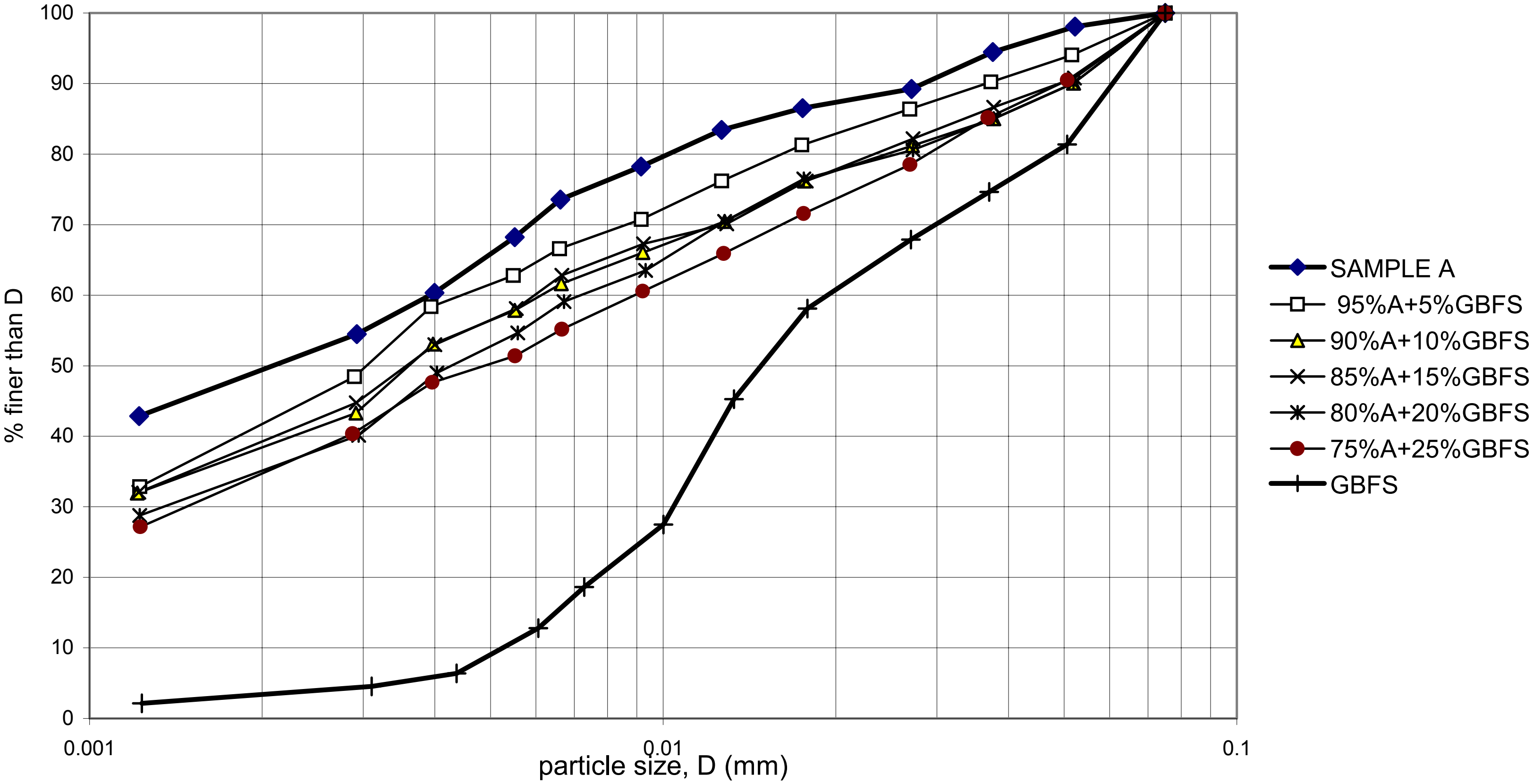

Figure 3.4. Grain Size Distribution Curves of Sample A, 100%GBFS, and GBFS Added Samples

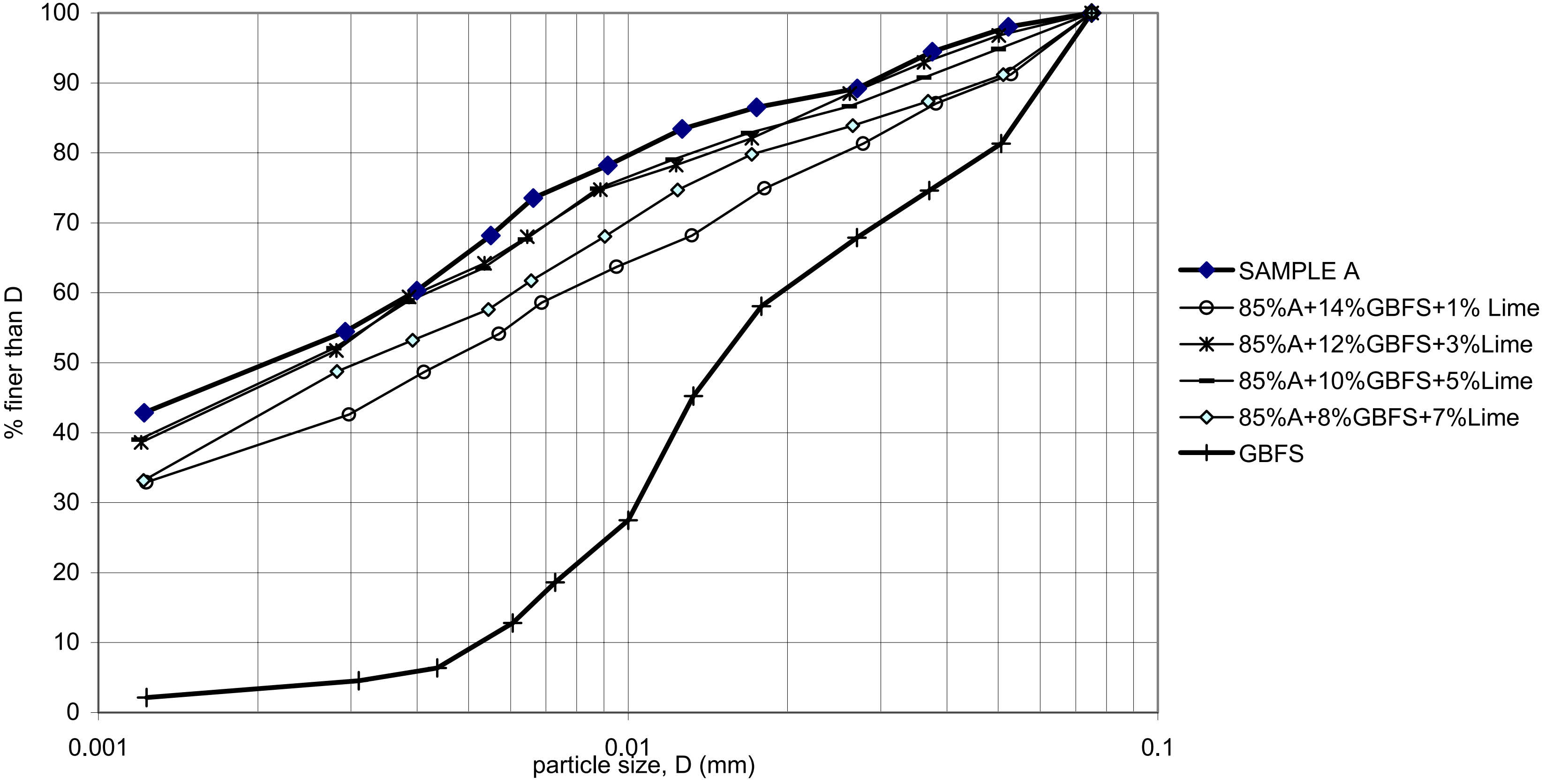

Figure 3.5. Grain Size Distribution Curves of Sample A, 100%GBFS, and GBFS+Lime Added Samples

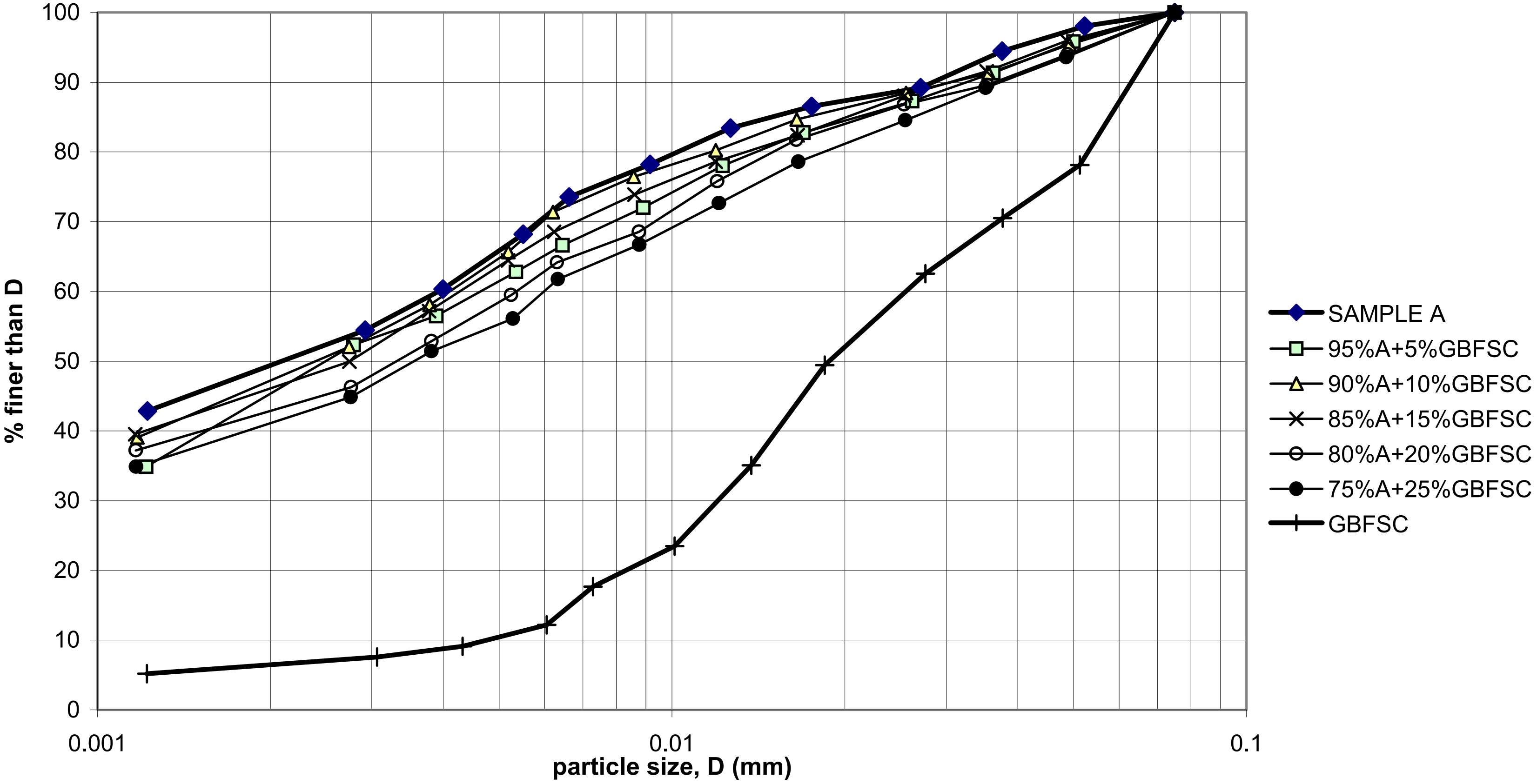

Figure 3.6. Grain size distribution curves of Sample A, 100%GBFSC, and GBFSC Added Samples

3.6. Testing Procedure

In this experimental study, "Free Swell Method" was used to determine the amount of swell. The samples were prepared as outlined in Figure 3.1 and compacted directly into consolidation ring to obtain a bulk density of 1.80 g/cm^3. (Figure 3.7). This value of bulk density with 10% moisture content gave a dry density of 1.64 g/cm^3.

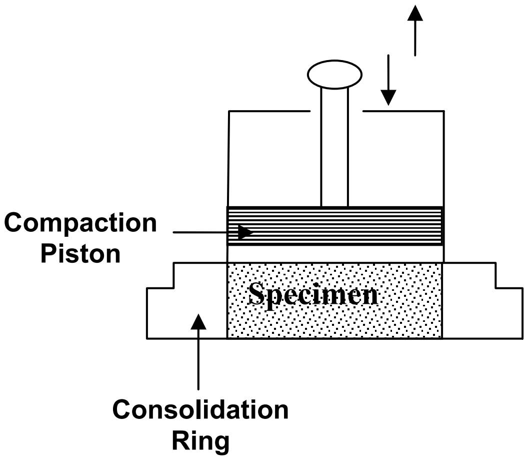

Figure 3.7. Compaction of Specimen into the Consolidation Ring

3.6.1. Free Swell Method

The specimen was prepared as explained in section 3.4. The consolidation ring containing the specimen was placed in the oedometer after placing filter papers on the top and bottom of the specimen not to clog the porous stones. An air-dry porous stone was placed on top of the specimen. After the oedometer was mounted on the loading device, the dial gauge measuring the vertical deflection was set to zero (Figure 3.8).

The specimen was inundated by applying water to the upper surface of the sample directly, and to the lower surface through standpipes. As soon as the specimen was inundated, swelling began.

The specimen was allowed to swell freely. Dial gauge readings showing the vertical swell of the specimen were recorded until the swell stopped. These data were used to calculate the time-swell relations and final swell of each sample upon inundation. After the sample stopped swelling, the final water content was determined in accordance with ASTM Test Method with designation number D2435 – 90.

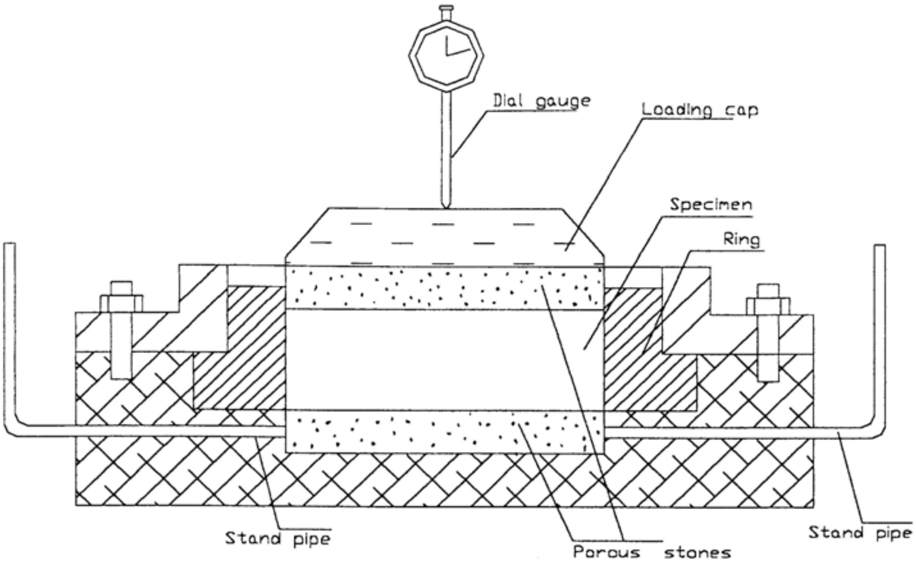

Figure 3.8. Free Swell Apparatus (Oedometer)

Free swell percent was calculated from the following formula:

Free Swell (%) = 100 $\Delta H/H$

Where ΔH is the change in the initial height of the specimen after it is inundated, and H is the original height of the specimen just before the inundation.

t_{50} is defined as the time to reach the 50% of the total swell. It is defined on the time-swell curves of each specimen (Figure 3.9).

