USE OF GRANULATED BLAST FURNACE SLAG, STEEL SLAG AND FLY ASH IN CEMENT-BENTONITE SLURRY WALL CONSTRUCTION

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Approval of the thesis:

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ABSTRACT

USE OF GRANULATED BLAST FURNACE SLAG, STEEL SLAG AND FLY ASH IN CEMENT-BENTONITE SLURRY WALL CONSTRUCTION

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Slurry walls have been widely used for more than 25 years to control the migration of contaminants in the subsurface. In the USA, vertical barriers are mostly constructed of soil-bentonite using the slurry trench method of construction. In this method, sodium bentonite is mixed with water to form a viscous slurry that is pumped into a trench during excavation to maintain the trench stability. The stable trench is then backfilled with a mixture of soil and slurry having a consistency of high slump concrete. These barriers have been designed primarily for low permeability, generally less than 10^{-9} m/s. Some investigations have pointed toward improved performance using admixtures that would provide low permeability. In this study, Soma thermal power plant fly ash, granulated blast furnace slag, lime, and steel slag are used as admixture to improve the performance of slurry walls. Permeability, compressive strength, slump, compressibility properties of the mixtures were found and checked for the minimum requirements. According to the findings of this study, granulated blast furnace slag (GGBS), fly ash and steel slag can be used at certain percentages and curing periods as additive in cement-bentonite barrier wall construction. Permeability of specimens having fly ash decreases by increasing fly ash content. Mixtures having 50 % of GGBS type I with 5 % of lime and 9% bentonite content gave acceptable results in 28 days of curing time. Specimens including 50 % of GGBS type II with 5 % of lime and 9% bentonite content gave the higher permeability value in 28 days of curing time with respect to GGBS type I. In addition, most of the mixtures prepared by steel slag gave the acceptable permeability values in 28 days of curing period. Unconfined compressive strength of all mixtures increase by increasing curing time. Cc, Cr, Cv, kcon values were found from consolidation test results. Permeability values found from consolidation tests are 10 times to 100 times higher than flexible wall k results for the same effective stress of 150 kPa. Generally, mv values are decreasing with increasing curing time. As mv decreases, D increases.

Keywords: Bentonite, Cement, Fly ash, Granulated Blast Furnace Slag, Lime, Slurry wall, Stabilization, Steel Slag.

ÖZ

GRANÜLE YÜKSEK FIRIN CURÜFU, ÇELİK CÜRUFU VE UÇUCU KÜLÜN ÇİMENTO-ENTONİT GEÇİRİMSİZ PERDE DUVARDA KULLANIMI

Talefirouz, Davood
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Geçirimsiz perdeler 25 yılı aşkın bir süredir yer altında kirletici maddelerin taşınmasını kontrol etmede geniş çaplı olarak kullanılmaktadır. ABD de, düşey bariyerler sıklıkla zemin-bentonit karışımı kullanılarak inşaa edilmektedir. Bu metotda sodium bentonit su ile karıştırılmakta ve kıvamlı bir çamur oluşmaktadır, bu çamur kazılmakta olan geçirimsiz perde duvar çukuruna pompalanmakta ve kazının stabilitesi sağlanmaktadır. Daha sonra kazı sırasında, içinde sodium bentonit olan çukur, zemin ve bentonit karışımı ile doldurulmaktadır, bu karışım yüksek slamplı beton kıvamındadır. Bu bariyerler esas olarak düşük hidrolik geçirgenlik için tasarlanırlar, genellikle 10^{-9} m/s den düşük değerler için. Bazı araştırmalarda bu geçirimsiz duvarların hidrolik iletkenliğinin bazı katkı maddeleri ile düşürülebildiği belirtilmektedir. Bu araştırmada, Soma termik santralinden çıkan uçucu kül, granüle yüksek fırın curufu, kireç ve çelik curufu katkı maddesi olarak kullanılarak geçirimsiz duvarların hidrolik iletkenliği düşürülmeye çalışılmaktadır. Bu karışımların hidrolik iletkenliğine, basınç mukavemetine, sıkışabilirliğine ve slamp kriterlerini sağlayıp sağlamadığına bakılmıştır. Bu çalışmanın sonuçları, uçucu kül, granüle yüksek fırın curufu, kireç ve çelik cürufunun, belirli yüzdelerde, çimento-bentonit geçirimsiz duvarların yapımında katkı maddesi olarak kullanılabileceğini göstermektedir. Uçucu kül içeren numunelerin geçirgenliği uçucu kül miktarı arttıkça artmaktadır. %50 GGBS Tip I-%5 Kireç-%9 Bentonit içeren numune 28 gün kür sonunda kabul edilebilir netice vermektedir. %50 GGBS Tip II-%5 Kireç-%9 Bentonit içeren numune 28 gün kür sonunda GGBS Tip I'li numuneye göre daha yüksek geçirgenlik vermektedir. Çelik cürufu ilaveli numunelerin çoğu 28 gün kür sonunda kabul edilebilir geçirgenlik değerleri vermiştir. Numunelerin serbest basınç mukavemeti kür zamanı arttıkça artmaktadır. Cc, Cr, Cv, kcon değerleri konsolidasyon deneyinden bulunmuştur. 150kPa efektif gerilme için, konsolidasyon deneyinden bulunan geçirgenlik (k) değerleri, esnek duvarlı permeametreden bulunan geçirgenlik değerlerinden 10 ila 100 kat fazladır. Genellikle, mv değerleri kür zamanı arttıkça azalmaktadır. mv değerleri azaldıkça, D artmaktadır.

Anahtar Kelimeler: Bentonit, Çimento,Uçucu Kül, Granüle Yüksek Fırın Curufu, Kireç, Geçirimsiz Perde Duvar, Stabilizasyon, Çelik Curufu

To My Parents...

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LIST OF ABBREVIATIONS

A	Specimen Cross Sectional Area
B	Pore Water Pressure
B	Bentonite
C	Cement
$\mathbf{C_c}$	Compression Index
$\mathbf{C_r}$	Swelling Index
$\mathbf{C_v}$	Coefficient of Consolidation
D	Constrained Modulus
$\mathbf{e_0}$	Initial Void Ratio
$\mathbf{e_1}$	Final Void Ratio
F	Fly ash
GGBS I	Ground Granulated Blast Furnace Slag Type one
GGBS II	Ground Granulated Blast Furnace Slag Type Two
$\mathbf{G_s}$	Specific Gravity
h	Head Loss
i	Hydraulic Gradient
k	Permeability
L	Lime
l	Length of Specimen
LDI	Laser Diffraction Instrument
LL	Liquid Limit
m	Mass of Mixture
$\mathbf{m_v}$	Coefficient of Volume Change
NP	Non-Plastic
PI	Plasticity Index
PL	Plastic Limit

PSD	Particle Size Distribution
Q	Out Flow Quantity
S	Steel Slag
UC	Unconfined Compressive Strength
$\mathbf{V}_1$	Initial Volume
$\mathbf{V}_2$	Final Volume
$\boldsymbol{\gamma}_w$	Unit Weight of Water
$\boldsymbol{\sigma}'_0$	Initial Effective Stress
$\boldsymbol{\sigma}'_1$	Final Effective Stress
$\Delta\mathbf{T}$	Time Interval
$\Delta\mathbf{u}$	Change of pore water pressure
$\Delta\boldsymbol{\sigma}_3$	Cell Pressure Increment

CHAPTER 1

INTRODUCTION

1.1 General

Slurry vertical barrier systems are widely used to control groundwater movements. A significant role of the barrier as remediation system is reducing the groundwater flow rate. In the United States, the most typical type of slurry materials that use in barrier wall is soil-bentonite (SB). On the contrary, cement-bentonite (CB) slurry wall are mostly constructed in the United Kingdom, the shear strength of these walls is considerably greater than soil-bentonite walls. For all methods, construction procedure involves trench excavation into subsurface to the desired depth and at the same time pumping of the slurry consist of about 95% of water and 4-6% bentonite by dry mass to maintain the walls stability. Cement-bentonite as slurry wall material is left to harden into the trench and let to hydration and curing. Cement-bentonite mixtures as slurry wall material are usually have hydraulic conductivity in the range of approximately 10^{-5} to 10^{-6} cm/s, while these limits for some sites could be insufficient.

1.2 Research Objective

The aim of this laboratory study is to use some industrial waste products as slurry wall material. The aim is to decrease the cement-bentonite walls permeability (the minimum permeability of 10^{-7} cm/s) and increasing the strength of the wall in long period of curing time. Different mixtures of cement, fly ash, lime, two types of ground granulated blast furnace slag and steel slag were evaluated for permeability, unconfined compressive strength and coefficient of volume change. Different percentages of materials in the mixtures were investigated, the effect of curing time on these mixtures were also investigated. It is tried to improve the permeability and strength of the cement-bentonite slurry wall.

1.3 Scope of the Research

The scope of this study is to consider the effect of industrial pozzolanic waste material (i.e. Ground granulated blast furnace slag (GGBS), steel slag and fly ash) and cement as a backfill material in the slurry trench wall. Two types of ground granulated blast furnace slag (GGBS), steel slag and fly ash as supplementary cementitious material replaced by Portland cement for each mix design. The permeability, unconfined compressive strength and compressibility properties of fly ash-CB, steel slag-CB and (GGBS)-CB mixtures, at different curing times, were investigated.

CHAPTER 2

LITERATURE SURVEY

Cement-bentonite slurry walls, Soil-bentonite slurry walls, Diaphragm walls, Vibrating beam walls, Plastic concrete walls, Deep cutoff walls, Composite slurry walls, Grouting barrier walls and Steel sheet pile walls are different types of vertical barrier walls.

2.1 Slurry Wall

Slurry wall as a vertical barrier is designed and constructed to control contaminant migration into the subsurface area. The main function of slurry wall is to encapsulate the contaminated area and minimize the horizontal movement of hazardous or non-hazardous waste into the groundwater, (Figure 2.1). These walls reduce the rate of the pollutant movement from the site. Slurry walls can be circumferential, down gradient or up gradient. Slurry walls are almost keyed into a stratum of low permeability. Permeability of 10^{-7} cm/sec specified for these walls. First a trench is excavated by clamshell, dragline or backhoe. The backfill material is replaced in the slurry trench. Resistance of the material in terms of chemical attacks, alkali reactivity, etc, is important. In the last decade, different plastic mixes have been used. This is significantly necessary when the cut off wall is constructed in seismic area where large displacements occur because of earthquake load.

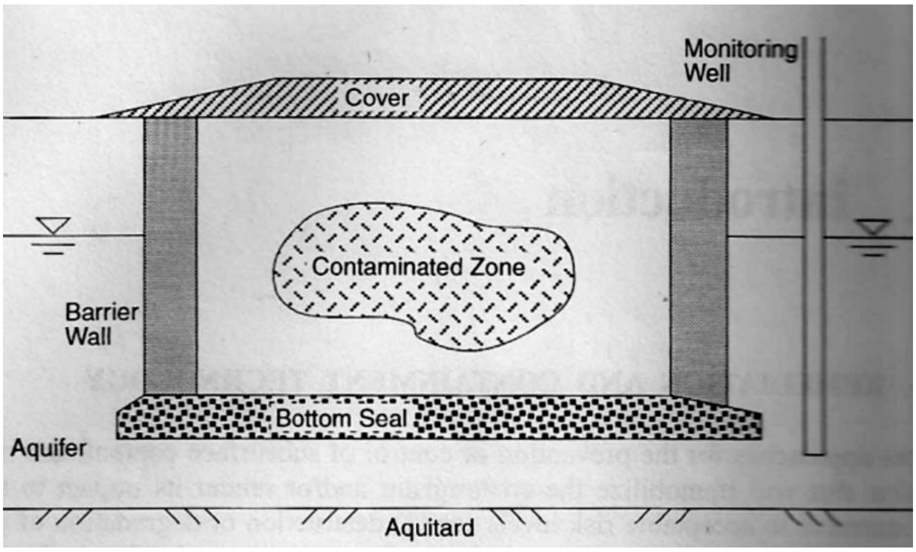


Figure 2.1 Slurry barrier remediation system for contaminated site

Slurry walls have been widely used in the case of passive barrier systems. The soil-based mixtures are widely used in the US. These mixtures are mostly mixes of bentonite-water slurry and excavated trench soils in the field. There are many investigations on clayey soils, which give low permeability as required to form the barrier. Fresh mixtures of backfill material in the slurry wall are supposed to have good workability and flowability. However, materials used as slurry usually expected to give a filter cake by acceptable low permeability along the wall/excavation face. These materials, however, can diminish the permeability to the (10^{-7} cm/sec to 10^{-9} cm/sec). On the other hand, most of the clays have organic content that could take potential source for hazardous bacterial growth and adsorb heavy metal attenuation. The self-hardening mixtures, however, involves cement, bentonite and water as well. Cement-bentonite slurry walls are excavated under a head of slurry mixed with water, bentonite and cement. Cement-bentonite slurry walls have permeability in the range of 10^{-5} to10^{-6} cm/sec see

Figure 2.2. Cement-water ratio is normally in the range of 0.15 to 0.25. In addition, the bentonite portion mixed by water as slurry is typically 3% to 5% by dry mass. Cement-bentonite as slurry wall material normally cannot have the minimum required permeability value of 10^{-7} cm/sec determined in the standard. These walls are often used where high strength of the wall is required.

2.2 Cement-Bentonite Slurry Walls

These kinds of slurry walls typically are excavated beneath a head of slurry of bentonite-water, and cement-bentonite backfill material is replaced. Cement-bentonite slurry walls have permeability not less than 10^{-5} to 10^{-6} cm/sec. Cement-bentonite slurry walls have restricted use for hazardous zones.

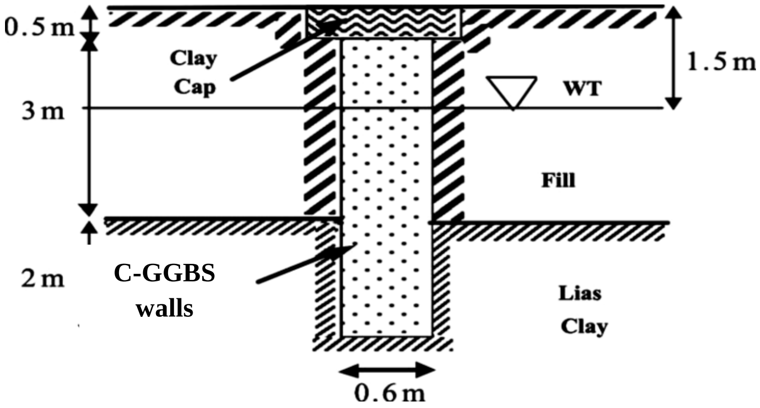


Figure 2.2 An example of slurry wall cross section

Since cement-bentonite slurry walls cannot limit the permeability to the desired value some industrial waste materials such as fly ash, steel slag and GGBS can improve and decrease it even below the 10^{-7} cm/s. Self-hardening barrier walls typically constructed in site using fly ash-cement-bentonite (F-CB), slag-cement-bentonite (S-CB) or ground granulated blast furnace slag-cement-bentonite (GGBS-CB) slurries. In the last two decades slag-CB slurry walls has constructed extensively in the U.K. Slurry having cementitious material such slag-CB typically sets slowly in long time to form a slurry wall with low permeability. Throughout the wall construction, some of the lateral soils inside of the wall can fall into the slurry, and if it is more than expected, it can affect the engineering properties of the wall. Because of intrinsic variability of material mixes, the U.K. National Specification (ICE 1999) requires the minimum laboratory permeability value of 10^{-7} cm/s for 90 days cured specimen.

For CB and Slag-CB slurry walls permeability change with curing periods, Opdyke and Evans (2005) and Jefferis (2008) have been reported the change in permeability during earlier months. The permeability of the tested specimens was less than 10^{-7} cm/s determined by ICE for the 90 days curing time. Joshi et al. (2010) have studied the effect of curing time on permeability for 11 years and the permeability was below (1.1×10^{-9} to 8×10^{-9} m/s) for laboratory samples, (5.8×10^{-9} to 1.7×10^{-8} m/s) for in situ tests, (2.4×10^{-9} to 5.6×10^{-7} m/s) for the block samples. Figure 2.3 gives the permeability test results (Joshi et al. 2012). Some advantages of these supplementary cementitious materials are:

- Resistance to chemical attack
- Resistance to alkali reactivity
- Increase workability
- Setting time retardation
- Reduce shrinkage
- Increase long term strength
- Reduce permeability
- Increase sulphate resistance

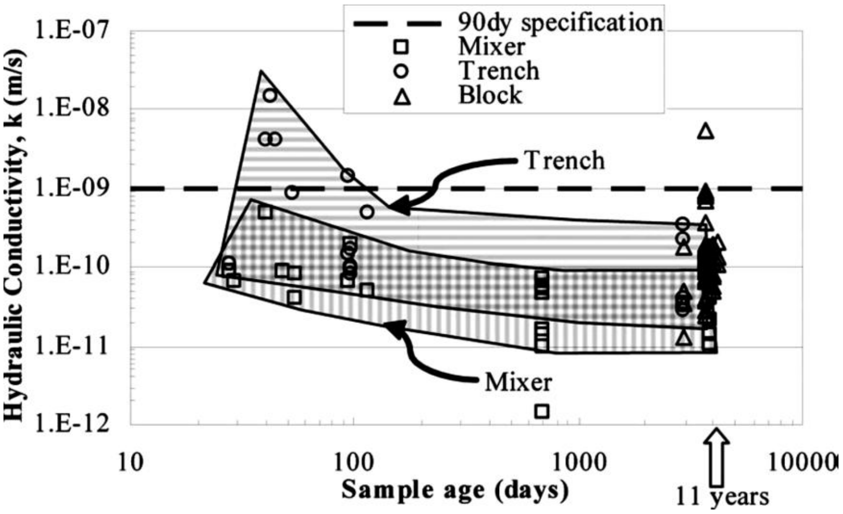
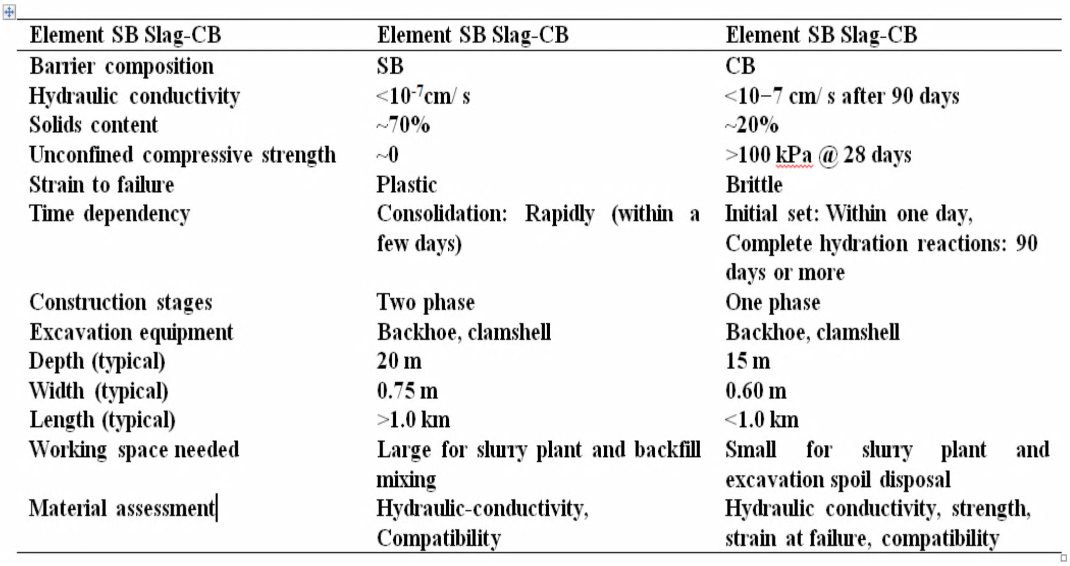


Figure 2.3 Laboratory permeability results in different cases (Joshi et al. 2010)

2.3 Use of GGBS and Bentonite in Slurry Walls

For the cement-bentonite slurry preparation, sodium bentonite is mixed with water and typically allowed to hydration before mixing it by cementitious material.
Essential factors of the Slag-CB and Soil-bentonite has summarized in Table 2.1

Table 2.1 SB and Slag-CB slurry wall properties (Evans and Dawson 1999).



Element SB Slag-CB	Element SB Slag-CB	Element SB Slag-CB
Barrier composition	SB	CB
Hydraulic conductivity	$<10^{-7}$cm/ s	<10−7 cm/ s after 90 days
Solids content	~70%	~20%
Unconfined compressive strength	~0	>100 kPa @ 28 days
Strain to failure	Plastic	Brittle
Time dependency	Consolidation: Rapidly (within a few days)	Initial set: Within one day, Complete hydration reactions: 90 days or more
Construction stages	Two phase	One phase
Excavation equipment	Backhoe, clamshell	Backhoe, clamshell
Depth (typical)	20 m	15 m
Width (typical)	0.75 m	0.60 m
Length (typical)	>1.0 km	<1.0 km
Working space needed	Large for slurry plant and backfill mixing	Small for slurry plant and excavation spoil disposal
Material assessment	Hydraulic-conductivity, Compatibility	Hydraulic conductivity, strength, strain at failure, compatibility

Note: SB=soil-bentonite; CB=cement-bentonite

The effect of blast furnace slag substitution on the permeability is illustrated in Figure 2.4 (Trietley 1996; Veracco and Smith 1997).
Opdyke and Evans (2005) prepared samples by using bentonite-water slurry where the batch slurry consisting of 5% sodium bentonite mixed with 95% tap water. All samples mixed by GGBS and Portland Cement Type I as cementitious material. Flexible wall permeameter was used to measure the permeability of all samples. For first step, samples have subjected to backpressure. A backpressure of 275 kPa was applied for 24 h. In addition, a cell pressure of 380 kPa applied to give the effective stress of 105 kPa. One month of curing was applied. Slag replacements of 0 to 70% have tested.

Because of low permeability of one month cured samples with 80 % to 90% of slag substitution, a hydraulic gradient of 25 was used. The permeability test results are shown in Figure 2.5 (Opdyke and Evans. 2005).

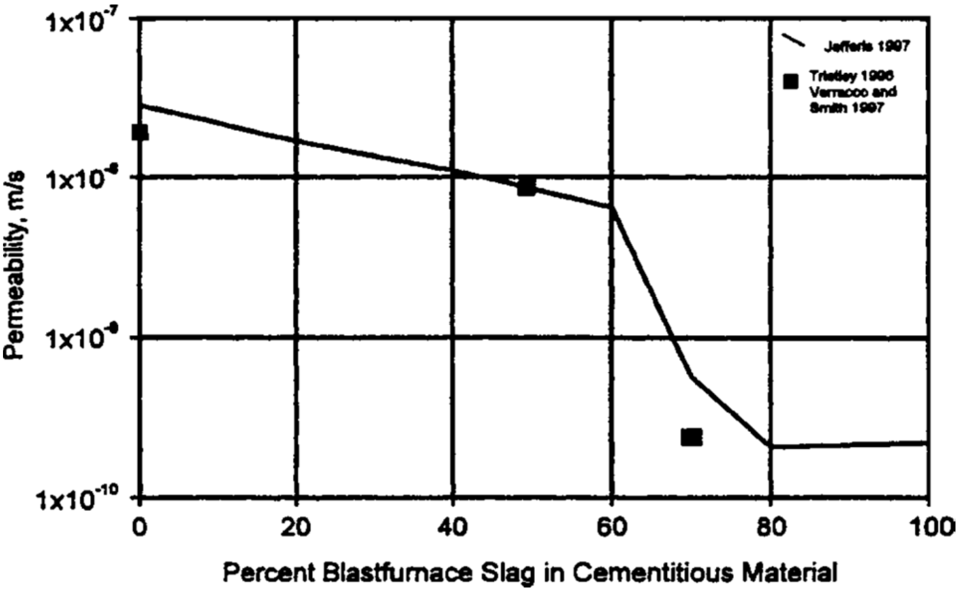


Figure 2.4 Slag replacement effect on permeability (Trietley 1996; Veracco and Smith 1997)

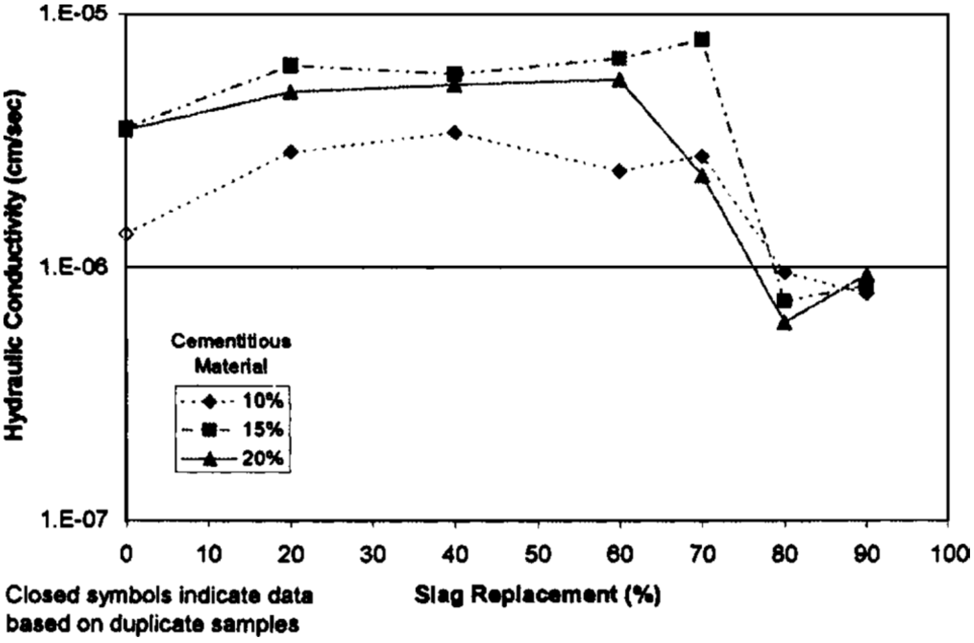


Figure 2.5 Permeability of one month cured samples (Opdyke and Evans. 2005)

It is noted that, for two months of curing, all mixtures by 80% of slag substitutions show the permeability of 1×10^{-6} cm/s (Figure 2.6) Opdyke and Evans (2005), also provided the permeability test results for three, six and twelve months in Figure 2.7, Figure 2.8, and Figure 2.9, respectively.

