USE OF FOUNDRY SAND AS A LANDFILL CAP LAYER MATERIAL

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ABSTRACT

USE OF FOUNDRY SAND AS A LANDFILL CAP LAYER MATERIAL

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A foundry is a kind of manufacture that generates metal castings by pouring molten metal into a preformed mold to yield the resulting hardened cast. Foundries buy specific and high quality silica sands which shape the outer form of mold cavity in casting and molding operations. These sands normally mixed with a small amount of bentonite in order to act as a binder material

Landfill capping is a kind of containment technology that is kind of barrier between the contaminated media and the surface. Cap performance varies, for example, compacted clay liners are effective if they retain certain moisture content, but they are susceptible to cracking if the clay material is dried out. Consequently, alternate cap designs can be considered for liner design at arid environments.

Within the scope of this thesis, use of foundry sand with some additives as a landfill cap layer material is examined. For this purpose, laboratory tests were performed with these samples: Foundry sand (For two different type of foundry sand: Green sand and Resin Bonded Sand) , Foundry sand+ Bentonite (various proportions), Foundry Sand+Bentonite+ Waste Rubber (with different shapes).

Samples were compacted to their 95 % of o.m.c and dry density. The following tests; Index properties, oedometer test, permeability k, constrained modulus D, split tensile Strength, Direct Shear tests were carried out for each sample.

It was found that increasing bentonite content (Ó9 %) decreased the hydraulic conductivity below the requirements (10^{-9} m/s) for all foundry sand. Adding rubber (3 %) to foundry sand bentonite mixture, increases the split tensile strength for all types of samples, it also increased hydraulic conductivities and only 1 result was found below the requirements

All these results showed that foundry sand with bentonite and rubber revealed good candidate for construction of a landfill cap layer material.

Keywords: Foundry Sand, Cap layer, bentonite, permeability, split tensile strength, flexibility.

ÖZ

DÖKÜM KUMLARININ KATI ATIK DEPOLAMA SAHASI ÖRTÜ TABAKASI OLARAK KULLANILMASI

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Dökümhaneler erimiş metallerin kalıplar içinde şekillendirilerek sert bir biçim aldıkları yerlerdir. Dökümhaneler kullandıkları kalıpların dış yüzeyindeki boşlukları biçimlendirmek için yüksek kaliteli özel boyutlarda silika içeren kumlar tedarik etmektedirler. Bu kumların içine bağlayıcı madde olarak bentonit kili katılmaktadır.

Katı atık depolama sahası örtü tabakası, atıkların yüzey ile temasını sınırlandırmaya yarayan bir teknolojidir. Bu örtü tabakasının performansı çeşitli faktörlere göre değişim göstermektedir. Örneğin sıkıştırılmış kil tabakaları nemliliklerini koruduklarında kaplama olarak efektif olarak kullanılabilmekte, ancak kuruduklarında çatlamaya meyilli olduklarından efektif olarak kullanılamamaktadır. Bu yüzden kurak bölgeler için çeşitli kaplama teknikleri göz önünde bulundurulmaktadır.

Bu çalışmada çeşitli katkılar ile döküm kumlarının katı atık depolama sahası örtü tabakası olarak kullanılabilirliği incelenmiştir. Bunun için

belirtilen numuneler üzerinde laboratuar deneyleri yapılmıştır. Deney yapılan nnumuneler sırasıyla;
Dökümhane Kumu (İki tip dökümhane kumu için), Dökümhane Kumu+Bentonit Kili (çeşitli oranlarda), Dökümhane Kumu+Bentonit Kili+Atık Lastik Tozu (çeşitli şekillerde) olarak sıralanmaktadır. Her bir numune optimum su içerikleri ve maksimum kuru birim hacim ağırlıklarının %95'ine kadar sıkıştırılmıştır. Her bir numune üzerinde sınıflandırma deneyleri, permeabilite k, ödometre modülü D, kopma dayanımı, ödometre, direk kesme testleri yapılmıştır.

Laboratuar sonuçlarına göre her tip dökümhane kumu için bentonit oranı %9'u geçtiğinde numunelerin genel hidrolik iletkenliği geçirimsiz kaplama yapımı için istenilen değerin altında (10^{-9} m/s) kalmaktadır. Kullanılmış lastik tozu kullanılması ise her bir numune için kopma dayanımını arttırmakta ancak permeabiliteyi de arttırdığından sadece bir numunenin genel hidrolik iletkenliği geçirimsiz kaplama yapımı için istenilen değerin altında kalmaktadır.

Sonuçların genel değerlendirmesi bentonit ve kullanılmış lastik tozu içeren dökümhane kumunun katı atık depolama sahası örtü tabakası olarak kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Dökümhane Kumu, Örtü Tabakası, bentonit, permeabilite, kopma dayanımı, esneklik

This thesis is dedicated to my unique family.

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LIST OF SYMBOLS AND ABBREVATIONS

SYMBOLS AND ABBREVATIONS

D	Constrained Modulus
GFN	Green Fineness Number
S_i	Initial Saturation
S.G	Specific Gravity
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
P	Compressive Load on Cylinder
D	Cylindrical Specimen Diameter
L	Length of the Cylinder
ů	Tensile Strength
ű'	Internal Friction Angle
c'	Cohesion
m_v	Average coefficient of volume change
k	permeability

CHAPTER 1

INTRODUCTION

Today society produces a huge volume of industrial wastes whereas their continuous increase requires strategies to recover and recycle these materials since their disposal by landfilling is limited by a decreasing availability of space, and increasing cost of disposal. (Yazogli M,2014). Therefore, regulations about refusals should be taken by using suitable impermeable barriers against contamination. There are different types of barriers commonly used in landfill areas including hazardous toxic materials and water lagoons such as clay clay-bentonite mixtures stabilized clay, synthetic liners including polymers. However, it can be clearly seen that the application of these materials can be extremely expensive due to the fact that appropriate clay material used in disposal areas cannot be found easily or the cost of synthetic liners may be a problem. In order to solve this problem, foundry sand or foundry sand bentonite mixtures either alone or combination with rubber and other material, might have potential to dispose of wastes in secure landfills.

Foundry sand, referred to as the mixture of sand and sodium bentonite or the mixture of sand and resin can be used as a hydraulic barriers in landfill areas. (Abichou et al., 1998). The manufacturers produce large amount of foundry sand as a byproduct every year and the effective usage of foundry sand might eliminate lots of environmental problems.

In addition, the same problems about disposal and utilization mentioned above are valid in rubber industry.

The geotechnical properties of foundry sand- bentonite mixture and foundry sand-bentonite-rubber mixture have been investigated from the perspective of their use as a landfill cap layer material. Cap layer material can be preferable if it provides required engineering properties such as low permeability (Ò10^{-9} m/s), high tensile strength and flexibility.

In order to get all these properties mentioned above, bentonite was used for low permeability; rubber was used for flexibility in this study.

The laboratory study which is performed during the thesis comprised of one dimensional consolidation, split tensile strength, index parameters and direct shear test.

Outline of thesis consist of 6 parts. In chapter 1, brief introduction is given for thesis. Chapter 2 is about past studies and investigations about foundry sand. In chapter 3, materials used in this thesis are mentioned. Experimental results are presented in Chapter 4 and discussions of results are given in Chapter 5. Finally, conclusion of thesis is given in chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1. Foundry Sand

Three sand types are commonly used in molding process namely: green sand, chemically bonded sand and shell molding sand (Javed and Lovell, 1994). There are two ways of sands used in foundries: to design the internal forms and cavities with casting in cores and the outside of the casting (Javed and Lovell,1994). Natural clays (e.g bentonite) and some chemical agents are bonded to the sand with some carbon additives (e.g coal dust) to gain permeability, strength and other properties There are two types of sand used in this study green sand (sand bentonite mixture) and resin bonded sand.

2.1.1. Green Sand

2.1.1.1. Green Sand Molding Process

It is formed by the bonding between bentonite and silica sand. The term green sand comes from the green color as a result of the pouring process of the metal into the mold. (Javed et al., 1994). The bentonite gives less permeability to the mixture (Abichou et al.,1998). The picture of Green Sand is presented in Figure 2.1 A flow chart of a green sand molding process is also presented in Figure 2.2 .The mixtures added to the silica sand to control the casting, increase the strength of mold and water. The major components of sand consists of 85 to 95% uniform quartz sand,

Figure 2.1 Green Sand (Adopted from http://www.jsmccormick.com/coremold.php)