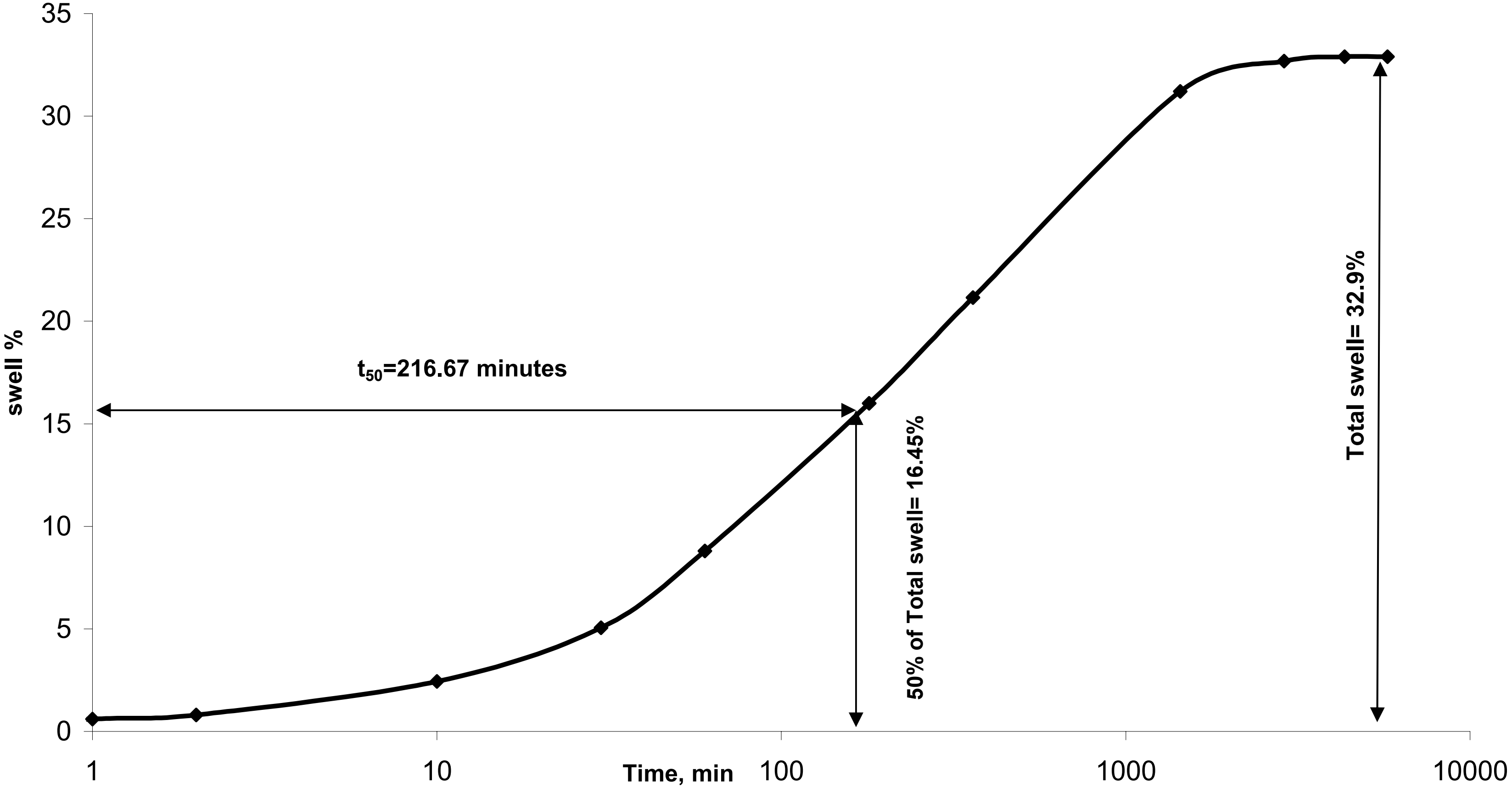

Figure 3.9. Determination of t_{50}

3.7. Experimental Program

The following four groups of test were done on Sample A and each of the 14 samples listed in Table 3.3.

(1) Hydrometer test, specific gravity test, Atterberg Limit tests, and shrinkage tests (Mercury Method, ASTM D427-92, 1992)
(2) Swell amounts were determined by free swell test without curing.
(3) Free swell test for each sample cured for 7 days was performed.
(4) Free swell test for each sample cured for 28 days was performed

Table 3.3. Samples for Experimental Study

(GBFS) Added Samples	(GBFS+Lime) Added Samples	(GBFSC) Added Samples
95% A +5%GBFS	85%A +14%GBFS+1%Lime	95% A +5%GBFSC
90% A +10%GBFS	85%A +12%GBFS+3%Lime	90% A +10%GBFSC
85% A +15%GBFS	85%A +10%GBFS+5%Lime	85% A +15%GBFSC
80% A +20%GBFS	85%A +8%GBFS+7%Lime	80% A +20%GBFSC
75% A +25%GBFS		75% A +25%GBFSC

3.8. Test Results

The results of the liquid limit and plastic limit tests of the samples are compared on Figure 3.10 and 3.11 respectively.

In Figure 3.12, variation of Plasticity Index according to the stabilizer added is plotted.

Figure 3.13 shows the effect of stabilizers on the shrinkage limit of the samples.

Figure 3.14 shows the effect of stabilizers on the specific gravity of the samples.

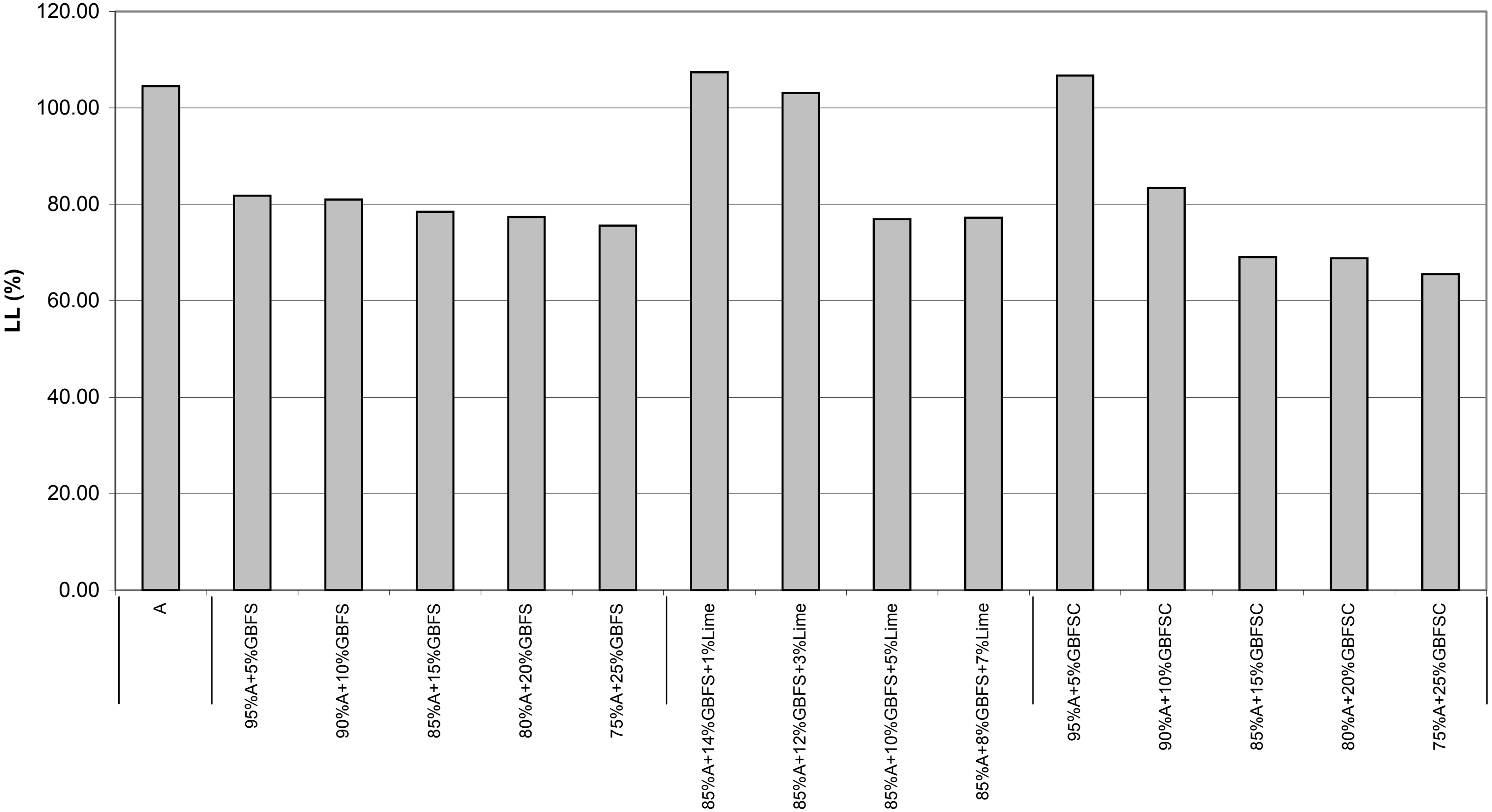

Figure 3.10. Effect of Stabilizers on the Liquid Limits of the Samples

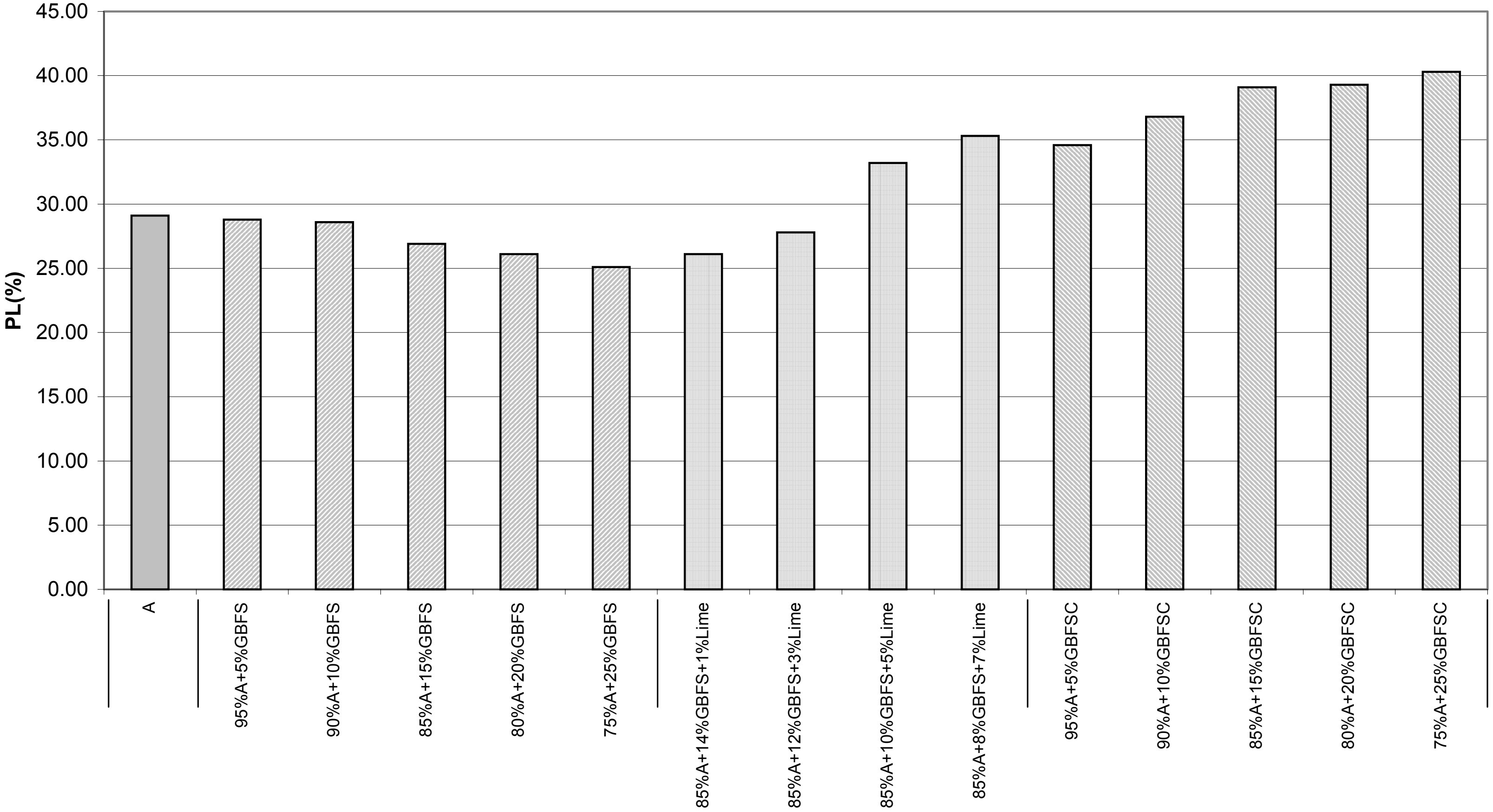

Figure 3.11. Effect of Stabilizers on the Plastic Limits of the Samples

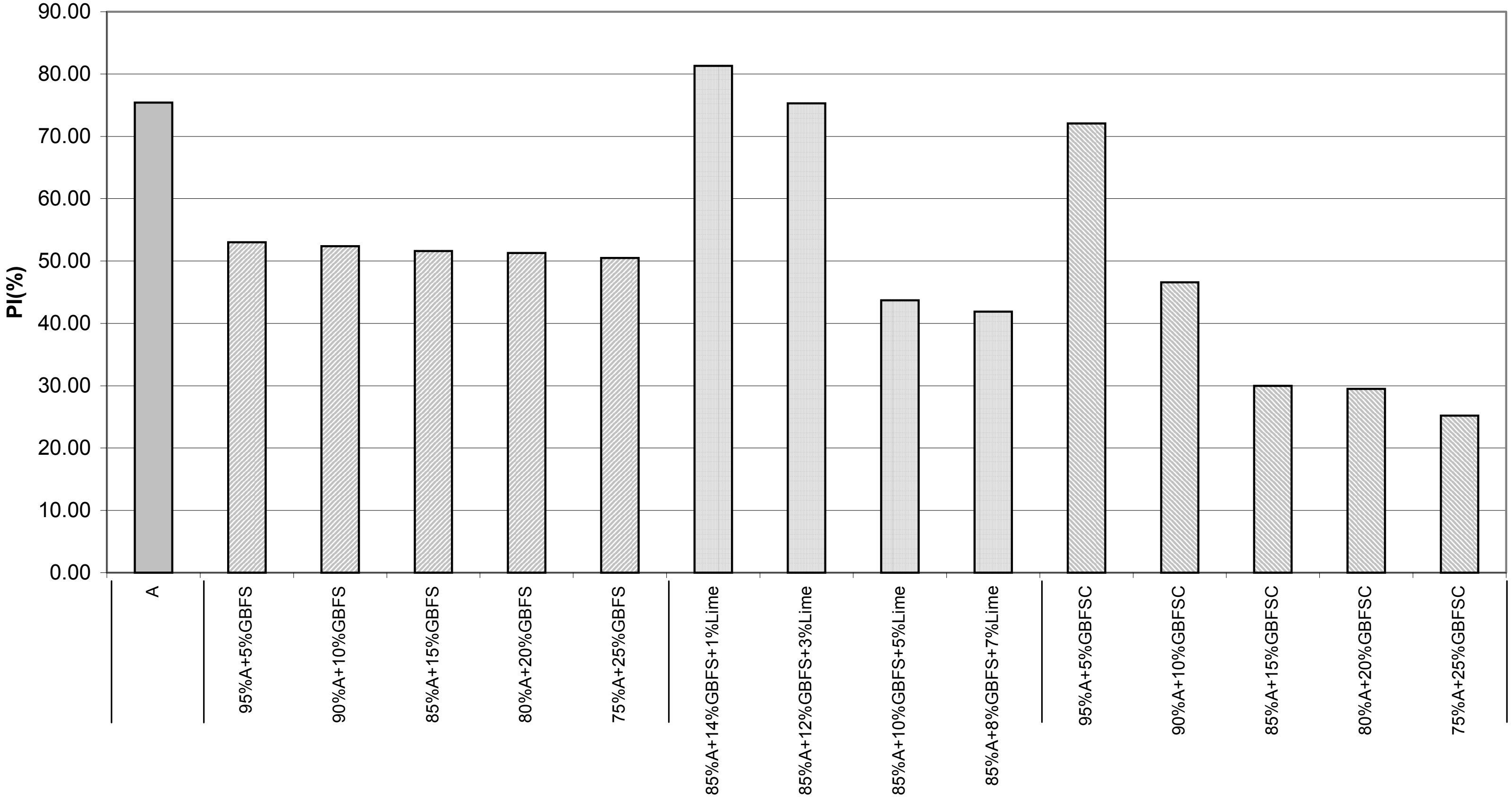

Figure 3.12. Effect of Stabilizers on the Plasticity Index of the Samples.