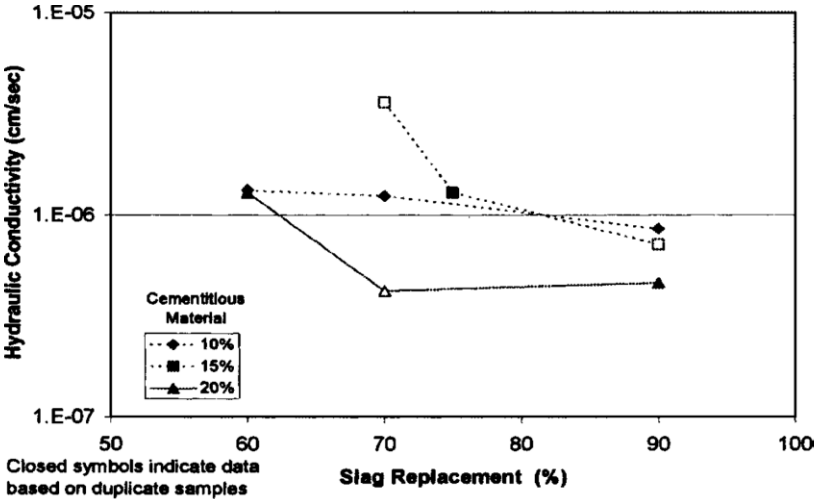


Figure 2.6 Permeability of two months cured samples (Opdyke and Evans. 2005)

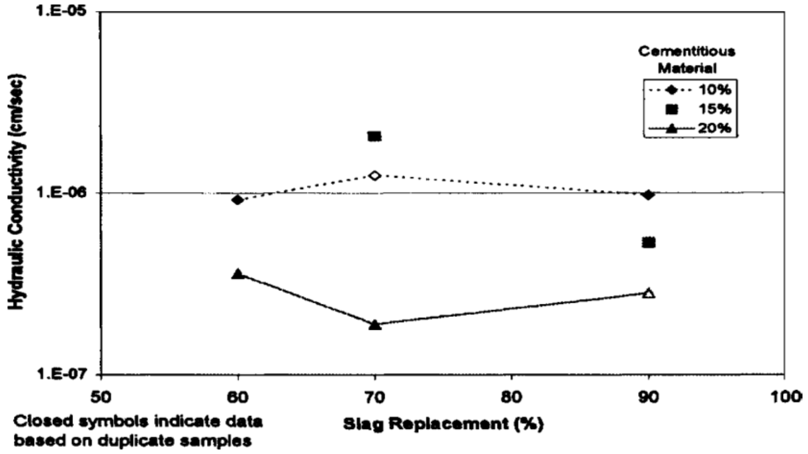


Figure 2.7 Permeability test results of three months cured samples (Opdyke and Evans. 2005)

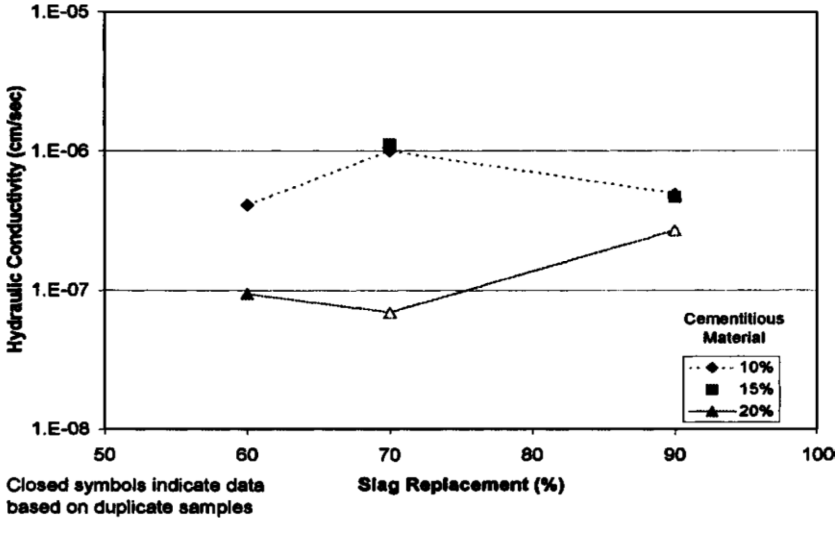


Figure 2.8 Permeability test results of six months cured samples (Opdyke and Evans. 2005)

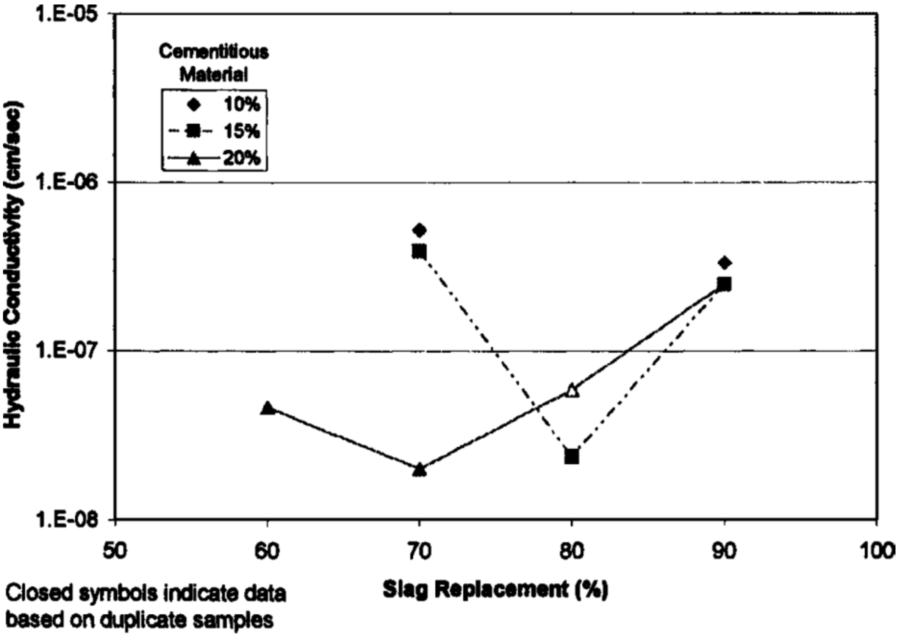


Figure 2.9 Permeability test results of twelve months cured samples (Opdyke and Evans. 2005)

As shown in Figures 2.7 to Figure 2.9, mixtures having 20% of cementitious material by slag replacement of 70% gave the minimum permeability values. In contrast, permeability has increased by increasing of slag replacement from 70% to 90%. For the same mixture designs, relationship between slag replacement and unconfined compressive strength is shown in Figure 2.10, (Opdyke and Evans. 2005). These test results show that by increasing cementitious material portion unconfined compressive strength increases. The relationship between slag replacement and strain at failure is given in (Figure 2.11).

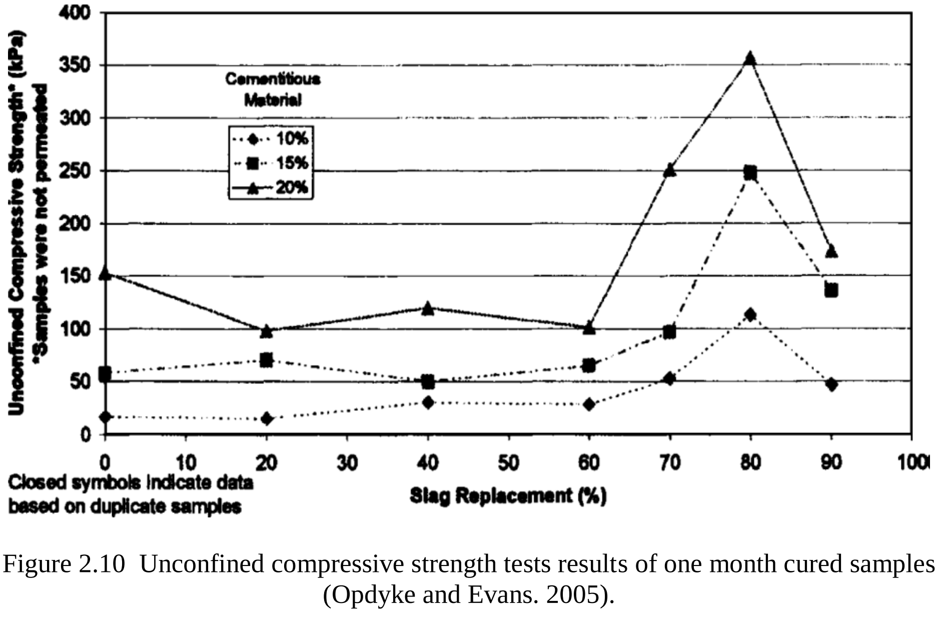


Figure 2.10 Unconfined compressive strength tests results of one month cured samples (Opdyke and Evans. 2005).

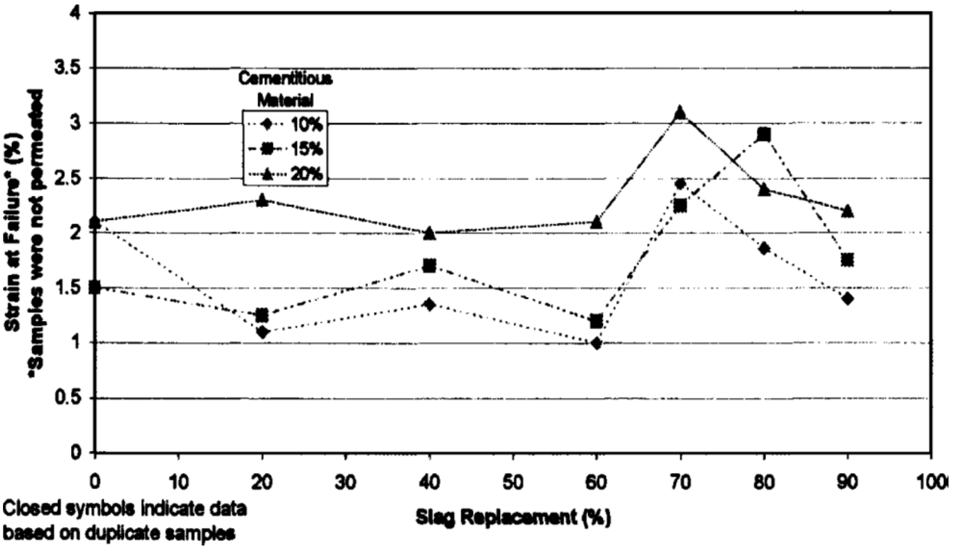


Figure 2.11 Slag replacement effect on strain at failure (Opdyke and Evans. 2005)

2.4 Use of Fly Ash-Cement-Bentonite in Slurry Walls

During burning of coal in the thermal power plant for electricity production, fly ash as waste material is produced. Fly ash fines, that are silt size, acts as non-plastic material and typically do not have surface charges. On the other hand, remained unburned carbon in the fly ash can adsorb many ions appear in the leachate (LaGrega et al. 1994). Fly ash containing large amount of carbon are especially good while the surrounded area has contaminants in the leachate. In addition, fly ash due to their alkalinity property could precipitate some of the heavy metals in the leachate. Most of the fly ashes are pozzolanic types that improve the strength and acquire capacity to reduce the permeability (Prashanth et al. 2001). Fly ash typically gives the higher permeability than clays (Bowders et al. 1990).

Chi-Pu reservoir of International Taoyuan Airport MRT system has constructed. To prevent the contamination of underground water stream of Shin-Jie river beneath the site it was necessary to construct the slurry barrier system. Dave et al. 2011, used fly ash to decrease the permeability of soil-cement material for the seepage cutoff walls for this application. For the mentioned study class F fly ash that produced in Lin-Kou power plant in Taiwan has been used for wall stability and waterproofing. Evaluation of the influence of fly ash to diminish the permeability has done by twelve tests. The specimens having diameter of 6.8 cm and height of 12 cm were used. The results of three different cement contents (5%, 7% and 9%), four different fly ash portions (0%, 11%, 13% and 15%) and three different curing times (7 days, 14 days and 28 days) are given in Figure 2.12, Figure 2.13 and Figure 2.14. Figure 2.15 - Figure 2.17 demonstrate the compressive strength and fly ash portion relationship for the different curing times.

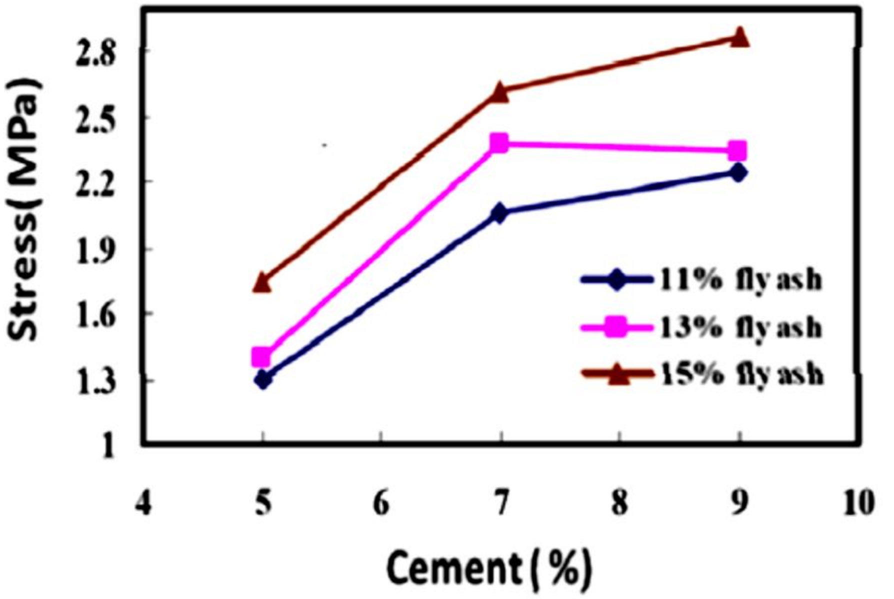


Figure 2.12 Effect of cement and fly ash content on strength of 7 days cured samples (Dave et al. 2011)

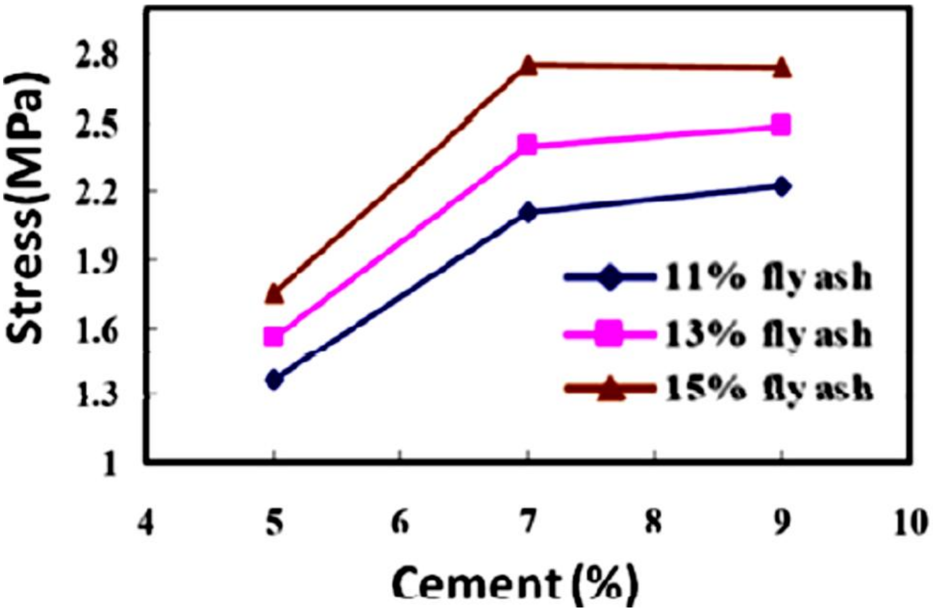


Figure 2.13 Effect of cement and fly ash content on strength of 14 days cured samples (Dave et al. 2011)

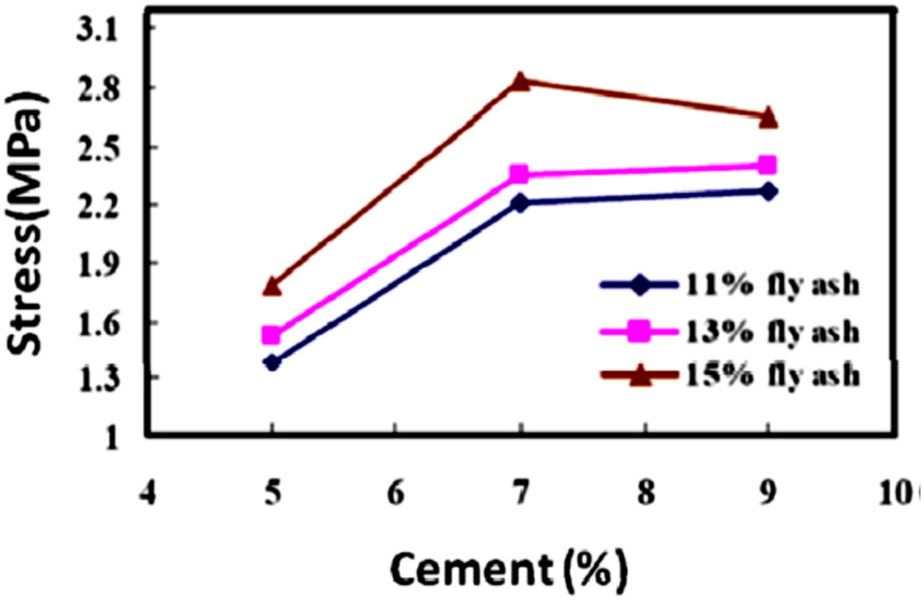


Figure 2.14 Effect of cement and fly ash content on strength of 28 days cured samples (Dave et al. 2011)

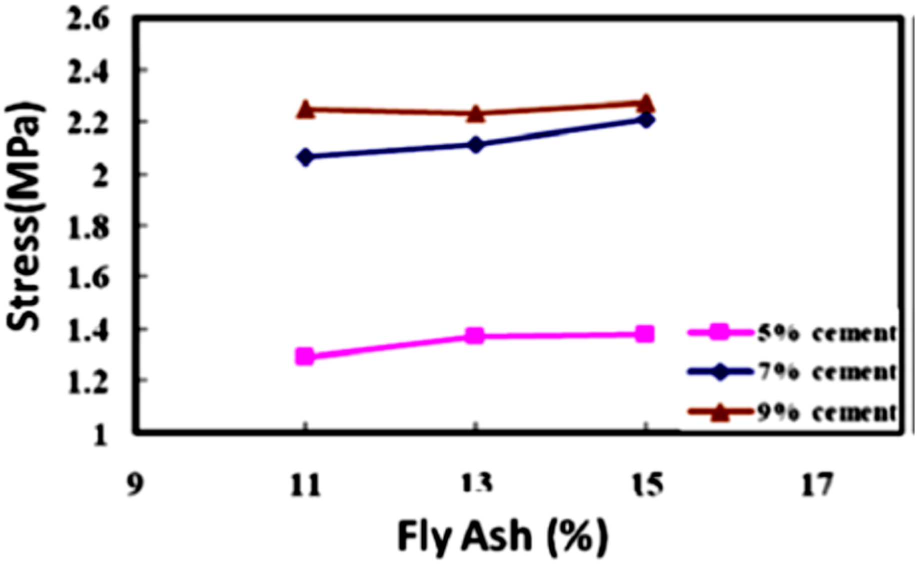


Figure 2.15 Effect of fly ash on strength, 7days cured samples (Dave et al. 2011)

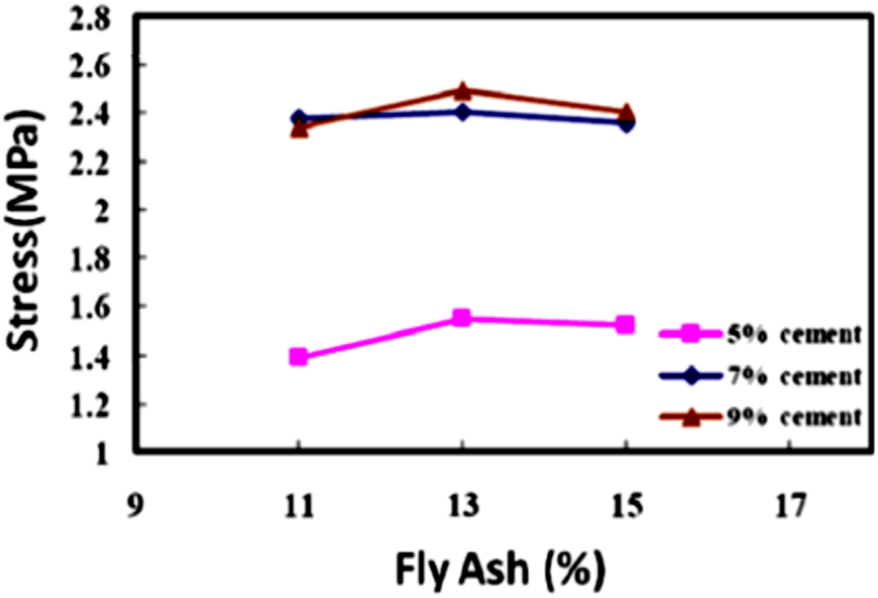


Figure 2.16 Effect of fly ash on strength, 14 days cured samples (Dave et al. 2011)

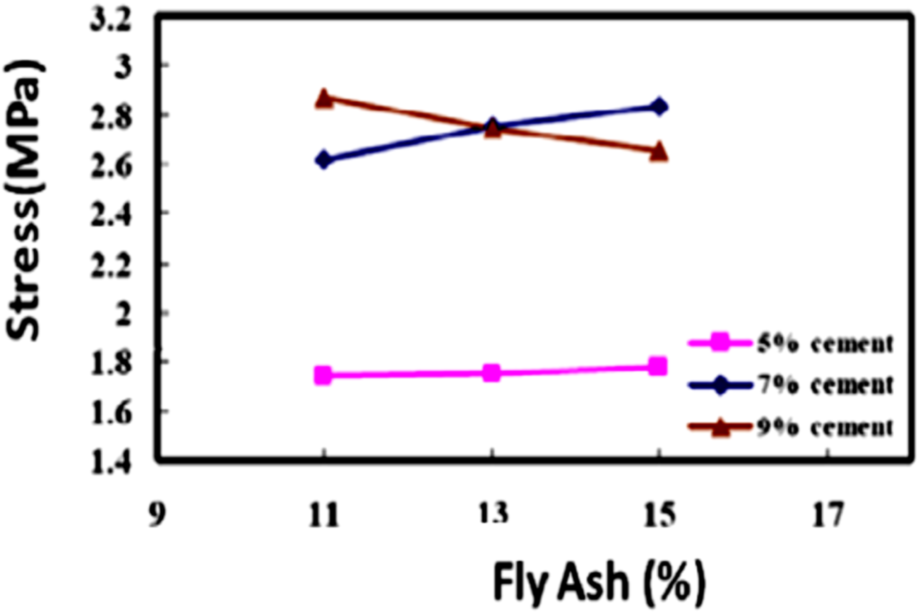
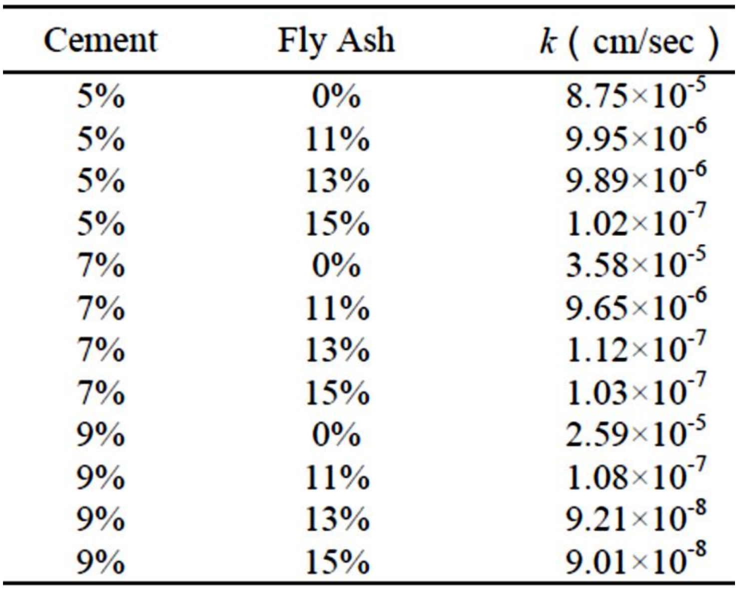


Figure 2.17 Effect of fly ash on strength, 28 days cured samples (Dave et al. 2011)

Dave et al. (2011) also gives the permeability test results for each mixture, see Table 2.2

Table 2.2 Permeability test results (Dave et al. 2011)



Cement	Fly Ash	k (cm/sec)
5%	0%	8.75×10^{-5}
5%	11%	9.95×10^{-6}
5%	13%	9.89×10^{-6}
5%	15%	1.02×10^{-7}
7%	0%	3.58×10^{-5}
7%	11%	9.65×10^{-6}
7%	13%	1.12×10^{-7}
7%	15%	1.03×10^{-7}
9%	0%	2.59×10^{-5}
9%	11%	1.08×10^{-7}
9%	13%	9.21×10^{-8}
9%	15%	9.01×10^{-8}

CHAPTER 3

SAMPLES AND EXPERIMENTAL METHODS

3.1 General

In this study, cement type I, Soma fly ash, two types of granulated blast furnace slag, steel slag, lime and sodium bentonite have been used. Supplementary cementitious materials (Soma fly ash, two types of granulated blast furnace slag, steel slag) were used to improve the slurry wall material properties. Permeability, strength, slump, consolidation parameters, properties of the mixtures have found and checked by the minimum requirements.