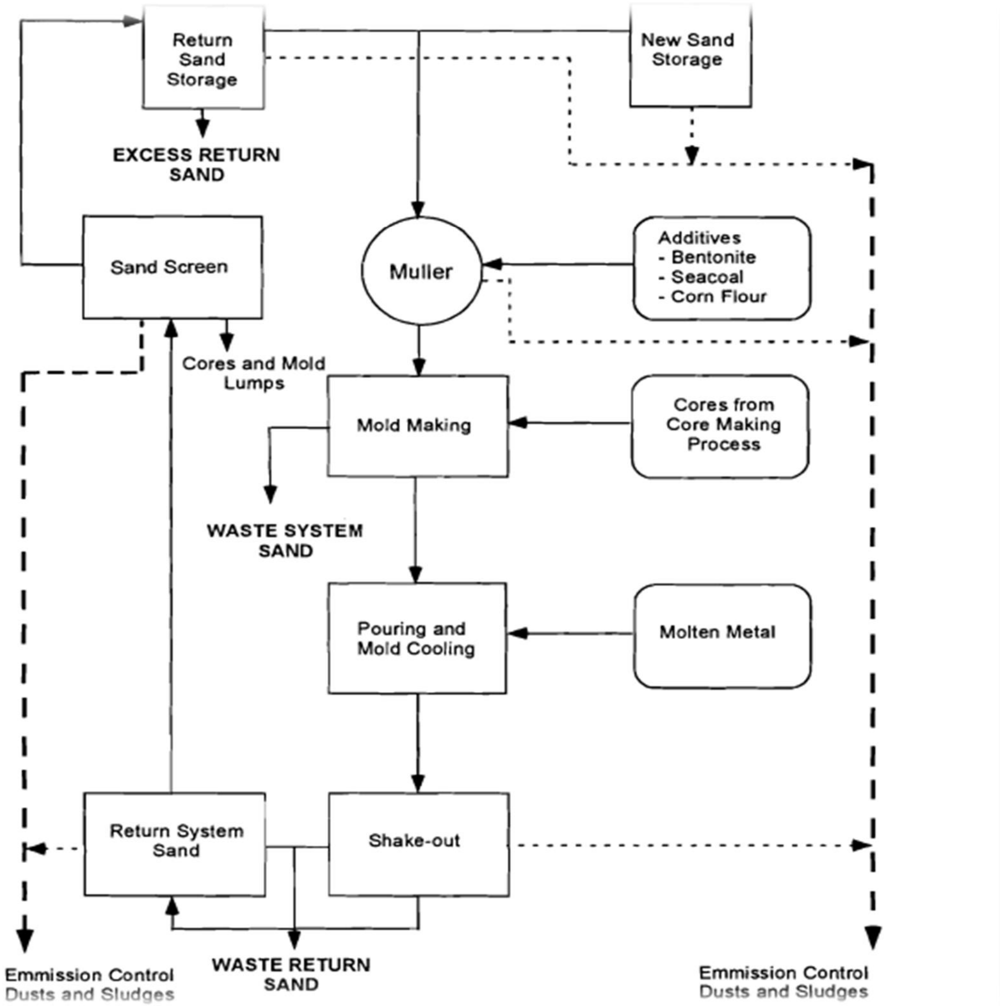


Figure 2.2 Flow chart of a green sand molding process (Abichou et al.,1998)

4 to 10% bentonite, 2 to 10% combustible additives and 2 to 5% water (Abichou et al.,1998).

Small amount of iron oxide is added to the bentonite in order to enhance the strength of the mold (Javed et al.,1994). Besides, to prevent common defects sea coal, cellulose and cereal can be used as additives. Sea coal which is commonly used for protection of sand from melting to the metal and for the composition of iron silicate occurred at sand-metal interface in generally used in malleable iron, ductile iron and gray iron castings to remove sand from casting (Abichou et al.,1998).

Great amount of sand is recycled back into the system by the removal of the green sand from casting in order to separate the cores and out of the interior of casting and to separate green sand stuck into the casting after the cooling of the metals. Due to the addition of core sand to the system by crushing and recirculating back, the properties of green sand is influenced directly. As a consequence, it is important to add base sand, bentonite and additives to satisfy required properties of the green sand, which causes the accumulation of sand above the storage capacities of foundries. (Abichou et al.,1998).

2.1.1.2.Consitutents of Green Sand

Sand

Subject to the needs of the casting process and availability of sand, mold-making industry uses 4 major types of sands: silica, olivine, chromite and zircon (Ziegler,1994). 85% of sand used in foundry industry is silica sand whereas other are used for only specialty castings. The physical and chemical properties of silica sand are presented in Table 2.1 and Table 2.2 respectively (Abichou et al.,1998).

Grain Fineness Number (GFN), which is a measurement of fineness, is the most crucial property of green sand. It is proportional to the fines content of sand. Besides, the rounded sand, preferable due to the less bentonite requirements and to provide durable molds and impurities which , is not preferred that is an ability to melting to the casting.

Table 2.1 Physical Properties of Silica Sand (Abichou et al.,1998)

Property	Description
Color	White/Brown
Hardness	6.0-7.0
Specific Gravity	2.20-2.67
Bulk Density KN/m^3 (lb/ft^3)	13.4 – 15.7 (85-100)
Thermal Expansion cm/cm (in./in.)	0.018
High Temperature Reaction	Acidic
Chemical Reaction	Acid-Neutral
Shape	Varies
Apparent Heat Transfer	Average
Fusion Point °C (°F)	1427-1760 (2600-3200)
Wettability with Molten Metal	Easily
Grain Distribution	2-5 sieve sizes
AFS GFN	25-180

Table 2.2 Chemical Characteristics of Silica Sand (Abichou et al.,1998)

Property	(%)
Silicon Dioxide - SiO_2	98.820
Magnesium Oxide -MgO	0.031
Aluminum Oxide - Al_2O_3	0.049
Iron - Fe_2O_3	0.019
Free Lime – CaO	0.006
Titanium Dioxide - TiO_2	0.012

Binders

There are two main binder types used in foundry industries namely clay binders and chemical binders. Chemical binders can be grouped as organic (Wood protein, cereal protein, oil etc.) and inorganic (Portland cement, sodium silicate etc.) Nevertheless, clay is widely used as binders in foundry sector.

For the green sand mixtures, sand gives high strength whereas clay gives plasticity and cohesion to the dried mold. There are 3 types of clays used in foundry such as sodium and calcium bentonite, which are in the form of mineral montmorillonite and fireclay which is in the form of kaolinite. Fireclay, can be used in the place of bentonite by duplicating the amount of clay used in bentonite is preferred according to the economic conditions (Amon,1996). Sodium bentonite preferred in iron and steel casting industry has a high green, hot and dry strength and it is a magnified sand stabilizer (Browler,1988). Calcium bentonite preferred in ferrous casting industry has similar properties compared to the sodium bentonite. It is preferred for developing the shakeout properties of mold by giving lower hot strength (Browler,1988).

Additives

Some binders can be used in order to eliminate some specific problems. There are 4 main additive types used as binders: Cereals, Seacoal, Cellulose, Chemicals. Cereals, consists of corn starch and wheat, are used for diminishing the brittleness of mold. Seacoal consisting of powdered coal is used for improving separation of casting and mold in order to obtain smoother surface. Cellulose consisting of flour, wood chips, etc. is used for absorbing excessive moisture to develop mixing and mold and casting separation. Chemicals consisting of surfactants, organic polymers, soda ash, wetting agents, chemical modifiers and are used for some special problems (Abichou et al.,1998).

Water

The homogeneity of sand grains and of the distribution of other additives are obtained by using water in order to obtain quality molds (Abichou et al.,1998).

2.1.2. Resin Bonded Sand

In order to get interior of desired shape, some processes are required such as pouring of metal into a mold during the metal casting. For this purpose and requirement of hollow interior, sand cores, prepared by using some chemicals and resin-coated sand , are used. Organic products, intensified in the molding sand and products are emitted into the air during casting, cooling, and casting shakeout process are generated by thermal decomposition of resin binder and sands. Besides, this sand is used in some foundry manufactories nowadays and there is not enough study in this area.

2.1.3. Use of foundry sand in different areas

There are several areas where foundry sand used outside metallurgy. These are listed below:

-Highway embankment

-Concrete and asphalt

-Foundation subgrade fill

-Landfill daily cover

-Generate Fill

-Parking Lot Subbas

-Flowable Fill

-Other (Foundry Sand Facts,2004)

Landfill dailiy cover and highway embankment are the most common used areas of foundry sands except metal casting. ((Foundry Sand Facts,2004)

2.2. Bentonite

Bentonite, formed preliminary from the montmorillonite, is one of the most important clay types in nature. Although there are two main types of montmorillonite types (calcium and sodium montmorillonite) and several minor types, bentonite generally refers to sodium montmorillonite (Sherma and Lewis., 1994).

It is generally obtained from the weathering of igneous rocks and volcanic ash. The properties of bentonite rely on its chemical composition, atomic structure and morphology due to the fact that bentonite is a member of smectite type of clay mineral (Grim and Güven.,1978).

The structure of bentonite consisting of unit cells which are formed by silica and alumina sheets by adjusting in the structure of alumina octahedral sheet is in between two silica tetrahedral sheets (Mitchell,1976). The Van der Walls bonds, as well as ties between unit cells by exchangeable cations, provide the water to enter between unit cells and to separate between each other. Because of the ability of bentonite of dispersion of water into relatively small particles, bentonite is considerably expansive clays. (Grim et. al.,1978).

High swelling potential and water absorption capacity give bentonite not only to its low hydraulic conductivity but also low hydrated shear strength. (Sharma and Lewis.,1994).

2.3 Rubber

Rubber is a part of the class of polymers which is predominantly organic and including long chain molecules, generated from backbone of carbon atoms, repeating itself and has a high molecular weight compounds. These long flexible and cross-linked molecules form a three dimensional molecular network (Blow, 1971)

Rubbers can be easily deformed under moderate forces without showing any breaking, due to its young modulus (1-10 MPa) which is considerably lower than other materials such as steel, compacted fly ash, aluminum alloys.