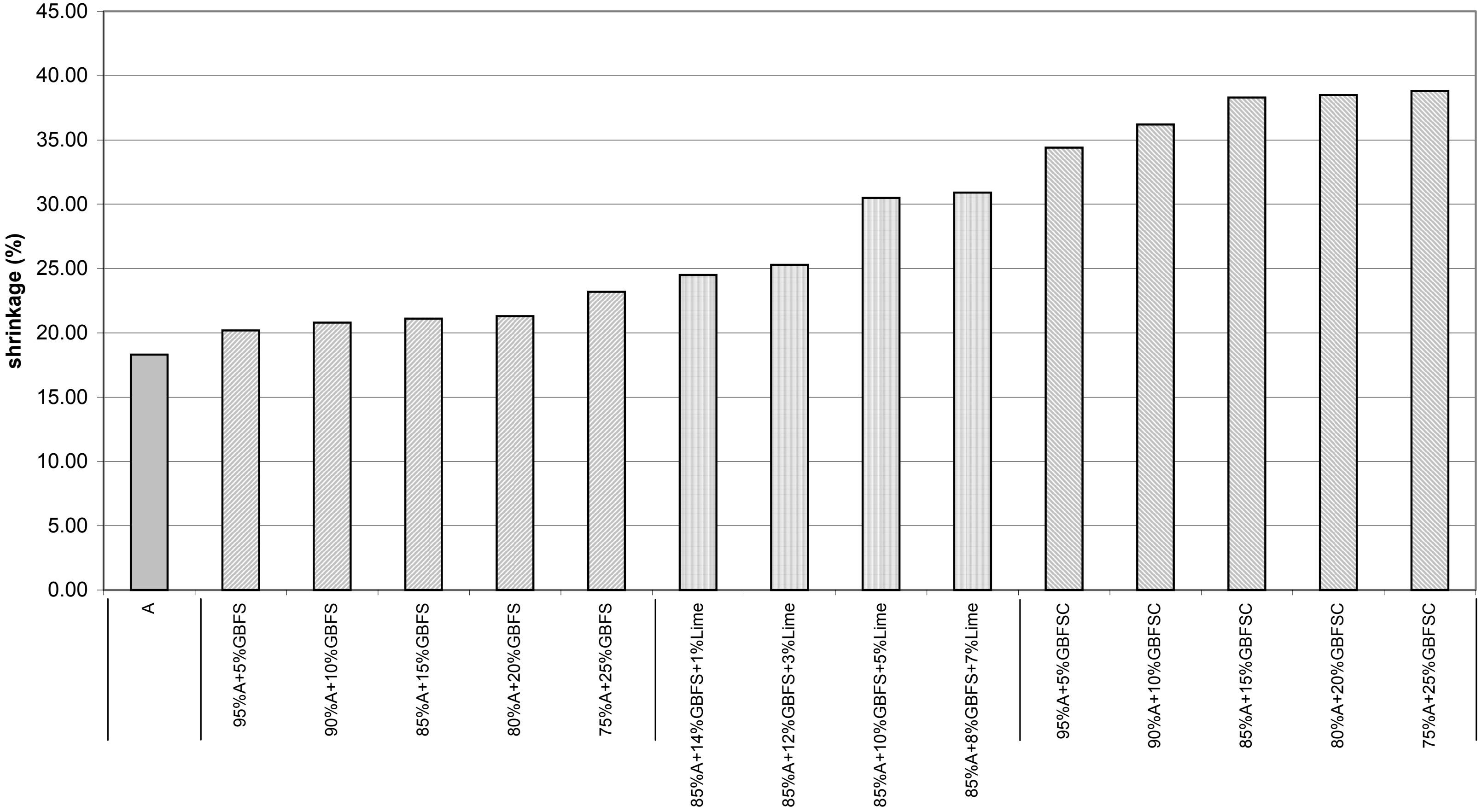

Figure 3.13. Effect of Stabilizers on Shrinkage Limits of the Samples

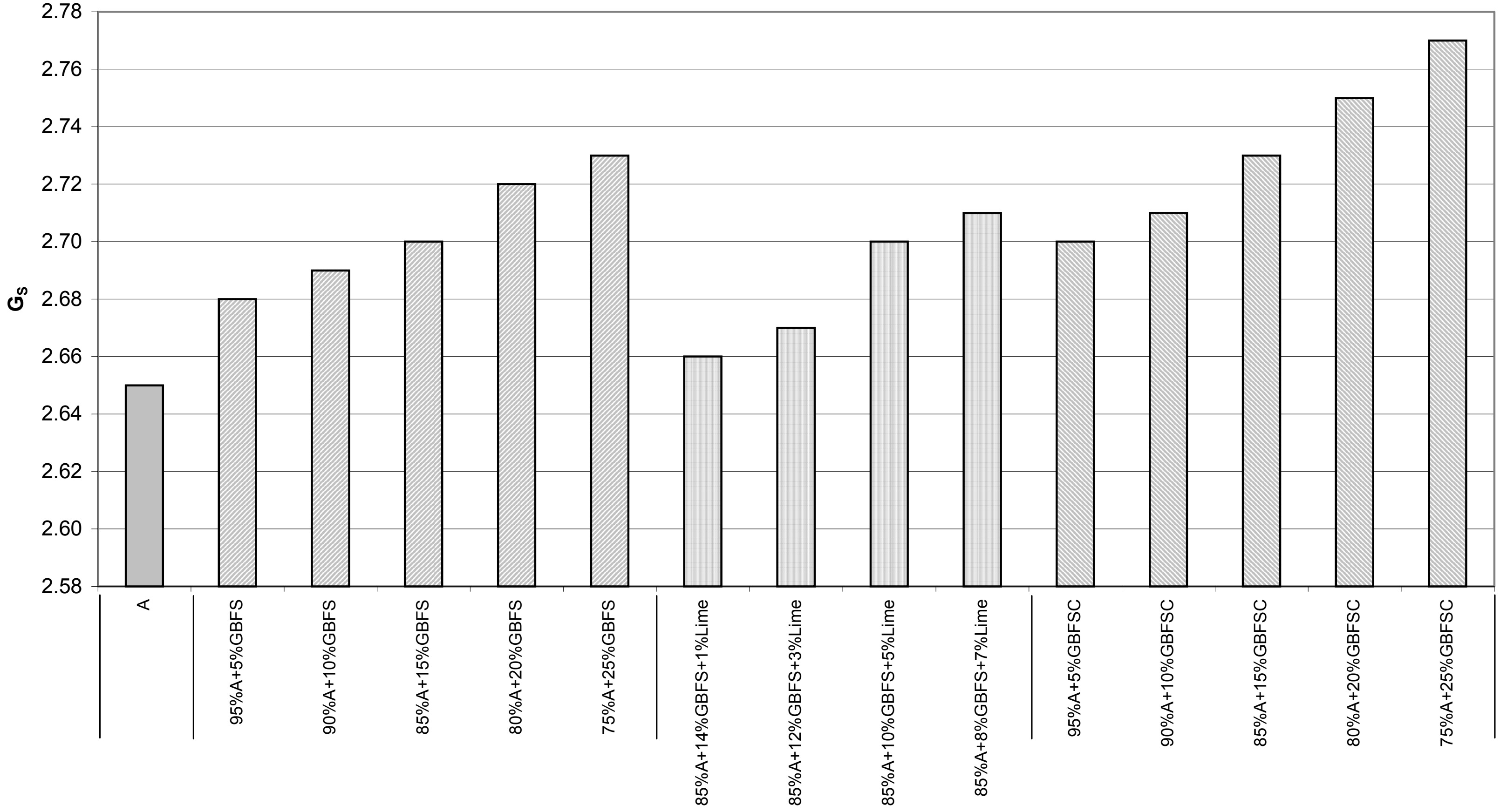

Figure 3.14. Effect of stabilizers on the Specific Gravity of the Samples

Swelling percentage versus time relationship for Sample A is plotted in Figure 3.15. It can be seen that the curve is a typical swell curve as stated in ASTM D-4546-96.

The swell percentage versus time relations of samples are shown in groups of GBFS, GBFS+Lime, and GBFSC added samples in figures in Appendix A.

Figure 3.16 shows the effect of stabilizers on the swell percentage of the samples with and without curing.

The results for rate of swell (inversely related to t_{50}) of samples are shown in Figure 3.17.

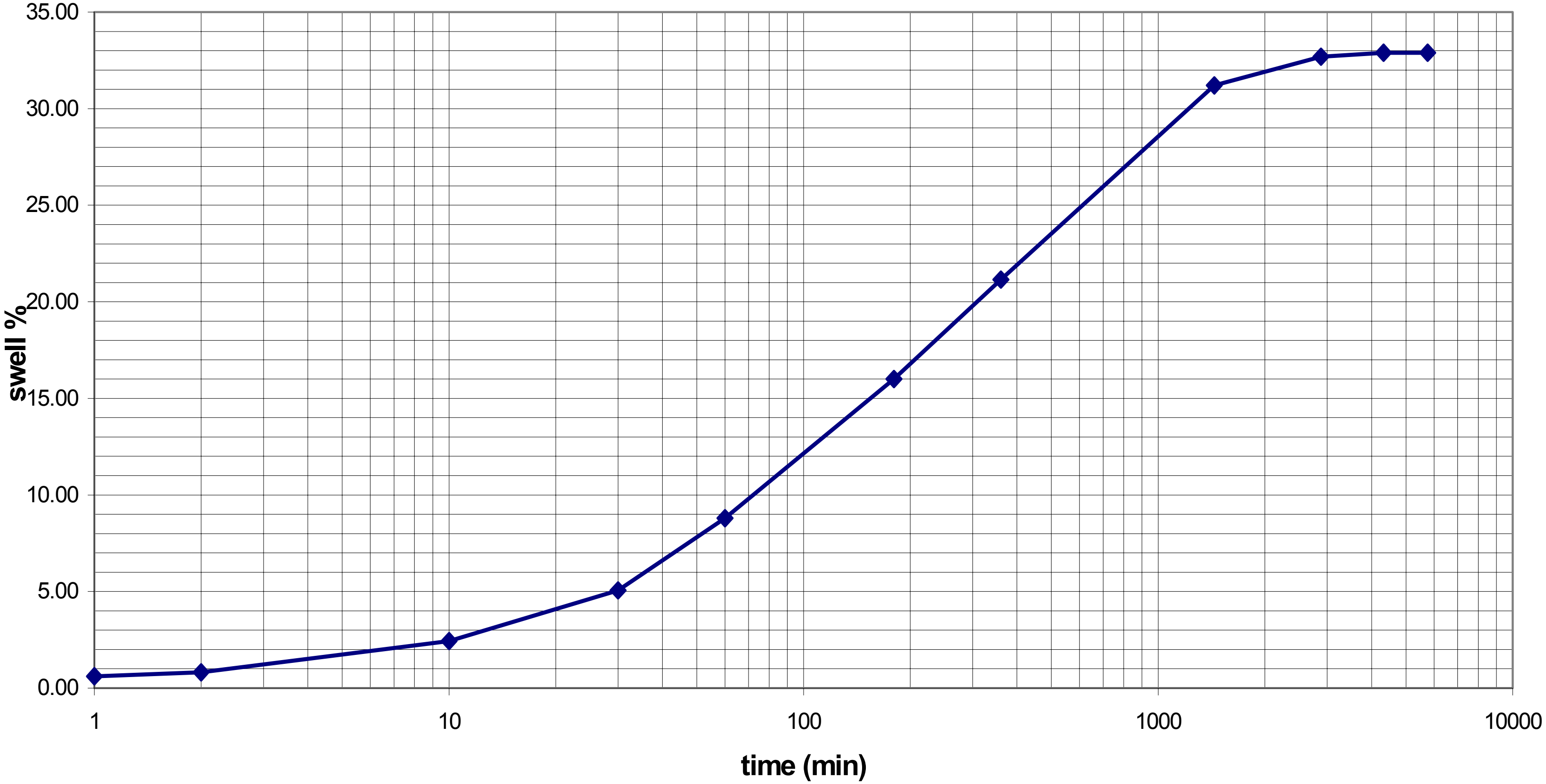

Figure 3.15. Swell Percentage versus Time Relationship for Sample A.

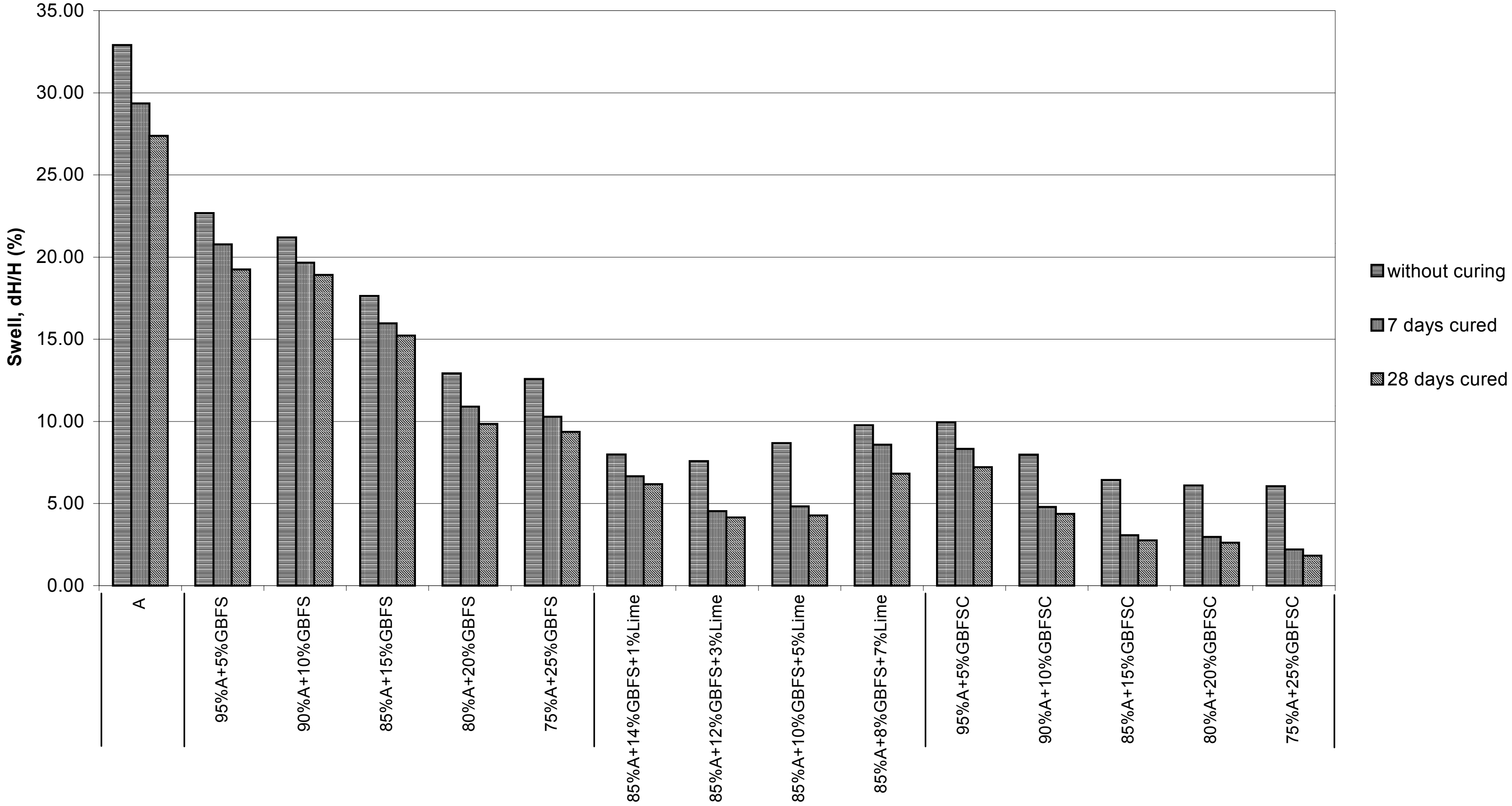

Figure 3.16. Effect of Stabilizers on the Swell Percentages of the Samples

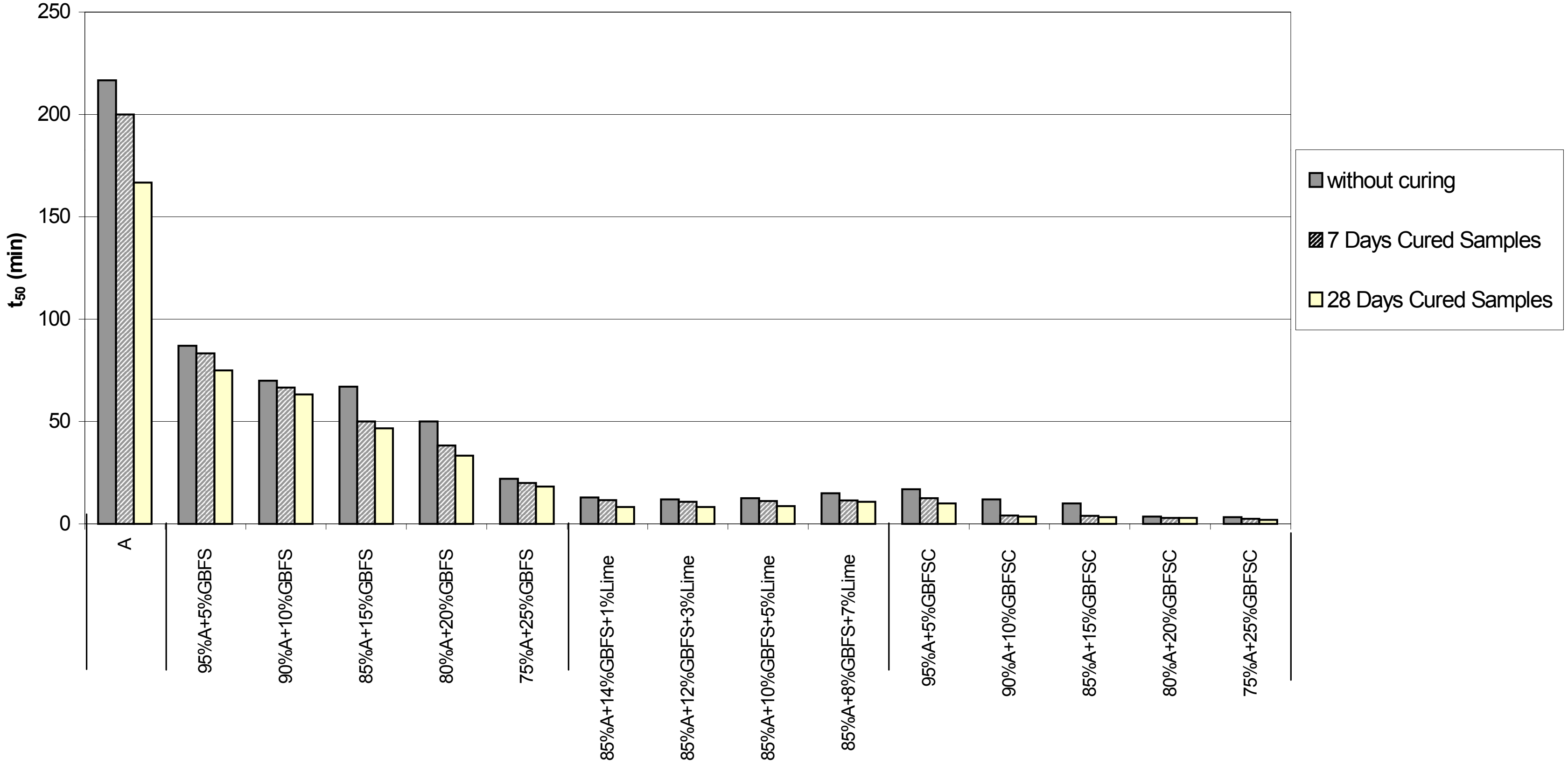

Figure 3.17. Variation of t_{50} with Stabilizers Added

3.9. Leachate Analysis and Results

Using industrial by-products or wastes in extensive soil stabilization works may cause environmental problems. Thus use of such materials may sometimes be restricted if potential hazards to the environment are identified.