The permeability, unconfined compressive strength, and compressibility of fly ash-CB, steel slag-CB, and GGBS-CB mixtures for various curing times were investigated. Fresh mixtures should have slump of 4-6 inch for slurry walls according to standard (Opdyke and Evans. 2005). All of the prepared mixtures have slump of 4-6 inch. In this study, the cementitious material content used in the slurry was 20% by dry mass. Remaining 80% of the slurry contains bentonite-water slurry. Two different batch slurries with different bentonite content were used. Bentonite contents of 5 % and 9 % by dry mass mixed by distilled water for batch slurries. The percentages of supplementary cementitious materials replaced by the Portland cement content are; 0 %, 20 %, 50 % and 80 %. All prepared samples cured in 100 % humidity room. Samples were tested after 7 days, 28 days, and 90 days of curing periods. Cured specimens were subjected to permeability test, unconfined compression test and compressibility test. Compressibility test results were used to find the coefficient of volume change (m_v), compression index (C_C), swelling index (C_r), coefficient of consolidation (C_v) and consolidation permeability value (k_{con}). For permeability test, the effect of three months of curing has been evaluated on the samples of 50% GGBS replacement and steel slag replacement. Nakamura et al. (1992) states that the effect of 50% GGBS replacement on compressive strength has better results than more replacements.

3.2 Mixture Design and Schedule

Tests were carried out in four series. First series contains fly ash-CB and GGBS-CB (GGBS type I). Replacement percent of cement for this series was 0%, 20%, 50% and 80%. Fly ash was produced in Soma thermal power plant in Turkey. Chemical composition of fly ash categorized it as class C fly ash. In the second series sample having 50% of GGBS replacement, which gives best results in previous series, has been modified. Lime content of 5% and bentonite content of 9% were used to reach higher strength and lower permeability. In the third series, GGBS type II was used to compare with the GGBS type I. This series of the study examines the strength and permeability properties of different kind of GGBS (type II). GGBS replaced by cement in amounts of 20%, 50%, and 80%. In this series, sample having 50% of GGBS replacement has been amended as well. Lime content of 5% and bentonite content of 9% were used to reach higher strength and lower permeability.

For the fourth series, steel slag was used as replacement of cementitious material. Cured specimens were subjected to both permeability and strength tests. Mixture design and cementitious material content were the same as in the third series. The effect of curing period of 7 days, 28 days, and 90 days were also investigated.

3.3 Material

3.3.1 Fly Ash

Fly ash used in this study was produced in Soma thermal power plant, in Manisa Turkey. Strength of fly ash in the long-term is dependent on the amount of calcium content. Chemical composition of Soma fly ash includes Al_2O_3 of about 30 % and CaO amount of 10 %. These mentioned components react with cement in long period and help to improve engineering properties. Table 3.1 gives the chemical composition of Soma fly ash. This composition demonstrates that the Soma fly ash is class C fly ash in accordance to ASTM C618-08. Class C fly ash has better self-hardening properties than class F. Fly ash slurry shows good workability and flowability. A sample and SEM micrographs of Soma fly ash are shown in Figure 3.1(a) and Figure 3.1(b), respectively.

Table 3.1 Chemical composition of Soma fly ash Analysed by SEM micrographs

Elements	(% by weight)
Al_2O_3	26.34
CaO	9.64
Fe_2O_3	6.67
K_2O	1.18
LOl	1.82
MgO	2.20
Na_2O	5.20
SiO_2	44.45
SO_3	1.50
TiO2	0.99
Total	99.99

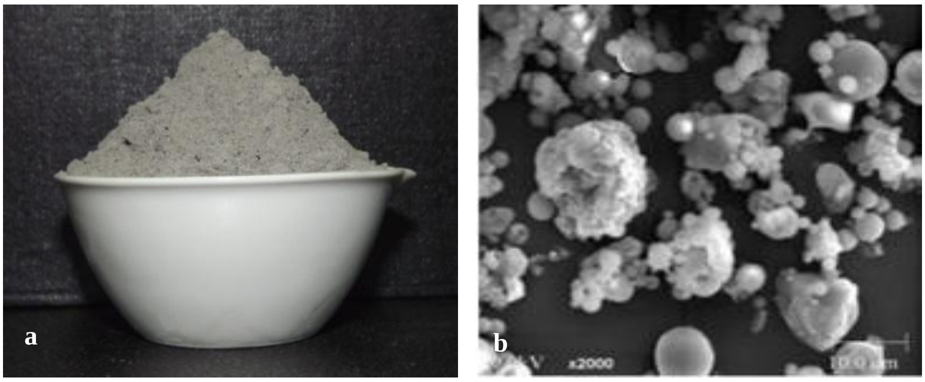


Figure 3.1(a) Soma Fly Ash, (b) SEM micrographs of Soma fly ash

3.3.2 Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag (GGBS) were produced as a by-product during iron manufacturing. Ground granulated blast furnace slag was dried and powdered after manufacturing. The composition of a GGBS depends on the raw materials during iron manufacturing. Moreover, main component of GGBS are Al_2O_3 (8 % to 24 %), CaO (30 % to 50 %), SiO_2 (28 % to 38 %) and MgO (1 % to 18 %). Typically, by the rising of CaO amount in the GGBS, its strength also increases.

Two types of GGBS, produced in Turkey by two different factories, were used in this study. Fresh mixture of GGBS-cement slurry shows better flowability and workability. This material has the moderate activity index (120) (specified by concrete and 50 % of slag replacement) according to ASTM C989-11. GGBS type I is in powder form and used directly after passing sieve number 50 Figure 3.2(a). On the other hand, GGBS type II is in sand size form and grinded in ball mill grinding operation, Figure 3.2(b) and Figure 3.2(c). Powdered GGBS was passed sieve number 100 after grinding. Powdered material achieved in silt size after grinding.

Figure 3.2 GGBS samples; (a) GGBS type I, (b) GGBS type II, (c) Powdered GGBS type II

Figure 3.3(a), shows the grinding system used for the first step powdering operation for sand size of GGBS type II. Figure 3.3(b) shows the second grinding operation on the material obtained from the first step, for powdering material to finer than 0.6 mm (passing sieve number 30). Finally, materials obtained from the second step were placed in the ball mill to powder the material to silt size (see Figure 3.3(c)). For each step of powdering, about 1 kg of material was introduced into the container. Balling mills and material occupy about half of the container volume, and grinding operation took 2 hours for each step. Typical chemical composition of ground granulated blast furnace slag is shown in Table 3.2.

Table 3.2 Typical chemical composition of GGBS

Constituent	**Composition (%)**
Aluminium Oxide (Al_2O_3)	**14-22**
Basicity (CaO/SiO_2)	**0.1-1.3**
Calcium Oxide (CaO)	**31 - 40**
Ferrous Oxide (FeO)	**0.1-1.9**
Magnesium Oxide (MgO)	**7-11**
Manganese Oxide (MnO)	**0.01-1.2**
Silicon Dioxide (SiO2)	**29-38**
Sulphur	**1-1.9**

Figure 3.3 Powdering procedure, (a) breaking operation, (b) operation step 2, (c) final powdering

3.3.3 Steel Slag

Steel slag is produced as by product during steel production. Steel slag typically involves magnesium and free lime. These two components never react by the silicate part of other material. In addition, these two components can expand and hydrate after mixing with water or even in humid environment. The volume change of up to the 10 % can cause problem in concrete, using of steel slag as aggregate in concrete with 35% to 45 % water content is unsuitable. On the other hand, tendency to expand could have some beneficial points in geotechnical application. Expansion however, could prevent cracking that increase permeability. Therefore, this characteristic of steel slag when mixed with around 80 % of water could be helpful for slurry wall application. Steel slag for this experimental study has been produced in Erdemir Iron and Steel Plant in Turkey. Initial steel slag were in gravel size before to use. Steel slags were powdered in the laboratory as explained before (see Figure 3.3(a), (b) and (c)). Figure 3.4(a) and (b) shows steel slag material before and after powdering. Typical chemical composition of steel slag is given in Table 3.3.

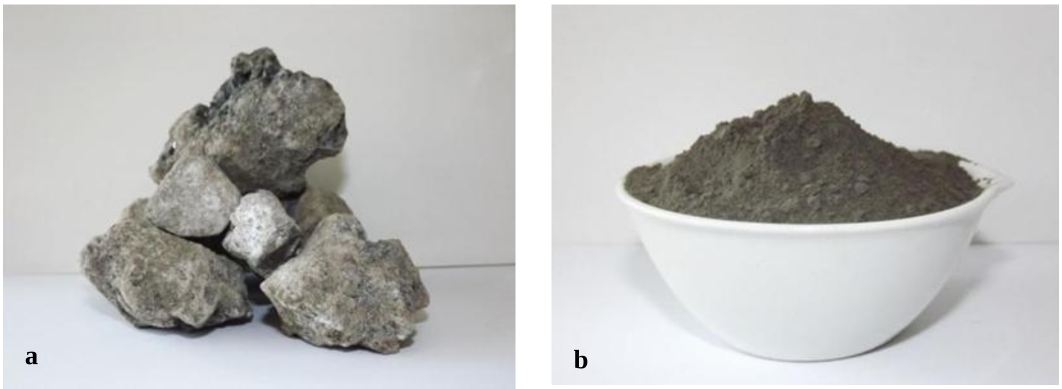


Figure 3.4 (a) steel slag , (b) powdered steel slag

3.3.4 Portland Cement

Cement type I (general-purpose, early strength gaining), has been used for this investigation. This type of cement gains early strength in a shorter time than normal cement. According to ASTM C150, cement type I was classified as CEM I, 42.5R, Clinker (95-100) Figure 3.5(a).

3.3.5 Permeability Test

Permeability test was carried out according to method E ASTM D5084-03 Constant Volume–Constant Head test. Permeability tests were conducted by triaxial cell permeameter system. A flexible membrane, two filter paper, two rubber O-rings, and two porous disks were used for specimen encapsulation (Figure 4.6). A porous disk put on permeameters pedestal and a filter paper placed on porous disk. Specimen was placed on the filter paper. The filter paper and a porous disc were placed on top of specimen, respectively. Flexible membrane set into the membrane expander, which has a hole for suction (Figure 4.7(a) and (b)).

Table 3.3 Chemical composition range of steel slag

Constituent	Composition (%)
Al_2O_3	**1-3**
CaO	**40-52**
FeO	**10-40** **(70 - 80 FeO, 20 -Fe2O3)**
Metallic Fe	**0.5-10**
MgO	**5-10**
MnO	**5-8**
P_2O_5	**0.5-1**
S	**< 0.1**
SiO_2	**10-19**

3.3.6 Bentonite

Powdered Karakaya sodium bentonite was used in batch slurry preparation (Figure 3.5(c)). The sodium bentonite adsorbs water 20 times more than calcium bentonite. This is due to great specific surface area of sodium bentonite comparing to calcium bentonite. Mineralogical properties and engineering properties of Karakaya bentonite are given in Table 3.4 and Table 3.5, respectively.

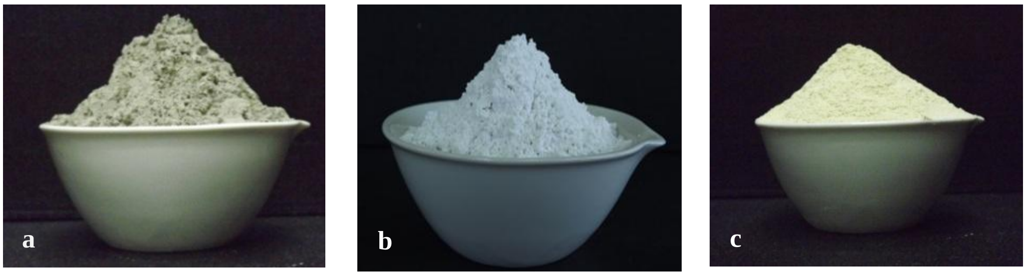


Figure 3.5 Materials, (a)Portland Cement, (b) Lime, (c) Karakaya Sodium Bentonite

Table 3.4 Mineralogical properties of the Karakaya bentonite

Mineralogical Component	By weight (%)
Quartz	**5**
Smectite	**71**
Zeolite	**19.50**
Others	**4.50**

Table 3.5 Engineering properties of the Karakaya bentonite

Parameter	Quantity
Dry density(Mg/m^3)	**0.8**
Natural density(Mg/m^3)	**0.87**
Water content (%)	**8**
Specific gravity	**2.17**
Void ratio (%)	**1.89**
Porosity (%)	**65**
Liquid limit (%)	**320**
Plastic limit (%)	**50**
Plasticity Index (%)	**270**
Cation exchange capacity (meq/100 g)	**55-60**

3.4 Experimental Setup

Experimental system for all tests in this study are:

- Plastic mold
- Dial gage
- Specific gravity G_s flask
- High speed electrical mixture

- Casagerande cup
- Laser diffraction instrument (LDS)
- Hydraulic jack (extruding) system
- Flexible-wall Permeameter
- Flow determination tube
- Unconfined compressive strength apparatus
- Consolidation apparatus

3.4.1 Plastic Mold

Plastic pipe (PPRC) with the length of 4 m and external diameter of 63 mm and internal diameter of 44 mm was cut to small pieces to produce sample molds. These plastic pipes are used to transport water under high pressure. Sample molds were prepared to a dimension, having 10 cm in height and 5 cm in internal diameter. Industrial scissors were used to cut each tube to the length of 0.6 m. Prepared tubes of 0.6 m in length were cut to 10 cm in length pieces. Finally, inside diameter of each mold was adjusted to 5 cm. This procedure was done very carefully and took several days. Dimension of the molds were in the range of 0.01 mm- 0.05 mm tolerances (See Figure 3.6).

3.4.2 Dial Gage

10 mm mechanical dial gages with a sensitivity of 0.001 mm were used for oedometer tests to measure vertical displacement (Figure 3.7). Two dial gages were used for unconfined compressive strength test. For the strain measurement, 25 mm dial gage by a sensitivity of 0.01 mm was used. For the vertical stress measurement, 25 mm dial gage with a sensitivity of 0.002 mm was used (see Figure 3.8(a) and (b)).

Figure 3.6 Plastic mold

Figure 3.7 Dial gage used for the consolidation test

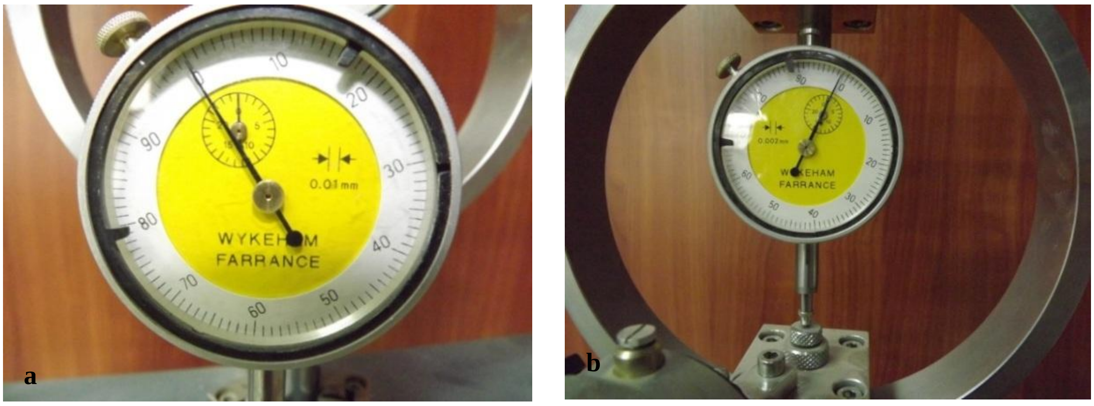


Figure 3.8 (a) dial gage for strain measurement, (b) dial gage for stress measurement

3.4.3 Specific Gravity (G_s) Flask

The standard chartlined flask was illustrated to mixtures G_s determination. This is manufactured by circular shape and two nakes in the flask. There are uniformity graduation and spacing in both nakes. 10 mm graduation nake adjusted between the glass supporter and upper reading nake. Illustrated glass has free of any striae, chemicall resistant, and low amount of thermal hysteresis. Upper reading nake has graduated from 18 mL to 24 mL, regarding final volume change. Ground glass stopper was used to intrupt kerosine evaporation during the test procedure (See Figure 3. 9).

3.4.4 High Speed Electrical Mixture

High-speed electrical mixture was used for bentonite-water mixing (Figure 3.10). It should be note that, there are two levels for the rotation speed of the device. For the initial mixing in early age of the batch slurry the low level of speed was selected. For the next days, it is used in high speed to have well-mixed slurry.

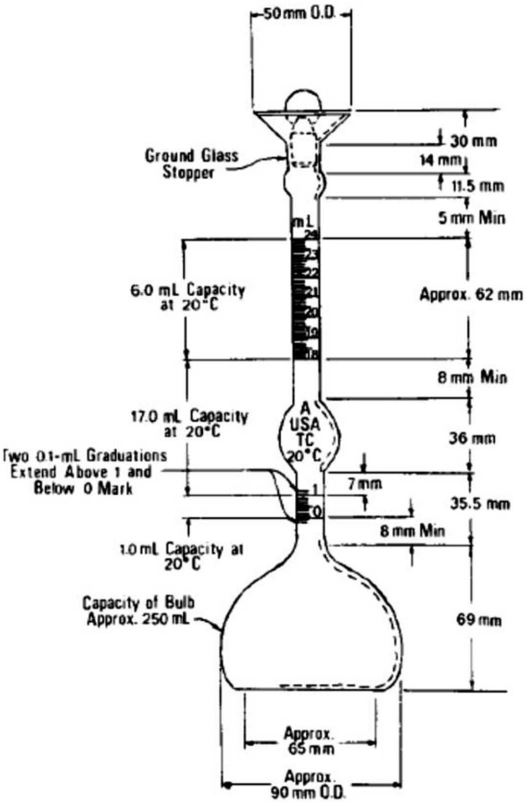


Figure 3.9 Graduation G_s flask

3.4.5 Casagrande Cup

The device is operated by hand. 25 drops gives the liquid limits of the soil for the related water content. Grooving tool made of non-corroding metal is used for grooving of samples placed into the cup. Grooving tool is also used for adjusting height of drop of device (see Figure 3.11).

3.4.6 Laser Diffraction Instrument (LDI)

The advantageous using of the laser diffraction instrument for particle size determination started from 1970s. This method can be applied to other materials such as; cement, ceramics, sand and even sprays. The laser instrument used for this investigation is shown in Figure 3.12. The main parts of this system (laser unit, preparation unit, and the computer) are given in Figure 3.13. Materials passed through the sieve number 200 must be used in this system.

Figure 3.10 Sharp edges rod

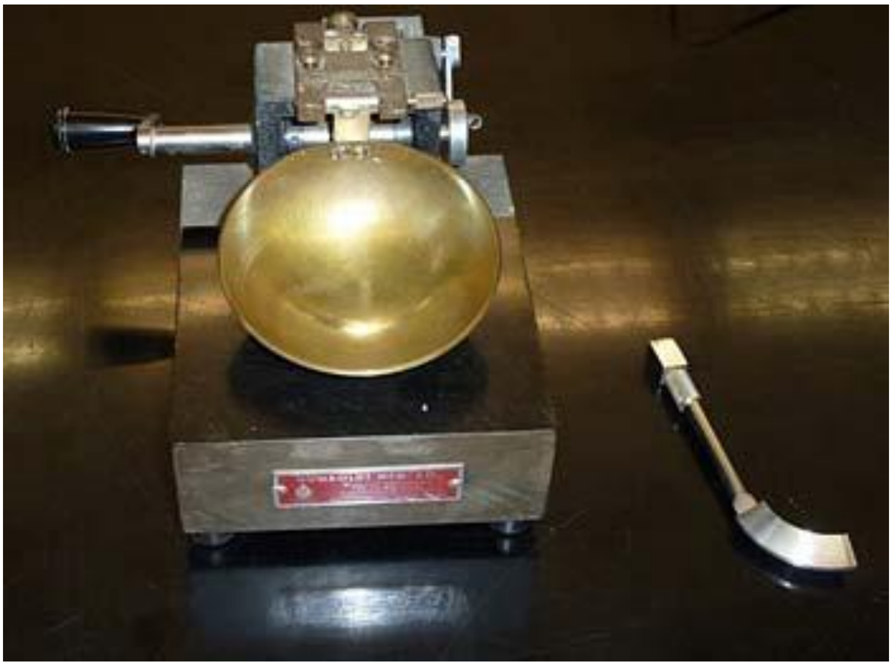


Figure 3.11 Casagrande device

Figure 3.12 Laser Diffraction Instrument

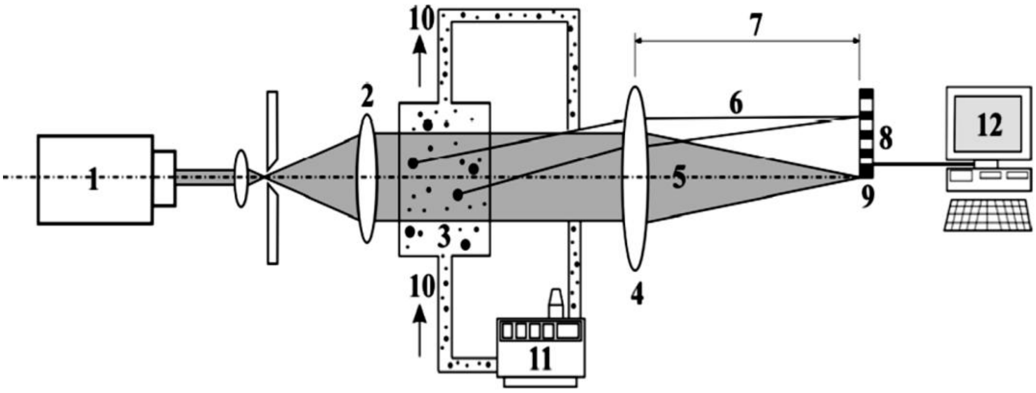


Figure 3.13 Laser diffraction instrument

The main 12 parts of (LDI) are consisting of; 1) Laser source, 2) Expander lens, 3) Measuring cell, 4) Fourier lens, 5) Inconspicuous ray that do not encounter with any particles , 6) Grains of the same size by multiplying the refracted rays, 7) Focal length of the lens, 8) Multi-element detector, 9) central detector, 10) Suspension flow direction, 11) Sample preparation unit, 12) Computer.

3.4.7 Hydraulic Jack (Extruding) System

This system is used to extrude samples for both unconfined compressive strength and permeability tests, Figure 3.14.

Figure 3.14 Hydraulic jack (extruding) system

3.4.8 Flexible-wall Permeameter

This method gives the coefficient of permeability (*k*). The liquid permeant used for this study was distilled water. In addition, the distilled water was used for back pressure system. Permeameter system was capable to maintain stable hydraulic pressure with the tolerance of ± 5 %. Both outflow and inflow volume measurements were done by vertical standpipe and graduated tail water tube, respectively. Cell pressure was applied by water into the permeameter cell. Cell pressure system was capable to control the pressure below the ± 5 % determined in ASTM D 5084-03 (Figure 3.15).

3.4.9 Flow Determination Tube

Inflow volume was measured by graduated tail water measurement system (U shape), (Figure 3.16). The backpressure was applied through tubes into the volume change measurement, after transferred into the specimen. Amount of exit water from specimen was measured in the outflow vertical standpipe.

Figure 3.15 Flexible wall permeameter apparatus

Figure 3.16 Graduated tail water measurement system.

3.4.10 Unconfined Compressive Strength Apparatus

The test apparatus is used to measure the strength of cohesive soils by strain control system (Figure 3.17). It measures stress in the range of 1kPa-8500 kPa.

Figure 3.17 Unconfined Compressive Strength Apparatus.

3.4.11 Consolidation Oedometer Apparatus

Operation system was manufactured to carry loads for long period. Specimen in a ring was placed between two porous disks having two sides of drainage. Consolidation test sample cured in the cutter ring having 63 mm internal diameter and 19 mm in height. During test, the specimen subjected to axial deformation by stress increase (Figure 3.18).

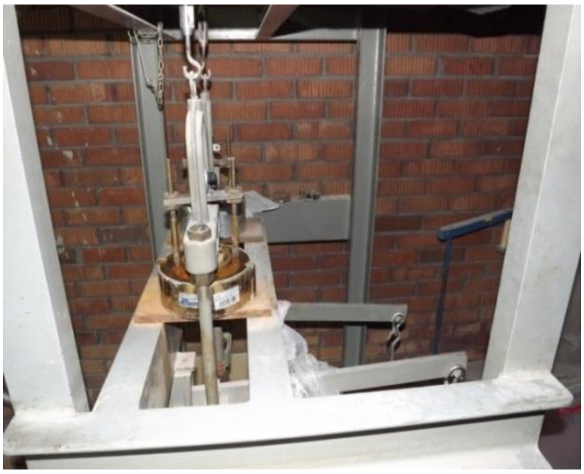


Figure 3.18 Consolidation (Oedometer) Apparatus

CHAPTER 4

SAMPLE PREPARATION AND TEST PROCEDURE

4.1 Introduction

In this experimental study, seven types of material (Portland cement type I, sodium bentonite, fly ash, GGBS type I, GGBS type II, steel slag, and lime) with different mixture design have been investigated in four series. For all series, samples were prepared for permeability, unconfined compressive strength, and compressibility tests. In addition, index tests (Atterberg limit, specific gravity, and particle size distribution) were carry out for all series. Mixture designs have two parts. For the first part, supplementary cementitious material was replaced by 0 %, 20%, 50%, and 80 % of cement content. In this part, fly ash, GGBS type I, GGBS type II, and steel slag were replaced by cement content. GGBS type I, GGBS type II, and steel slag replacement of 50 % gave the optimum results in the first part. For the second part, optimum replacements amended by 5 % lime and 9 % of bentonite. Lime content of 5 %, replaced once with cement then by supplementary cementitious material. Bentonite content of 9 % in batches slurry used to modify designs with 5 % lime content. For all series, 7 days and 28 days of cured samples were subjected to the permeability, strength, and compressibility tests. Furthermore, 50% replacements of GGBS type I and for all mixtures of steel slag were tested after 90 days of curing time.