(Allen,1972) . In other words, rubber tends to undergo large deformation without changing its original shape (Gent,1978). As a summary, it differentiates from other materials according to its elasticity and stiffness (Allen,1972). Strength is also substantial property of rubber which has a tensile strength between 10 to 30 MPa when it is cross-linked shape and this strength is considerably higher than other materials of comparable stiffness (Allen,1972).

In order to show its full potential, all rubber molecule chains have to be with cross-linked with each other. To obtain this full potential, traditional method of heating raw rubber with sulphur and other chemical used by entire manufacturing industry (called vulcanization) is implemented (Allen,1972). It is a kind of reaction that effects the intermolecular bonds by increasing reactive force and reducing permanent deformation, after the removal of the deforming force i.e., enhances elasticity whereas it reduces plasticity (Coran, 1978).

Although vulcanization process is a very advantageous process for rubbers, there is a limitation for hardness and modulus range obtained only by vulcanization. Therefore, in order to harden and cheapen the product and obtaining other objects such as improving quality, facilitating manufacture, resistance to abrasion and tearing, mineral fillers in the form of powder are added to the product.

Tires, used in production of rubber, have 3 main components: carcass, tread and sidewall. The components of the tires are presented in Figure 2.3. Each component, made from different rubbers or different blends, implements a different function. In this study, the rubber obtained from the tread of tires is used. For this tread, it is best to be good grip and minimum wear. In addition to this, no matter which types of tire, the service conditions influences the composition of each component (Allen,1972).

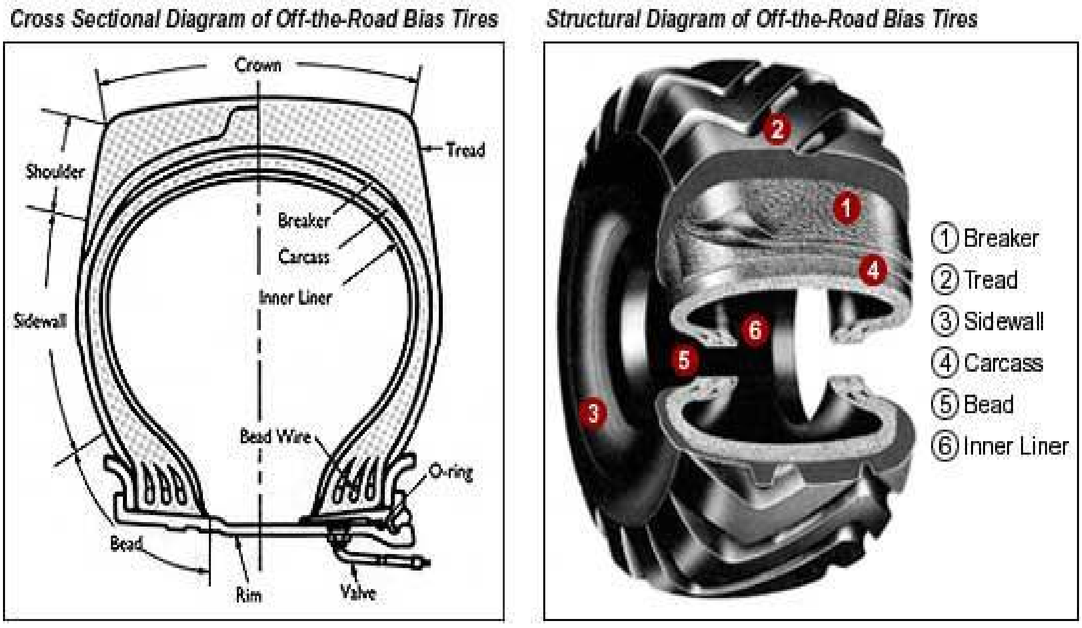


Figure 2.3 Components of Tires (Adopted from http://www.eastmanautotyres.com/otr-technology.html)

2.4. Factors Controlling the Convenience of a Material for a Low-Permeability Liner

The convenience of liner material used for construction relies on the factors mentioned below:

1. Permeability, the measure of hydraulic conductivity used for providing containment of leachate, should be less than 10^{-7} cm/s which is referred under most of the state codes.

2. The material should have a resistance and durability to destructive forces such as wet/dry and freeze/thaw cycles which cause the separation of the bonding in the material.

3. The material should compete with leachate which means that the material should have an absorptive capacity for crucial pollutants, not to extract harmful materials from inside to the leachate solution in order to protect its strength and low permeability when contact with the leachate solution.

4. The material should be constructible, which means that workability of material should be sufficient according to placement and field conditions (Edil et al., 1992, cited in Yılmaz,2000).

2.5. Engineering Properties of Foundry Sand Reuse in Landfill Covers

2.5.1. Index Properties

Abichou et al. (1998) conducted tests about all index properties of the 16 different foundry sand sample for which have liquid limit between non plastic to 29% and the plasticity index ranges from non-plastic to 7% which means that the plasticity of the foundry sand has a correlation with active bentonite content which depends on temperature and additives. The bentonite content varies between 0 and 16 % and affects the plasticity directly. The specific gravity, affected by the source of the base sand and additives of quality and quantity changes between 2.53 to 2.73.

All results are given in Table 2.3. Abichou et al. (2000) also stated about all index properties of the 12 different foundry sand samples. The summary of this study is presented in Table 2.4.

2.5.2. Particle size distribution

Abichou et al. (1998) conducted tests about particle size distribution of the 16 different foundry sand mixtures which are consisted of uniform fine sand and the fines content changes from 10 % to 15 % generally. The particle size distribution of the all foundry sand types are presented in Figure 2.4.

Abichou et al. (2000) also stated that particle size distribution of 12 foundry sand mixtures are uniform fine sand and the fines content changes from 10 % to 16.4 % generally.

2.5.3. Compaction

Compaction charactesistics of the sand bentonite mixtures are essentially important for the foundry sand. Permeability (Hydraulic Conductivity) of the foundry sand can be determined for the 100% of dry density with optimum water content or 95 % of dry density with related water content.

Abichou et al. (2000) conducted the compaction characteristics of the 12 different foundry sand samples by using standard, reduced and modified proctor results of Kenny et al. (1992) who concluded that the maximum dry unit weight of the foundry sand bentonite mixtures rises up to bentonite content 16 % and then suddenly decreased. Hovell et al. (1997) stated that dry density of the soil, diminishes with increasing bentonite content from 10 % to 20 % due to swelling potential of bentonite and gradation of sand,. Abichou et al. (2000) stated points about water content- bentonite content relationship for reduced, modified and standard Proctor tests. The trends shows that, despite the fact that fine-grained soils show typical behavior in compaction, bentonite content does not show any correlation with optimum water content.

Table 2.3 Specific Gravity, Attenberg Limits, Percent Fines and Bentonite Content (Abichou et al.,1998)

Sand	Specific Gravity	Liquid Limit	Plastic Limit	Plasticity Index	Percent Fines	Bentonite Content
1	2.62	NP	NP	NP	10.7	5.1
2	2.54	21	18	3	12.7	6.6
3	2.64	NP	NP	NP	4.3	Chemically Bonded
4	2.53	18	17	1	14.3	7
5	2.52	20	18	2	11.3	7.5
6	2.64	NP	NP	NP	2.7	Washed Green Sand
7	2.56	27	19	8	12.1	8.5
8	2.63	23	19	4	13.2	10.5
9	2.54	23	18	5	12.4	8.4
10	2.61	20	17	3	10.2	6.6
11	NT	NT	NT	NT	NT	NT
12	2.58	23	17	6	16.4	10.2
13	2.54	21	18	3	13.2	10
14	NT	29	22	7	15	16
15	NT	27	20	7	14	13
16	2.73	NP	NP	NP	10	4.7

Notes: (i) NP = Non Plastic
(ii) NT = Not Tested

Table 2.4 Index Properties and Classifications of Foundry Sand Used in Study (Abichou et al.,2000)

Sand (1)	Specific gravity (2)	Liquid limit (3)	Plasticity Index (4)	Percent fines (5)	USCS classification (6)	Bentonite content (7)
Base sand	2.66	NP	NP	1.1	SP	0
1	2.62	NP	NP	10.7	SP-SM	5.1
2	2.54	21	3	12.7	SM	6.6
3	2.53	18	1	14.3	SM	7.0
4	2.52	20	2	11.3	SW-SM	7.5
5	2.56	27	8	12.1	SC	8.5
6	2.54	23	5	12.4	SC-SM	8.4
7	2.61	20	3	10.2	SP-SM	6.6
8	2.58	23	6	16.4	SC-SM	9.3
9	2.54	21	3	13.2	SM	10.0
10	2.51	29	7	15.0	SC	16.0
11	2.51	27	7	14.0	SC	13.0
12	2.73	NP	NP	10.0	SP-SM	4.7

Note: NP = nonplastic.