Leaching is the process by which soluble constituents are dissolved from a solid material (such as rock, soil, or waste) into a fluid by percolation or diffusion. Thus, when fill materials come into contact with liquid (including percolating rainwater, surface water, groundwater, and liquids present in the fill material), constituents in the solid phase will dissolve into the liquid forming a leachate. The extent to which the constituents dissolve into the contact liquid will depend upon site and material-specific conditions (chemical, physical, and biological factors) and the length of time involved. The composition of the leachate generated from the material and its potential impact on water quality are key factors in evaluating the suitability of the material for use as fill (Department of Ecology, 2003).

Figure 3.18 presents a conceptualized view of the water balance at a hypothetical site at which fill material has been emplaced. Water enters the site via net precipitation (that is, precipitation minus evapotranspiration), run-on, and groundwater or surface water intrusion. In the figure, fill material can be subject to leaching due to exposure to moisture present within the fill material, infiltrating precipitation, run-on, and due to placement in a saturated environment.

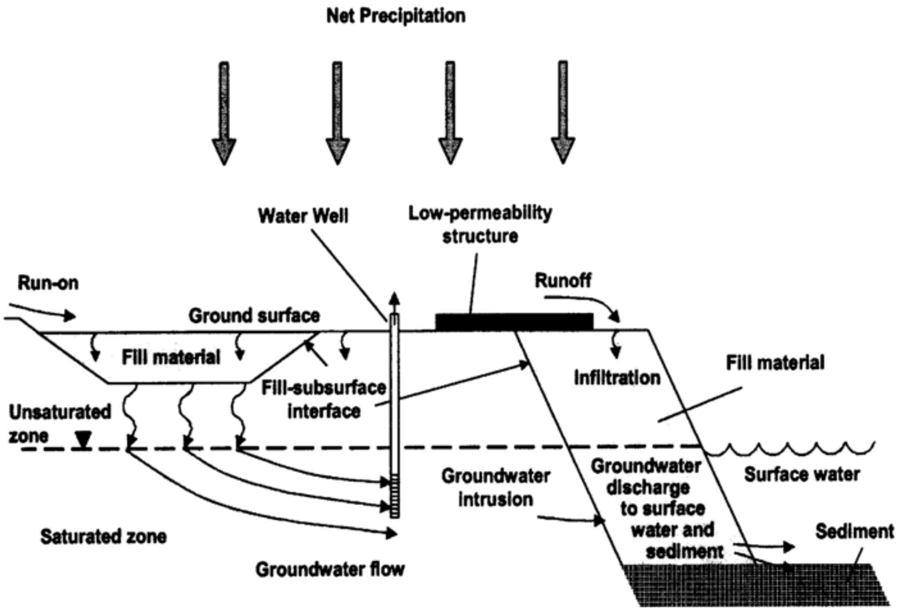

Figure 3.18. Conceptual Model of Water Balance at a Fill Site (after Department of Ecology, 2003)

In this thesis, the Granulated Blast Furnace Slag (GBFS) is used as the main stabilizing agent for Sample A. GBFS is known to involve toxic elements whose amounts may vary depending on the raw material and the steel production plant. These toxic elements may be Pb, Zn, Cu, Ni, Fe, Mn, As, Co, Cd etc (Furimsky, 2002).

The main point in the Leachate Analysis is that, it measures the amount of these elements passing to the water from the waste or fill site. In a simple analogy, the samples prepared in this study corresponds to the fill material shown in Figure 3.18, and water used for dissolving the heavy metals in the fill material corresponds to the rainfall dropping on the fill material.

In this study, Batch Leaching procedure has been used. This method is used widely in environmental chemistry applications. The Batch Extraction tests typically involve mixing a sample of waste or other fill material with a specific amount of leaching solution (1:20 ratio of waste to water in mass) without renewal of the leaching solution. The mixing is performed over a relatively short time period (eg.18 hours) by a shake extractor with the aim of reaching equilibrium conditions. The mixing is followed by filtration and analysis of the filtered liquid phase (the laboratory leachate) (ASTM 3987-85,1999).

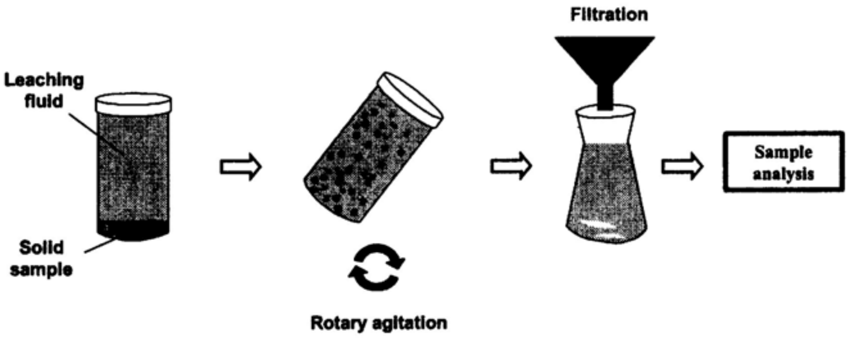

Figure 3.19. Simplified Schematic of a Batch Equilibrium Leaching Procedure (after Department of Ecology, 2003)

In this experimental study, Granulated Blast Furnace Slag (GBFS), Granulated Blast Furnace Slag Cement (GBFSC), and the samples containing the largest amount of Granulated Blast Furnace Slag (GBFS), and Granulated Blast Furnace Slag Cement (GBFSC) were used to obtain leachates. There were eight samples in the leachate study:

1. 100% GBFS
2. 100% GBFSC
3. 75% Sample A +25% GBFS (no curing)
4. 75% Sample A + 25% GBFSC (no curing)
5. 75% Sample A +25% GBFS (7 days cured)
6. 75% Sample A + 25% GBFSC (7 days cured)
7. 75% Sample A +25% GBFS (28 days cured)
8. 75% Sample A + 25% GBFSC (28 days cured)

The samples for leachate extraction were prepared in the Soil Mechanics Laboratory of DSİ at Esenboğa, and brought to the Environmental Chemistry Laboratory of Environmental Engineering Department of Middle East Technical University.

70 g of each sample were taken and mixed with 1.4 liters of distilled water in a special flask. The solid-water mixture was left to rotary agitation for 18 hours and the leachate water was separately filtered and extracted from the solution via 45 micron filter paper as stated in ASTM 3987-85 (Figure 3.19).

The leachate water of each sample was kept in separate bottles and brought to Chemistry Laboratory of DSİ at Esenboğa for chemical analysis for heavy metals by means of Atomic Absorption Device.

The results of leachate analysis for heavy metals are given in Table 3.4.

Table 3.4. Results of Leachate Analysis

	Heavy Metals (mg/L)			
SAMPLES	**Zn**	**Cu**	**Pb**	**Mn**
100%GBFS	0.00	0.00	0.20*	0.08*
100%GBFSC	0.00	0.00	0.51*	0.07*
75%A+25%GBFS (No Cure)	0.00	0.00	0.00	0.06*
75%A+25%GBFSC (No Cure)	0.00	0.00	0.46*	0.11*
75%A+25%GBFS (7 days Cured)	0.61	0.02	0.35*	0.10*
75%A+25%GBFSC (7 days Cured)	0.00	0.00	0.02	0.08*
75%A+25%GBFS (28 days Cured)	0.33	0.00	0.23*	0.12*
75%A+25%GBFSC (7 days Cured)	0.00	0.00	0.75*	0.11*
Max. Permissible Level for Drinking (TS-266, 1997)	5.00	3.00	0.05	0.05
Max. Permissible Level for Irrigation (Official Newspaper, 1991)	2.00	0.2	5.00	0.2

* Values exceeding the limits for Drinking or Irrigation water.

Table 3.4. Results of Leachate Analysis (Continued)

	Heavy Metals (mg/L)			
SAMPLES	**Fe**	**Cd**	**Co**	**Ni**
100%GBFS	0.12	0.03*	0.00	0.29*
100%GBFSC	0.09	0.02*	0.09*	0.33*
75%A+25%GBFS (No Cure)	0.14	0.04*	0.00	0.04
75%A+25%GBFSC (No Cure)	0.12	0.01*	0.00	0.23*
75%A+25%GBFS (7 days Cured)	1.30*	0.03*	0.00	0.22*
75%A+25%GBFSC (7 days Cured)	0.08	0.02*	0.02	0.21*
75%A+25%GBFS (28 days Cured)	0.16	0.03*	0.00	0.19*
75%A+25%GBFSC (28 days Cured)	0.09	0.05*	0.10	0.22*
Max. Permissible Level for Drinking (TS-266, 1997)	0.2	0.005	Not Given	0.05
Max. Permissible Level for Irrigation (Official Newspaper, 1991)	5.00	0.01	0.05	0.2

* Values exceeding the limits for Drinking or Irrigation water.

CHAPTER 4

DISCUSSION OF TEST RESULTS

4.1. Effects of GBFS and GBFSC Addition on the Grain Size Distribution of Expansive Soil

Addition of stabilizers GBFS and GBFSC caused a shift in the grain size distribution of samples away from Sample A to the coarser side. GBFS and GBFSC has a more coarser grain size distribution than Sample A. Thus, the shift in grain size distribution of samples to the coarser side may be either due to dilution of fine particles by adding GBFS and GBFSC or due to some pozzolanic reaction taking place within the soil particles resulting in the flocculation of small particles to coarser ones.

To be sure about the reason of getting coarser grain size distribution by adding stabilizers, Figure B.1. and Figure B.2. was plotted on Appendix B.

On Figure B.1. measured grain size distributions of Sample A, GBFS and Sample 75%A+25%GBFS was plotted. A calculated grain size distribution of Sample 75%A+25%GBFS was derived from the measured grain size distributions of Sample A and GBFS, and plotted on the same graph. It can be seen on Figure B.1. that calculated grain size distribution of Sample 75%A+25%GBFS is generally on the finer side than measured grain size distribution of Sample 75%A+25%GBFS. Thus it can be concluded that the reason for getting coarser grain size distributions is mainly due to sticking fine particles to form coarser grains as a result of pozzolanic reactions and flocculation of clay particles.

On Figure B.2, measured grain size distributions of Sample A, GBFSC and Sample 75%A+25%GBFSC was plotted. A calculated grain size distribution of Sample 75%A+25%GBFSC was derived from the measured grain size distributions of Sample A and GBFSC, and plotted on the same graph. It is seen that, calculated and measured grain size distributions of Sample 75%A+25%GBFSC are very close. Thus, it can be concluded that the shift in grain size distribution of samples to the coarser side may mainly be due to dilution of fine particles by adding GBFSC.

4.2. Effects of GBFS, GBFS+Lime and GBFSC Addition on the Liquid Limit (LL) of Expansive Soil (Table 4.1)

Liquid limit values of the samples generally decreased with addition of stabilizers except for small increases of 2.8% for Sample 85%A+14%GBFS+1%Lime, and 2.1% for Sample 95%A+5%GBFSC.

Addition of 5%GBFS caused a decrease of 21.7% in Liquid Limit of Sample A. Decrease in liquid limit continued with increasing GBFS percentages in the samples.

For GBFS+Lime added samples, there was an increase of 2.8% in the liquid limit for Sample 85%A+14%GBFS+1%Lime. With the increase of lime and decrease of GBFS in the GBFS+Lime blends, liquid limit decreased by 26%.

For GBFSC added samples, effect on liquid limit is similar to that of GBFS+Lime added samples. There was a small increase of 2.1% in the liquid limit for Sample 95%A+5%GBFSC. Liquid limit decreased gradually with the increase of GBFSC in the samples.

Table 4.1. Percent Changes in Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), Shrinkage Limit (SL), Swelling Percentage, and Rate of Swell (t_{50}). (without cure)

SAMPLES	**% Change in LL**	**% Change in PL**	**% Change in PI**	**% Change in SL**	**% Change in swell**	**% Change in t_{50}**
A	0.0	0.0	0.0	0.0	0.0	0.0
95%A+5%GBFS	21.7	1.0	29.7	-9.8	31.1	60.0
90%A+10%GBFS	22.5	1.7	30.5	-13.0	35.6	67.7
85%A+15%GBFS	24.9	7.6	31.6	-14.5	46.4	69.2
80%A+20%GBFS	25.9	10.3	32.0	-15.5	60.7	76.9
75%A+25%GBFS	27.7	13.7	33.0	-25.4	61.7	90.0
85%A+14%GBFS +1%Lime	-2.8	10.3	-7.8	-32.1	75.7	93.8
85%A+12%GBFS +3%Lime	1.3	4.5	0.1	-36.3	77.0	94.6
85%A+10%GBFS +5%Lime	26.4	-14.1	42.0	-63.2	73.6	94.2
85%A+8%GBFS +7%Lime	26.1	-21.3	44.4	-65.3	70.3	93.1
95%A+5%GBFSC	-2.1	-18.9	4.4	-83.4	69.8	92.3
90%A+10%GBFSC	20.2	-26.5	38.2	-92.7	75.8	94.6
85%A+15%GBFSC	33.9	-34.4	60.2	-103.6	80.5	95.4
80%A+20%GBFSC	34.2	-35.1	60.9	-104.7	81.5	98.3
75%A+25%GBFSC	37.3	-38.5	66.6	-106.2	81.6	98.5

“+” Decrease, “-“ Increase

4.3. Effects of GBFS, GBFS+Lime and GBFSC Addition on the Plastic Limit (PL) of Expansive Soil (Table 4.1)

Plastic limit decreased only by 1% by addition of 5%GBFS to the sample. By increasing the amount of GBFS, decrease in plastic limit continued. Adding 25%GBFS caused a decrease of 13.7% in the plastic limit.

There is no consistent relation between the plastic limit and GBFS+Lime content of the samples. While 14%GBFS+1%Lime and 12%GBFS+3%Lime addition caused a decrease in plastic limit, 10%GFS+5%Lime and 8%GBFS+7%Lime caused increases in plastic limits of the samples.

GBFSC addition to the samples caused increases in plastic limit. The increase in the plastic limit became larger with the increase in the amount of GBFSC.

4.4. Effects of GBFS, GBFS+Lime and GBFSC Addition on the Plasticity Index (PI) of Expansive Soil (Table 4.1)

There was a 29.7% decrease in the plasticity index of sample by adding 5%GBFS. Additions up to 25%GBFS only caused a maximum decrease of 33% in plasticity index of samples.

There is no consistent relation between the plasticity index and GBFS+Lime content of the samples. Addition of 14%GBFS+1%Lime to the sample caused an increase of 7.8% in the plasticity index, while 8%GBFS+7%Lime addition caused in a decrease of 44.4% in the Plasticity Index. It seems that 3%Lime content in GBFS+Lime blends is a critical value, for which the behavior of the soil sample changes rapidly.

All GBFSC added samples caused decrease in the plasticity index. Rate of decrease increased with the amount of GBFSC added.

5%GBFSC addition caused a decrease of 4.4%, while 25%GBFSC addition caused a decrease of 66.6% in plasticity index.

4.5. Effects of GBFS, GBFS+Lime and GBFSC Addition on the Shrinkage Limit (SL) of Expansive Soil (Table 4.1)

Shrinkage limit of the samples decreased with the increased amounts of additives.

Shrinkage limit was increased by 9.8% with 5%GBFS addition. The increase in shrinkage limit continued with the increased amount of GBFS addition. 25%GBFS caused a 25.4% increase in shrinkage limit when compared to that of Sample A.