4.2 Sample Preparation

4.2.1 Batch Slurry Preparation

Karakaya Sodium Bentonite produced in Turkey was examined for bentonite-water slurry preparation. The batch slurry portion in all samples was 80 % of total mixture weight. While the remaining 20 % portion of mixtures, involves cementitious material. Two mixture of batch slurry was prepared by different bentonite content. For the first one, mixtures were prepared using 5 % of bentonite by dry weight mixed in 95 % distilled water. While for the second one, 9 % of dry weight bentonite mixed into the 91 % distilled water as batch slurry. For batch slurry preparation, desired weight of dry bentonite was added to distilled water. Then it mixed by hand using steel spatula for 5 minutes in gallon. Mixed slurries in gallons were kept to hydration in 100 % humidity room. Hydration period for batch slurries was 7 days. It should be point out that, this long period of hydration gives better viscosity for batch slurry. Prepared slurries, mixed by high-speed electrical mixtures every day for 7 days (Figure 4.1). A rod having vane blade was attached to the mixer. Use of high-speed mixture for batch slurry preparation helps to have slurry that is more homogenious. It typically took 2 to 5 minutes for each mixing. Distilled water at 22˚C temperature shows pH value of 6.69. Bentonite-water slurry at 19.5˚C for 5 % and 9 % betonite content gives the pH values of 9.1 and 8.87, respectively.

Figure 4.1 High-speed slurry mixer

4.2.2 Specific Gravity (G_s) Sample

Cementitious material could not examined in accordance to ASTM D854-10 for Gs determination. This test method covers determination of the specific gravity of soil solids by Pycnometer. The procedure takes more than 3 hours. Cementitious materials hardened after 15 minutes, due to this reason, Gs was determined according to ASTM C188-09. For this method, Kerosine is used in graduated flask for volume change determination (Figure 4.2). The standard specified the use of 64 g cement and 50 g other pozzolanic material for Gs determination.

Figure 4.2 Specific gravity Test Flask

4.2.3 Atterberg Limit Sample

Around 200 g of dry mixture was separated for Atterberg limit tests. Material passed sieve number 40 for at least five times according to ASTM D4318-10. Atterberg limits are used to estimate the engineering behavior of the material in natural water content. About 30 g of each sample was used for plastic limit test. Liquid and plastic limit tests of each mixture have to be done in 20 minutes. Cementitious material can loss its plastic properties if it is mixed for more than 15 minutes.

4.2.4 Particle Size Distribution (PSD)

For geotechnical practice, conventional hydrometer test method used to determine the particle size distribution of fine particles. It takes 24 hours. However, cementitious material starts to flocculate in a short time (in four minutes). Particle size distribution of mixtures in this experiment determined by laser diffraction system, Figure 4.3 (Özer et al. 2010). About 30 g of each mixture prepared and mixed by distilled water having 5% sodium hexametaphosphate by electrical mixer device for 15 minutes. About 3g of mixture used for PSD by laser diffraction method.

Figure 4.3 Laser diffraction system

4.2.5 Permeability and Unconfined Compression Test Samples

Cementitious material and bentonite put into the oven to dry, a day before sample preparation. In the mixing days, cementitious materials were mixed according to mix design. Dry mixtures are passed sieve number 40, for at least five times to have uniform mixture. Cementitious material portion in total mixture was 20% by weight. For instance, 5 kg of prepared slurry consist of 1 kg of cementitious material and 4 kg of batch slurry. Dry material mixed by hand using steel spatula for five minutes in a plastic pan. It should be note that, all of the fresh mixtures have slump ranges in between 4 inches to 6 inches. This gives desired workability of fresh slurry during implementation at the site. Plastic cylindrical molds having 5 cm of internal diameter (external diameter of mold was 63 mm) and 10 cm in height were used. All of the plastic molds have been washed and internal side of the mold was lubricated before the mixture was placed in. A thin plastic nylon was placed below the each mold. This was done due to interrupting of water or fresh mixture escaping below the molds. Placed mixture in the molds shrinked in earlier curing times. To solve this problem, a thin cylindrical plastic mold of 3 cm in height was stocked on each mold. Fresh mixtures were placed into the molds up to the top of thin plastic mold (Figure 4.4). A miniature electrical vibrator was used for fresh mixtures vibration for 10 second. During placing mixture into the mold, small air bubbles were occurred. Fresh mixture was vibrated for 10 second in the molds. Prepared specimens were placed into the 100 % humidity room at temperature of 20 ±2 ˚C. Fresh specimens were placed into the plastic container, which was full of water, after two days of curing. Six specimens were prepared for every test day. Two of the specimens with no damages were used for each experiment. Samples for strength tests were in the same size of permeability test samples. One of them was subjected to permeability and the next two to unconfined compressive strength tests.

Figure 4.4 Mixture placement into the mold

4.2.6 Consolidation Samples

All of the mixtures were tested for compressibility. Consolidation cutter ring (having the internal diameter of 6.3 cm and height of 1.9 cm) was used as a mold. Metal rings having 15 cm in diameter and 3 cm in height was used as a container mold. A thin nylon was used at the bottom of the ring. Inner part of the cutter ring was lubricated. Two cutter rings were placed into the big ring. Then fresh mixture was placed to fill the big ring (Figure 4.5(a), and (b)). Fresh mixtures were vibrated for 10 seconds.

Figure 4.5 (a) Placing for consolidation cutter ring, (b) Prepared sample

4.3 Test Procedure

4.3.1 Gs Test Procedure

Specific gravity (Gs) of mixtures were found according to ASTM C188-09. The test method covers the “(Standard Test Method for Density of Hydraulic Cement)”. Kerosine by the density greater than “0.73 g/mL at 23 ± 2°”, was used in a flask for density determination. A graduated flask was used for density change measurement, Figure 4.6. Flask was immersed into water bath for one hour to get stable temperature. 64 g of mixture was placed in the flask slowly. It took between 10 to 15 minutes. Flask having kerosine and material was immersed again into the water bath. After one hour, when the level of Kerosine is stable, the volume change is recorded. The quantity of mixture’s mass and differences between volume change values, used for density determination. Clean flask was put into the oven for 24 hours for drying.

$$G_S = \frac{m}{(v_2 - v_1)} \tag{4.4}$$

Where;
Gs : Specific gravity
m : Mass of mixtures
V_1 : Initial volume
V_2 : Final volume

Figure 4.6 Specific Gravity Test Flask

4.3.2 Atterberg Limit Test Procedure

4.3.2.1 Plastic Limit

Cementitious materials are typically silt size. GGBS, steel slag, and fly ash do not have adsorption capacity to maintain the ionic compounds. Liquid limit and plastic limit of mixtures were determined by wet preparation methods according to ASTM D4318-10. 200 g of dry mass of mixtures "(no material retain on 425-µm (No. 40) sieve)" was prepared for the test. Prepared dry mixtures were passed sieve No. 30 for at least five times to achieve well- mixing. About 30 g of material prepared for liquid limit test, was separated for plastic limit tests. Distilled water was added to the sample until it is possible to roll without sticking on hand. Then sample was rolled between the glass plate and fingers until some cracks were appeared and rolls separated to smaller parts and water content of each sample was determined (Figure 4.7).

4.3.2.2 Liquid Limit

Wet preparation method was used. Adequate amount of distilled water was added to dry mixture and mixed by hand using steel spatula for 3 minutes. Prepared wet mixture did not allowed to hydrate for at least 16 hours specified in standard. Cementitious material gets hardened during mentioned time. Then prepared mixture was placed into the cup with spatula in desired amount without air entrapped. Material was grooved by grooving tools in two equal parts (Figure 4.8). Number of blows was recorded for groove's closing. This was continued for five times having groove's closing in the blow ranges of 14 to 20, 20 to 30, 30 to 40, and 40 to 50. Dry mixtures or water, was added to the previous liquid limit testing sample to achieve mentioned blow ranges. For each liquid limit test a small piece of material from cup was taken for water content determination. Liquid limit test gives the range of required water content to close lips dependin on number of drops.

Figure 4.7 Plastic limit test sample

Figure 4.8 Liquid limit test sample

4.3.3 PSD Test Procedure

A laser diffraction system by a wavelength of about 633 nm has been used for PSD analysis in this study. It could measure the particle sizes in the range of 0.1 to 2000 mm. An electrical instrument having 1-liter of sample capacity was used for sample preparation (Figure 4.9).

An ultrasonic device was used to produce nominal frequency around 40 kHz. About 5 % of Sodium hexametaphosphate mixed in distilled water for mixture dispersion. Then a background measurement was taken. Then, a small sample from prepared dry mixture was added into the sample bath. Samples was added into the bath until the obscuration quantity shows the range of 15 % to 30 %. PSD analyses and scattering typically took around 5 minutes. PSD histogram was displayed online during analysing, (Figure 4.10).

Figure 4.9 Sample preparing instrument

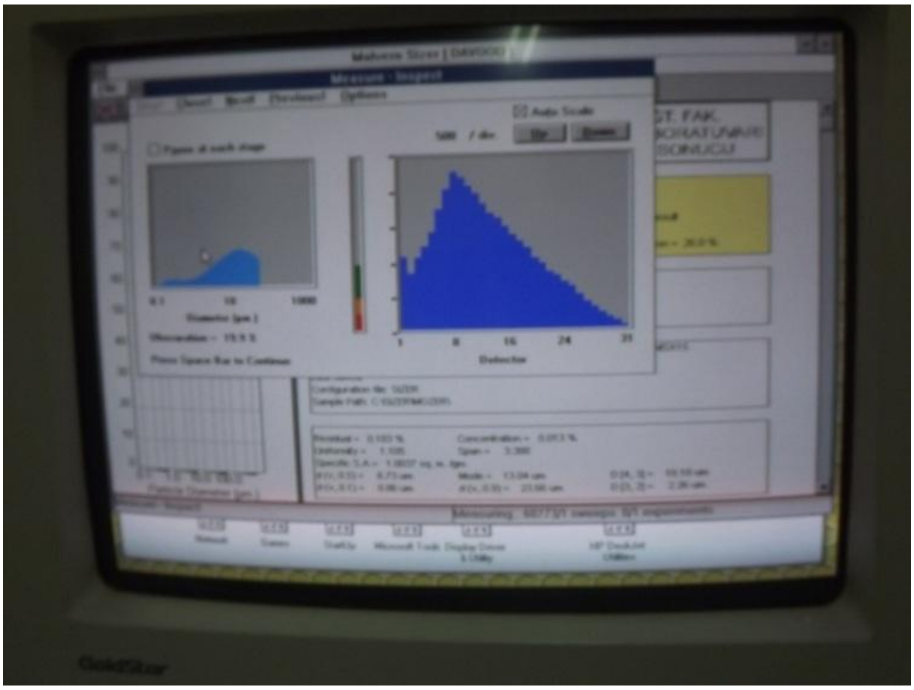


Figure 4.10 Sample analysing histogram

4.3.4 Permeability Test

Permeability test was carried out according to method E ASTM D5084-03 Constant Volume–Constant Head test. Permeability tests were conducted by triaxial cell permeameter system. A flexible membrane, two filter paper, two rubber O-rings, and two porous disks were used for specimen encapsulation (Figure 4.11). A porous disk put on permeameters pedestal and a filter paper placed on porous disk. Specimen was placed on filter paper. A filter paper and a porous disc were placed on top of specimen, respectively. Flexible membrane set into the membrane expander, which has a hole for suction (Figure 4.12(a) and (b)).

After the specimen placement on permeameter has been finished, permeameter cell was adjusted and lock carefully. After that, permeameter cell allowed to fill of distilled water. Then all of the valves were closed before any pressure application. Two flexible O-rings situated around the stretcher and placed around the pedestal (Figure 4.13). O-rings were placed around the pedestal and top caps.

Figure 4.11 Flexible membrane, O-rings, Filter papers, and Porous discs

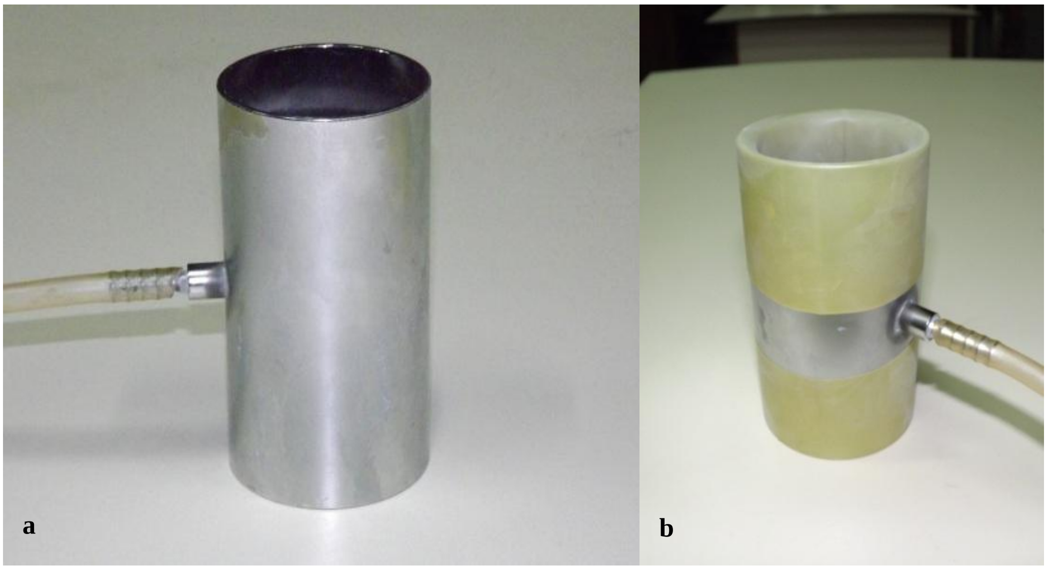


Figure 4.12 (a) Membrane expander, (b) Membrane placed in expander

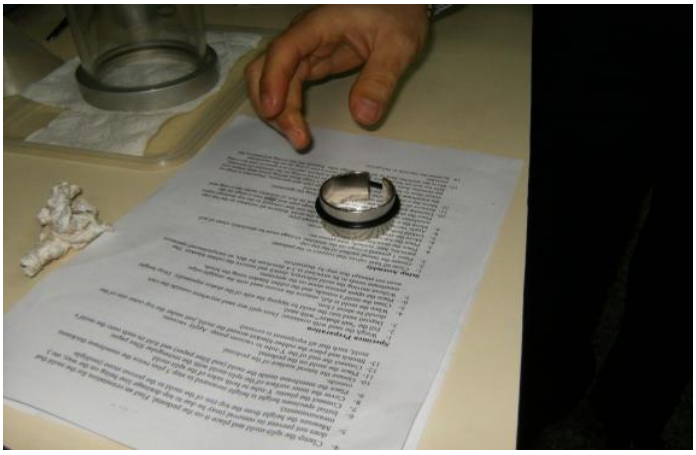


Figure 4.13 O-ring placement on stretcher

Initially, backpressure was applied for saturation of the sample for 24 hours. In all permeability tests, backpressure was 100 kPa and cell pressure was 200 kPa. The backpressure was increased at least for 15-min intervals and increased between 35 and 75 kPa. Hydraulic gradient of about i=100 was applied to all specimens. Hydraulic gradient calculation can be formulated as;

$$i = \frac{h}{L} \qquad (4.1)$$

Where;
i: Hydraulic gradient
h: Average head loss across the sample ((h1 + h2)/2), m of water
L: Length of specimen, m

Before the permeability tests, pore water pressure parameter B value is calculated by $B=\Delta u/\Delta\sigma_3$ where Δu is the change of pore pressure and $\Delta\sigma_3$ is cell pressure increment. The coefficient of B value, obtained from the pore pressure variation after cell pressure increase of 100 kPa. Skempton theory used for pore pressure coefficient B (Skempton 1954). For all samples $B \geq 0.95$ considered as saturation condition, and it took several hours to reach $B \geq 0.95$. The saturation backpressure was applied during the permeability test (Oweiss, S, and Khera, Raj P. 1998). Pore water pressure parameter B value, was calculated by the following formula;

$$B = \frac{\Delta u}{\Delta \sigma_3} \tag{4.2}$$

Where;
B: Pore water pressure parameter
Δu: Change of pore pressure
$\Delta\sigma_3$: Cell pressure increment

Backpressure of 100 kPa and cell pressure of 200 kPa kept constant during permeability measurement. Effluent and influent volumes have been recorded. All specimens were subjected to permeability test for 7 days and 28 days of curing periods. In addition, some of the samples has also considered for 90 days of curing. Normally, permeability tests for each sample took two or three days but never more than four days. After the permeability tests, setup was disassembled. Final dimensions of specimen was measured, Figure 4.14. At least two tests were carried out for each mixture, if the results are not close to each other, the third one was done. Finally, sample weight has been recorded and placed in the oven to dry for 24 hours, Figure 4.15. Determination of *k* value was calculated by the formula of:

$$k = \frac{Q.L}{A.h.\Delta t} \tag{4.3}$$

Where;
k : Permeability, cm/s
Q : Out flow quantity for given time interval, cm^3/s
A : Specimen cross section area, cm^2
h : Average head loss in the sample, $((h_1+h_2)/2)$, cm
Δt : Time interval, (t_2-t_1)

Influent and effluent readings were taken for permeability measurement, and water temperature has been recorded. Water viscosity correction at the recorded temperature was applied.

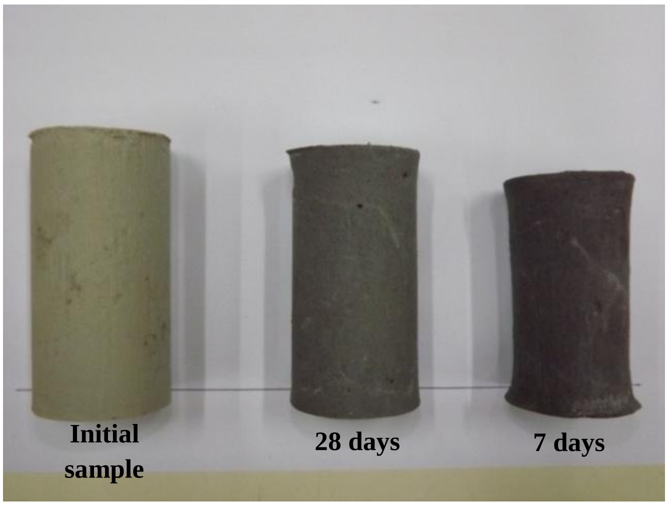


Figure 4.14 Dimension change for 7 days and 28 days of curing

Figure 4.15 Disassembled sample after permeability test

4.3.5 Unconfined Compressive Strength Test

Cured samples were taken from humidity room in test days. Similar size of specimens used for permeability and strength test. Specimens were tested for unconfined compressive strength test according to ASTM D2166-06. Thin plastic nylon at the bottom of the molds was removed. Then thin cylindrical plastic molds that were placed on top of the molds were cut carefully. Excess sample on top of the mold has been trimmed slowly. Then mold were placed on hydraulic jack to extrude samples. Extruded specimen put on the center of loading platen. It should be noted that, specimens for qu test had height-to-diameter ratio of 2, specified in standard. Loading rate of compression machine was adjusted to 0.5 mm/min. The top platen of loading device was on the upper side of specimen (Figure 4.16). Deformation indicators (dial gages) were adjusted to zero before the test. Load was applied at a vertical strain rate of 0.5 mm/min. Stress and strain values were recorded during the test, until strain reach to 15 % or time to failure exceeded 15 minutes. Loading is applied until stress values started to decrease while strain was still increasing. Specimens of 7 days of curing, typically started to bleeding under loading before failure occurred, see Figure 4.17. After the test, specimen was weighted and put into the oven for 24 hours to find specimen’s water content.

Figure 4.16 Unconfined compression test

Figure 4.17 Specimen bleeding during loading

4.3.6 Consolidation Test

Mixtures for both 7 and 28 days of curing were examined for one-dimensional consolidation test. The aim of this part of study was to find the coefficient of volume change, (mv) parameter for each sample.

The GGBS-CB and fly ash-CB in first series were examined in fixed-ring consolidometer (brass rings having 63 mm diameter and 19 mm height). The coefficient of volume change (mv), compression index (Cc), swelling index (Cr), coefficient of consolidation (Cv) and hydraulic conductivity k were found. After the equilibrium was attained as determined by nearly constant reading in the deformation reading dial, a pressure increment ratio of two was employed (Sivapullaiah, P. and Lakshmikantha, H, 2004). Each load increment was applied for 24 hours. Loading increments have started from 12 kPa up to 1600 kPa. The unloading were applied as one fourth of previous loading value. The unloading procedures were also applied for one day. For an increment of effective stress from σ_0' to σ_1', the height of specimen deforms from h_0 to h_1. The coefficient of volume change for void ratio from e0 to e1 is determined by the mention relationship:

$$mv = \frac{1}{1+e_0}\ \frac{e_0 - e_1}{\sigma'_1 - \sigma'_0} \qquad (4.5)$$

Where;

m_v: Coefficient of volume change (for each loading)
e_0: Initial void ratio
e_1: Final void ratio
σ'_1: Initial effective stress
σ'_0: Final effective stress

$$c_v = \frac{k}{\gamma_w \times m_v} \qquad (4.6)$$

Where;
C_v: Coefficient of consolidation
γ_w: Unit weight of water
m_v: Coefficient of volume change

$$k = c_v \,.\, m_v \,.\, \gamma_w \qquad (4.7)$$

Where;
k: Hydraulic conductivity of consolidation test
C_v: Coefficient of consolidation
γ_w: Unit weight of water

$$D = \frac{1}{m_v} \qquad (4.8)$$

Where;
D: Constrained modulus
m_v: coefficient of volume change

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Specific Gravity

This test was done on each material and mixtures. Table 5.1 demonstrates the Gs values of the mixtures (prepared as 20 % of cementitious material). The Gs results of series one and series two have been collected in Table 5.1. Gs values of Series 3 and series 4 are given in Table 5.2. The maximum Gs value was belong to steel slag (3.40), while the lowest Gs value was for fly ash (1.80).

Table 5.1 Gs values of series 1 and series 2

Series	Material	Mixture	Replacement (%)	Bentonite content (%)	Gs
1	**Fly ash**	**C-S-F**	**(100-0-0)**	**5**	**2.82**
		C-F	**(20-80)**		**2.03**
		C-F	**(50-50)**		**2.32**
		C-F	**(80-20)**		**2.57**
2	**GGBS type I**	**C-S**	**(20-80)**		**2.73**
		C-S	**(50-50)**		**2.76**
		C-S	**(80-20)**		**2.80**
		(C-S-L)	**(50-45-5)**		**2.73**
		(C S-L)	**(45-50-5)**		**2.66**
		(C-S-L)	**(50-45-5)**	**9**	**2.70**
		(C-S-L)	**(45-50-5)**		**2.63**
	Cement	**C**	**100**	**0**	**2.89**
	Fly ash	**F**		**0**	**1.80**
	GGBS I	**S**		**0**	**2.86**
	Lime	**L**		**0**	**2.27**
	Bentonite	**B**		**100**	**2.17**

Note: C-F (20-80), fly ash replacement of 20 %. C-S (20-80), GGBS type I replacement of 20%. C-S-L (50-45-5), cement-GGBS type I, lime with indicated replacement.

Table 5.2 Gs values of series 3 and series 4

Series	Material	Mixture	Replacement (%)	Bentonite content (%)	Gs
3	**GGBS type II**	**C-S**	**(20-80)**	**5**	**2.70**
		C-S	**(50-50)**		**2.79**
		C-S	**(80-20)**		**2.78**
		(C-S-L)	**(50-45-5)**		**2.76**
		(C-S-L)	**(45-50-5)**		**2.74**
		(C-S-L)	**(50-45-5)**	**9**	**2.76**
		(C-S-L)	**(45-50-5)**		**2.68**
4	**Steel slag**	**C-S**	**(20-80)**	**5**	**3.10**
		C-S	**(50-50)**		**3.00**
		C-S	**(80-20)**		**2.89**
		(C-S-L)	**(50-45-5)**		**2.94**
		(C-S-L)	**(45-50-5)**		**2.97**
		(C-S-L)	**(50-45-5)**	**9**	**2.85**
		(C-S-L)	**(45-50-5)**		**2.95**
	GGBS II	**S**	**100**	**0**	**2.84**
	Steel slag	**S**	**100**	**0**	**3.40**

Note: C-S (20-80), GGBS and steel slag replacement of 20 %. C-S-L (50-45-5), cement-GGBS type I or steel slag, lime with indicated replacement.

5.2 Atterberg Limit

Atterberg limit values for all series are shown in Table 5.3 and Table 5.4. Table 5.4 shows the Atterberg limit values for series3 and series 4. Liquid limit increases as bentonite content increases to the 9 %. The maximum and minimum values were presented for GGBS type II and steel slag replacement, respectively.

Table 5.3 Atterberg limit values of series 1 and series 2

Series	Material	Mixture	Replacement (%)	Bentonite content (%)	LL (%)	PL (%)	PI (%)
1	**Fly ash**	**C-S-F**	**(100-0-0)**	**5**	**39.40**	**25**	**14.40**
		C-F	**(20-80)**		**NP**	**NP**	**NP**
		C-F	**(50-50)**		**NP**	**NP**	**NP**
		C-F	**(80-20)**		**NP**	**NP**	**NP**
	GGBS type I	**C-S**	**(20-80)**		**40.45**	**23.20**	**17.25**
		C-S	**(50-50)**		**42.25**	**27**	**15.25**
2		**C-S**	**(80-20)**		**40.30**	**25.70**	**14.60**
		(C-S-L)	**(50-45-5)**		**42.60**	**26.10**	**16.50**
		(C-S-L)	**(45-50-5)**		**41.20**	**23.50**	**17.70**
		(C-S-L)	**(50-45-5)**	**9**	**62**	**24**	**38**
		(C-S-L)	**(45-50-5)**		**57.10**	**27.4**	**29.70**

Note: C-F (20-80), fly ash replacement of 20 %. C-S (20-80), GGBS type I replacement of 20%. C-S-L (50-45-5), cement-GGBS type I, lime with indicated replacement.

Table 5.4 Atterberg Limit values for series 3 and series 4.