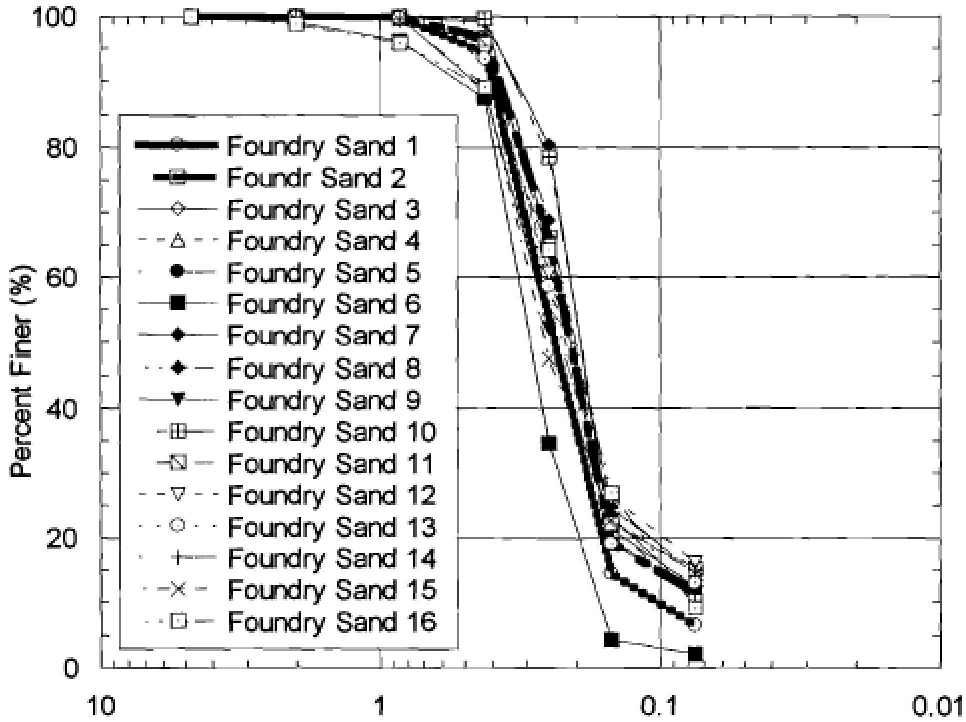


Figure 2.4 Particle Size Distribution for All Foundry Sands (Abichou et al.,1998)

2.5.4. Hydraulic Conductivity

Hydraulic conductivity test can be performed in field or laboratory. Due to the setup advantages, laboratory test can be used for liners. However, past investigations clearly showed that field permeability test gives more accurate results than the laboratory permeability tests (Daniel et al. 1986, cited in Yılmaz,2000)

There are several factors which affect the laboratory permeability tests in the laboratory. The degree of saturation (must be equal to the 100 %), air bubbles in the specimen and, temperature variation directly affects the permeability test in laboratory (Bowles,1988).

In this thesis only the laboratory permeability tests were performed. Due to this reason, laboratory permeability tests were investigated carefully.

The relation between compaction water content and hydraulic conductivity can be determined by using standard, modified and reduced proctor test. (Abichou et al., 2000). Abichou et al. (2000) shows the relationships between optimum water contents, maximum dry unit weights and hydraulic conductivity at optimum water content for reduced, standard and modified proctor effort for 12 different foundry sands by using falling head permeability test. The results are given in Figure 2.5.

Although the standard proctor test was performed subsequently for all foundry sands in which low hydraulic conductivity can be obtained likely, It was not possible to perform modified proctor test for sands 10 and 11 (where bentonite content 13% and 16% orderly) due to the very low hydraulic conductivity when performing standard proctor efforts and it was useless to perform reduced proctor effort for sand 1 due to the fact that hydraulic conductivity of this sand was Ó1x10^{-7} cm/s while performing standard proctor effort. As a result of these, 9 of 12 foundry sands (75% of foundry sands) satisfy the hydraulic conductivity requirement (kÒ10^{-7} cm/sec). it is shown in Table 2.5.

Following subsections summarize various factors which affect permeability of such foundry sands compacted to the 100% maximum dry density.

Table 2.5 Optimum Water Contents, Maximum Dry Unit Weights and Hydraulic Conductivity at Optimum Water Content for Reduced, Standard and Modified Proctor Effort (Abichou et al.,2000)

		Reduced Proctor			Standard Proctor			Modified Proctor		
Sand (1)	Bentonite content (%) (2)	Optimum water content (%) (3)	Maximum dry unit weight (KN/m^3) (4)	Hydraulic conductivity (cm/s) (5)	Optimum water content (%) (6)	Maximum dry unit weight (KN/m^3) (7)	Hydraulic conductivity (cm/s) (8)	Optimum water content (%) (9)	Maximum dry unit weight (KN/m^3) (10)	Hydraulic conductivity (cm/s) (11)
1	5.1	NT	NT	NT	9.6	18.39	5.4×10^{-7}	8.0	18.84	3.2×10^{-7}
2	6.6	15.4	16.48	1.8×10^{-8}	1.25	17.89	9.0×10^{-9}	11.1	18.72	7.1×10^{-9}
3	7.0	NT	NT	NT	10.8	17.96	2.1×10^{-7}	9.8	18.80	NT
4	7.5	16.1	16.92	2.8×10^{-8}	13.0	18.19	2.4×10^{-8}	11.6	19.27	9.2×10^{-9}
5	8.5	16.2	16.71	4.5×10^{-9}	12.2	17.30	6.1×10^{-9}	9.7	18.68	9.0×10^{-9}
6	8.4	14.7	16.82	3.5×10^{-8}	11.6	18.24	1.6×10^{-8}	9.4	19.28	9.5×10^{-9}
7	6.6	16.1	16.57	9.6×10^{-9}	12.7	17.90	3.5×10^{-8}	10.8	18.50	6.9×10^{-9}
8	10.2	15.3	16.78	1.8×10^{-7}	11.5	18.18	9.7×10^{-8}	10	19.02	7.2×10^{-8}
9	10.0	14.8	16.85	3.1×10^{-8}	11.0	18.27	2.2×10^{-8}	9.8	19.32	1.1×10^{-8}
10	16.0	13.5	14.40	5.4×10^{-8}	15.5	16.20	8.5×10^{-9}	NT	NT	NT
11	13.0	15.0	16.00	9.5×10^{-9}	15.0	16.90	9.0×10^{-9}	NT	NT	NT
12	4.7	NT	NT	NT	12.3	17.26	5.3×10^{-5}	11.1	18.57	NT

Note: NT = not tested.

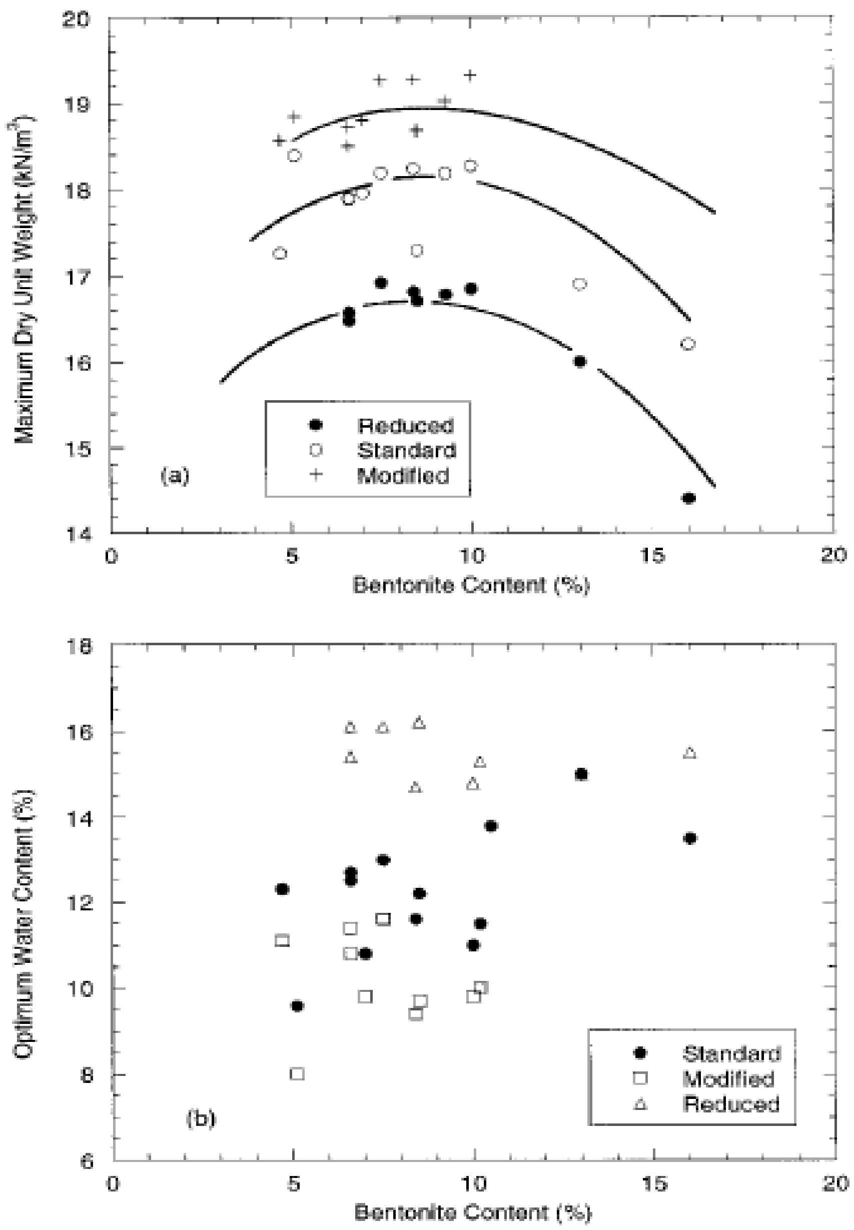


Figure 2.5 Bentonite-water content relationship for different proctor efforts (Abichou et al.,2000)

Compaction Water Content and Effort

Van Veen (1983) , Buetler (1985) and Garlanger et al (1987) concluded that depending on the bentonite content (5% to 10%), the permeability of foundry sand ranges from 10^{-6} to 10^{-9} cm/sec generally. Although there is limited information for the relationship between permeability and bentonite content, they stated that sand-bentonite compacted liners could be compacted at or above optimum water content.