GBFS+Lime added samples had a greater effect on shrinkage limit than GBFS added samples. The increase in shrinkage limit was 32.1% for 14%GBFS+1%Lime, and 65.3% for 8%GBFS+7%Lime.

GBFSC added samples had the most powerful effect on the shrinkage limit. Only 5%GBFSC addition caused an increase of 83.4% in the shrinkage limit. The increase in shrinkage limit was 106.2% for 25%GBFSC added sample.

4.6. Effects of GBFS, GBFS+Lime and GBFSC Addition on the Activity of Expansive Soil (Table 3.2)

There is no consistent outcome of Effects of GBFS, GBFS+Lime and GBFSC addition on the activity of expansive soil.

GBFS added samples caused a decrease in the activity of samples when compared to that of Sample A. However, this decrease was not directly related to the amount of GBFS added.

14%GBFS+1%Lime and 12%GBFS+3%Lime addition caused an increase in the activity of samples whereas 10%GFS+5%L and 8%GBFS+7%Lime addition caused a decrease.

5%GBFSC addition caused an increase in the activity of sample when compared to that of Sample A. However, the activity of samples containing more than 5%GBFSC was decreased. This decrease in the activity is not consistently related to the amount of GBFSC in the samples.

4.7. Effects of GBFS, GBFS+Lime and GBFSC Addition on the Specific Gravity (G_S) of Expansive Soil (Table 3.2)

All GBFS, GBFS+Lime and GBFSC additions caused increases in the specific gravity of samples when compared to the specific gravity of Sample A (G_S=2.65).

4.8. Effects of GBFS, GBFS+Lime and GBFSC Addition on the Swelling of Expansive Soil (Table 4.1)

Swell percentage was decreased by all types and amounts of additives.

5%GBFS addition caused a decrease of 31.1% in the swell when compared to the swell of Sample A. the decrease in swell continued with the increasing amounts of GBFS in the samples. 25%GBFS addition caused a decrease of 61.7% in the swell percentage.

GBFS+Lime blends were more effective than GBFS additions in decreasing the amount of swell. 14%GBFS+1%Lime caused a decrease of 75.7% in the swell percentage. This is remarkable since 15%GBFS addition caused a 46.4% decrease in the swell amount. The decrease in the swell was 70.3% for 8%GBFS + 7%Lime added sample.

GBFSC added samples had the most powerful effect on the swell amount. Only 5%GBFSC addition caused a decrease of 69.8% in the swell amount. The decrease in the swell in the sample containing

15%GBFSC was 80.5%. Samples having more than 15%GBFSC content also resulted in decrease of swell up to 81.6%.

4.9. Effects of GBFS, GBFS+Lime and GBFSC Addition on the Rate of Swell of Expansive Soil (Table 4.1)

Rate of Swell is best described by t_{50}. As defined earlier, t_{50} is the time required to reach 50% of the total swell of the sample after inundation. Thus, if t_{50} is larger, rate of swell is slower. t_{50} values of samples were decreased by all types and amounts of additives.

GBFS added samples decreased the t_{50} by amounts ranging from 60% to 90% depending on the amount of GBFS. Decrease in the t_{50} was gradually increased with the increased amounts of GBFS.

GBFS+Lime blends added samples also decreased t_{50}, but the decrease was nearly constant. All GBFS-Lime added samples caused a decrease of t_{50} by about 93-94%.

GBFSC added samples also had a similar effect on t_{50}. 5%GBFSC added sample caused 92.3% decrease while 25%GBFSC added sample caused a 98.5% decrease in t_{50}. Decrease in t_{50} was weakly related to the amount of GBFSC in the samples.

The general tendency of decreasing t_{50} is mainly due to flocculation of clay particles with the addition of stabilizers. Flocculation causes the particles to stick on to each other leaving larger capillary canals for water seepage and results in increase in the rate of swell and decrease in t_{50}.

4.10. Effects of Curing on the Swelling Percentage

Curing Samples for 7days and 28 days generally resulted in some decrease in the swelling percentage (Table 4.2). Swell percentage (dH/H) value of each sample was the highest without cure, and lowest with curing for 28 days (Figure 3.16). Thus, it can be concluded that, for each sample:

$$(dH/H)_{\text{without cure}} > (dH/H)_{\text{7 days curing}} > (dH/H)_{\text{28 days curing}}$$

Applying curing for samples for 7 days or 28 days may help the pozzolanic reactions which occur within the clay and stabilizers. Curing may have resulted in a more cementitious soil matrix, which provides samples more resistance against swelling.

Table 4.2. Percent Changes in Swelling Percentage and Rate of Swell for No Curing, 7 days Curing and 28 Days Curing.

SAMPLES	**% change in dH/H**			**% change in t_{50}**		
	Without Curing	**7 days Curing**	**28 days Curing**	**Without Curing**	**7 days Curing**	**28 days Curing**
A	0.0	0.0	0.0	0.0	0.0	0.0
95%A+5%GBFS	31.1	29.2	29.7	60.0	58.3	55.0
90%A+10%GBFS	35.6	33.0	30.9	67.7	66.7	62.0
85%A+15%GBFS	46.4	45.6	44.4	69.2	75.0	72.0
80%A+20%GBFS	60.7	62.9	64.1	76.9	80.8	80.0
75%A+25%GBFS	61.7	65.0	65.8	90.0	90.0	89.0
85%A+14%GBFS +1%Lime	75.7	77.3	77.4	93.8	94.2	95.0
85%A+12%GBFS +3%Lime	77.0	84.5	84.8	94.6	94.6	95.0
85%A+10%GBFS +5%Lime	73.6	83.5	84.4	94.2	94.4	94.8
85%A+8%GBFS +7%Lime	70.3	70.8	75.1	93.1	94.3	93.5
95%A+5%GBFSC	69.8	71.7	73.7	92.3	93.8	94.0
90%A+10%GBFSC	75.8	83.7	84.0	94.6	97.9	97.8
85%A+15%GBFSC	80.5	89.5	90.0	95.4	98.0	98.0
80%A+20%GBFSC	81.5	89.9	90.4	98.3	98.5	98.2
75%A+25%GBFSC	81.6	92.5	93.3	98.5	98.8	98.8

4.11. Effects of Curing on the Rate of Swell

As a result of curing, rate of swell of the samples was generally increased slightly, the t_{50} values being decreased. The order

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

was generally followed by each sample.(Figure 3.17).

4.12. Results of Leachate Analysis

Since GBFS is a waste or by-product of the steel industry, it is not surprising that heavy metals are present in it.

The results of leachate analysis and the maximum allowable concentrations of heavy metals (Zn, Cu, Pb, Mn, Fe, Cd, Co, and Ni) for drinking water and irrigation are presented in (Table 3.4). There is no consistent relationship between the amount of GBFS or GBFSC used in the sample and the concentrations of heavy metals dissolved in the water. Effect of curing on the concentrations of heavy metals are not consistent with the amounts of GBFS or GBFSC used in the samples, either.

The atomic absorption test results indicated that the concentrations of Pb, Mn, Cd, and Ni in the leachates were above the maximum permissible level for drinking water.

The atomic absorption test results also indicated that the concentrations of heavy metals for all samples, except for Cd, Co and Ni, were below the maximum permissible level for irrigation water. However, the presence of small quantities of Cd, Co, and Ni in the leachates of the mixtures cannot be ignored.

CHAPTER 5

COST ANALYSIS

Cost analysis of different alternatives is essential in civil engineering applications to find the best and the cheapest solution especially if the work includes earthworks, such as cut and fill.

In this study, the following three alternatives are considered to perform cost analysis for overcoming an expansive soil problem in a civil engineering work although they may not result in the same amount of decrease in swell percentage of expansive soil.

1. Replacement of expansive soil (Sample A) with non-expansive soil found in the area of construction.
2. Stabization of expansive soil (Sample A) with ground Granulated Blast Furnace Slag (GBFS) in the ratio of 25% GBFS and 75% Sample A in dry mass.
3. Stabization of expansive soil (Sample A) with Granulated Blast Furnace Slag Cement(GBFSC) in the ratio of 25% GBFSC and 75% Sample A in dry mass.

To simplify the analysis, following assumptions are made.

1. In all alternatives, bulk density of compacted soil is 1.80 g/cm^3, and dry density of compacted soil is 1.64 g/cm^3. That is, all the fills have 10% moisture content.
2. In the compacted state, individual dry densities of non-expansive soil, GBFS, and GBFSC are all 1.64 g/cm^3, which makes a good estimation of volumes of each constituent in the stabilized soils.

3. Non-expansive soil, GBFS, and GBFSC are in the dry state prior to mixing and compaction.
4. All the soils, GBFS, and GBFSC are 10% larger in volume in their loose state, which decreases their dry density by 10%.
5. Compaction is done by a compactor having a capacity to compact 50 m^3 soil in one hour into the desired density.
6. An ordinary worker is capable to prepare 1 m^3 of expansive soil with GBFS (Alternative 2) or expansive soil with GBFSC (Alternative 3) mixtures in 2.5 hours.
7. Water source is 7 km away from the construction site in all the alternatives.
8. Dump site is 5 km away from the construction site in all the alternatives.
9. 1450000 TL=1 US $.

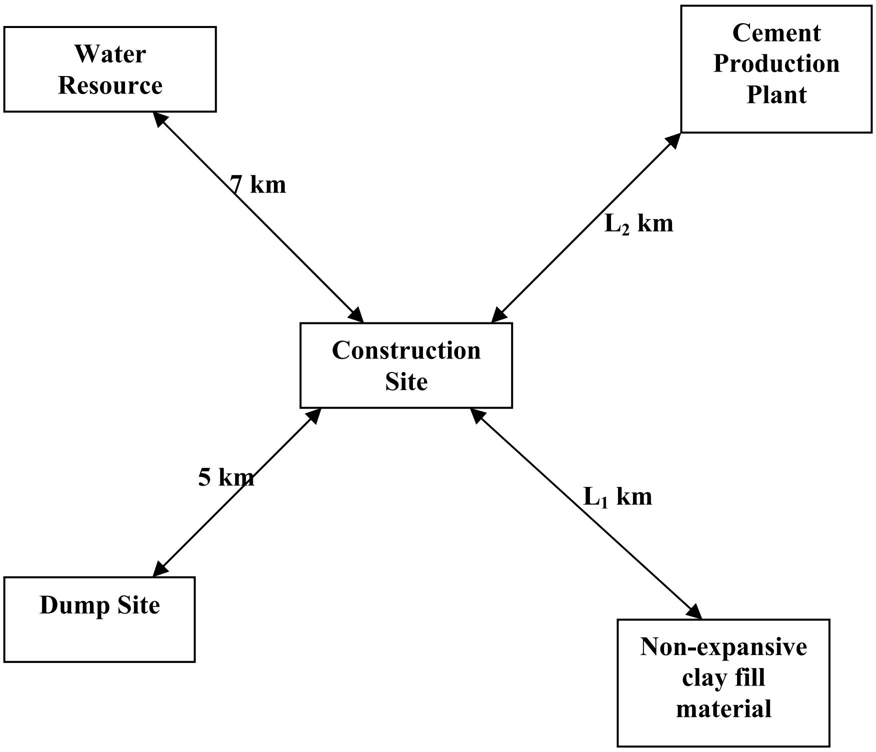

Figure 5.1. Layout for Alternatives.

The cost of $1m^3$ fill will be calculated based on the State Hydraulic Works Unit Prices for Civil Engineering Works, and GBFS and GBFSC prices of İskenderun-OYSA Cement Production Plant for the year 2004 (Güler and Avcı,1993).

From the assumption that all stabilized samples have a bulk density of 1.8 g/cm^3, 1 m^3 fill volume will have a mass of 1800 kg. Besides, from the assumption that all stabilized soils have 10% water content,

$$M_{water}=0.10xM_{solids} \qquad (1)$$

$$M_{solids}+M_{water}=1800 \text{ kg} \qquad (2)$$

Where M_{solids} is the mass of solid particles and M_{water} is the mass of water in 1 m^3 fill volume. From the equations 1 and 2 above,

M_{solids}=1636 kg and M_{water}=164 kg in 1 m^3 fill volume.

The density of water being 1000kg/m^3, the volume of water in a 1 m^3 compacted fill is 0.164 m^3.

The proposed alternatives are explained below.

5.1. Alternative 1

This alternative can be summarized as the replacement of expansive soil with a more suitable, non-expansive fill material which can be found near the construction site.

The items of work to be done, the item number of the work, and the unit prices are given in Table 5.1. L_1 is the distance (in km) of the available non-expansive fill material to the construction site. Cost is calculated as a function of L_1.

Table 5.1. Cost Calculation for Alternative 1. (DSİ-BFC, 2004)

Item No	Description of the Work	Unit	Unit Price (US $)	Amount	Cost (US $)
15.006/1	Excavation of expansive soil	m^3	1.17	1.00	1.17
07.006/1	Transportation of excavated expansive soil to dump site (L_{dump}=5 km)	m^3	1.90	1.10	2.09
15.006/1	Excavation of non-expansive soil	m^3	1.17	1.00	1.17
07.006/1	Transportation of excavated non-expansive soil to construction site (L_1 km)	m^3	$0.10L_1+1.37$	1.100	$0.11L_1+1.51$
15.025	Placement of non-expansive soil in construction site	m^3	0.27	1.00	0.27
07.005/1	Transportation of Water (L_{water}=7 km)	m^3	1.29	0.164	0.21
15.D.1	Watering of fill	m^3	0.85	0.164	0.14
15.052	Compaction of fill	Hour	31.04	0.02	0.62

Total Cost for Alternative 1 = $7.04+ 1.51L_1$ ($\$/m^3$)

5.2. Alternative 2

This alternative can be summarized as the in-situ stabilization of expansive soil with 25% GBFS (by mass). GBFS is taken supplied from a GBFS grinding cement production plant from a distance of L_2 km away from the construction site. The items of work to be done, the item number of the work, and the unit prices are given in Table 5.2.

Table 5.2. Cost Calculation for Alternative 2 (DSİ-BFC, 2004)

Item No	Description of the Work	Unit	Unit Price (US $)	Amount	Cost (US $)
15.006/1	Excavation of expansive soil	m^3	1.17	1.00	1.17
07.006/1	Transportation of GBFS to the construction site (L_2 km)	m^3	$0.10L_2+1.37$	0.275	$0.03L_2+0.38$
Special Price	Cost of GBFS	m^3	36.09	0.275	9.72
01.501	Mixing GBFS with the expansive soil (workmanship)	m^3	3.19	1.10	3.51
15.025	Placement of stabilized soil in construction site	m^3	0.27	1.00	0.27
07.005/1	Transportation of Water (L_{water}=7 km)	m^3	1.29	0.164	0.21
15.D.1	Watering of fill	m^3	0.85	0.164	0.14
15.052	Compaction of fill	Hour	31.04	0.02	0.62

Total Cost for Alternative 2 = $16.02 + 0.03L_2$ ($\$/m^3$)

5.3. Alternative 3

This alternative can be summarized as the in-situ stabilization of expansive soil with 25% GBFSC (by mass). GBFSC is taken supplied from a GBFSC cement production plant from a distance of L_2 km away from the construction site. The items of work to be done, the item number of the work, and the unit prices are given in Table 5.3.

Table 5.3. Cost Calculation for Alternative 3 (DSİ-BFC, 2004)

Item No	Description of the Work	Unit	Unit Price (US $)	Amount	Cost (US $)
15.006/1	Excavation of expansive soil	m^3	1.17	1.00	1.17
07.006/1	Transportation of GBFSC to the construction site (L_2 km)	m^3	$0.10L_2+1.37$	0.275	$0.03 L_2 +0.38$
Special Price	Cost of GBFSC	m^3	56.93	0.275	15.66
01.501	Mixing GBFSC with the expansive soil (workmanship)	m^3	3.19	1.10	3.51
15.025	Placement of stabilized soil in construction site	m^3	0.27	1.00	0.27
07.005/1	Transportation of Water (L_{water}=7 km)	m^3	1.29	0.164	0.21
15.D.1	Watering of fill	m^3	0.85	0.164	0.14
15.052	Compaction of fill	Hour	31.04	0.02	0.62

Total Cost for Alternative 3 = $21.96 + 0.03L_2$ ($\$/m^3$)

5.4. Comparison of Alternatives

Making use of the cost functions calculated above, the distances L_1 or L_2 versus Cost per m^3 graphs are plotted in Figure 5.2.

The graph shows the outcome of the economic analysis. From the graph, the following conclusions can be made.

1. If non-swelling soil source is closer than 6 km from the construction site, Alternative 1 (use of non-swelling soil source) is more economical than the other two alternatives.
2. If non-swelling soil source is 6 to 10 km from the construction site, Alternative 1 is more economical than Alternative 3 (use of GBFSC),but more expensive than Alternative 2 (use of GBFS).
3. If non-swelling soil source is further than 10 km from the construction site, Alternative 1 is a more expensive solution than the other two alternatives.
4. Use of GBFS for stabilizing the expansive soil is always more economical than use of same amount of GBFSC, but GBFSC reduces swell percentage of Sample A more than GBFS does. Besides, according to the leachate analysis, GBFSC without cure almost satisfies irrigation water standards. In the environmental point of view, use of GBFCS is more advantageous.