Series	Material	Mixture	Replacement (%)	Bentonite content (%)	LL (%)	Pl (%)	PI (%)
3	GGBS type II	C-S	(20-80)	5	39.90	23.20	16.70
		C-S	(50-50)		38.2	22	16.20
		C-S	(80-20)		37.50	19.70	17.80
		(C-S-L)	(50-45-5)		37.15	23	14.15
		(C-S-L)	(45-50-50)		39.90	22.30	17.60
		(C-S-L)	(50-45-5)	9	51.80	20	31.80
		(C-S-L)	(45-50-5)		49	20.15	28.85
4	Steel slag	C-S	(20-80)	5	39	17.50	21.50
		C-S	(50-50)		36.5	21.75	14.75
		C-S	(80-20)		44	23.52	20.48
		(C-S-L)	(50-45-5)		37	22.80	14.20
		(C-S-L)	(45-50-5)		31	20.80	10.20
		(C-S-L)	(50-45-5)	9	30.3	19	11.3
		(C-S-L)	(45-50-5)		31	21	10

Note: C-S (20-80), GGBS and steel slg replacement of 20 %. C-S-L (50-45-5), cement-GGBS type I or steel slag, lime with indicated replacement.

5.3 Particle Size Distribution (PSD)

Dry materials used in the mixtures passed sieve number 40. Each material individually passed the sieve number 40 before mixing by other materials. Mixtures passed sieve number 200 were analysed by PSD instrument. Materials remained between sieve number 40 and number 200, were analysed by sieves number 50 and number 100 as well. The data from both analysis were incorporated together to get unique particle size distribution of the samples. Results were found for all of the 25 samples.

These were found by introducing 3g of each sample into the mixture reservoir and mixing it for five minutes. Laser diffraction system adjusted to determine fines size between 0.1 µm to 80 µm. Fine particle reading system normally took 3 to 5 minutes. Mixtures having GGBS type I showed smaller range than GGBS type II and steel slag that were grinded in laboratory. Smallest fine range belongs to cement while the largest one presented by GGBS type II and steel slag.

Table 5.5 and Table 5.6 gives the particle size distribution of each mixture in each series for clay and silt size. Fines smaller than 0.002 mm (2µm) were categorized as clay size. Particles sizes between 0.002 mm (2µm) and 0.075 mm (75 µm) covers the quantitative values of silt size. This test evaluated for all replacement and amended mixtures. All mixtures contains some sand size particles that analysed by sieves mentioned above. All serieses (PSD) curves are given in Appendix A.

Table 5.5 First series and second series PSD portions

Series	Material	Mixture	Replacement (%)	Bentonite content (%)	Clay Size (%)	Silt size (%)	Sand Size (%)
1	Fly ash	C-F-S	(100-0-0)	5	24	76	0
		C-F	(20-80)		7	76	17
		C-F	(50-50)		8	81	11
		C-F	(80-20)		13	75	12
	GGBS type I	C-S	(20-80)		14	68	18
		C-S	(50-50)		17	67	16
		C-S	(80-20)		16	68	16
2		(C-S-L)	(50-45-5)		15	70	15
		(C-S-L)	(45-50-5)		16	69	15
		(C-S-L)	(50-45-5)	9	17	73	10
		(C-S-L)	(45-50-5)		17	70	13

Note: C-S (20-80) and C-F (20-80) Cement, GGBS and fly ash replacement of 80 %. C-S-L (50-45-5), cement-GGBS type I with indicated replacement.

Table 5.6 Third and fourth series PSD portions

Series	Material	Mixture	Replacement (%)	Bentonite content (%)	Clay size (%)	Silt size (%)	Sand size (%)
3	GGBS type II	C-S	(20-80)	5	7	79	14
		C-S	(50-50)		10	79	11
		C-S	(80-20)		13	76	11
		(C-S-L)	(50-45-5)		5	41	54
		(C-S-L)	(45-50-5)		9	72	19
		(C-S-L)	(50-45-5)	9	8	74	18
		(C-S-L)	(45-50-5)		7	71	22
4	Steel slag	C-S	(20-80)	5	10	76	14
		C-S	(50-50)		13	76	11
		C-S	(80-20)		15	77	8
		(C-S-L)	(50-45-5)		12	76	12
		(C-S-L)	(45-50-5)		13	81	6
		(C-S-L)	(50-45-5)	9	12	75	13
		(C-S-L)	(45-50-5)		12	73	15

Note: C-S (20-80), GGBS and steel slg replacement of 20 %. C-S-L (50-45-5), cement-GGBS type I or steel slag, lime with indicated replacement.

5.4 Permeability Test

5.4.1 First Series

The permeability test results on specimens cured for 7days, 28 days, and for some samples 90 days are illustrated in this chapter. These tests results show the effect of each mix properties. Figure 5.1 gives the effect of curing period and fly ash replacement on permeability. Without fly ash replacement and even with fly ash replacement up to 80%, permeability is in the range of 8.09×10^{-6} cm/s to 6.18×10^{-7} cm/s for 7 days curing. On the other hand, this range for 28 days of curing for the same mixtures is between 3.65×10^{-6} cm/s to 1.32×10^{-6} cm/s. Results for both curing periods show that by increasing fly ash content permeability has been decreased. In contrast, based on data presented in the mentioned Figure, permeability values rise for 28 days curing period comparing to 7 days curing period.

However, a substantial decrease in permeability of 28 days cured sample having no fly ash replacement was seen. Previous studies however, stated that permeability of mixtures having fly ash will decrease upto 6 months of curing age.

In this series with the same mix designs, GGBS type I has been evaluated for the same curing periods. Figure 5.2 present that the GGBS-CB material gives acceptable results of permeability. The value is below the 10^{-7} cm/s for the replacement of 50 % and 90 days of curing period. For this mixture, GGBS substitution of 50 % shows the best results for this series of study. This value will also decrease by increasing curing time. This important feature of GGBS type I indicated that it could be used as additive in CB barrier walls.

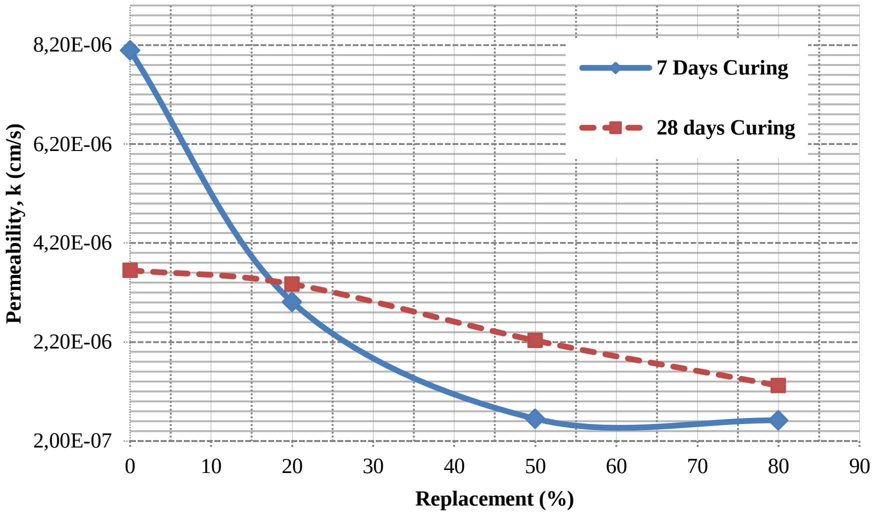


Figure 5.1 Permeability results for fly ash replacements

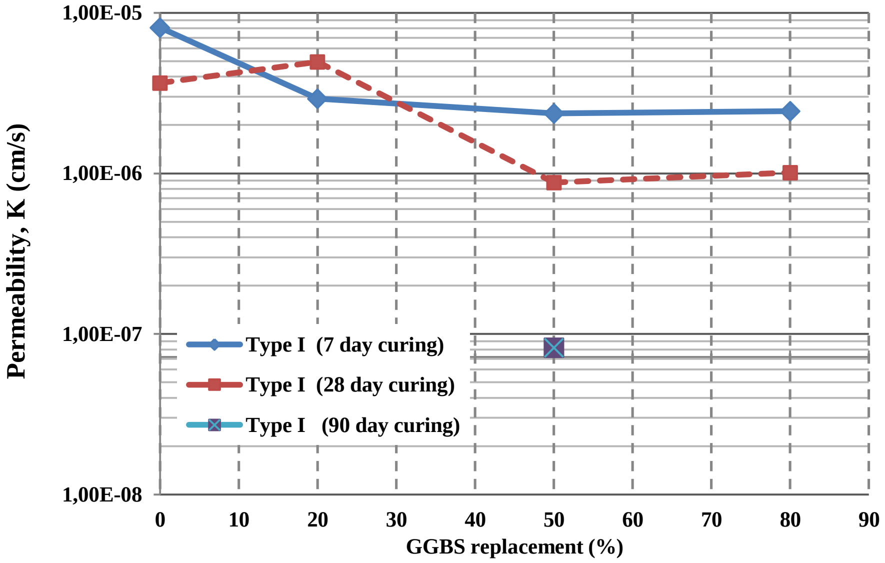


Figure 5.2 Permeability test for GGBS type I

5.4.2 Second Series

For this series of study, GGBS type I replacement of 50 % which gave the best permeation results has been modified. This mixture amended by lime content of 5 % for the mentioned mixture. In this series, at first 5 % lime was mixed by 45 % of GGBS and 50 % of cement then 5 % lime mixed by 45% cement and 50 % GGBS. Figure 5.3 shows the samples permeability results for these mixtures. Supplementary cementitious material mixed by batches slurry having bentonite content of 5 %. Samples were tested for 7 days and 28 days of curing period.

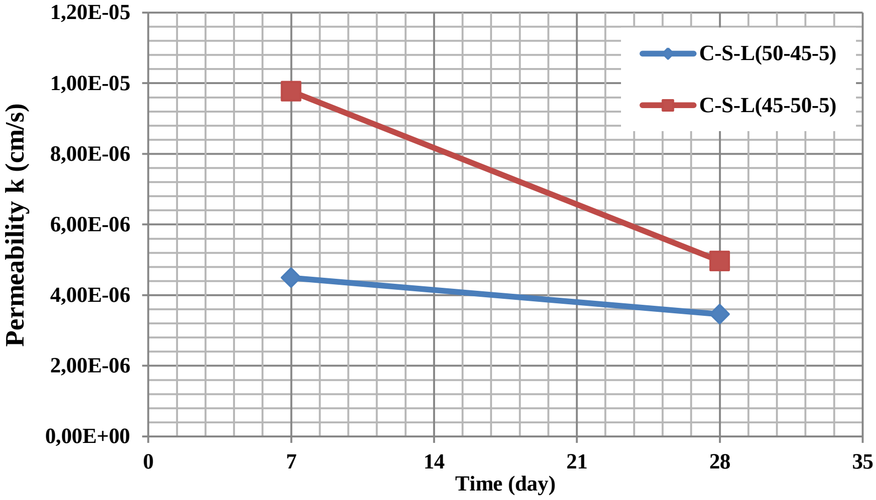


Figure 5.3 Mixture having 5 % of lime and 5 % of bentonite

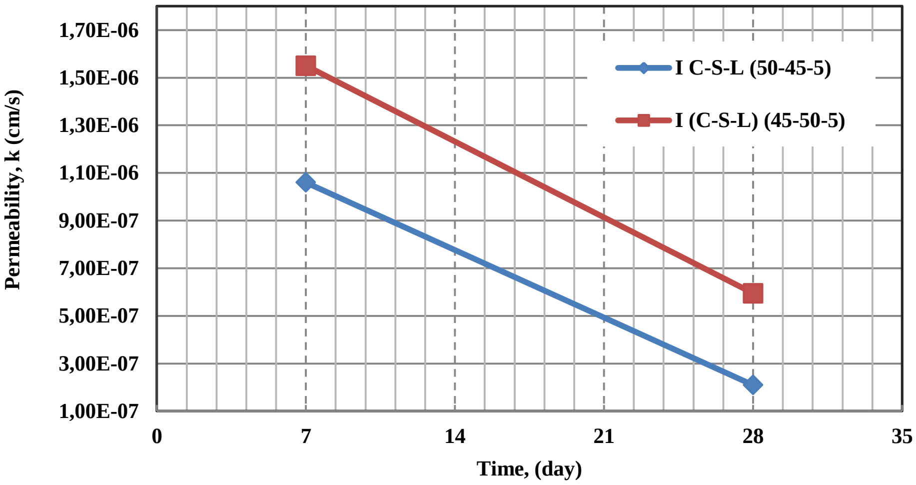


Figure 5.4 Amended mixtures by 9 % of bentonite

For both mixtures the permeation quantities have been increased from one week to one month curing period. The results increased form 4×10^{-6} to 9×10^{-6} in one week and from 4×10^{-6} to 5×10^{-6} in one month of curing. Results present that the addition of 5 % of lime into the mixtures could increase permeability during long-term. Minimum permeability value of 10^{-7} cm/s could not achieve.

As mentioned above, mixture improved by adding further bentonite. Bentonite content of 9 % used to prepare batches slurry, which adsorbs more water and give higher viscosity. Figure 5.4 shows dramatic reduction of permeability into the desired level for 28 days of curing (from 10^{-6} cm/s to 10^{-7} cm/s).

5.4.3 Third Series

Another type of GGBS was examined for this series, GGBS replacement of 20 %, 50%, and 80 % were evaluated. This type of GGBS (GGBS type II), however, gives different results than GGBS type I. This mixture also gave the lowest permeability value for 28 days cured sample. Besides, for the other mixture designs (20 % and 80 % replacement) the quantities were higher than one-week curing. On the other hand, it has potential for 50 % replacement to reach lower permeability in long-term as illustrated below (see Figure 5.5). In (Figure 5.5) the scatter in data point may be due to human errors during samle preparation.

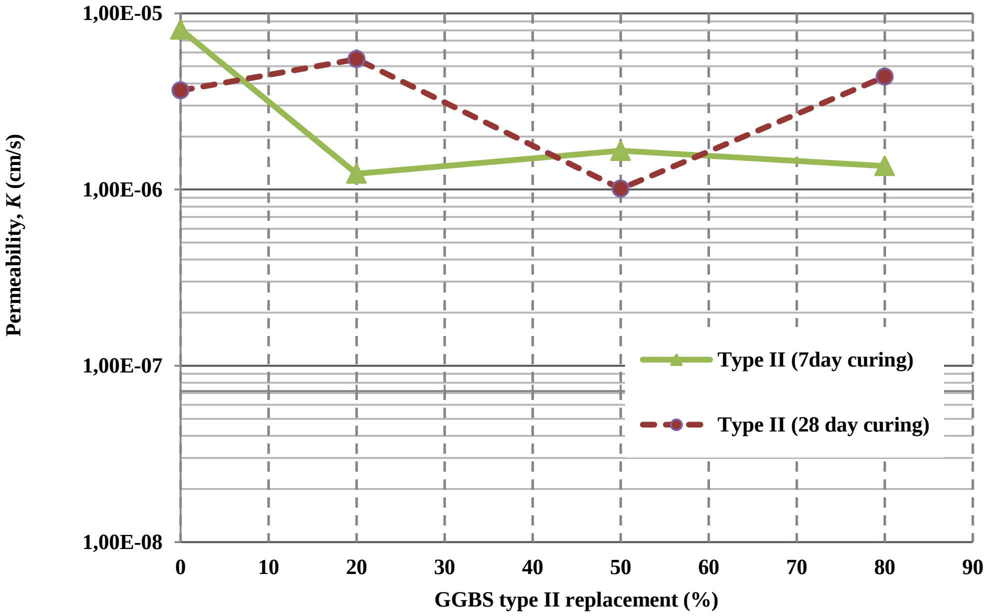


Figure 5.5 GGBS type II permeability test results

Next, modification process was done on this GGBS replacement of 50 %. It was amended by lime and more bentonite content (9%) as illustrated in series two. Both mixture for this modification presented similar values for 28 days of curing period. The 7 days cured samples including 50 % of cement, gave acceptable value than 50 % of GGBS replacement (Figure 5.6). Remarkable permeability reduction comes up with lime addition. Using of 9 % bentonite content into the batches slurry give the chance to examine them even in 7 days. It should be noted, k of around 10^{-7} is achieved in 28 days while standard ask it for at least 90 days of curing time (Figure 5.7).

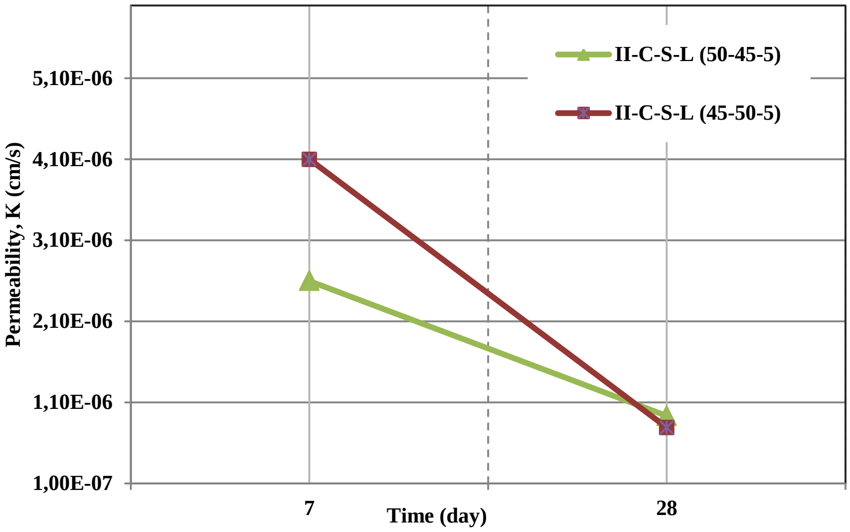


Figure 5.6 Amended GGBS type II with 5 % bentonite content

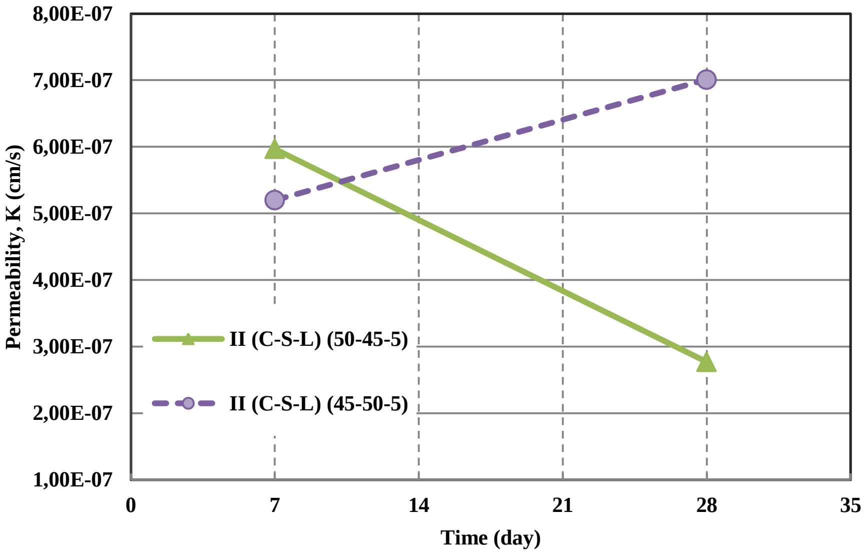


Figure 5.7 Amended GGBS type II with % 9 bentonite content

5.4.4 Fourth Series

Steel slag was examined in this series of study. Fascinating results was achieved for 28 days of curing. Figure (5.8) gives that sample having 50 % steel slag replacement or more, shows lower permeability. For the mentioned substitutions, there are increases in k values for 90 days curing. Conversely, permeability of steel slag replacement of 80 % slightly reduces in the long-term.

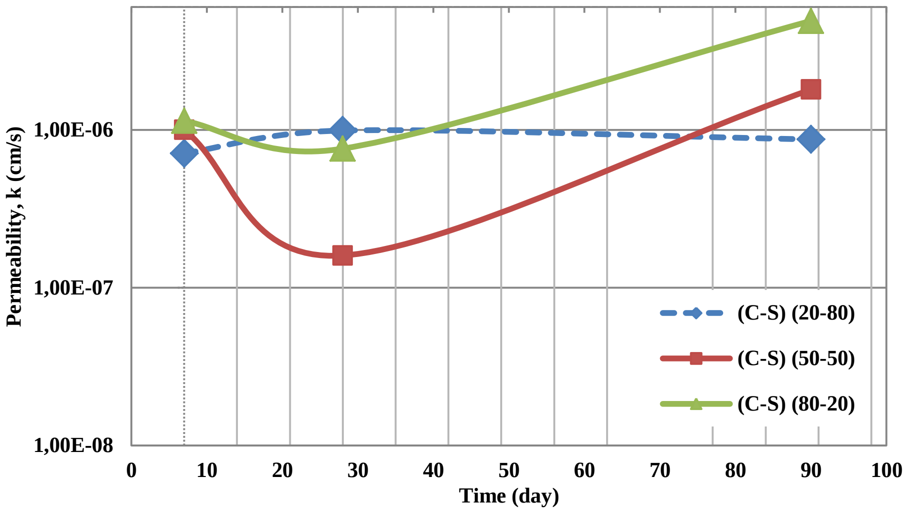


Figure 5.8 Steel slag permeability results

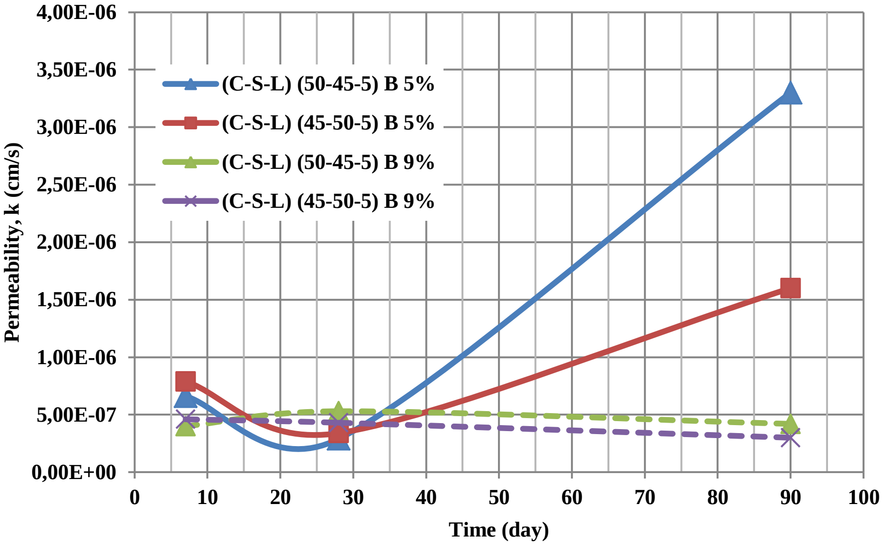


Figure 5.9 Amended mixture of cement-steel slag samples

Steel slag replacement of 50 % also examined by adding of 5 % of lime and bentonite content of 9 % in batch slurry. Like previous mixtures of steel slag without modifying, these show lowest k value for 28 days curing. It gave the mentioned values for batches having 5 % of bentonite (Figure 5.9). Modification results by 9 % bentonite content shows permeability reduction slightly from 28 days to 90 days of curing. It has been reduced from 5.7×10^{-7} cm/s to 4.2×10^{-7} cm/s and from 4.3×10^{-7} cm/s to 3×10^{-7} cm/s, respectively. Permeability of samples including 5 % of bentonite batches slurry, have been increased from 28 days to 90 days age. It should be noted that, permeability test results achieved in laboratory are generally lower than those measured in the field (Oweiss and Khera1998).

5.4.5 Permeability Data Sheet

All series flexible wall permeability results for desired curing period are summarized below.

Table 5.7 Permeability tests values

Series	Material	Mixture	Replacement (%)	B (%)	Permeability *k* (cm/sec)		
					Curing Time (day)		
					7	28	90
1	Cement Fly ash	C-S-F	(100-0-0)	5	8.09E-06	3.65E-06	--
		C-F	(80-20)		3.01E-06	3.3 E-06	--
		C-F	(50-50)		6.50E-07	2.36E-06	--
		C-F	(20-80)		6.18E-07	1.32E-06	--
	Cement GGBS I	C-S	(80-20)		2.92E-06	4.95E-06	--
		C-S	(50-50)		2.36E-06	8.72E-07	8.20E-08
		C-S	(20-80)		2.44E-06	1.01E-06	--
2	Cement GGBS I Lime	(C-S-L)	(50-45-5)		4.49E-06	9.77E-06	--
		(C-S-L)	(45-50-5)		3.46E-06	4.97E-06	--
		(C-S-L)	(50-45-5)	9	1.06E-06	2.77E-07	--
		(C-S-L)	(45-50-5)		1.55E-06	5.95E-07	--
3	Cement GGBS II Lime	C-S	(80-20)	5	1.23E-06	5.50E-06	--
		C-S	(50-50)		1.66E-06	1.01E-06	--
		C-S	(20-80)		1.36E-06	4.37E-06	--
		(C-S-L)	(50-45-5)		2.60E-06	9.93E-07	--
		(C-S-L)	(45-50-5)		4.46E-06	8.82E-07	--
		(C-S-L)	(50-45-5)	9	5.97E-07	2.77E-07	--
		(C-S-L)	(45-50-5)		5.82E-07	7.01E-07	--
4	Cement Steel Slag Lime	C-S	(80-20)	5	1.14E-06	7.68E-07	4.95E-06
		C-S	(50-50)		1.00E-06	1.69E-06	1.88E-06
		C-S	(20-80)		7.00E-07	9.92E-07	8.76E-07
		(C-S-L)	(50-45-5)		6.65E-07	2.98E-07	3.37E-06
		(C-S-L)	(45-50-5)		7.90E-07	3.43E-07	1.06E-06
		(C-S-L)	(50-45-5)	9	4.00E-07	5.39E-07	4.24E-07
		(C-S-L)	(45-50-5)		4.62E-07	4.30E-07	3.00E-07

Not: B= Bentonite Content

5.5 Unconfined Compressive Strength

5.5.1 First Series

At any given GGBS or fly ash replacement, unconfined compressive strength shows different values. Figure 5.10 gives the unconfined compressive strength test results of first series. Cement-GGBS and cement-fly ash samples were evaluated for 7 days and 28 days of curing. Minimum strength value of 100 kPa was determined for slurry walls at 90 days curing age. Mixtures having fly ash substitution of 20 % and 50 % support the mentioned range at 28 days of curing. All of the samples including fly ash give the strength below the 100 kPa for one week. On the other hand, cement-GGBS samples came with higher strength for 28 days. The maximum one was belong to GGBS replacement of 50 %. By increasing GGBS replacement to 50 %, it caused to increase in strength up to the 388 kPa.