Reschke and Haug (1991) performed investigation about the factors affecting hydraulic conductivity of foundry sands by using different types of bentonites and mixtures of sands in order to measure the hydraulic conductivities and they concluded that the major factors influencing the permeability of sand-bentonite mixtures were bentonite distribution, quality and quantity.

Noir and Wong (1992) studied foundry sands having dry of optimum water content and near optimum water content. They found that 9% of dry of optimum water content has only five times higher hydraulic conductivity than optimum water content.

It reveals that molding water content is not crucial factor for designing of foundry sands due to the requirement of separation of clods and facilitates remolding of water. (Noir and Wong,1992).

Kenny et al. (1992) investigated the relationships of compacted foundry sand with different bentonite and water contents. Kenny et al. (1992) stated that molding water content affects the permeability whereas compaction water content does not considerably due to the bentonite aggregation provides a non-uniform bentonite distribution, outcoming in open channels, and so higher hydraulic conductivity, at low water content. Besides, Kenny et al. (1992) pointed out that existence of empty voids filled with no bentonite is the most substantial factor contributing to the hydraulic conductivity of foundry sand. They also stated that although dry unit.

weight is not particularly important for permeability, molding water content, affecting distribution of bentonite, affects the hydraulic conductivity.

Kraus et al. (1997) investigated the relationship between permability and compaction water content by using eight specimens of foundry sand mixture with average bentonite content 12 %, with standard and modified proctor. According to these results, hydraulic conductivity of these specimens is not affected sensitively from molding water content and compaction effort.

Abichou et al. (2000) stated that the typical relationships, compacted to hydraulic conductivities Ò$1x10^{-7}$ cm/sec, were determined by using reduced, modified and standard proctor efforts for different foundry sand samples. The typical relationship for sand 8 is shown in Figure 2.6. As the behavior of natural clays, the hydraulic conductivity has an inverse relation with water content. In order to get lower hydraulic conductivity, the higher compaction effort is required at similar compaction effort generally. The hydraulic conductivity does not show considerable amount of change (less than one order of the magnitude) over a range of 20% water content. Besides, changing the compaction efforts does not affect hydraulic conductivity considerably (less than 8 times and generally less than a factor of 4) regardless of which side of optimum water content (Wet or dry).

Abeele (1986) stated that, Sand bentonite mixtures show different hydraulic conductivity changes (dramatic decrease between 0 to 5 %) by changing of bentonite content up to the 10 % and then it shows the same hydraulic conductivity as bentonite.

Haug and Wong (1992), Hitoshi et al. (1995), Howell and Shakelford (1997) reported that there is inverse correlation between hydraulic conductivity and bentonite content until it reaches a lower limit of bentonite content amount related with the bentonite. This point depends on the gradation of sand and type of bentonite.

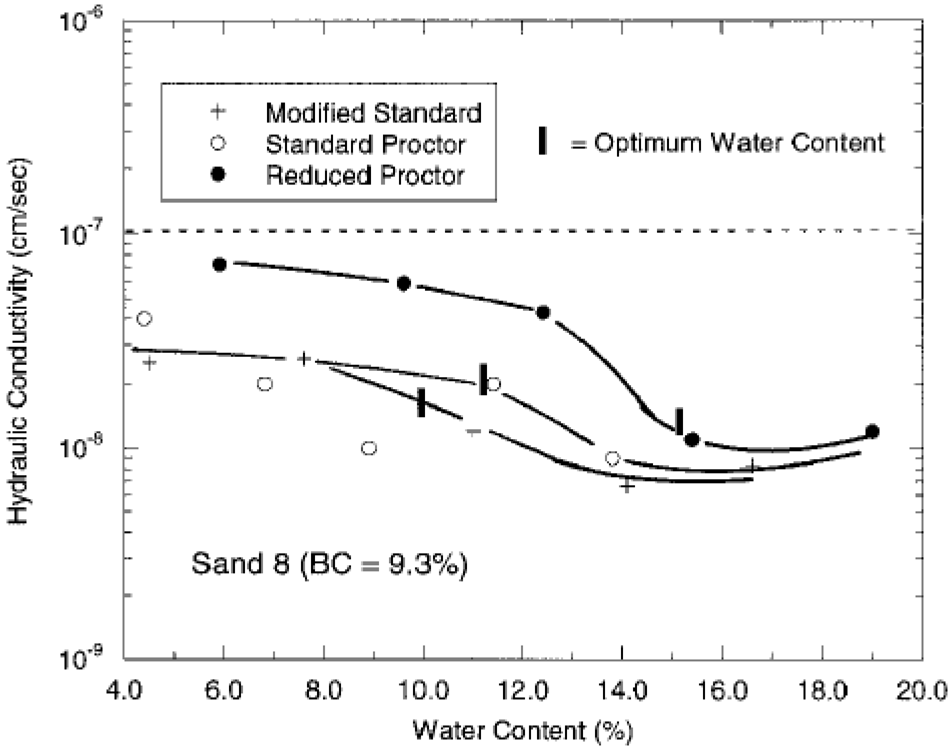


Figure 2.6 Hydraulic conductivity water content relationship for different proctor efforts (Abichou et al.,2000)

Kenny et al. (1992) pointed out that compacted foundry sand with up to 8% bentonite content has much higher hydraulic conductivity than foundry sand having higher bentonite content. It can be observed that hydraulic conductivity slightly decrease from 8 to 12 % bentonite content due to filling of all voids with sand grains like a matrix.

Abichou et al. (2000) investigated that the behavior of hydraulic conductivity with bentonite content at optimum water content with standard, reduced and modified proctor efforts. Increasing of bentonite content results in decreasing the hydraulic conductivity up to the 5 % bentonite content and hydraulic conductivity approximately remains constant for bentonite content >7%. The requirement of acceptable hydraulic conductivity is satisfied while bentonite content is Ó6 % for all points. This relationship is shown in Figure 2.7.

<u>Atterberg Limits</u>

Abichou et al. (2000) investigated the behavior of hydraulic conductivity with liquid limit (LL) and Plasticity Index (PI) at optimum water content with standard, reduced and modified proctor efforts. Due to the inverse correlation between hydraulic conductivity versus bentonite content and direct correlation between bentonite content versus LL and PI, while LL and PI increases, hydraulic conductivity decreases. The acceptable requirement of hydraulic conductivities Ò $1x10^{-7}$ cm/sec is satisfied for foundry sands having LLÓ20% and PIÓ2% regardless of compaction effort. The graph of hydraulic conductivity changes with bentonite content is given in Figure 2.8.

<u>Initial Degree of Saturation</u>

Abichou et al. (2000) examined the relation between hydraulic conductivity and initial degree of saturation. Initial saturation (S_i) is used for compaction control. Specimens compacted to higher initial saturation, causing reduced the hydraulic conductivity, increased the dry unit weight and compaction water content,

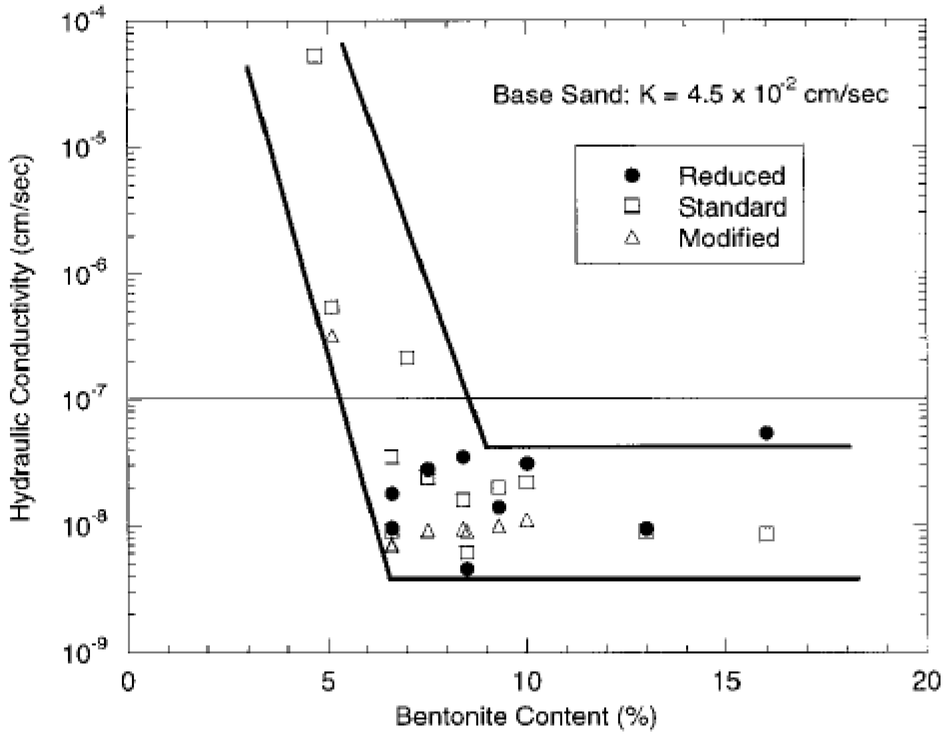


Figure 2.7 Hydraulic Conductivity Bentonite Content relationship at optimum water content (Abichou et al.,2000)