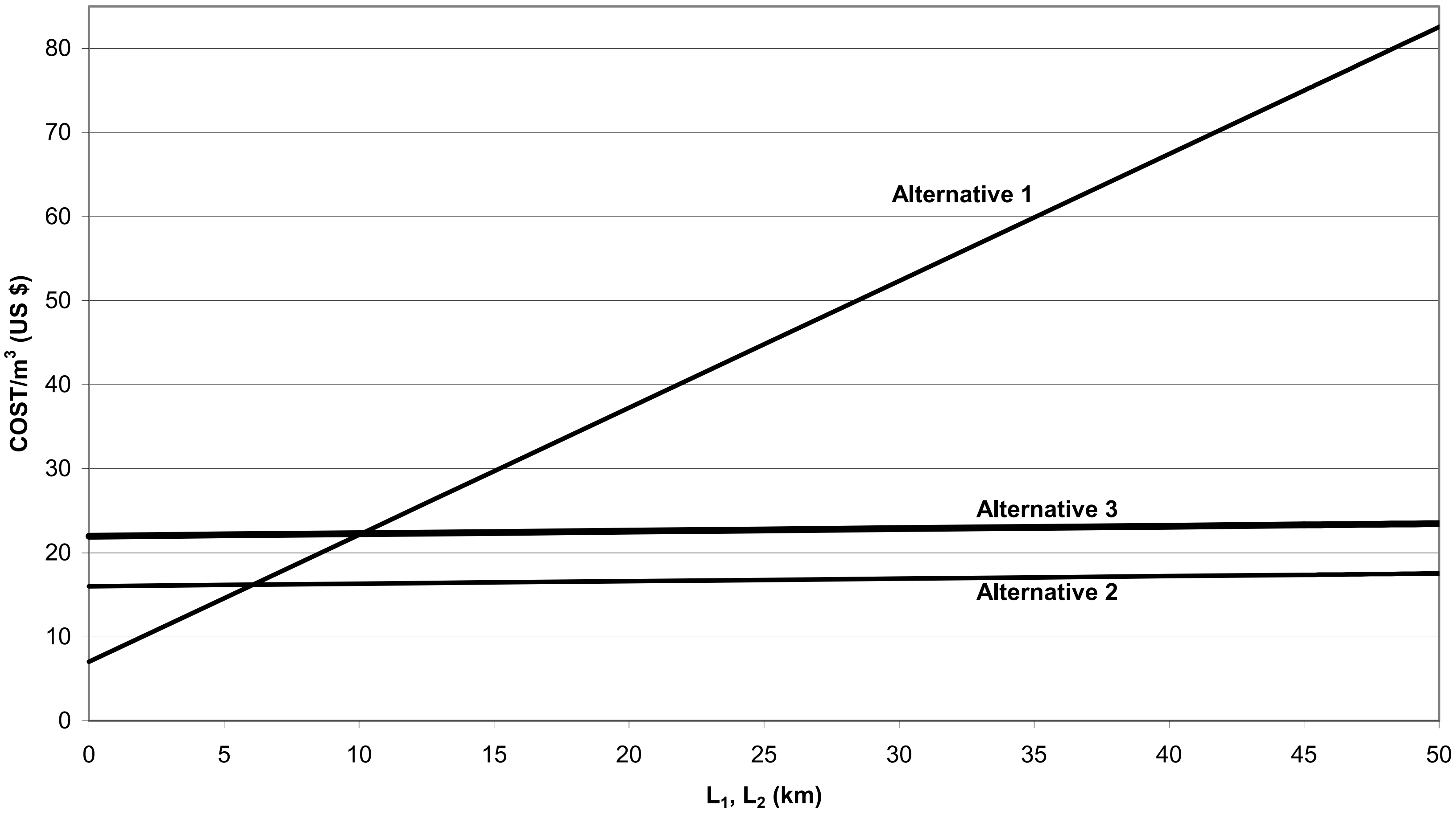

Figure 5.2. Comparison of Alternatives

CHAPTER 6

CONCLUSIONS

The effects of Granulated Blast Furnace Slag (GBFS), GBFS-Lime blends, and Granulated Blast Furnace Slag Cement (GBFSC) on the volume change of an expansive soil sample, Sample A, was presented in this study. GBFS and GBFSC were utilized up to 25% dry mass ratio in the samples. GBFS-Lime blends were utilized in constant amount, 15% of the total dry mass, but the ratio of GBFS-Lime was changed to obtain the optimum amount of lime in the blend.

Secondly, leachate analysis of 25% GBFS and 25% GBFSC added samples with no cure, 7 days cure and 28 days cure is done. Leachate analysis of 100% GBFS and 100% GBFSC is also performed.

Based on the results of the experiments, following conclusions are warranted:

1. Addition of GBFS, GBFS-Lime blends, and GBFSC altered the grain size distribution of expansive soil sample (Sample A). Clay fractions decreased and silt fractions increased upon adding GBFS, GBFS-Lime blends and GBFSC.

2. The changes in grain size distributions of Sample A were mainly due to addition of silt sized particles present in GBFS, GBFS-Lime blends and GBFSC. Pozzolanic reactions or cation exchange process resulting in the flocculation of fine clay

particles also affected the grain size distributions of treated samples.

3. GBFS addition decreased the liquid limit of Sample A. 14%GBFS+1%Lime addition slightly increased the liquid limit and other GBFS+Lime additions decreased the liquid limit. 5%GBFS addition slightly increased the liquid limit and other GBFSC additions decreased the liquid limit of the expansive soil sample.
4. GBFS addition caused decrease in the plastic limit of Sample A. 14%GBFS+1%Lime and 12%GBFS+3%Lime addition caused a decrease in the plastic limit whereas other GBFS+Lime additions caused an increase in the plastic limit of the expansive soil sample. GBFSC additions caused an increase in the plastic limit.
5. Plasticity index is decreased for all GBFS, GBFS+Lime and GBFSC additions, except for 14%GBFS+1%Lime added to Sample A.
6. Addition of GBFS, GBFS+Lime and GBFSC increased the shrinkage limit of Sample A.
7. Addition of GBFS, GBFS+Lime and GBFSC increased the specific gravity (G_s) of Sample A.
8. 15%, 20% and 25% GBFSC addition shifted the expansive soil sample from CH to MH according to the Unified Soil Classification System.
9. Activity of Sample A decreases with the addition of GBFS, GBFS+Lime and GBFSC, except for 14%GBFS+1%Lime, 12%GBFS+3%Lime and 5%GBFSC additions.
10. GBFS, GBFS+Lime and GBFSC additions decrease the swell percentage of Sample A.
11. GBFS, GBFS+Lime and GBFSC additions decrease the t_{50} values.

12. Curing is more effective in reducing the t_{50} values than reducing the swell percentage.

13. 12%GBFS+3%Lime blend is the optimum of GBFS-Lime blends since it gives the minimum of swell percentage and t_{50} values of this group for no curing, for 7 days curing and for 28 days curing.

14. 75% A + 25% GBFS gives 9% swell after 28 days of curing and almost satisfies irrigation water standards (except Cd). This may be the choice if we consider economy (Alternative 2), swell percentage and environmental factors.

15. 75% A + 25% GBFSC gives the minimum swell percentage (2%) after 28 days of curing. But 75% A + 25% GBFSC gives 6% swell without curing which also satisfies the irrigation water standards. This may be the best choice if we consider environmental factors, economy (Alternative 3), and swell percentage.

16. GBFS and GBFSC should not be used to stabilize expansive soils in regions near to the drinking water wells.

Recommendation for Future Research

In this study, swelling percentages and t_{50} values were determined for a water content of 10%, for all soil samples. The same samples may show different swelling behavior with changing initial water content. Thus, this study may be extended by determining the effect of initial water content on swelling behavior of expansive soils.

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APPENDIX A

Swell percentage versus time relationship of the samples are given in Appendix A.

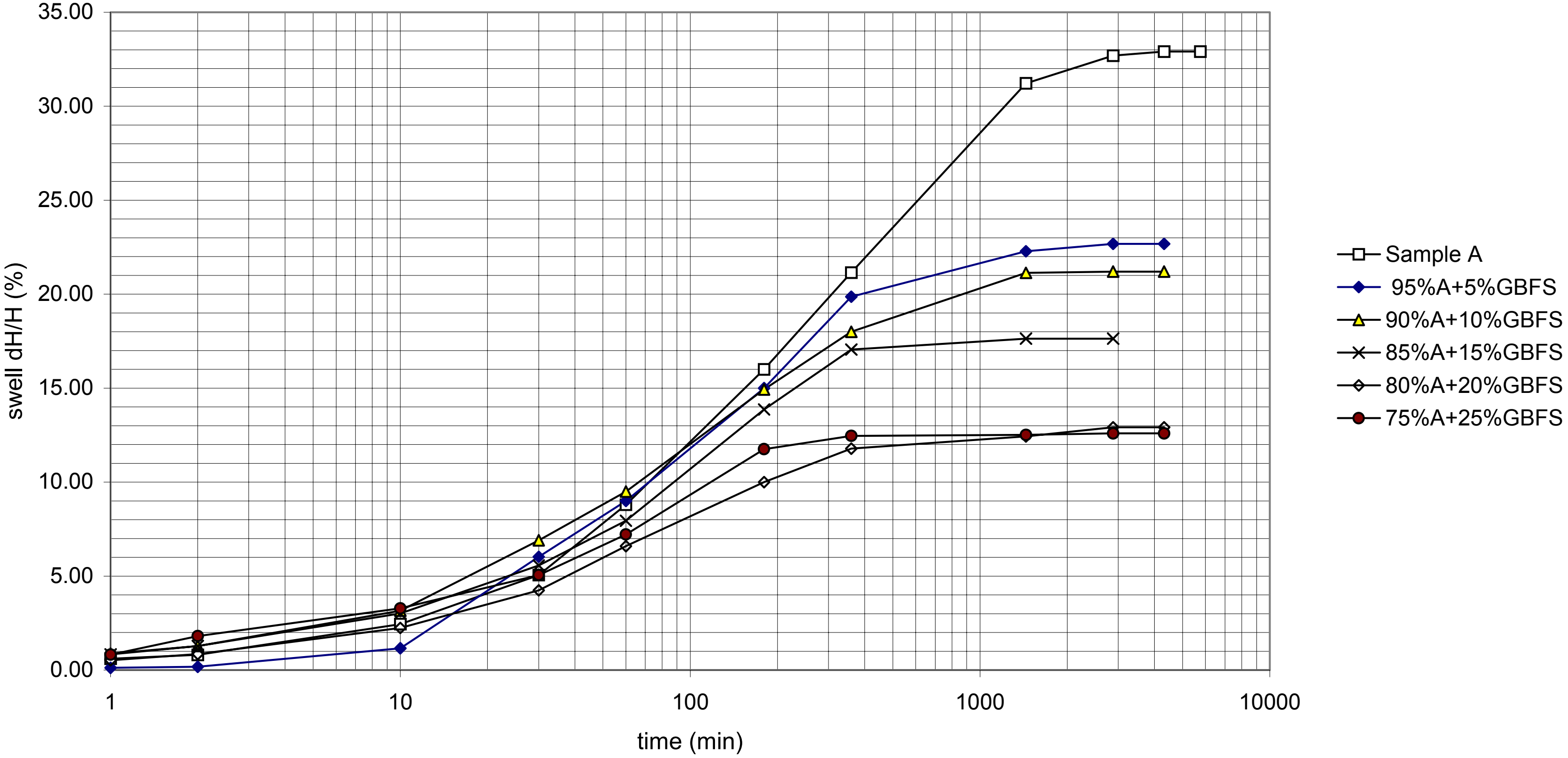

Figure A.1. Swell Percentage versus Time Relationship for Sample A and GBFS Added Samples (Without Cure)

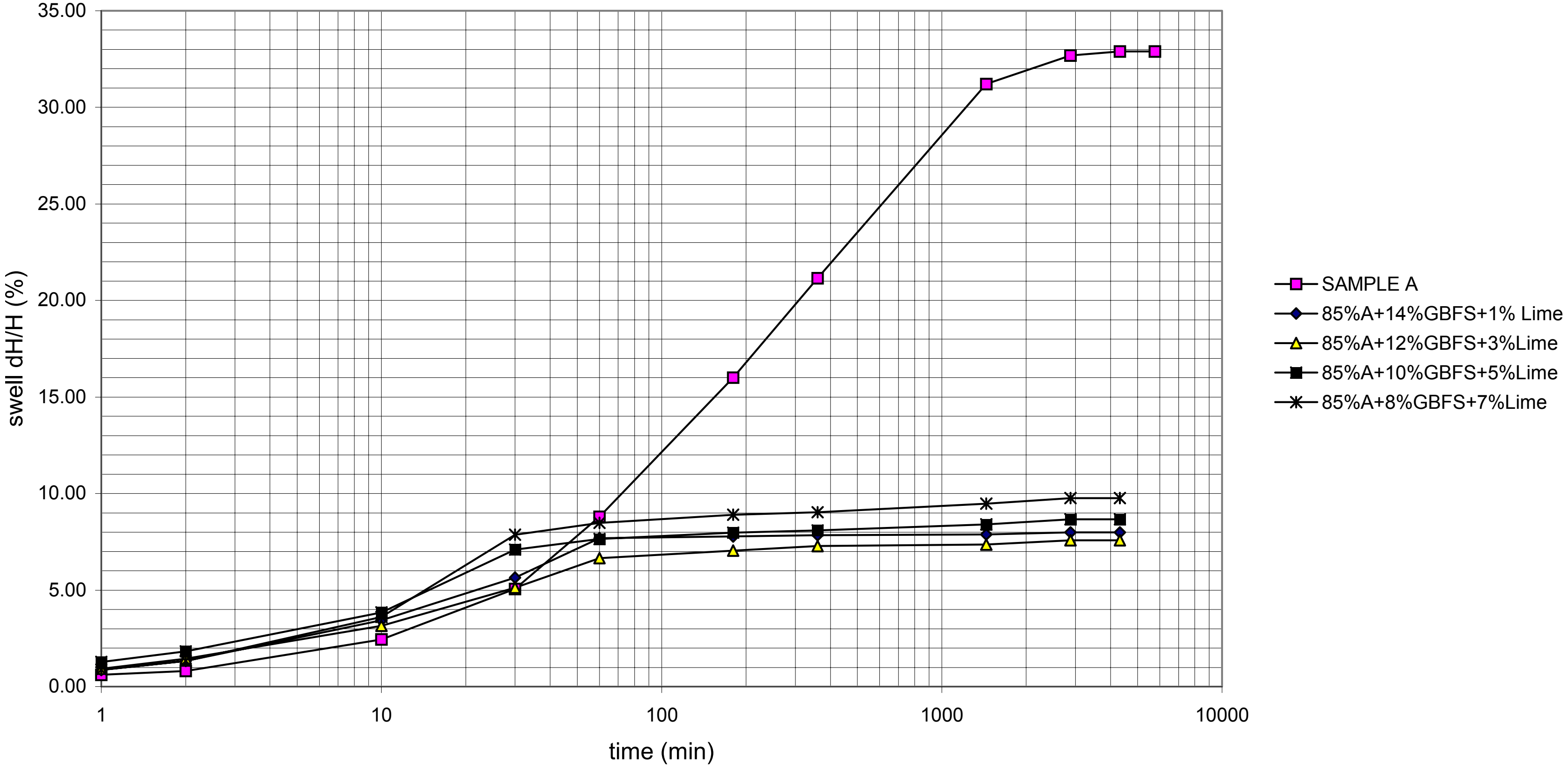

Figure A.2. Swell Percentage versus Time Relationship for Sample A and GBFS+Lime Added Samples (Without Cure)