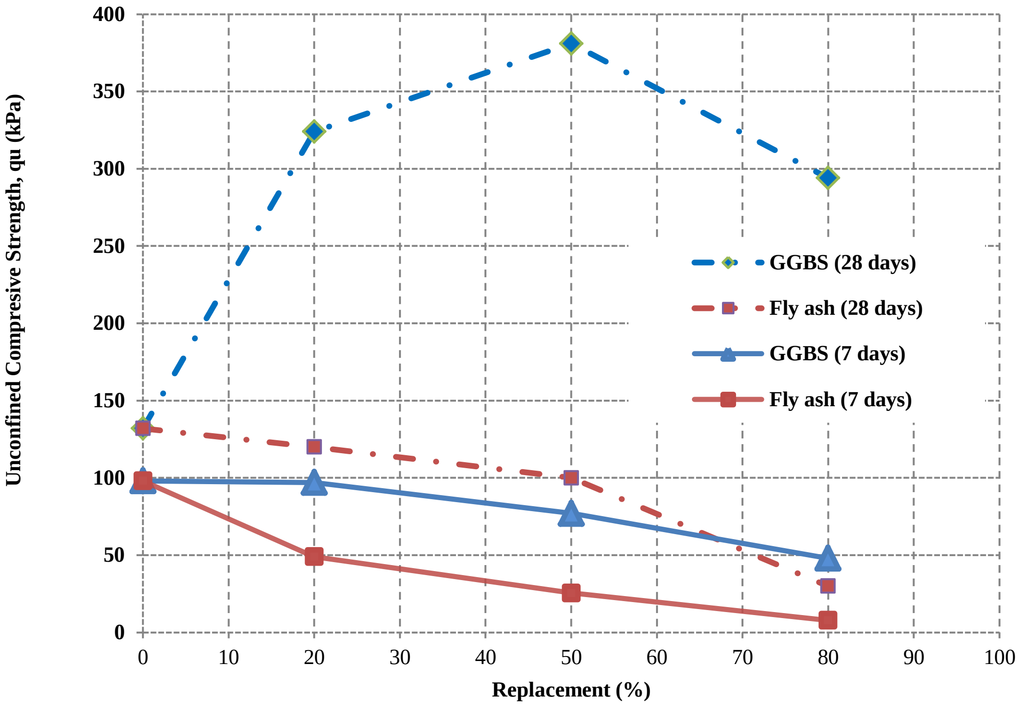


Figure 5.10 Strength test of cement-GGBS and CB-fly ash

5.5.2 Second Series

The modification were done on unconfined compressive strength samples as well. GGBS replacement of 50 % was amended by 5 % lime and 9 % of bentonite content to reduce permeability or increase strength. In this series, samples were subjected to unconfined compressive strength test at 7 days and 28 days of curing time. Figure 5.11 shows the effect of amendment on mixtures. As illustrated in (Figure 5.11) mixture having addition of lime gave lower strength than GGBS replacement. However, they are still higher than marked range specified in the standard. It gave the values of 292 kPa and 198 kPa for 45 % and 50 % GGBS replacement at 28 days of curing period, respectively. Bentonite content of 9 % was investigated as well. The data revealed the influence of more bentonite on strength. Sample having GGBS content of 45 % shows the strength of 515 kPa in 28 days of curing. Another sample by 50 % of GGBS replacement presented the value of 400 kPa for the same curing period.

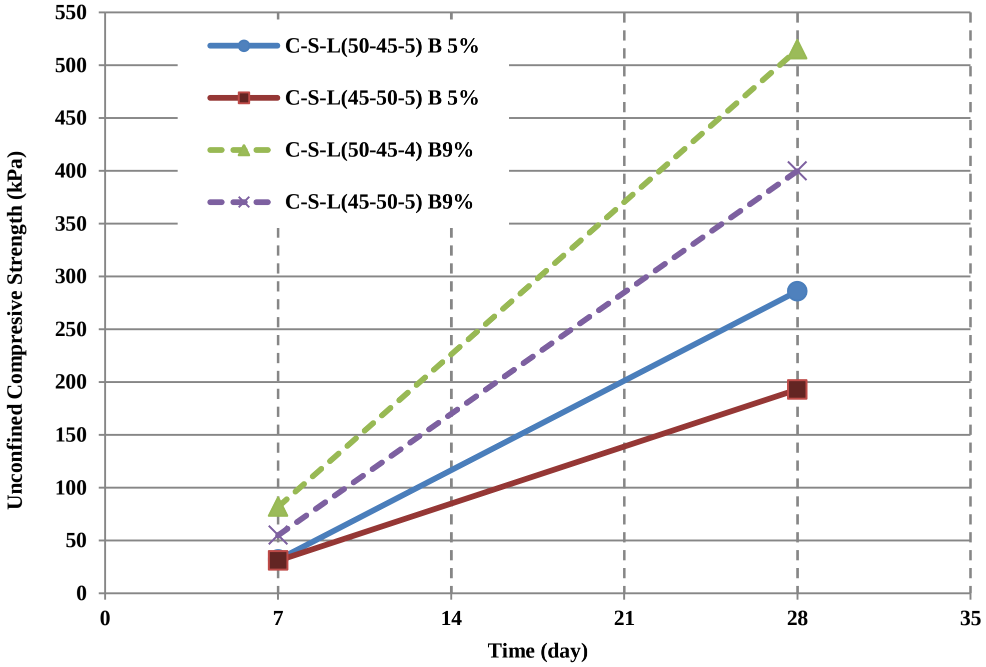


Figure 5.11 Amended mixtures of second series

5.5.3 Third Series

GGBS type II was tested for unconfined compressive strength as well. Figure 5.12 shows the curing effect of different mixtures. One-week curing period did not give adequate strength. For 28th days of curing, there is increase in the strength.

GGBS type II replacement of 50 % was also examined for modification. Mixtures having lime and 5 % of bentonite are actually below the minimum strength value as given in (Figure 5.12). Figure 5.13 demonstrate that lime content has decreased the mixtures strength. It should be noted that, there isn’t any significant difference between 50 % or 45 % GGBS replacement results. The bentonite content of 9 % has positive effect on strength results (Figure 5.13). It raised strength above 200 kPa in 28 days of curing. The sample containing 45 % of GGBS gave value a little bit more than 50 % replacement. The values of 230 kPa and 210 kPa were achieved for 45 % and 50 % of GGBS type II replacement, respectively.

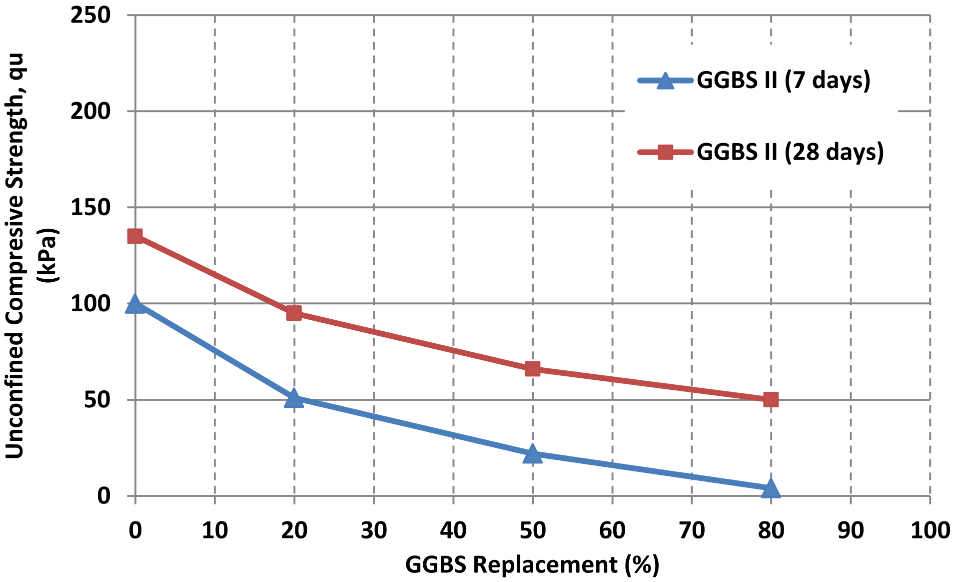


Figure 5.12 GGBS type II strength test

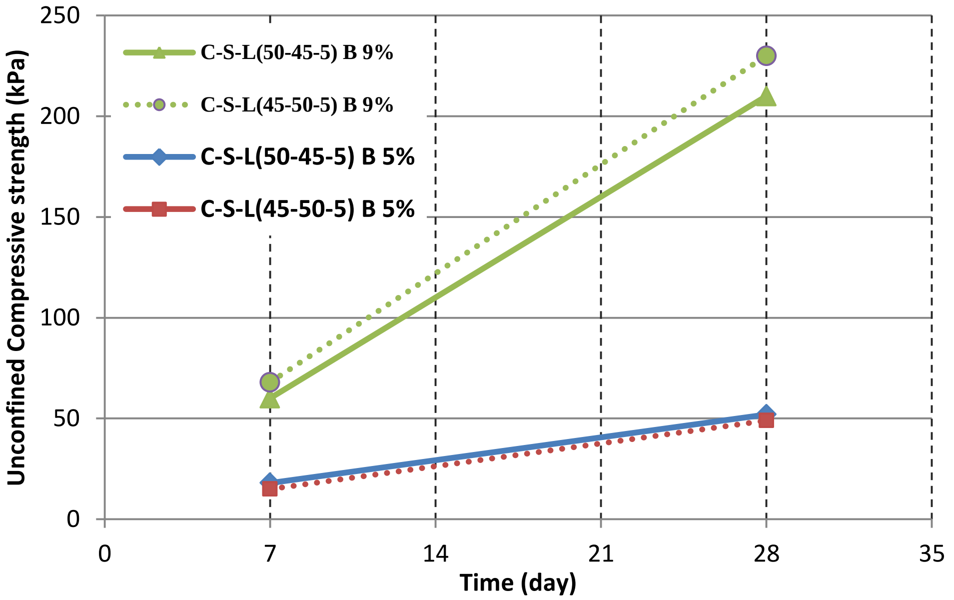


Figure 5.13 Unconfined compressive strength results of GGBS type II

5.5.4 Fourth Series

Steel slag was investigated in this part of study. 20 %, 50 %, and 80% of steel slag replacement were used. These mixtures could not give the minimum strength. Steel slag replacement of 80 %, shows higher values than other mixtures (Figure 5.14). All samples reached to failure below the range of 100 kPa even for 90 days of curing period. Like the previous series, these mixtures were modified for 50 % replacement. The highest value was achieved for steel slag replacement of 50 % by 9 % of bentonite content. Sample having steel slag replacement of 50 % having 5 % bentonite content is slightly above the 100 kPa for 90 days of curing (Figure 5.15).

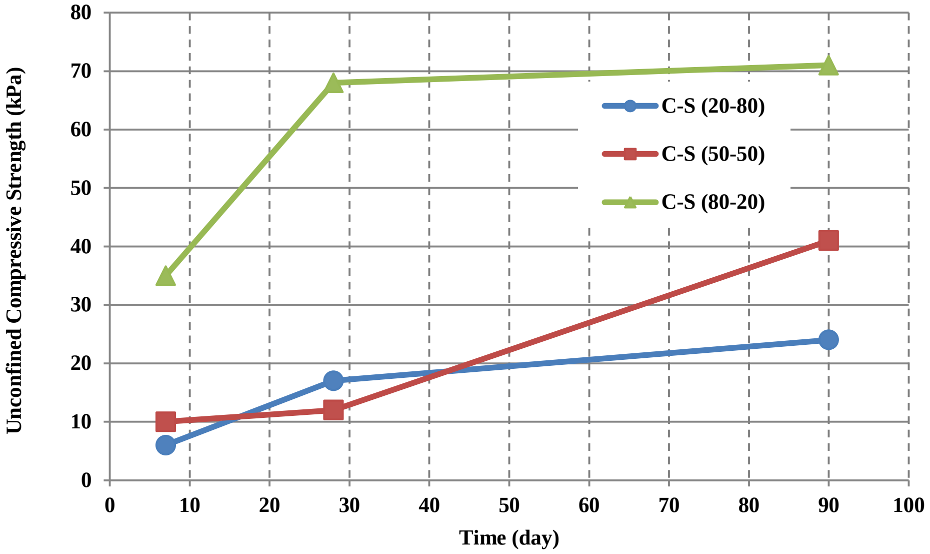


Figure 5.14 Strength test result of cement-steel slag

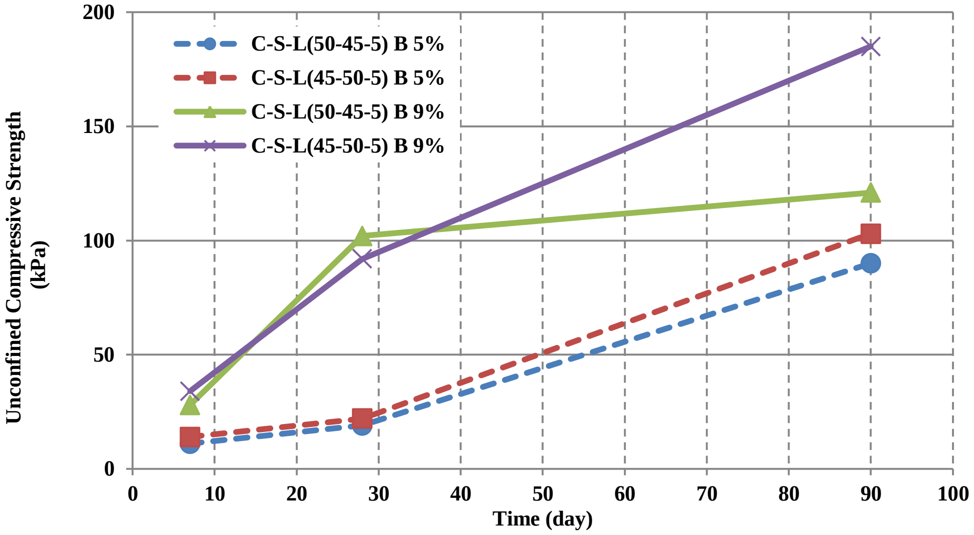


Figure 5.15 Strength test of cement-steel slag

5.5.5 UC Test Data Sheet

Table 5.8 Unconfined Compressive Strength results

Series	Material	Mixture	Replacement (%)	B (%)	UC (kPa)		
					Curing Time (day)		
					7	28	9
1	Cement Fly ash	C-S-F	(100-0-0)	5	99	133	--
		C-F	(80-20)		70	120	--
		C-F	(50-50)		26	105	--
		C-F	(20-80)		8	30	--
	Cement GGBS I	C-S	(80-20)		103	325	--
		C-S	(50-50)		78	380	--
		C-S	(20-80)		49	295	--
2	Cement GGBS I Lime	(C-S-L)	(50-45-5)		32	286	--
		(C-S-L)	(45-50-5)		32	193	--
		(C-S-L)	(50-45-5)	9	80	505	--
		(C-S-L)	(45-50-5)		54	393	--
3	Cement GGBS II Lime	C-S	(80-20)	5	50	93	--
		C-S	(50-50)		22	65	--
		C-S	(20-80)		4	49	--
		(C-S-L)	(50-45-5)		17	50	--
		(C-S-L)	(45-50-5)		14	47	--
		(C-S-L)	(50-45-5)	9	58	205	--
		(C-S-L)	(45-50-5)		67	225	--
4	Cement Steel Slag Lime	C-S	(80-20)	5	35	69	67
		C-S	(50-50)		1	12	41
		C-S	(20-80)		6	17	24
		(C-S-L)	(50-45-5)		10	19	41
		(C-S-L)	(45-50-5)		13	23	100
		(C-S-L)	(50-45-5)	9	28	100	120
		(C-S-L)	(45-50-5)		34	91	182

Not: B= Bentonite Content

5.6 Consolidation Test

5.6.1 Consolidation Parameters

The settlement of saturated specimens in this experimental study is specified by using one dimensional consolidation theory. Void ratio values for all specimens were between; 4.5 to 7.5 due to high quantity of water content. Consequently, for most of the specimens, settlement outputs were higher than other stiff soils. Coefficient of volume change (m_v) was determined for all tests of all stress increments. The quantities of mv were not constant during increasing of stress range since stress-strain curves were not linear. The constrained modulus D was specified for each load increment in each series. This parameter directly affected by variation in void ratio and load increment. Appendix B gives the values of coefficient of volume changes (m_v) and constrained modulus D for all mixtures in each load increment. Compression index Cc and swelling index Cr are obtained from loading and unloading slopes from e-Log σ´ graphs, respectively. Using of high water content mixtures during sample preparation, takes all values above of cohesive soils. For example, compression index parameters C_c were found between 1 to 7.5 in all mixtures. It should be noted that, by increasing curing time from 7 days to 28 days in all mixtures values of C_c and C_r were decreased. This is due to hardening of specimens by increasing of curing time, which is normally predictable.

Degree of coefficient of consolidation C_v was evaluated from root time method for 150 kPa pressure. Consolidation permeability k_{con} was evaluated for mentioned pressure for 90% of consolidation. This was tested at hydraulic gradient i of 1. On the other hand, hydraulic gradient i, which introduced for flexible wall permeability test was around 100. The results found from consolidation permeability K_{con} test are 10 to 100 times higher than flexible wall permeability test results. Differences in k values between two methods, affected from several factors. In materials that behave like soft consistency material, permeability reduced with increasing gradient. In addition, by the time of large effective stress loading, high gradients values at the downstream end of each specimen cause to change either specimen volume or nature of the voids. However, in a flexible wall permeameter, the cracks could become closer during applying of high confining pressure. Permeability values for consolidation tests were evaluated for U=90% whereas consolidation did not complete at this stage. Test results for C_c, C_r, C_v, k_{con} and k_{fw} parameters for all series are categorized below.

5.6.1.1 First Series

Table 5.9 First series values for 7 days curing time with Bentonite content of 5%

Material	Mixture	Replacement %	C_c	C_r	C_v	K_{con} (cm/s)	K $_{(flexible\ wall)}$ (cm/s)
Fly ash	**(C-F-S)**	**(100-0-0)**	**2.64**	**0.711**	**5.1E-06**	**1.95E-06**	**8.09E-06**
	(C-F	**(80-20)**	**3.35**	**0.89**	**5.26E-06**	**3.62E-05**	**3.01E-06**
	(C-F)	**(50-50)**	**2.20**	**0.049**	**7.98E-06**	**8.46E-05**	**6.50E-07**
	(C-F)	**(20-80)**	**2.49**	**0.049**	**3.42E-06**	**4.02E-05**	**6.18E-07**
GGBS I	**(C-S)**	**(80-20)**	**2.25**	**0.049**	**1.22E-05**	**8.29E-05**	**2.92E-06**
	(C-S)	**(50-50)**	**2.60**	**0.066**	**6.64E-06**	**2.26E-05**	**2.36E-06**
	(C-S)	**(20-80)**	**1.72**	**0.066**	**5.01E-06**	**4.02E-05**	**2.44E-06**

Table 5.10 First series values for 28 days curing time with Bentonite content of 5%

Material	Mixture	Replacement %	C_c	C_r	C_v	Kcon (cm/s)	K $_{(flexible\ wall)}$ (cm/s)
Fly ash	**(C-F-S)**	**(100-0-0)**	**2.30**	**0.033**	**6.93E-06**	**3.37E-05**	**3.65E-06**
	(C-F)	**(80-20)**	**2.82**	**0.049**	**7.71E-06**	**2.44E-05**	**3.37E-06**
	(C-F)	**(50-50)**	**2.10**	**0.049**	**6.12E-06**	**3.43E-05**	**2.36E-06**
	(C-F)	**(20-80)**	**2.41**	**0.73**	**1.28E-05**	**9.82E-05**	**1.32E-06**
GGBS I	**(C-S)**	**(80-20)**	**2.45**	**0.049**	**1.26E-05**	**3.08E-05**	**4.95E-06**
	(C-S)	**(50-50)**	**2.10**	**0.066**	**7.59E-06**	**2.54E-05**	**8.72E-07**
	(C-S)	**(20-80)**	**1.86**	**0.033**	**7.20E-06**	**7.95E-05**	**1.01E-06**

5.6.1.1 Second Series

Table 5.11 Second series values for 7 days curing time

Material	Mixture	Replacement %	B %	C_c	C_r	C_v	K_{con} (cm/s)	$K_{\text{(flexible wall)}}$ (cm/s)
GGBS I	(C-S-L)	(50-45-5)	5	2.48	0.056	8.17E-06	5.60E-05	4.49E-06
	(C-S-L)	(45-50-5)		2.81	0.059	7.52E-06	1.82E-05	3.46E-06
	(C-S-L)	(50-45-5)	9	3.58	0.159	9.70E-06	1.59E-05	1.55E-06
	(C-S-L)	(45-50-5)		2.94	0.078	7.67E-06	5.29E-05	1.06E-06

Note: B= Bentonite

Table 5.12 Second series values for 28 days curing time

Material	Mixture	Replacement %	B %	C_c	C_r	C_v	K_{con} (cm/s)	$K_{\text{(flexible wall)}}$ (cm/s)
GGBS I	(C-S-L)	(50-45-5)	5	1.95	0.03	6.44E-06	1.07E-05	9.97E-06
	(C-S-L)	(45-50-5)		1.01	0.048	3.98E-06	2.24E-05	4.97E-06
	(C-S-L)	(50-45-5)	9	1.79	0.058	9.10E-06	3.36E-05	2.70E-07
	(C-S-L)	(45-50-5)		1.12	0.049	3.87E-06	3.02E-05	5.95E-07

Note: B= Bentonite

5.6.1.2 Third Series

Table 5.13 Third series values for 7 days curing time

Material	Mixture	Replacement %	B %	C_c	C_r	C_v	K_{con} (cm/s)	$K_{\text{(flexible wall)}}$ (cm/s)
GGBS II	(C-S)	(80-20)	5	2.74	0.066	1.19E-05	4.25E-05	1.36E-06
	(C-S)	(50-50)		2.34	0.033	6.62E-06	5.02E-05	1.66E-06
	(C-S)	(20-80)		2.75	0.066	1.82E-05	1.34E-05	1.24E-06
	(C-S-L)	(50-45-5)		4.61	0.27	1.18E-05	1.95E-05	2.61E-06
	(C-S-L)	(45-50-5)		4.15	0.08	1.24E-05	3.80E-05	4.46E-06
	(C-S-L)	(50-45-5)	9	2.92	0.116	5.26E-06	2.45E-05	5.83E-07
	(C-S-L)	(45-50-5)		2.65	0.049	6.06E-06	3.13E-05	5.97E-07

Note: B= Bentonite

Table 5.14 Third series values for 28 days curing time

Material	Mixture	Replacement %	B %	C_c	C_r	C_v	K_{con} (cm/s)	$K_{(flexible\ wall)}$ (cm/s)
GGBS II	**(C-S)**	**(80-20)**	**5**	**3.37**	**0.066**	**4.61E-06**	**3.61E-05**	**4.37E-06**
	(C-S)	**(50-50)**		**2.85**	**0.083**	**8.94E-06**	**3.61E-05**	**1.01E-06**
	(C-S)	**(20-80)**		**2.57**	**0.083**	**8.94E-06**	**6.54E-05**	**5.50E-06**
	(C-S-L)	**(50-45-5)**		**1.89**	**0.038**	**3.45E-05**	**3.66E-05**	**9.33E-07**
	(C-S-L)	**(45-50-5)**		**2.89**	**0.049**	**6.28E-06**	**9.19E-05**	**8.82E-07**
	(C-S-L)	**(50-45-5)**	**9**	**3.65**	**0.083**	**1.38E-05**	**6.31E-05**	**2.77E-07**
	(C-S-L)	**(45-50-5)**		**6.24**	**0.64**	**6.54E-06**	**2.06E-05**	**7.02E-07**

Note: B= Bentonite

5.6.1.3 Fourth Series

Table 5.15 Fourth series values for 7 days curing time

Material	Mixture	Replacement %	B %	C_c	C_r	C_v	K_{con} (cm/s)	$K_{(flexible\ wall)}$ (cm/s)
Steel Slag	**(C-S)**	**(80-20)**	**5**	**2.62**	**0.049**	**4.84E-06**	**3.91E-05**	**1.15E-06**
	(C-S)	**(50-50)**		**1.96**	**0.04**	**3.12E-06**	**4.19E-05**	**1.03E-06**
	(C-S)	**(20-80)**		**3.11**	**0.099**	**1.17E-05**	**2.33E-04**	**7.03E-07**
	(C-S-L)	**(50-45-5)**		**1.72**	**0.049**	**6.12E-06**	**8.26E-05**	**6.65E-07**
	(C-S-L)	**(45-50-5)**		**1.29**	**0.018**	**4.78E-06**	**5.88E-05**	**7.91E-07**
	(C-S-L)	**(50-45-5)**	**9**	**3.07**	**0.049**	**1.25E-05**	**1.04E-04**	**4.03E-07**
	(C-S-L)	**(45-50-5)**		**7.42**	**0.049**	**4.40E-06**	**3.07E-05**	**4.62E-07**

Note: B= Bentonite

Table 5.16 Fourth series values for 28 days curing time

Material	Mixture	Replacement %	B %	C_c	C_r	C_v	K_{con} (cm/s)	$K_{(flexible\ wall)}$ (cm/s)
Steel Slag	**(C-S)**	**(80-20)**	**5**	**2.10**	**0.049**	**4.90E-06**	**3.68E-05**	**7.68E-07**
	(C-S)	**(50-50)**		**5.61**	**0.049**	**8.23E-06**	**8.99E-05**	**1.70E-06**
	(C-S)	**(20-80)**		**4.56**	**0.049**	**5.51E-06**	**4.66E-05**	**9.93E-07**
	(C-S-L)	**(50-45-5)**		**6.87**	**0.083**	**5.84E-06**	**5.30E-05**	**2.98E-07**
	(C-S-L)	**(45-50-5)**		**5.83**	**0.055**	**2.40E-06**	**3.19E-05**	**3.44E-07**
	(C-S-L)	**(50-45-5)**	**9**	**2.84**	**0.066**	**7.27E-06**	**1.50E-05**	**5.39E-07**
	(C-S-L)	**(45-50-5)**		**3.60**	**0.033**	**5.61E-06**	**1.18E-05**	**4.30E-07**

Note: B= Bentonite

CHAPTER 6

CONCLUSION

6.1 Conclusion

Cement-Bentonite barrier walls have been constructed in many parts of the world, and there are significant advantages of use of GGBS, Fly ash and Steel slag in barrier wall construction. The advantages are higher strength, lower permeability, and economy. In addition, barrier walls involving GGBS or fly ash may have beneficial environmental effects for these projects.