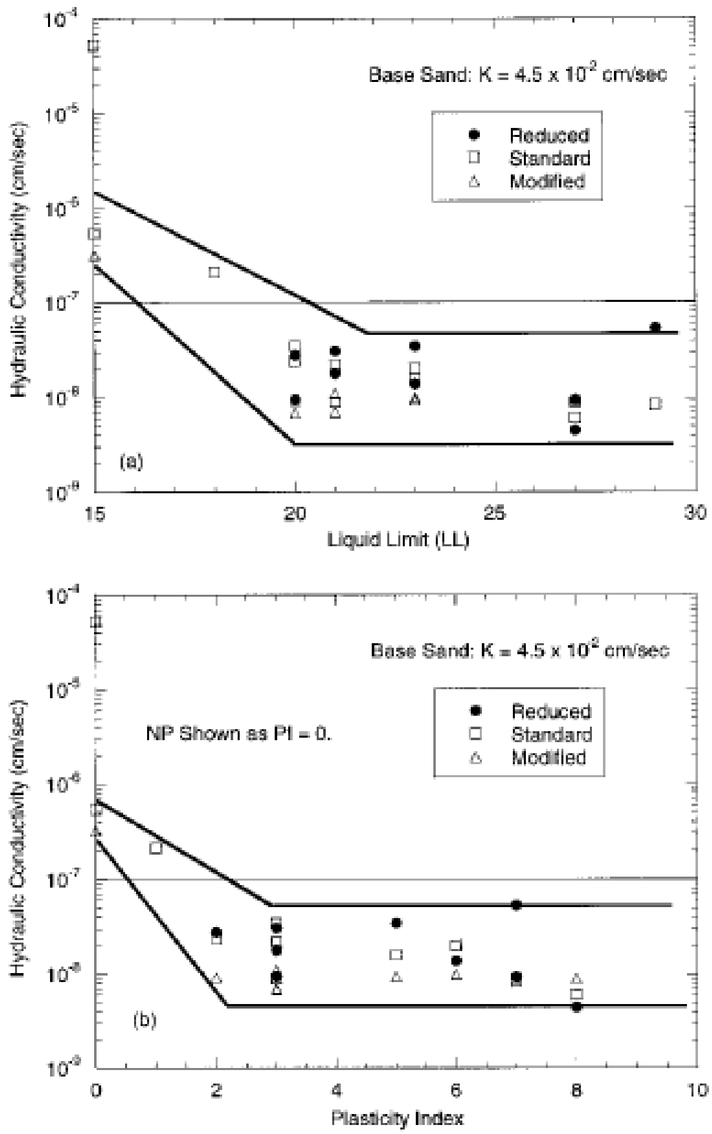


Figure 2.8 Hydraulic Conductivity at Optimum Water Content versus Standard Proctor Versus (a) Liquid Limit; (b) Plasticity Index (Abichou et al.,2000)

are compacted wetter conditions relative to the line of optimums.

All specimens having bentonite content <6% has hydraulic conductivity >$1x10^{-7}$ cm/sec whereas bentonite content >6% has hydraulic conductivity < $1x10^{-7}$ cm/sec. The hydraulic conductivity, always smaller than $1x10^{-7}$ cm/sec, decreases gently with increasing S_i which is apparent in the trend line drawn through medians of data for BC>6 %. It means, hydraulic conductivity limit (< $1x10^{-7}$ cm/sec) can be satisfied for a broad range of compacted conditions. It is presented on Figure 2.9.

Impact of Freeze-Thaw

Wong and Haug (1991) studied about the effects of freeze-thaw cycling on hydraulic conductivity of foundry sands by prepearing 4.5, 6.0, 13 and 25 % bentonite content specimens by using standard proctor and flexible wall permeameters. The procedure of tests can be started with determination of hydraulic conductivities, continues with freezing of specimen down to the -20 celcius degree for minimum 6 hours, then finalize with thawing process at room temperature. It is reported that hydraulic conductivity is decreased by freeze-thaw cycling. This decline is greater for sand bentonite mixtures having lower bentonite content because freeze-thaw cycling helps hydration of bentonite by providing redistribution of bentonite into spaces between sand grains.

Kraus et al. (1997) investigated about the effects of the freeze-thaw cycling on hydraulic conductivity of foundry sand by constructing test pad. 8 specimens of the same sand bentonite mixture were compacted on test pad. The specimens were put in refrigerator for freezing procedure during 24 hours in accordance with ASTM D 6035-96. This procedure was repeated by considering desired number of freeze-thaw cycles before determining hydraulic conductivity of specimens. Kraus et al. (1997) concluded that freeze thaw cycling has no considerable effects on hydraulic conductivity of sand bentonite mixtures like it has on that of clayey soils.

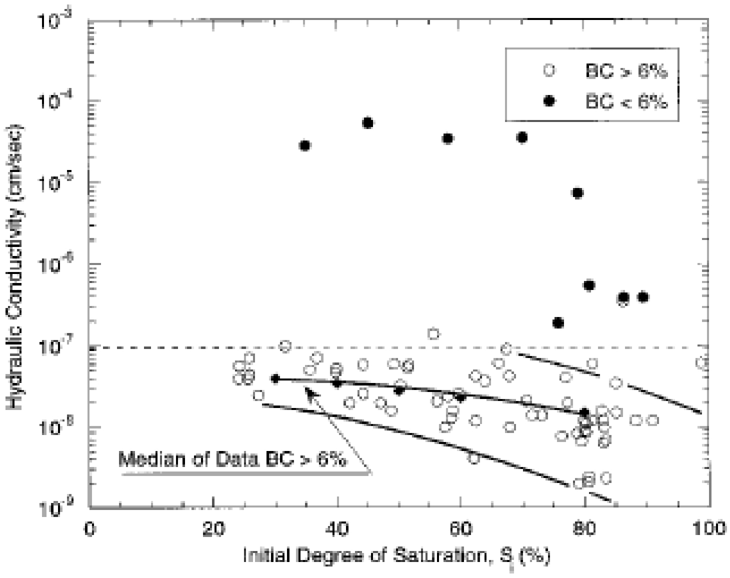


Figure 2.9 Hydraulic Conductivity at Optimum Water Content versus Degree of Saturation (Abichou et al.,2000)

Abichou et al. (2000) investigated about the effects of the freeze-thaw cycling on hydraulic conductivity of foundry sand by using 9 different foundry sand specimens. These tests were performed by determining initial hydraulic conductivity and hydraulic conductivity at the end of the each freeze thaw cycling. Abichou et al. (2000) concluded that hydraulic conductivity of the sand bentonite mixtures showed no visible change in hydraulic conductivity. The results are presented in Table 2.6.

Impact of Dessication

There are limited studied the effect of impact of dessication on hydraulic conductivity for foundry sands. Alberect (1996) investigated soil bentonite mixtures with bentonite content 10 %. After 3 dessication cycles, the hydraulic conductivity does not change considerably. This prove foundry sand has a resistance against wet-dry cycling due to the low plasticity, compaction at water contents drier than optimum of foundry sand.

Table 2.6 Hydraulic Conductivity changes versus Freeze Thaw Cycles (Abichou et al, 2000)

Sand (1)	Specimen (2)	Initial hydraulic conductivity (cm/s) (3)	Hydraulic Conductivity Ratio (K_r)							
			1 cycle (4)	2 cycles (5)	3 cycles (6)	4 cycles (7)	5 cycles (8)	6 cycles (9)	8 cycles (10)	10 cycles (11)
2	A	6.1×10^{-8}	1.85	0.87	NT	NT	0.98	NT	NT	0.94
2	B	4.7×10^{-8}	1.24	1.1	NT	NT	1.84	NT	NT	1.1
4	A	3.4×10^{-8}	NT	NT	0.95	NT	NT	0.56	NT	NT
4	B	3.0×10^{-8}	NT	NT	0.65	NT	NT	1.1	NT	NT
5	A	1.6×10^{-8}	0.85	0.8	0.7	0.9	0.95	NT	NT	0.9
5	B	1.3×10^{-8}	0.7	1.05	1.2	0.85	1.1	NT	NT	1.1
6	A	6.2×10^{-8}	NT	9.4	NT	NT	8.77	NT	NT	NT
7	A	3.5×10^{-8}	1.02	1.1	1.79	NT	0.98	NT	NT	0.96
7	B	6.1×10^{-8}	1.7	1.06	2.46	NT	1.23	NT	NT	1.87
9	A	5.1×10^{-8}	0.79	NT	0.86	NT	NT	0.75	0.8	NT

Note: NT = not tested.

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Materials Used

Various studies about permeability of sand bentonite mixtures (green sand) have been reported in the past years. The physical and chemical properties of the sand bentonite mixtures were investigated by many researchers. However, there are not any reported investigations about physical and mechanical properties of the green sand mixed with bentonite and rubber and resin bonded sand mixed with bentonite and rubber. The purpose of this study is to determine the permeability, strength and consolidation behavior of the green sand mixed with bentonite and rubber and resin bonded sand mixed with bentonite separately and to combine these two mixtures according to the requirements for the construction of a liner. The flowchart of this study is given in Figure 3.1.