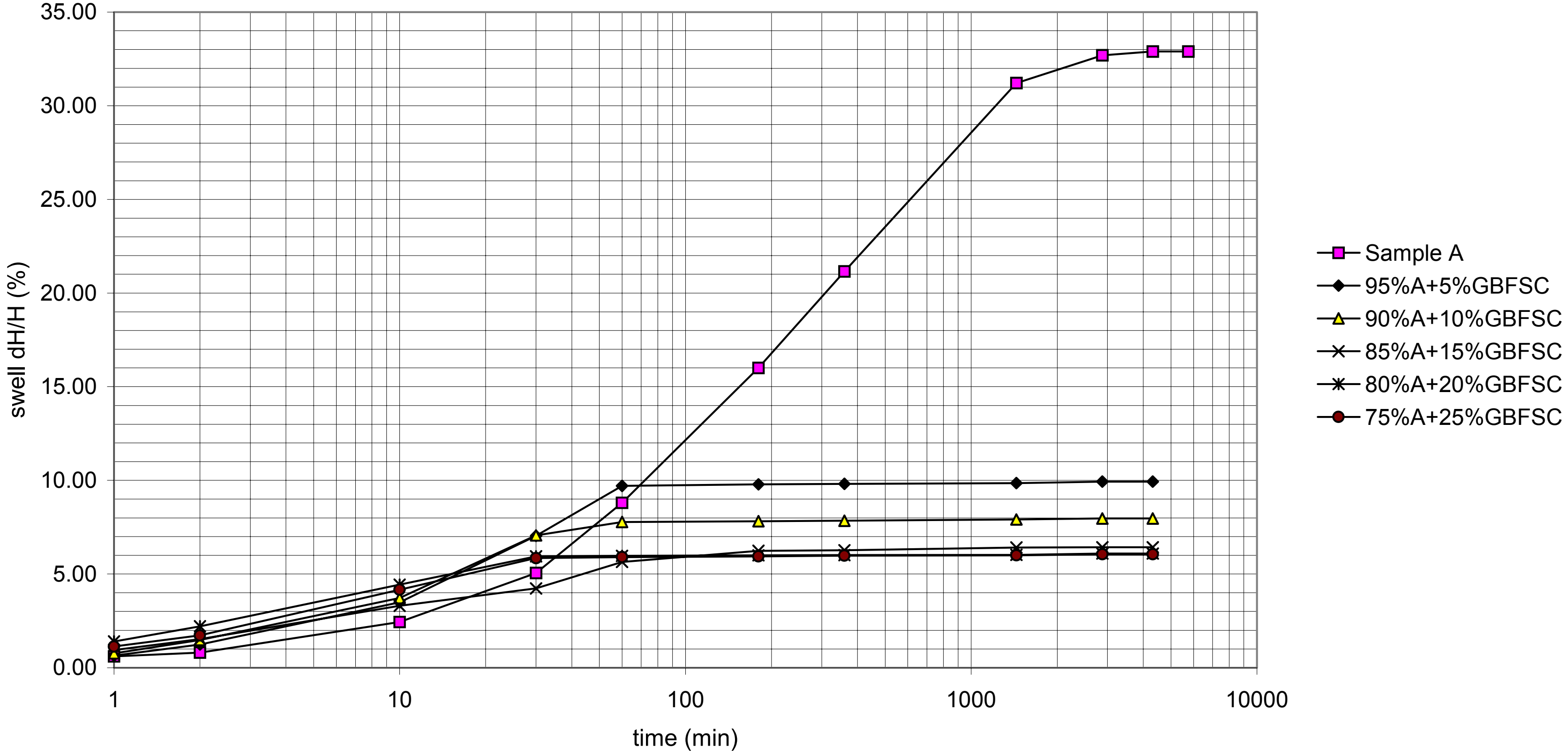

Figure A.3. Swell Percentage versus Time Relationship for Sample A and GBFSC Added Samples (Without Cure)

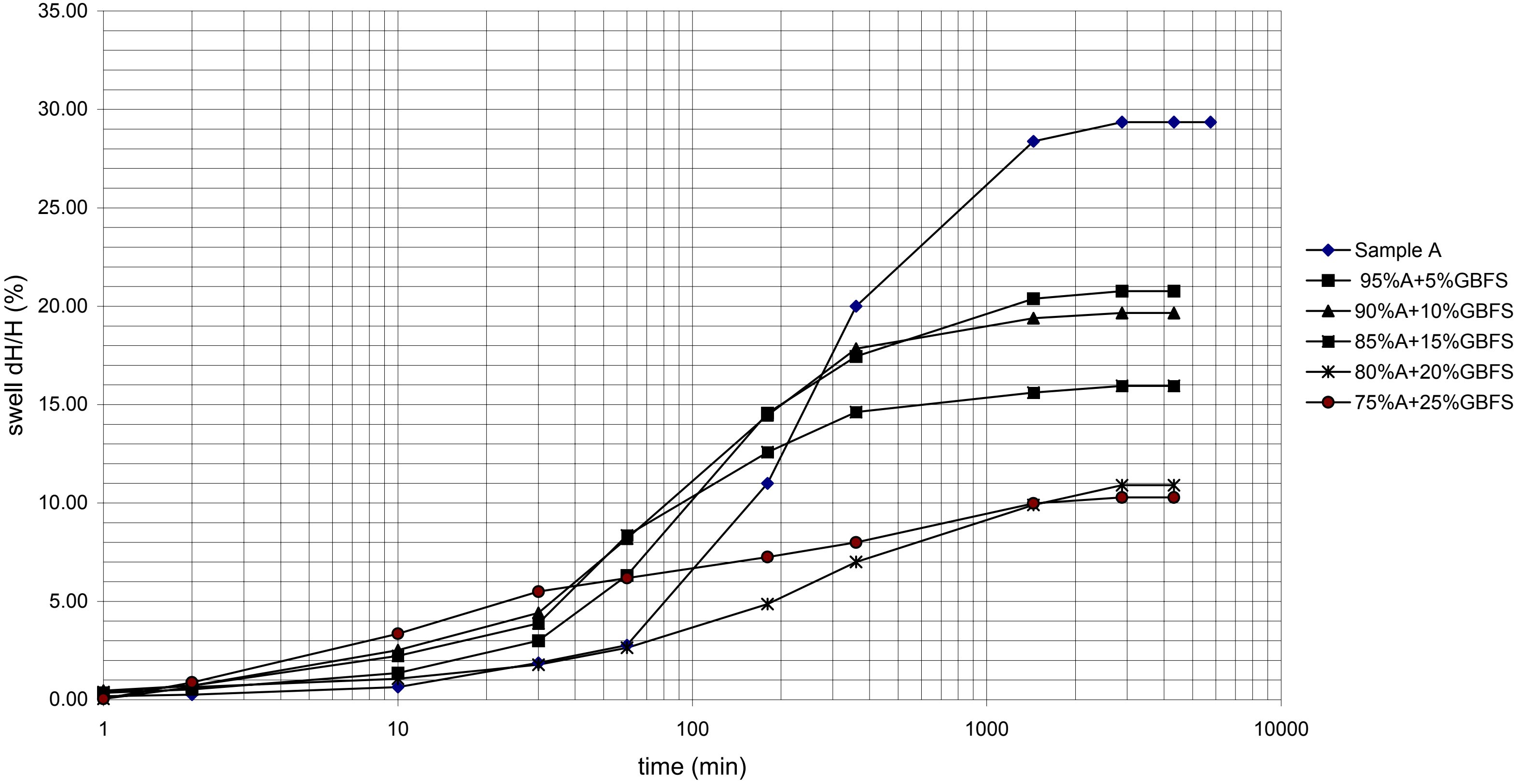

Figure A.4. Swell Percentage versus Time Relationship for Sample A and GBFS Added Samples (After 7 Days Curing)

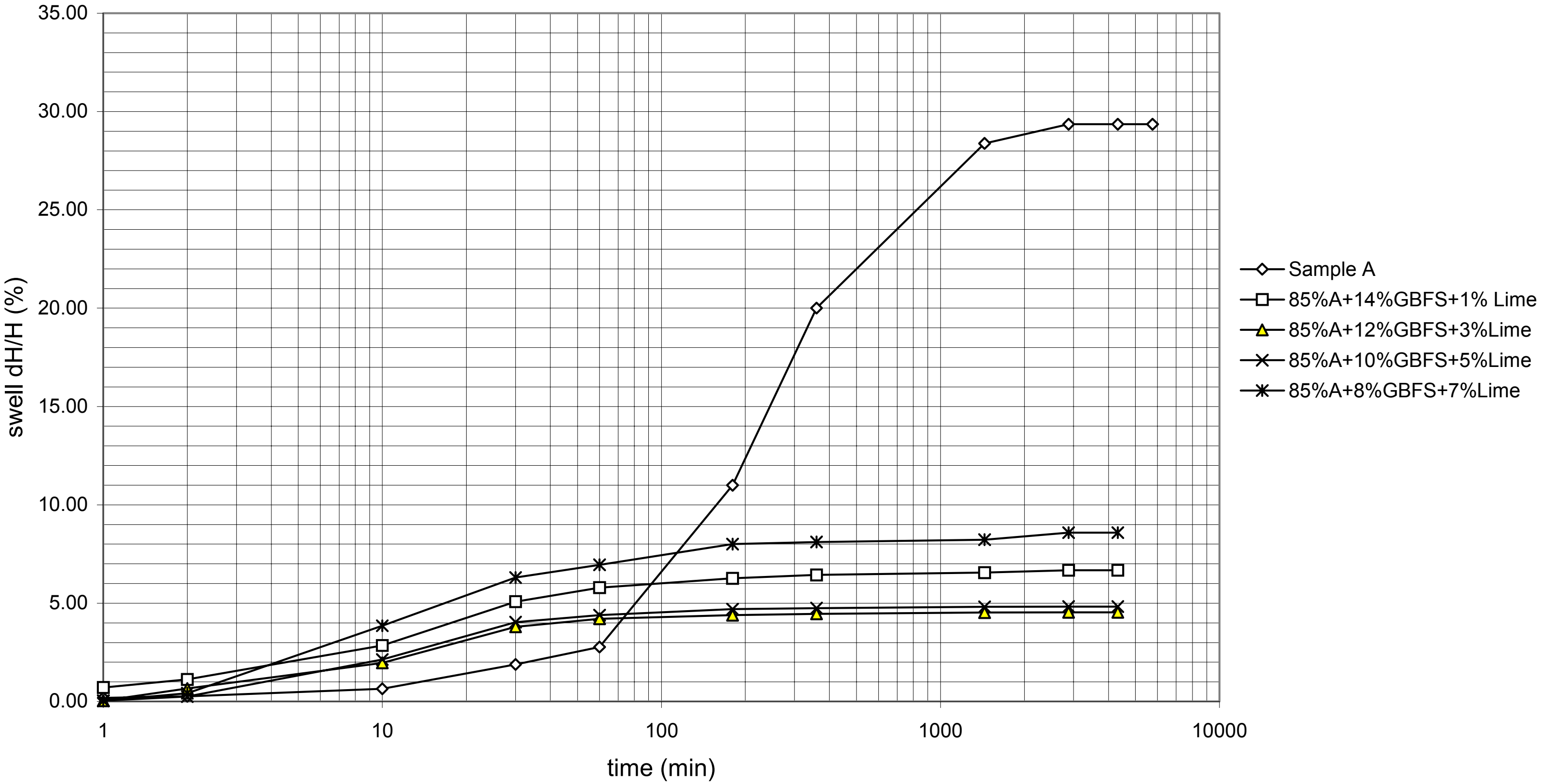

Figure A.5. Swell Percentage versus Time Relationship for Sample A and GBFS-Lime Blends Added Samples (After 7 Days Curing)

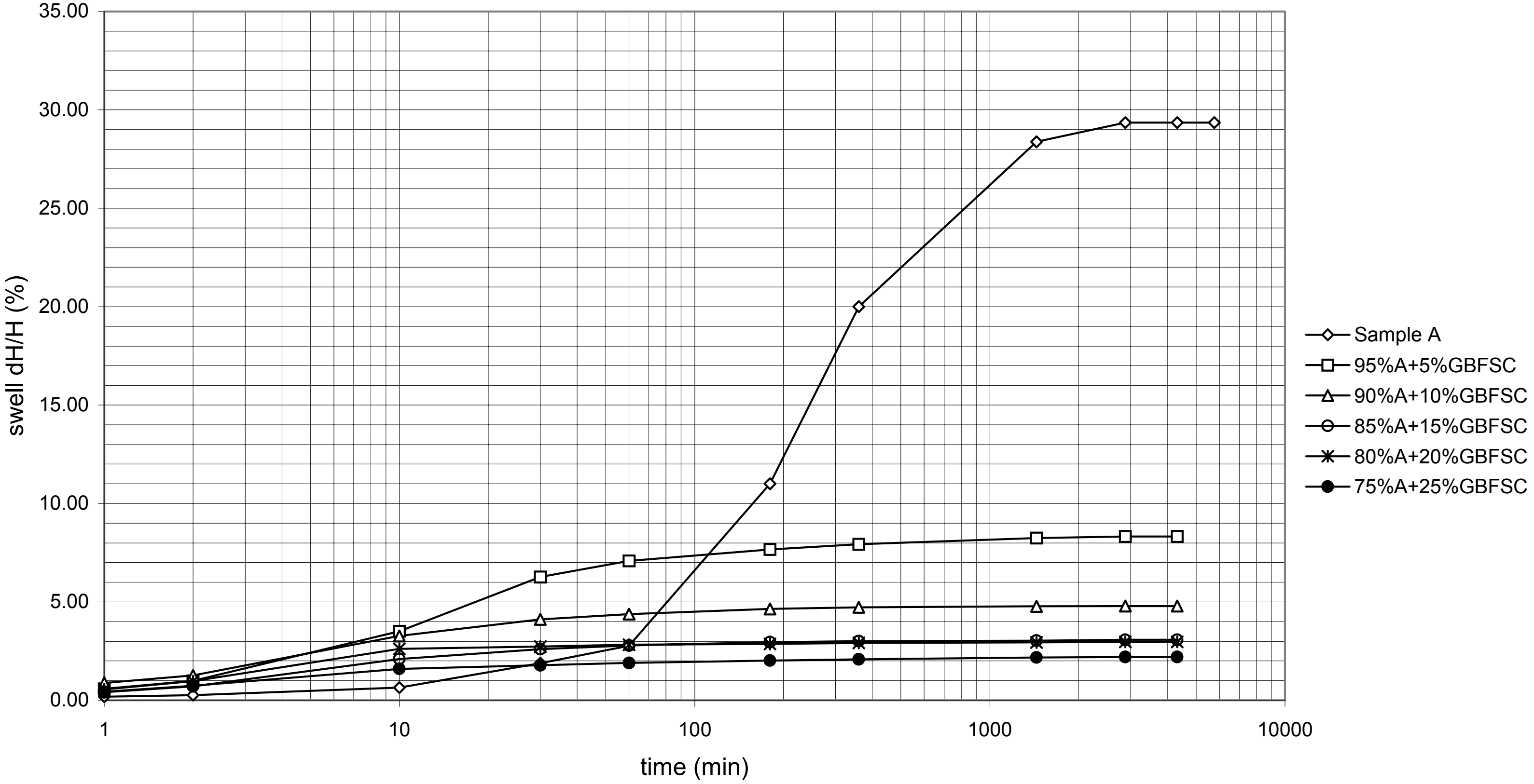

Figure A.6. Swell Percentage versus Time Relationship for Sample A and GBFSC Added Samples (After 7 Days Curing)

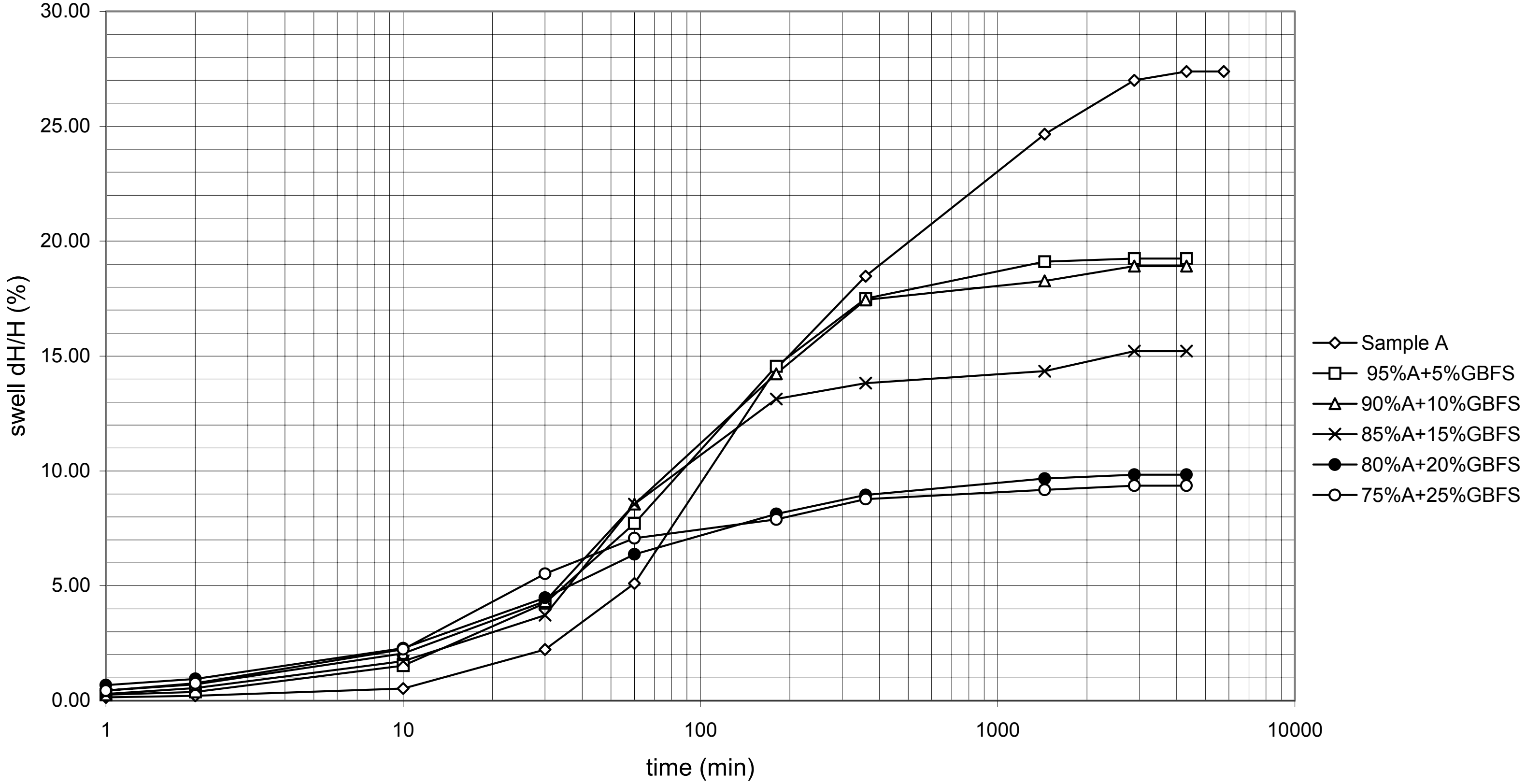

Figure A.7. Swell Percentage versus Time Relationship for Sample A and GBFS Added Samples (After 28 Days Curing)