The following conclusions are drawn from the study:

- Specific gravity of a mixture is affected by the G_s value of each material. The lowest G_s value belongs to fly ash while the steel slag has the highest one.
- The maximum liquid limit value belongs to GGBS type I mixture by 9 % bentonite content. On the other hand, the minimum liquid limit value belongs to mixture of steel slag.
- According to particle size distributions (PSD) of all mixtures, Clay sizes of the mixtures were in the range of 7 % to 17 %, whereas the silt sizes were in the range of 41 % to 81 %.
- Fresh mixtures of the prepared samples satisfies the slump range mentioned in the standard. Bentonite content affects the slurry viscosity and mixtures having 9 % bentonite gave the slumps lower than mixtures having 5 % of bentonite.
- In the first series, permeability of specimens having fly ash decreases by increasing fly ash content. For the second series, 50 % of GGBS type I with 5 % of lime and 9% bentonite content gave acceptable results in 28 days of curing time. For the third series, 50 % of GGBS type II with 5 % of lime and 9% bentonite content gave the higher permeability value in 28 days of curing time considering GGBS type I. Steel slag has been used in fourth series. Most of the mixtures in this series gave the acceptable permeability values in 28 days of curing period. For this series, the mixture by 9 % of bentonite content, permeability tends decrease even after 90 days.
- Unconfined compressive strength of all mixtures increase by increasing curing time. The maximum values for the amended mixtures belong to mixtures with 9 % of bentonite content.
- C_c, C_r, C_v, k_{con} values were found form consolidation test results. Permeability values found from from consolidation tests are 10 times to 100 times higher than flexible wall k results for the same effective stress of 150 kPa. These differences may be due to:
    1. Big differences in hydraulic gradient i values. The value of i for consolidation test was 1 whereas this value was 100 in flexible-wall permeability test. In addition, in a material of low density and soft consistency permeability decreases by increasing hydraulic gradient.
    2. Permeability was calculated for 90 % of consolidation in oedometer test.
- Coefficient of volume change (m_v) and constrained modulus D were investigated to all series as well. Generally, m_v values are decreasing with increasing curing time. As m_v decreases, D increased.

GGBS, Fly ash and Steel slag can be used, at certain percentages and curing periods, as additive in Cement-Bentonite barrier wall construction, but amount of additive should be determined after the permeability, strength and compressibility tests and the minimum permeability, strength and compressibility values according to the standards should be satisfied.

6.2 Recommendation for Future Research

In this study, use of GGBS, Fly ash and Steel slag in cement-bentonite barrier wall were studied and permeability, strength, and compressibility tests were performed. Although performed 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. . Flexibility and durability of the mixtures can be found. In addition, economical analysis of the use of these additives may be considered. Leachate analysis of these mixtures can be carried out.

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ASTM, Standard C188 – 09, “Standard Test Method for Density of Hydraulic Cement,” ASTM International,West Conshohocken, PA.

ASTM, Standard C989-11, “Standard Specification for Slag Cement for Use in Concrete and Mortars,” ASTM International,West Conshohocken, PA.

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APPENDICIES A

Particle Size Distribution (PSD)

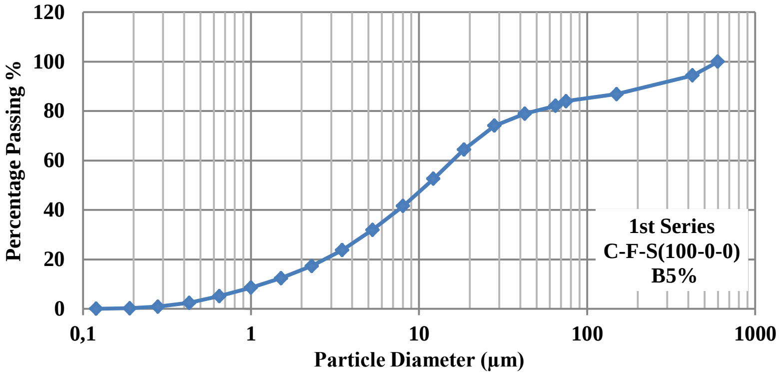

Figure A.1 – Particle Size Distribution of first series C-F-S (100-0-0) Bentonite content 5%

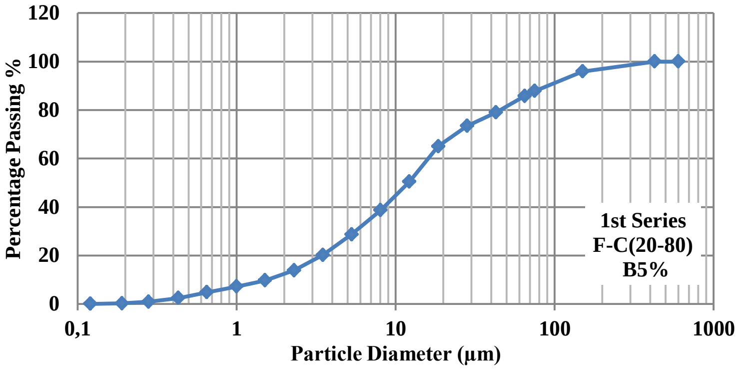

Figure A.2 – Particle Size Distribution of first series F-C (20-80) Bentonite content 5%

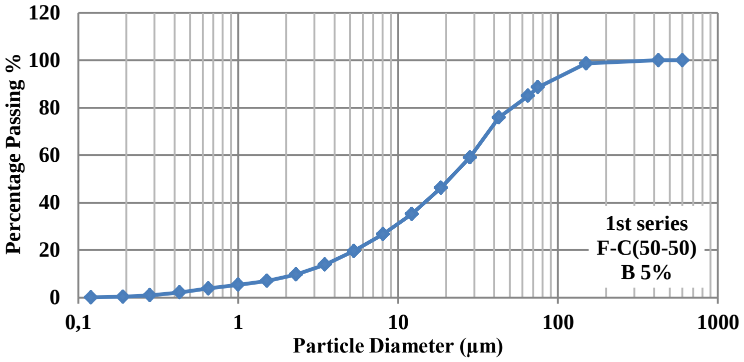

Figure A.3 – Particle Size Distribution of first series F-C (50-50) Bentonite content 5%

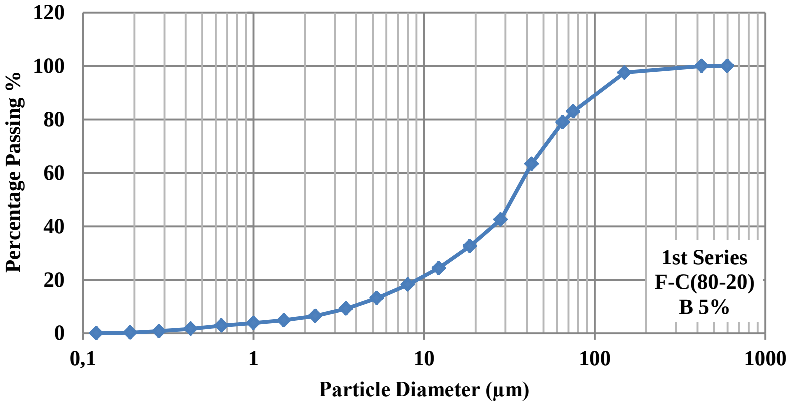

Figure A.4 – Particle Size Distribution of first series F-C (80-20) Bentonite content 5%

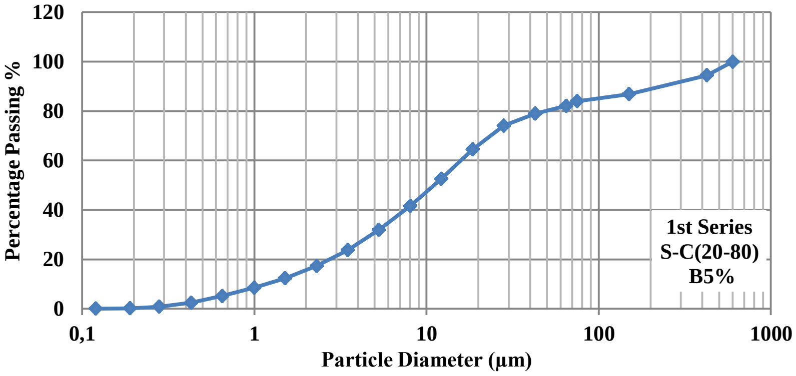

Figure A.5 – Particle Size Distribution of first series S-C (20-80) Bentonite content 5%

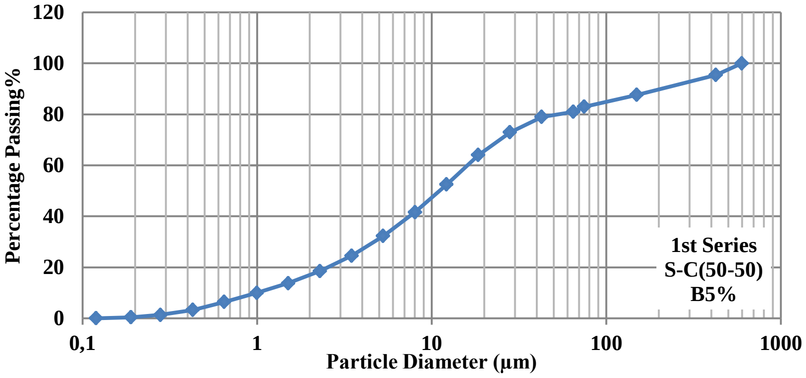

Figure A.6 – Particle Size Distribution of first series S-C (50-50) Bentonite content 5%

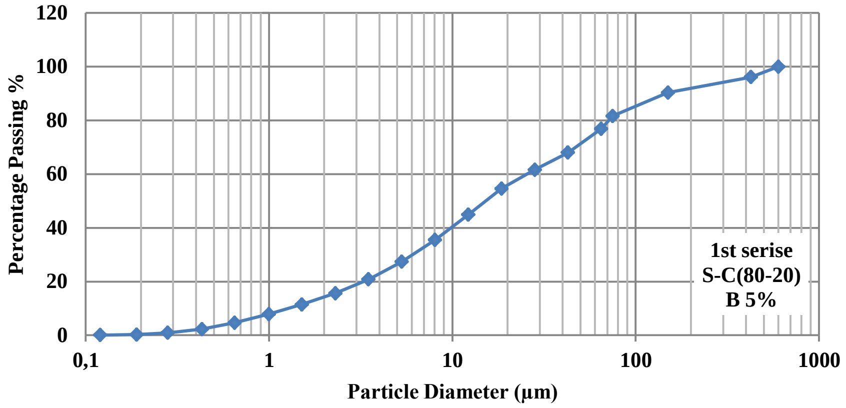

Figure A.7 – Particle Size Distribution of first series S-C (80-20) Bentonite content 5%

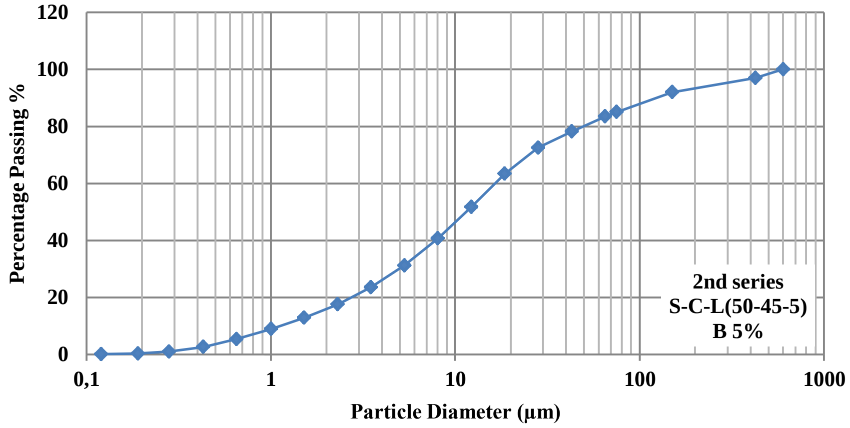

Figure A.8 – Particle Size Distribution of second series S-C-L (50-45-5) Bentonite content 5%

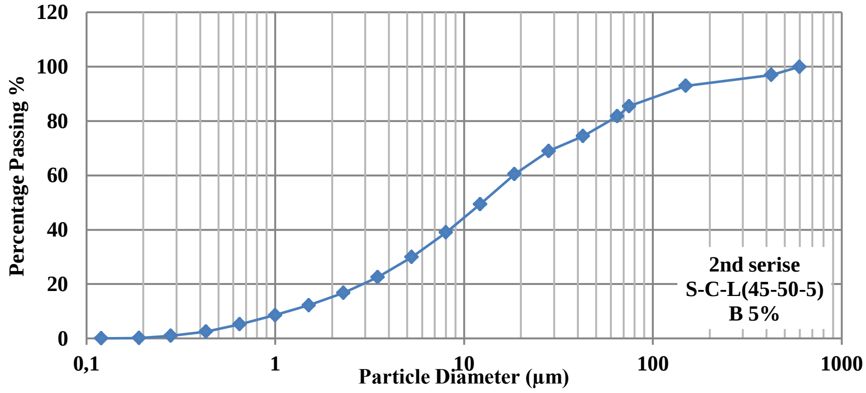

Figure A.9 – Particle Size Distribution of second series S-C-L (45-50-5) Bentonite content 5%

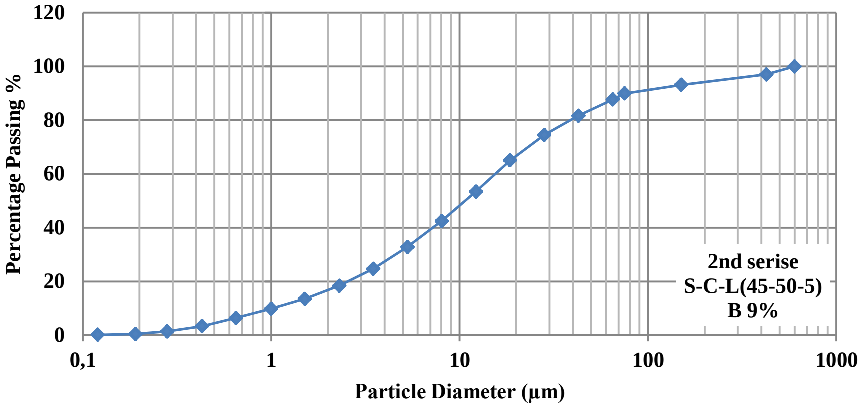

Figure A.10 – Particle Size Distribution of second series S-C-L (45-50-5) Bentonite content 9%

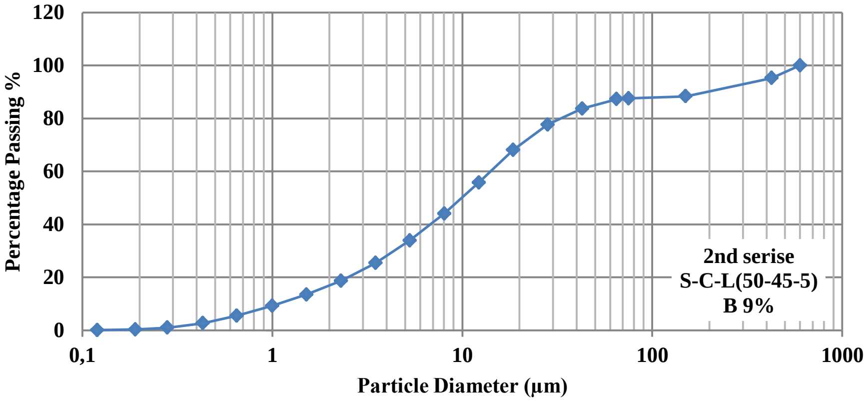

Figure A.11 – Particle Size Distribution of second series S-C-L (50-45-5) Bentonite content 9%

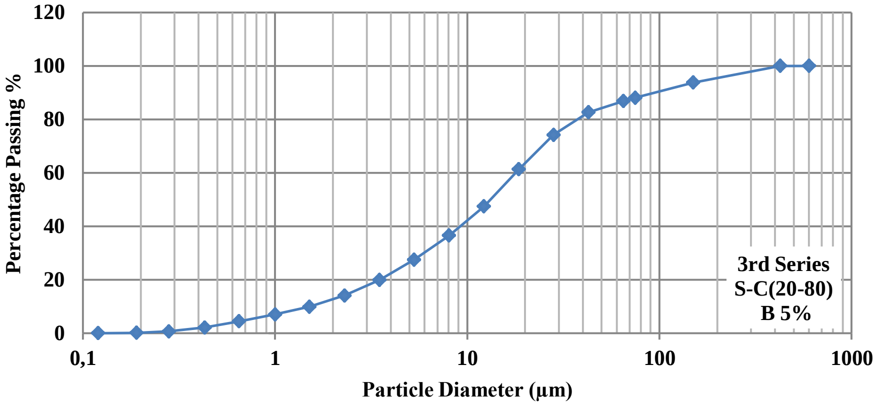

Figure A.12 – Particle Size Distribution of third series S-C (20-80) Bentonite content 5%

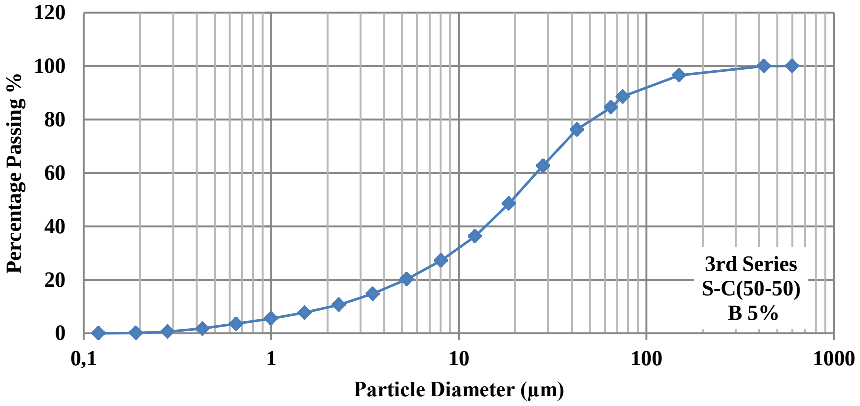

Figure A.13 – Particle Size Distribution of third series S-C (50-50) Bentonite content 5%

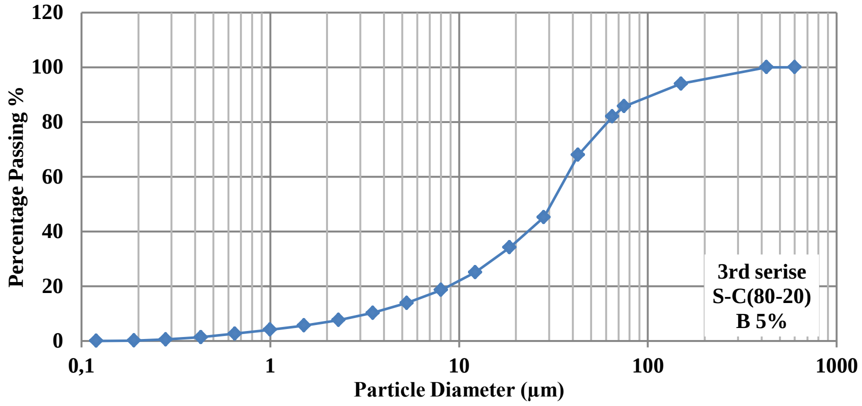

Figure A.14 – Particle Size Distribution of third series S-C (80-20) Bentonite content 5%

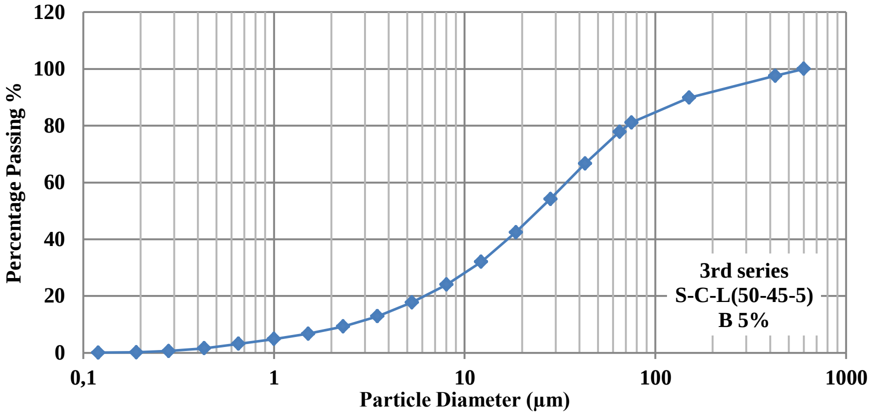

Figure A.15 – Particle Size Distribution of third series S-C-L (50-45-5) Bentonite content 5%

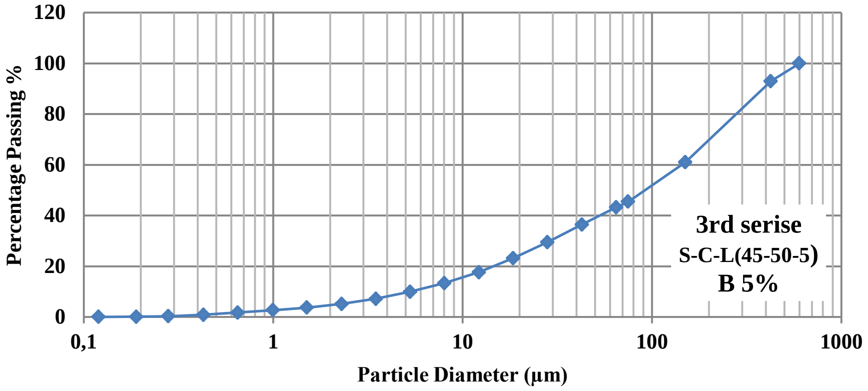

Figure A.16 – Particle Size Distribution of third series S-C-L (45-50-5) Bentonite content 5%

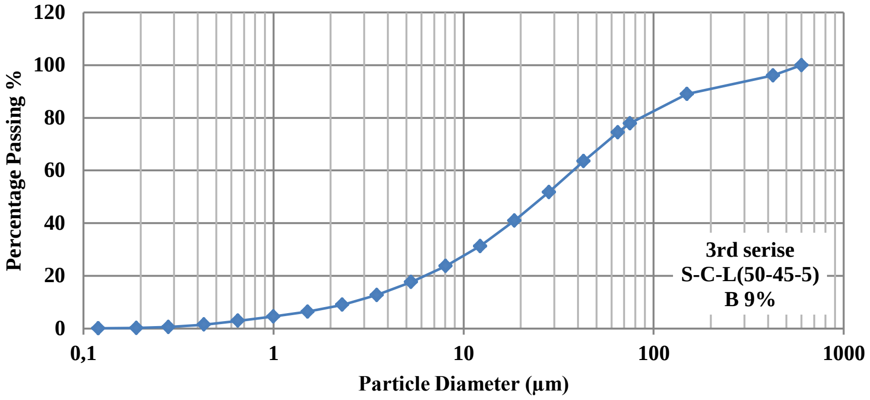

Figure A.17 – Particle Size Distribution of third series S-C-L (50-45-5) Bentonite content 9%

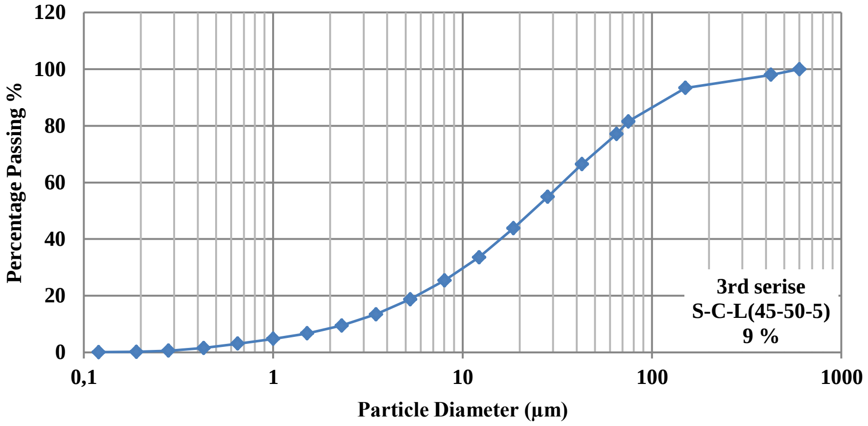

Figure A.18 – Particle Size Distribution of third series S-C-L (45-50-5) Bentonite content 9%

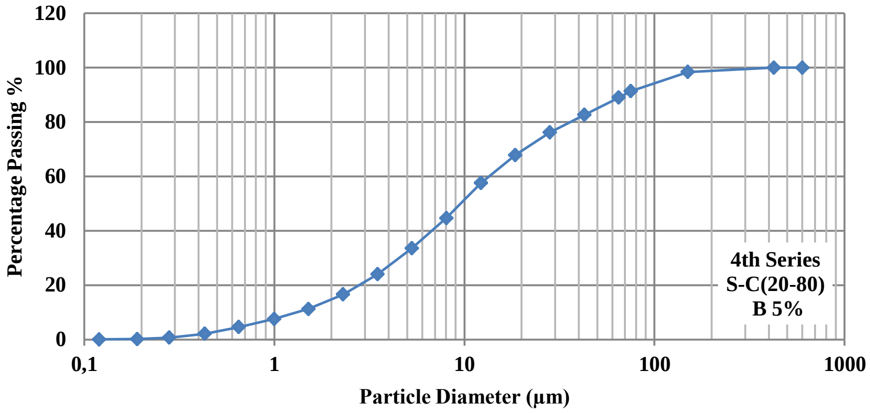

Figure A.19 – Particle Size Distribution of fourth series S-C (20-80) Bentonite content 5%