3.1.1 Green Sand

The green sand used for this study was obtained from METU Department of Metallurgical and Material Engineering Foundry Sand Laboratory. This green sand is a waste material and samples are stored in sealed bags in order to protect against moisture and contaminant effects against environment. The content of green sand is presented on Table 3.1.

The index properties of this green sand used in experiments are given in Table 3.2 and grain size distribution curve plotted in Figure 3.2. Grain size distribution curve pointed out that green sand is dominantly sand sized material in

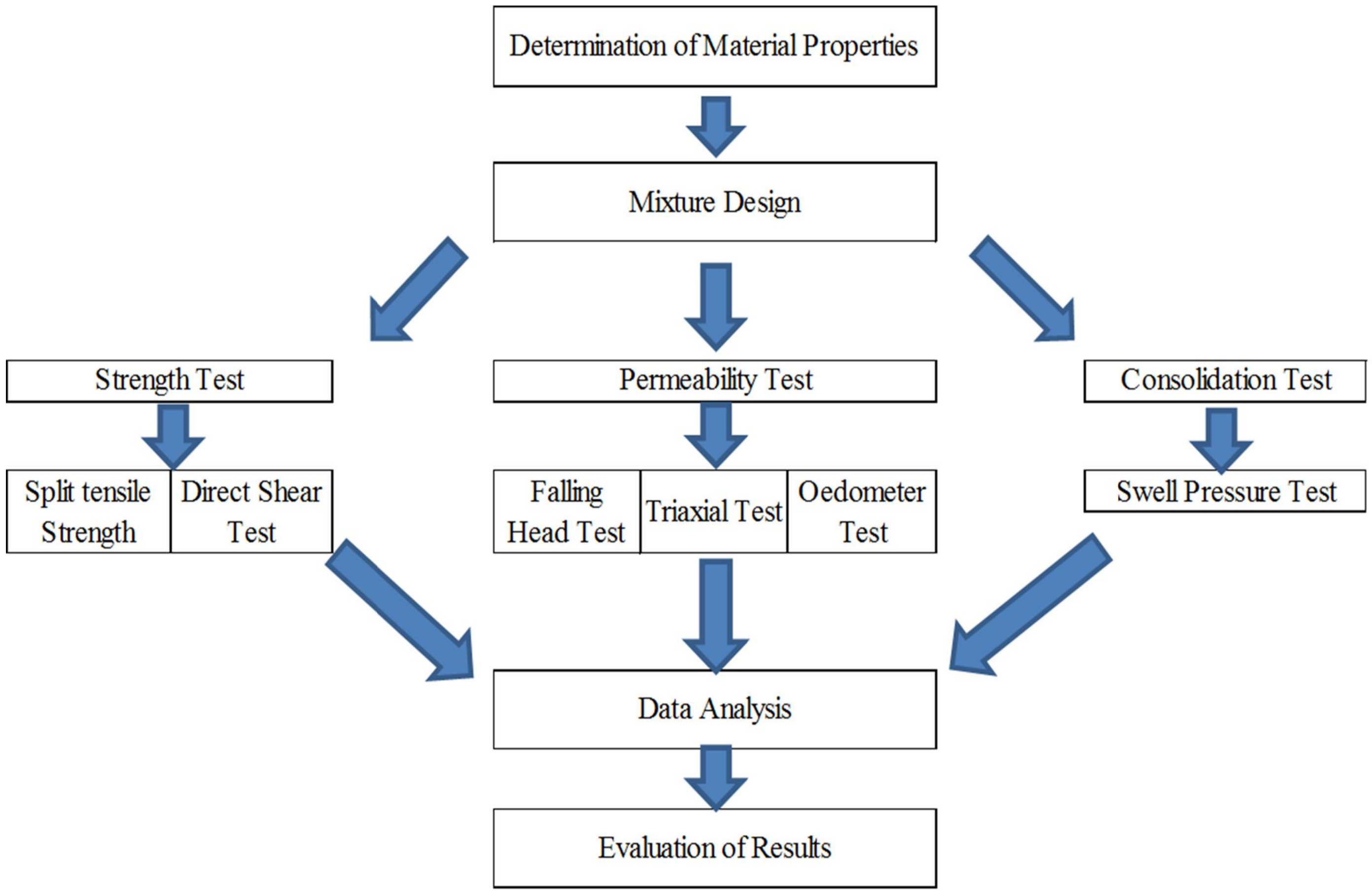


Figure 3.1 Flowchart of this study

Table 3.1 Content of Green Sand

Content of Green Sand	%
Silica Sand	80.0
Bentonite	14.0
Water	4.0
Coal Dust	2.0

Table 3.2 Index Properties of Green Sand

Specific Gravity	2.69
Maximum Dry Density (Mg/m^3)	1.947
Optimum Water Content (%)	12.40
>2mm (Gravel Size) %	0
0.074-2.00 mm (Sand Size) %	75.8
0.002-0.074 mm (Silt Size) %	23.42
<0.002 mm (Clay Size) %	1.2
Plasticity	N.P

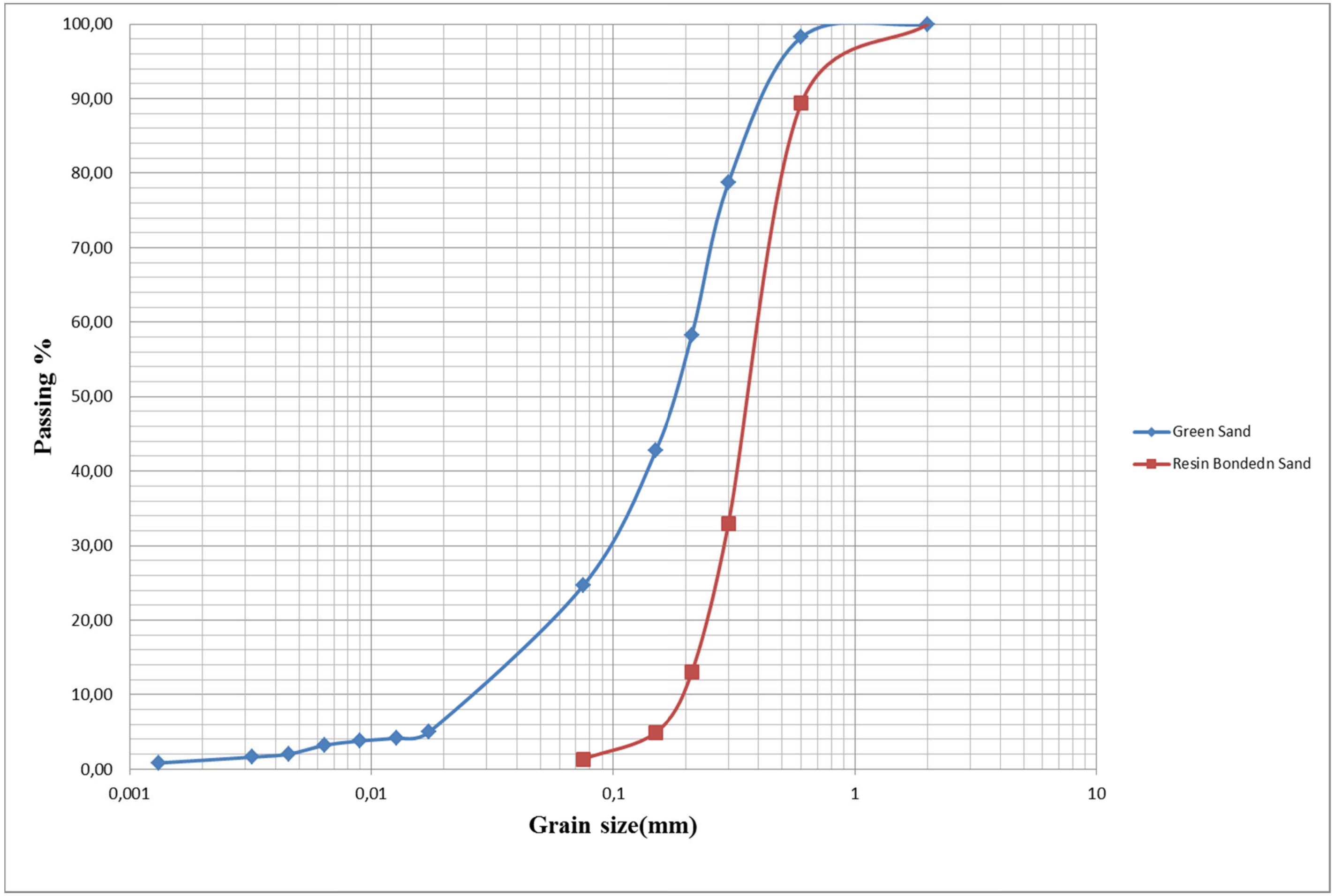


Figure 3.2 Gradation Curve of Green Sand and Resin Bonded Sand

this study. The specific gravity value was obtained by using standard pycnometer method (ASTM D-854). The particle size analyses were performed by sieve (ASTM D-6913) and hydrometer analyses according to the ASTM D-422. Maximum dry density and optimum moisture content relation were obtained by standard proctor test (ASTM D-698). There was no plasticity observed for green sand and it was green-gray in color. It is shown in Figure 3.3

3.1.2 Resin Bonded Sand

This type foundry sand is a waste material and samples are stored in sealed bags in order to protect against moisture and contaminant effects in the environment. The content of resin bonded sand is presented on Table 3.3.