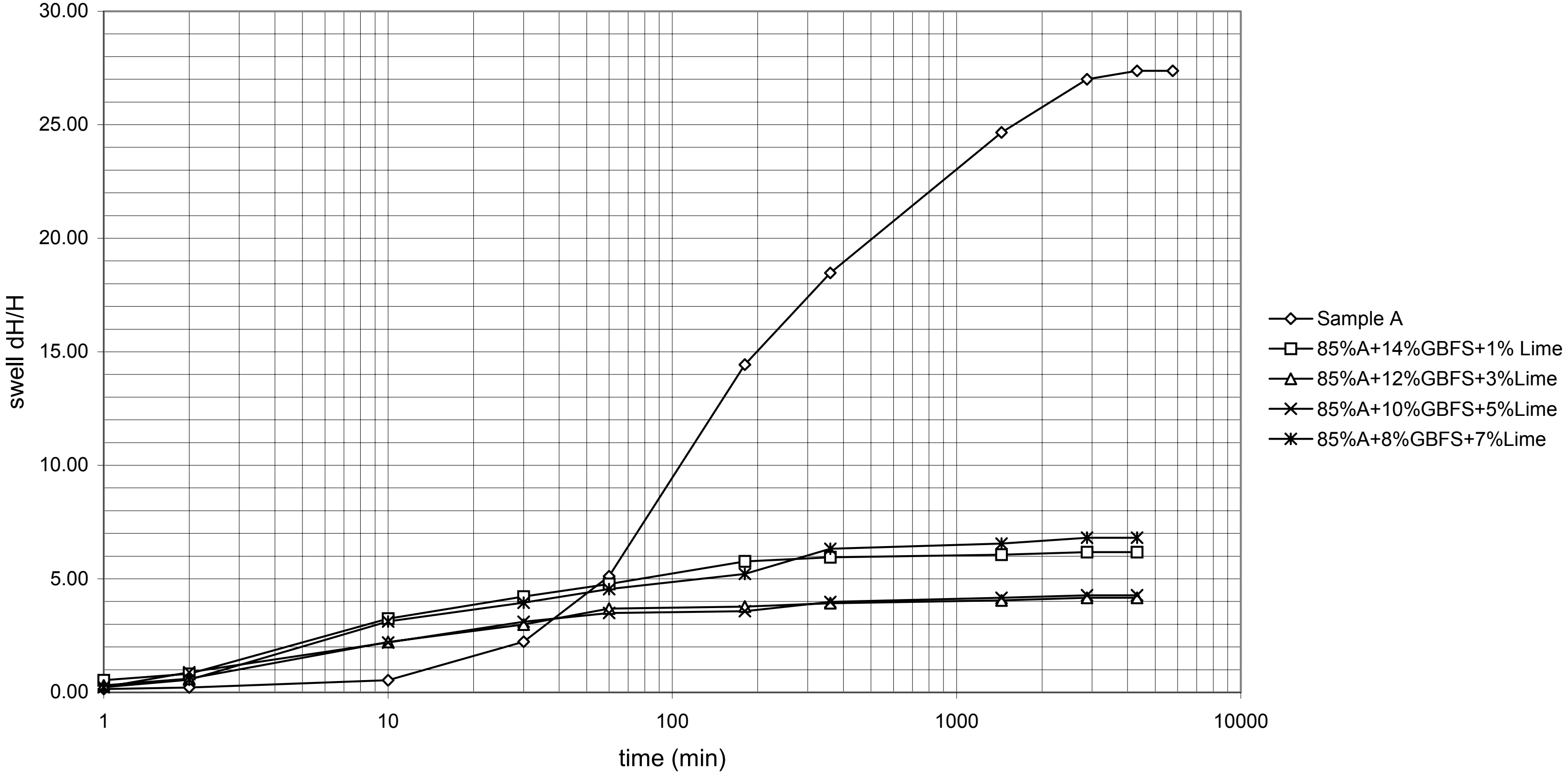

Figure A.8. Swell Percentage versus Time Relationship for Sample A and GBFS-Lime Added Samples (After 28 Days Curing)

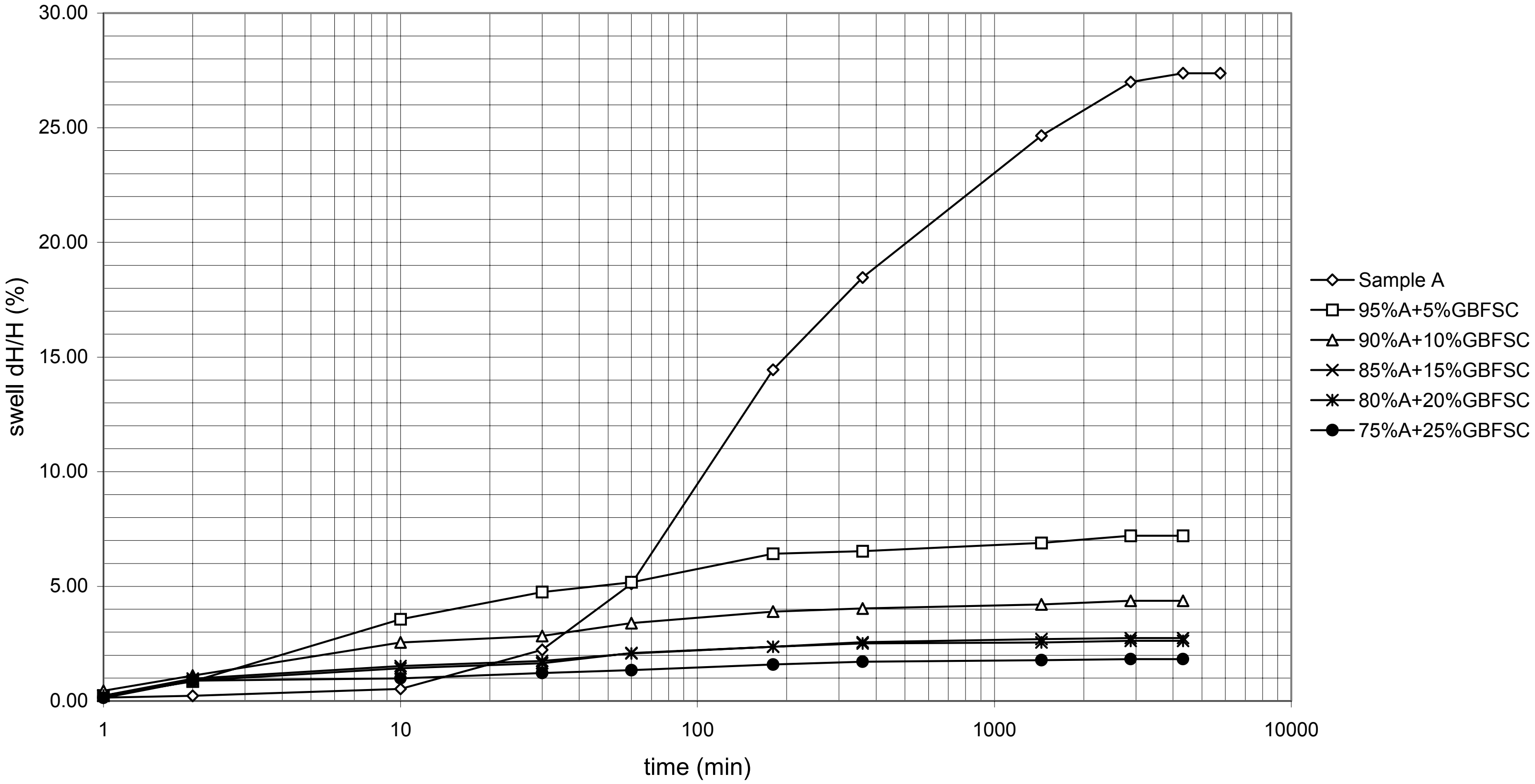

Figure A.9. Swell Percentage versus Time Relationship for Sample A and GBFSC Added Samples (After 28 Days Curing)

APPENDIX B

Grain Size Distributions of Sample A, 75% Sample A+25%GBFS, Calculated 75% Sample A+25%GBFS and 100% GBFS are plotted on the same graph in Figure B.1.

Grain Size Distributions of Sample A, 75%Sample A+25%GBFSC, Calculated 75% Sample A+25%GBFSC and 100% GBFSC are plotted on the same graph in Figure B.2.

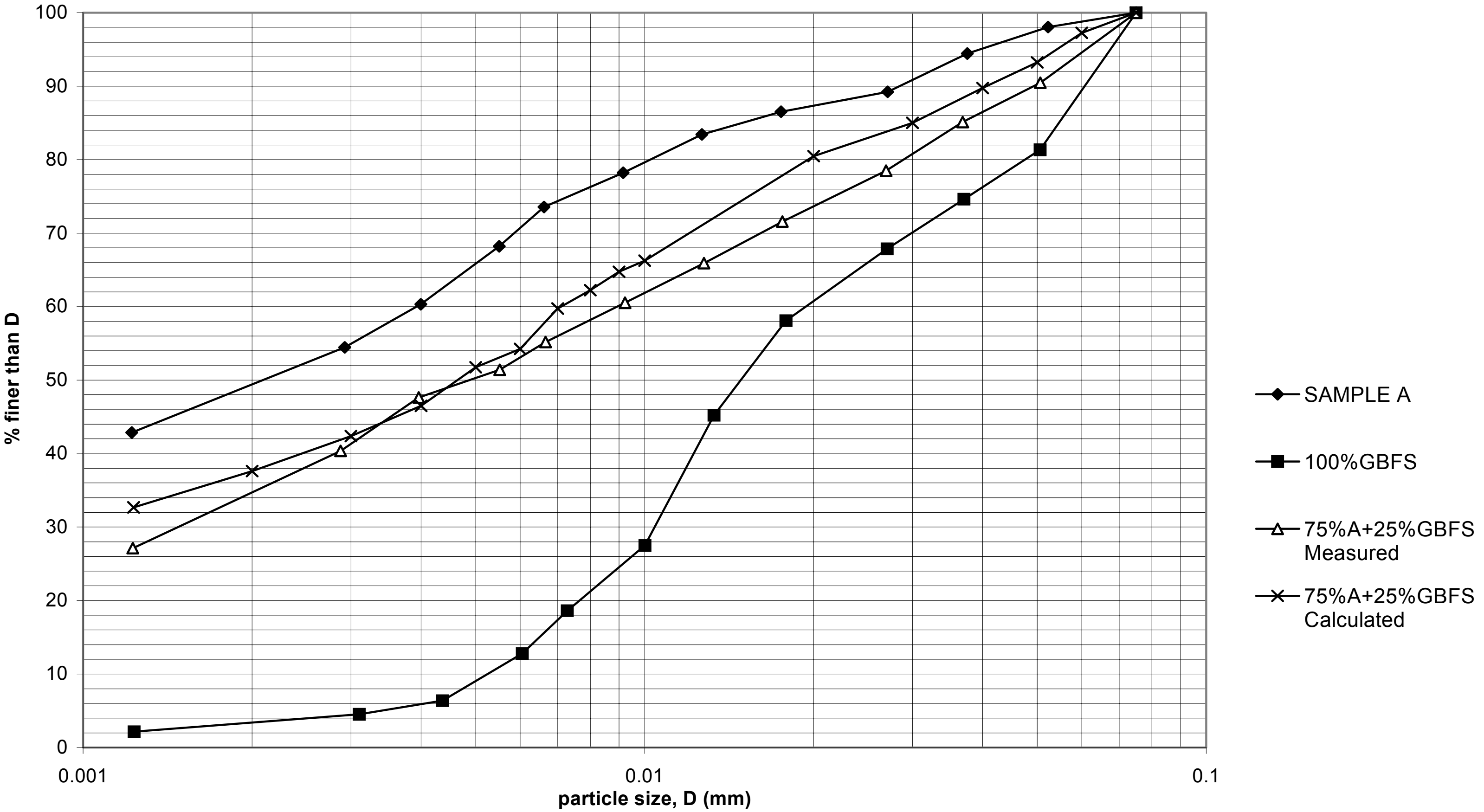

Figure B.1. Grain Size Distributions of Sample A, 75% Sample A+25%GBFS, Calculated 75% Sample A+25%GBFS and 100% GBFS.

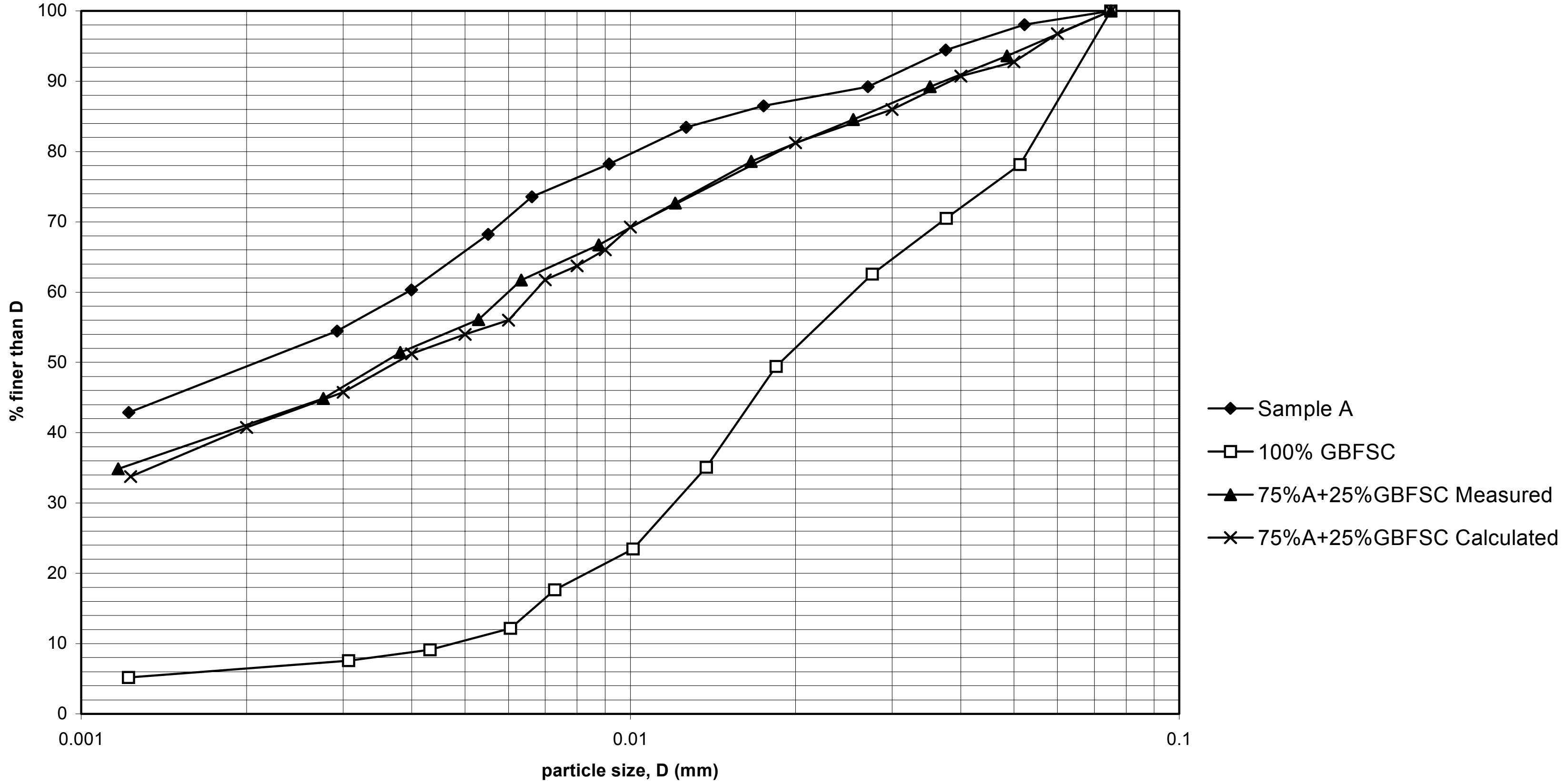

Figure B.2. Grain Size Distributions of Sample A, 75%Sample A+25%GBFSC, Calculated 75%Sample A+25%GBFSC and 100%GBFSC.