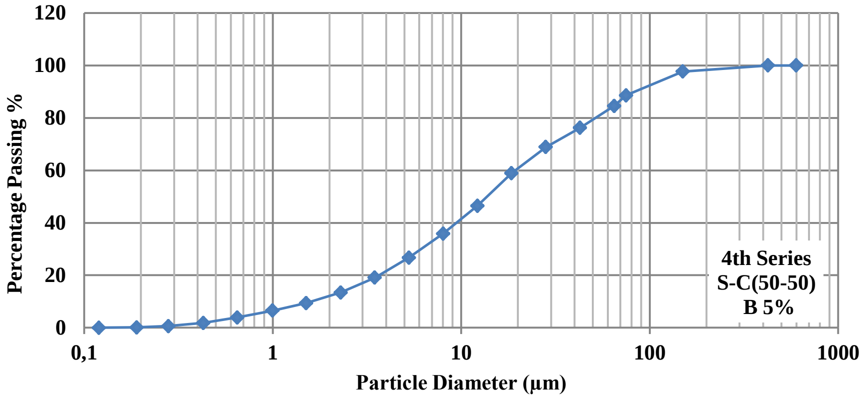

Figure A.20 – Particle Size Distribution of fourth series S-C (50-50) Bentonite content 5%

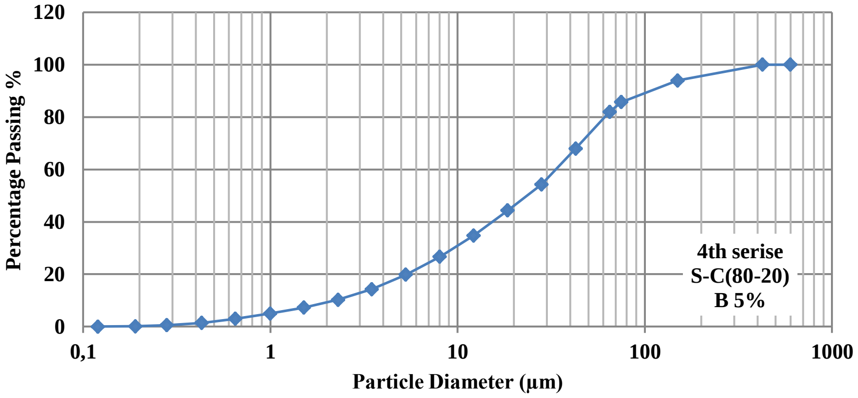

Figure A.21 – Particle Size Distribution of fourth series S-C (80-20) Bentonite content 5%

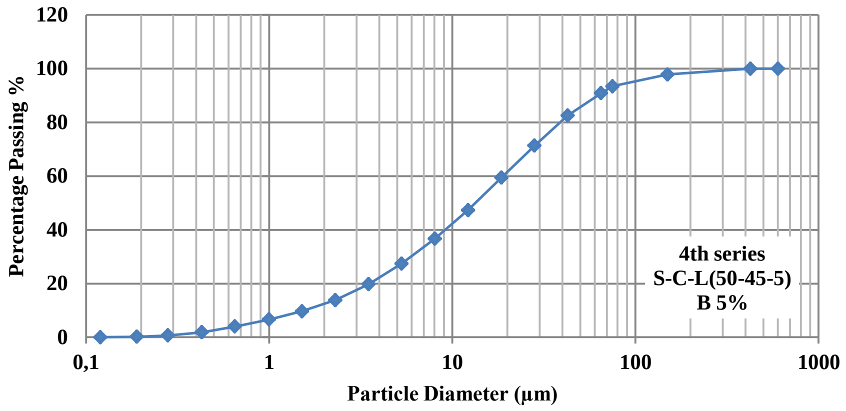

Figure A.22 – Particle Size Distribution of fourth series S-C-L (50-45-5) Bentonite content 5%

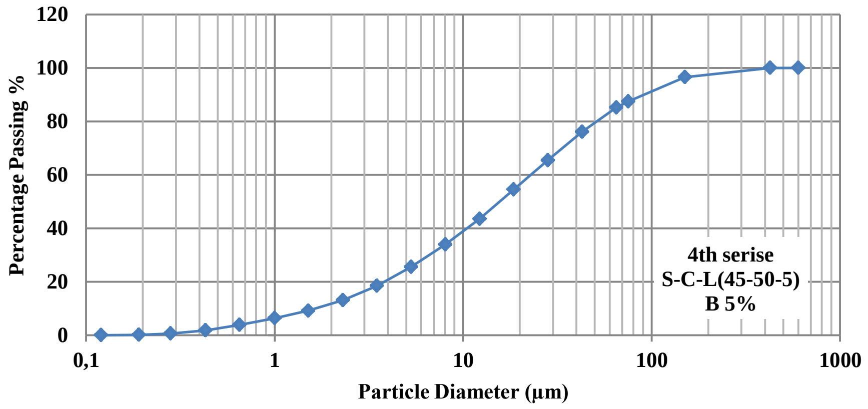

Figure A.23 – Particle Size Distribution of fourth series S-C-L (45-50-5) Bentonite content 5%

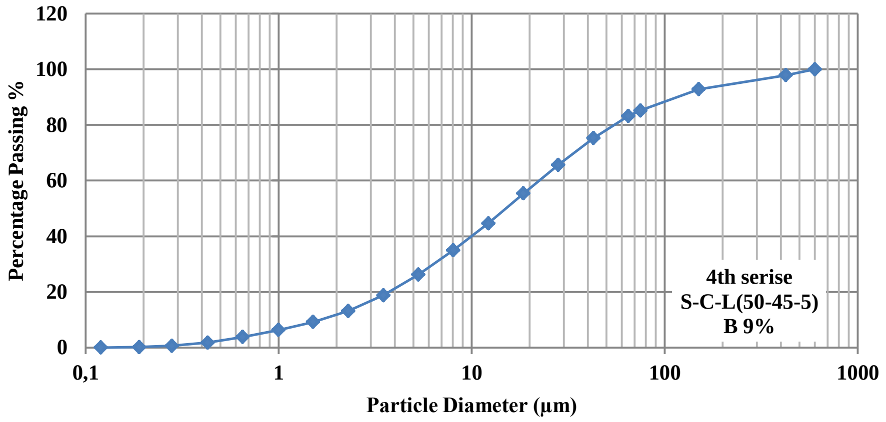

Figure A.24 – Particle Size Distribution of fourth series S-C-L (50-45-5) Bentonite content 9%

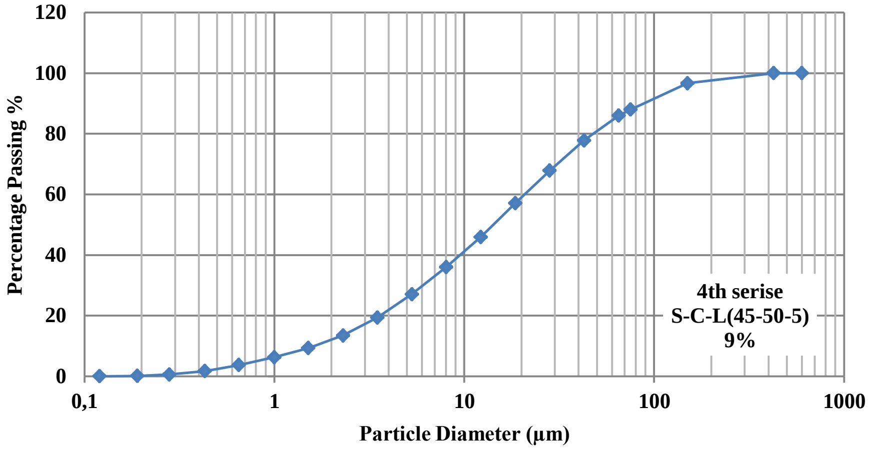

Figure A.25 – Particle Size Distribution of fourth series S-C-L (45-50-5) Bentonite content 9%

APPENDICIES B

Coefficient of Volume Change (m_v)

Table B. 1 – First Series (C-F-S) (100-0-0) m_v and D values

		C-F-S(100-0-0)			
		Curing time (day)			
		7		**28**	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m2)**	**m_v (M2/KN)**	**D (kN/m2)**
12.5	**5**	**0.0030**	**325**	**0.0067**	**147**
25		**0.0008**	**1250**	**0.0024**	**416**
50		**0.0016**	**625**	**0.0012**	**833**
100		**0.0004**	**2500**	**0.0008**	**1250**
200		**0.0006**	**1666**	**0.0006**	**1666**
400		**0.0010**	**1000**	**0.00065**	**1538**
800		**0.0016**	**597**	**0.0030**	**330**
1600		**0.0011**	**869**	**0.0002**	**4444**
400		**0.0003**	**2790**	**1.66E-05**	**60000**
100		**0.0001**	**10000**	**6.67E-05**	**15000**
25		**0.0002**	**3750**	**0.00013**	**7500**

Not: B= Bentonite Content

Table B. 2 – First Series (C-F) (80-20) m_v and D values

		C-F (80-20)			
		Curing time (day)			
		7		**28**	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m^2)**	**m_v (m^2/kN)**	**D (kN/m^2)**
12.5	**5**	**0.0056**	**178**	**0.0065**	**152**
25		**0.0032**	**312**	**0.0032**	**312**
50		**0.0024**	**416**	**0.0016**	**625**
100		**0.0046**	**217**	**0.0022**	**454**
200		**0.0039**	**256**	**0.0017**	**588**
400		**0.0053**	**188**	**0.0021**	**465**
800		**0.0019**	**526**	**0.0018**	**555**
1600		**0.0015**	**661**	**0.0012**	**816**
400		**0.0004**	**2222**	**2.5E-05**	**40000**
100		**6.67E-05**	**15000**	**3.34E-05**	**30000**
25		**0.00013**	**7500**	**0.00026**	**3750**

Not: B= Bentonite Content

Table B. 3 – First Series (C-F) (50-50) m_v and D values

		C-F (50-50)			
		Curing time (day)			
		7		**28**	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m^2)**	**m_v (m^2/kN)**	**D (kN/m^2)**
12.5	**5**	**0.0224**	**44**	**0.0015**	**665**
25		**0.0072**	**138**	**0.0048**	**208**
50		**0.008**	**125**	**0.0024**	**416**
100		**0.0072**	**138**	**0.0038**	**263**
200		**0.0057**	**175**	**0.0032**	**312**
400		**0.0038**	**263**	**0.00255**	**392**
800		**0.0014**	**677**	**0.0017**	**588**
1600		**0.0008**	**1250**	**0.00073**	**1355**
400		**0.00002**	**40000**	**2.5E-05**	**40000**
100		**6.67E-05**	**15000**	**6.67E-05**	**15000**
25		**0.00013**	**7500**	**0.00026**	**3750**

Not: B= Bentonite Content

Table B. 4 – First Series (C-F) (20-80) m_v and D values

		C-F (20-80)			
		Curing time (day)			
		7		**28**	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m^2)**	**m_v (m^2/kN)**	**D (kN/m^2)**
12.5	**5**	**0.013**	**76**	**0.0061**	**162**
25		**0.023**	**43**	**0.004**	**250**
50		**0.011**	**89**	**0.004**	**250**
100		**0.008**	**121**	**0.0048**	**208**
200		**0.0050**	**200**	**0.0045**	**222**
400		**0.0024**	**416**	**0.0029**	**338**
800		**0.0005**	**1739**	**0.0015**	**655**
1600		**0.0009**	**1066**	**0.0012**	**816**
400		**2.5E-05**	**40000**	**0.0003**	**2727**
100		**6.67E-05**	**15000**	**3.33E-05**	**30000**
25		**0.0001**	**7500**	**0.00013**	**7500**

Not: B= Bentonite Content

Table B. 5– First Series (C-S) (80-20) m_v and D values

		C-S (80-20)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m^2)	m_v (m^2/kN)	D (kN/m^2)
12.5	5	0.006	156	0.0064	156
25		0.004	250	0.0024	416
50		0.0004	2500	0.0016	625
100		0.005	200	0.0014	714
200		0.0033	303	0.0016	625
400		0.003	333	0.0018	540
800		0.0021	476	0.0016	597
1600		0.0006	1538	0.0010	987
400		2.5E-05	40000	2.5E-05	40000
100		3.33E-05	30000	6.66E-05	15000
25		0.0013	750	0.00026	3750

Not: B= Bentonite Content

Table B. 6 – First Series (C-S) (50-50) m_v and D values

		C-S (50-50)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m^2)	m_v (m^2/kN)	D (kN/m^2)
12.5	5	0.004	250	0.0024	416
25		0.0024	416	0.0016	625
50		0.0056	178	0.0112	89
100		0.001	1000	0.0024	416
200		0.0027	370	0.0006	1666
400		0.0025	400	0.00085	1176
800		0.0016	625	0.0012	800
1600		0.0011	860	0.00095	1038
400		3.33E-05	30000	3.33E-05	30000
100		6.67E-05	15000	6.67E-05	15000
25		0.00013	7500	0.00013	7500

Not: B= Bentonite Content

Table B. 7 – First Series (C-S) (20-80) m_v and D values

		C-S (20-80)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m^2)	m_v (m^2/kN)	D (kN/m^2)
12.5	5	0.019	51	0.002	348
25		0.0096	104	0.0024	416
50		0.0004	2500	0.0008	1250
100		0.0062	161	0.0008	1250
200		0.0028	357	0.0005	2000
400		0.0027	370	0.0008	1250
800		0.0016	606	0.0009	1025
1600		0.00047	2105	0.0009	1095
400		3.33E-05	30000	1.67E-05	60000
100		6.67E-05	15000	6.67E-05	15000
25		0.0004	2500	0.0002	3750

Not: B= Bentonite Content

Table B. 8– Second Series (C-S-L) (50-45-5) m_v and D values

		C-S-L (50-45-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m^2)	m_v (m^2/kN)	D (kN/m^2)
12.5	5	0.0088	113	0.0038	258
25		0.0020	484	0.0041	243
50		0.0035	284	0.0009	1091
100		0.0048	204	0.0010	939
200		0.0026	373	0.0009	1087
400		0.0021	475	0.0012	776
800		0.0014	670	0.0011	878
1600		0.0011	890	0.0009	1111
400		2.82E-05	35385	1.53E-05	65261
100		6.22E-05	16084	5.91E-05	16908
25		0.0001	7371	0.0001	5535

Not: B= Bentonite Content

Table B. 9 – Second Series (C-S-L) (45-50-5) m_v and D values

		C-S-L (45-50-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m^2)	m_v (m^2/kN)	D (kN/m^2)
12.5	5	0.008	120	0.007	142
25		0.008	113	0.003	252
50		0.001	766	0.0007	1427
100		0.003	299	0.002	412
200		0.003	276	0.0008	1220
400		0.002	413	0.0008	1142
800		0.0006	1650	0.001	902
1600		0.0002	4136	0.001	942
400		2.42E-05	41311	2.98E-05	33555
100		8.62E-05	11599	8.94E-05	11185
25		0.0002	4487	0.0001	6494

Not: B= Bentonite Content

Table B. 10 – Second Series (C-S-5) (50-45-5) m_v and D values

		C-S-L (50-45-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	9	0.0019	521	0.0044	223
25		0.0018	613	0.0009	1035
50		0.0014	680	0.0118	84
100		0.0010	954	0.0037	270
200		0.0006	1506	0.0008	1201
400		0.0010	998	0.0004	2007
800		0.0013	736	0.0014	697
1600		0.0013	741	0.0006	1572
400		7.83E-05	12769	2.94E-05	33923
100		9.19E-05	10872	8.34E-05	11990
25		0.0001	5516	0.0009	1073

Not: B= Bentonite Content

Table B. 11 – Second Series (C-S-5) (45-50-5) m_v and D values

		C-S-L (45-50-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	9	0.003	333	0.002	500
25		0.002	500	0.0008	1250
50		0.001	1000	0.034	29
100		0.0009	1111	0.0054	185
200		0.0006	1667	0.0006	1667
400		0.0010	1000	0.0003	3333
800		0.0015	667	0.0024	417
1600		0.0016	625	0.0005	2000
400		6.43E-05	15552	5.44E-05	18382
100		8.95E-05	11173	4.54E-05	22026
25		0.0002	5000	0.0004	2500

Not: B= Bentonite Content

Table B. 12– Third Series (C-S) (80-20) m_v and D values

		C-S (80-20)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	5	0.0106	94	0.0120	83
25		0.0024	417	0.0048	208
50		0.0028	357	0.0056	179
100		0.0022	455	0.0062	161
200		0.0021	476	0.0033	303
400		0.0036	278	0.0034	290
800		0.0023	430	0.0022	444
1600		0.001	1000	0.0014	708
400		3.33E-05	30000	3.33E-05	30000
100		1E-04	10000	6.67E-05	15000
25		0.0001	7500	0.0002	3750

Not: B= Bentonite Content

Table B. 13 – Third Series (C-S) (50-50) m_v and D values

		C-S (50-50)			
		Curing time (day)			
		7		**28**	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m2)**	**m_v (M2/ kN)**	**D (kN/m2)**
12.5	**5**	**0.0007**	**1365**	**0.0168**	**60**
25		**0.0024**	**417**	**0.0056**	**179**
50		**0.0028**	**357**	**0.0060**	**167**
100		**0.0042**	**238**	**0.0054**	**185**
200		**0.0051**	**196**	**0.0036**	**278**
400		**0.0032**	**313**	**0.0030**	**328**
800		**0.0019**	**519**	**0.0020**	**488**
1600		**0.0005**	**1818**	**0.0011**	**889**
400		**1.67E-05**	**60000**	**4.17E-05**	**24000**
100		**0.0001**	**7500**	**1E-04**	**10000**
25		**0.0001**	**7500**	**0.0001**	**7500**

Not: B= Bentonite Content

Table B. 14 – Third Series (C-S) (20-80) m_v and D values

		C-S (20-80)			
		Curing time (day)			
		7		**28**	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m2)**	**m_v (M2/ kN)**	**D (kN/m2)**
12.5	**5**	**0.0071**	**141**	**0.0023**	**391**
25		**0.0036**	**273**	**0.0008**	**1250**
50		**0.0038**	**258**	**0.0016**	**625**
100		**0.0056**	**179**	**0.0014**	**714**
200		**0.0033**	**303**	**0.0023**	**435**
400		**0.0014**	**714**	**0.0026**	**385**
800		**0.0014**	**690**	**0.0018**	**541**
1600		**0.0013**	**741**	**0.0010**	**988**
400		**3.33E-05**	**30000**	**4.16E-05**	**24000**
100		**1E-04**	**10000**	**6.67E-05**	**15000**
25		**0.0002**	**3750**	**0.0002**	**3750**

Not: B= Bentonite Content

Table B. 15– Third Series (C-S-L) (50-45-5) m_v and D values

		C-S-L (50-45-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m2)**	**m_v (M2/ kN)**	**D (kN/m2)**
12.5	5	0.007	143	0.0005	2000
25		0.005	200	0.005	200
50		0.0032	313	0.0011	909
100		0.0012	833	0.0009	1111
200		0.0009	1111	0.0006	1667
400		0.001	1000	0.0021	476
800		0.001	1000	0.00034	2941
1600		0.001	1000	0.0008	1250
400		3.37E-05	29674	1.54E-05	64935
100		1.22E-04	8197	4.67E-05	21413
25		0.0002	5000	0.0001	10000

Not: B= Bentonite Content

Table B. 16 – Third Series (C-S-L) (45-50-5) m_v and D values

		C-S-L (45-50-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m2)**	**m_v (M2/ kN)**	**D (kN/m2)**
12.5	5	0.008	125	0.0008	1250
25		0.004	250	0.004	250
50		0.0028	357	0.0012	833
100		0.0022	455	0.001	1000
200		0.0013	769	0.0007	1429
400		0.002	500	0.0023	426
800		0.0015	656	0.00095	1053
1600		0.0015	640	0.0010	920
400		4.17E-05	24000	2.5E-05	40000
100		1E-04	10000	6.67E-05	15000
25		0.0002	3750	0.0001	7500

Not: B= Bentonite Content

Table B. 17 – Third Series (C-S-5) (50-45-5) m_v and D values

		C-S-L (50-45-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	9	0.0008	1250	0.0072	137
25		0.0024	417	0.0008	1250
50		0.0040	250	0.0016	625
100		0.0030	333	0.0020	500
200		0.0028	357	0.0046	217
400		0.0027	364	0.0013	741
800		0.0021	460	0.0008	1250
1600		0.0011	899	0.0013	727
400		5.83E-05	17143	4.17E-05	24000
100		1E-04	10000	6.67E-05	15000
25		0.0001	7500	0.0002	3750

Not: B= Bentonite Content

Table B. 18 – Third Series (C-S-5) (45-50-5) m_v and D values

		C-S-L (45-50-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	9	0.0752	13	0.0400	25
25		0.0024	417	0.0024	417
50		0.0040	250	0.0020	500
100		0.0032	313	0.0012	833
200		0.0031	323	0.0041	244
400		0.0026	377	0.0021	476
800		0.0020	494	0.0010	976
1600		0.0009	1013	0.0023	426
400		2.5E-05	40000	0.0003	3077
100		1E-04	10000	6.67E-05	15000
25		0.0001	7500	0.0001	7500

Not: B= Bentonite Content

Table B. 19– Fourth Series (C-S) (80-20) m_v and D values

		C-S (80-20)			
		Curing time (day)			
		7		28	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m2)**	**m_v (M2/ kN)**	**D (kN/m2)**
12.5	**5**	**0.0904**	**11**	**0.0050**	**199**
25		**0.0024**	**417**	**0.0040**	**250**
50		**0.0032**	**313**	**0.0048**	**208**
100		**0.0052**	**192**	**0.0052**	**192**
200		**0.0048**	**208**	**0.0040**	**250**
400		**0.0032**	**313**	**0.0029**	**345**
800		**0.0019**	**519**	**0.0017**	**580**
1600		**0.0009**	**1013**	**0.0008**	**1159**
400		**2.5E-05**	**40000**	**2.5E-05**	**40000**
100		**6.67E-05**	**15000**	**1E-04**	**10000**
25		**0.0001**	**7500**	**0.00013**	**7500**

Not: B= Bentonite Content

Table B. 20 – Fourth Series (C-S) (50-50) m_v and D values

		C-S (50-50)			
		Curing time (day)			
		7		28	
σ´c (kPa)	**B %**	**m_v (m^2/kN)**	**D (kN/m2)**	**m_v (M2/ kN)**	**D (kN/m2)**
12.5	**5**	**0.0062**	**161**	**0.0084**	**119**
25		**0.0049**	**204**	**0.0056**	**179**
50		**0.0124**	**80**	**0.0096**	**104**
100		**0.0099**	**100**	**0.0070**	**143**
200		**0.0065**	**153**	**0.0054**	**185**
400		**0.0036**	**273**	**0.0034**	**290**
800		**0.0011**	**889**	**0.0019**	**526**
1600		**0.0006**	**1604**	**0.0021**	**473**
400		**2.04E-05**	**48916**	**0.00001**	**40000**
100		**8.17E-05**	**12229**	**6.67E-05**	**15000**
25		**0.0002**	**4586**	**0.0001**	**7500**

Not: B= Bentonite Content

Table B. 21 – Fourth Series (C-S) (20-80) m_v and D values

		C-S (20-80)			
		Curing time (day)			
		7		28	
σ′c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	5	0.0369	27	0.0508	20
25		0.0200	50	0.0128	78
50		0.0244	41	0.0208	48
100		0.0132	76	0.0062	161
200		0.0076	132	0.0044	227
400		0.0090	110	0.0014	714
800		0.0005	1905	0.0055	182
1600		0.0009	1013	0.00068	1455
400		0.00005	20000	0.00002	40000
100		0.0005	2000	3.33E-05	30000
25		0.0008	1250	0.0001	7500

Not: B= Bentonite Content

Table B. 22– Fourth Series (C-S-L) (50-45-5) m_v and D values

		C-S-L (50-45-5)			
		Curing time (day)			
		7		28	
σ′c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	5	0.0087	114	0.0075	133
25		0.0072	139	0.0048	208
50		0.0116	86	0.0040	250
100		0.0094	106	0.0054	185
200		0.0065	154	0.0060	167
400		0.0027	370	0.0038	263
800		0.0012	800	0.0015	635
1600		0.0006	1481	0.0025	386
400		2.5E-05	40000	4.17E-05	24000
100		6.67E-05	15000	0.0003	3000
25		0.00026	3750	0.0028	357

Not: B= Bentonite Content

Table B. 23 – Fourth Series (C-S-L) (45-50-5) m_v and D values

		C-S-L (45-50-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	5	0.0048	204	0.0075	133
25		0.0090	111	0.0144	69
50		0.0110	90	0.0075	133
100		0.0092	108	0.0070	142
200		0.0058	172	0.0100	100
400		0.0019	526	0.0018	549
800		0.0009	1026	0.0011	904
1600		0.0006	1443	0.0021	456
400		9.39E-06	106386	2.77E-05	36035
100		2.79E-05	35803	7.83E-05	12763
25		8.16E-05	12248	0.0001	5470

Not: B= Bentonite Content

Table B. 24 – Fourth Series (C-S-5) (50-45-5) m_v and D values

		C-S-L (50-45-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	9	0.005	186	0.003	313
25		0.004	250	0.004	250
50		0.002	500	0.002	500
100		0.005	185	0.001	714
200		0.004	250	0.001	1000
400		0.003	286	0.002	476
800		0.002	444	0.001	571
1600		0.001	842	0.001	792
400		2.5E-05	40000	3.33E-05	30000
100		1E-04	10000	1E-04	10000
25		0.0001	7500	0.0001	7500

Not: B= Bentonite Content

Table B. 25 – Fourth Series (C-S-5) (45-50-5) m_v and D values

		C-S-L (45-50-5)			
		Curing time (day)			
		7		28	
σ´c (kPa)	B %	m_v (m^2/kN)	D (kN/m2)	m_v (M2/ kN)	D (kN/m2)
12.5	9	0.0033	301	0.0046	217
25		0.0032	313	0.0032	313
50		0.0032	313	0.0020	500
100		0.0044	227	0.0012	833
200		0.0041	244	0.0017	588
400		0.0032	313	0.0027	364
800		0.0021	465	0.0024	412
1600		0.0007	1333	0.0015	667
400		2.5E-05	40000	1.67E-05	60000
100		0.0001	10000	6.67E-05	15000
25		0.0002	3750	0.0002	3750

Not: B= Bentonite Content