The index properties of this resin bonded sand used in the experiments are given in Table 3.4 and grain size distribution curve plotted in Figure 3.2. Grain size distribution curve pointed out that foundry sand is dominantly sand sized material in this study. The specific gravity value was obtained by using standard pycnometer method (ASTM D-854). The particle size analyses were performed by sieve analysis according to the ASTM D-422. Hydrometer analysis is not carried out for resin bonded sand because the initial reading taken from hydrometer was very low. Maximum dry density and optimum moisture content relation were obtained by standard proctor test (ASTM D-6913). There was no plasticity observed for foundry sand and it was gray in color. Resin bonded sand is presented in Figure 3.4.

3.1.3 Rubber

Two types of rubber were used for this study namely pulverized form and strip form. Both forms were obtained from Eskiкehir Osmangazi University. All types were obtained from the tread part of the tire. They were stored in dark room in order to protect against environmental effect. It was very hard to them determine index properties of strip form of rubber due to the shape of the material so during the laboratory tests it was assumed to have the same index properties as pulverized form of rubber. Grain size distribution of the rubber is given in Figure 3.5 and index properties of pulverized rubber used is given in Table 3.5 respectively. The pictures of pulverized and strip rubber are shown in Figure 3.6 and 3.7 respectively.

Figure 3.3 Green sand

Table 3.3 Content of Resin Bonded Sand

Content of Resin Bonded Sand	%
Silica Sand	92.00
Water	3.00
Resin	4.00
Other ingredients	1.00

Table 3.4 Index Properties of Resin Bonded Sand

Specific Gravity	2.70
Maximum Dry Density (Mg/m^3)	1.726
Optimum Water Content (%)	12.10
>2mm (Gravel Size) %	0
0.074-2.00 mm (Sand Size) %	98.64
Plasticity	N.P

Figure 3.4 Resin bonded sand

Table 3.5 Index Properties of Pulverized Rubber

Specific Gravity	0.64
>2mm (Gravel Size) %	0
0.074-2.00 mm (Sand Size) %	96.00
Silt and Clay size (<0.075 mm) %	4.00
Plasticity	N.P

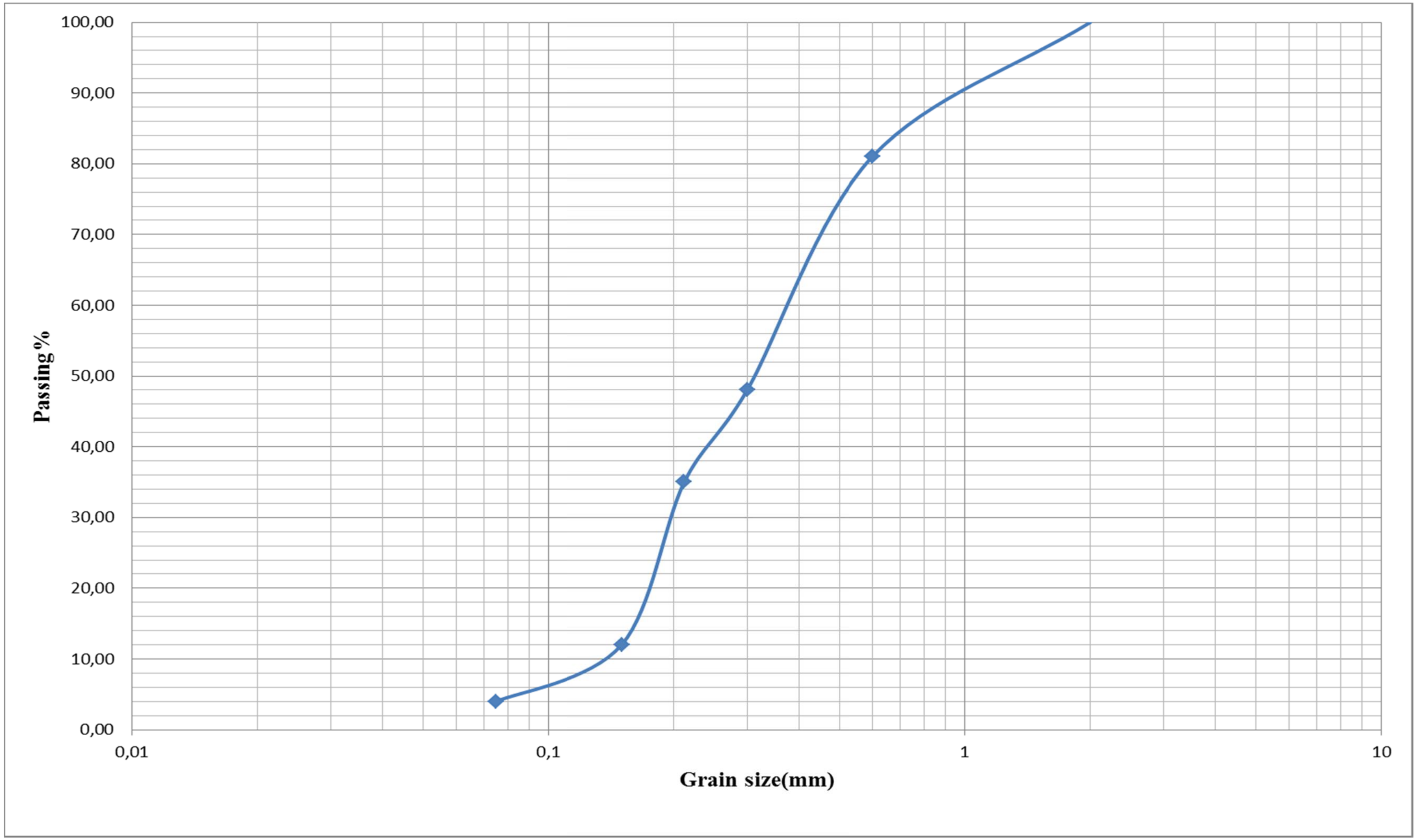


Figure 3.5 Gradation curve of rubber

Figure 3.6 Pulverized Rubber

Figure 3.7 Strip Rubber

3.1.4 Bentonite

Bentonite used for this study was taken from Karakaya Bentonite Factory in Ankara. The chemical composition of bentonite used in this study is given in Table 3.6. The specific gravity of bentonite was calculated as 2.36 and percent weight passing No200 sieve was 97.5 %.

3.2 Mixture Design

All mixture design used in this study was based on dry weight percentages of total mixture. First of all, the properties of green sand and resin bonded sand were determined. Then, in order to investigate the behavior of increasing the bentonite content on both green sand and resin bonded sand, the amounts of bentonite mixtures were added to the sands. Then according to their permeability test results, the mixtures having permeability less than $1x10^{-7}$ cm/sec were determined and the amount of rubber were added to the sand bentonite mixtures. The mixture design is given in Table 3.7.

Table 3.7 Mixture Design of This Study

Sample No	Mixture
1	100 % Green Sand
2	97 % Green Sand +3 %Bentonite
3	94 % Green Sand +6 %Bentonite
4	91 % Green Sand+9%Bentonite
5	88% Green Sand +9% Bentonite+ 3% Pulverized Rubber
6	88% Green Sand +9% Bentonite+ 3% Strip Rubber
7	100 % Resin Bonded Sand
8	97 % Resin Bonded Sand +3 %Bentonite
9	94 % Resin Bonded Sand +6 %Bentonite
10	91 % Resin Bonded Sand+9%Bentonite
11	88% Resin Bonded Sand +9% Bentonite+ 3% Pulverized Rubber
12	88% Resin Bonded Sand +9% Bentonite+ 3% Strip Rubber

Table 3.6 Chemical Composition of Bentonite Used (Adopted from www.karakaya.com)

Oxides	Percent
SiO_2	61.28 %
Al_2O_3	17.79 %
Fe_2O_3	3.01 %
CaO	4.54 %
Na_2O	2.70 %
MgO	2.10 %
K_2O	1.24 %
Loss of ignition	7.34 %

3.3 Index Properties of Mixtures Used

Grain size analysis, Atterberg Limit Tests and Specific Gravity Tests were performed for all mixtures. The methods and results are given in subsection mentioned below.

3.3.1 Grain Size Distribution

Each mixture was subjected to grain size analysis which includes sieve analysis for soil retaining No 200 sieve and hydrometer analysis for soil passing No 200 sieve after samples were washed through No 200 sieve. Gradation curve for each mixture is plotted in Figure 3.8 and Soil classification according to the USCS system is given in Table 3.8.

3.3.2 Specific Gravity

The specific gravity values were calculated for all mixtures according to the ASTM D-854 (specific gravity of soil solids). All calculation results are presented in Table 3.9.

There were some difficulties observed for mixtures including rubber content due to the low density of the rubber, floating on the water. In order to eliminate this problem paraffin oil was used instead of water in specific gravity. Rubber accumulation around the inlet of the pycometer after air-extraction process in desiccator caused problem for specific gravity test however it was neglected. As it can be seen from Table 3.9, while bentonite percent increased, the specific gravity decreased depending on the type of sand. Besides, theoretical calculation of specific gravities do not totally equal to the laboratory results. Because, all samples were cured in 1 week in specific gravity bottle and due to the chemical reactions between bentonite and water slightly difference results were obtained.

3.3.3 Consistency Limits

In order to determine the consistency limits including liquid limit, plastic limit and plasticity index, Atterberg Limit test were performed according to the ASTM D-4318 Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity

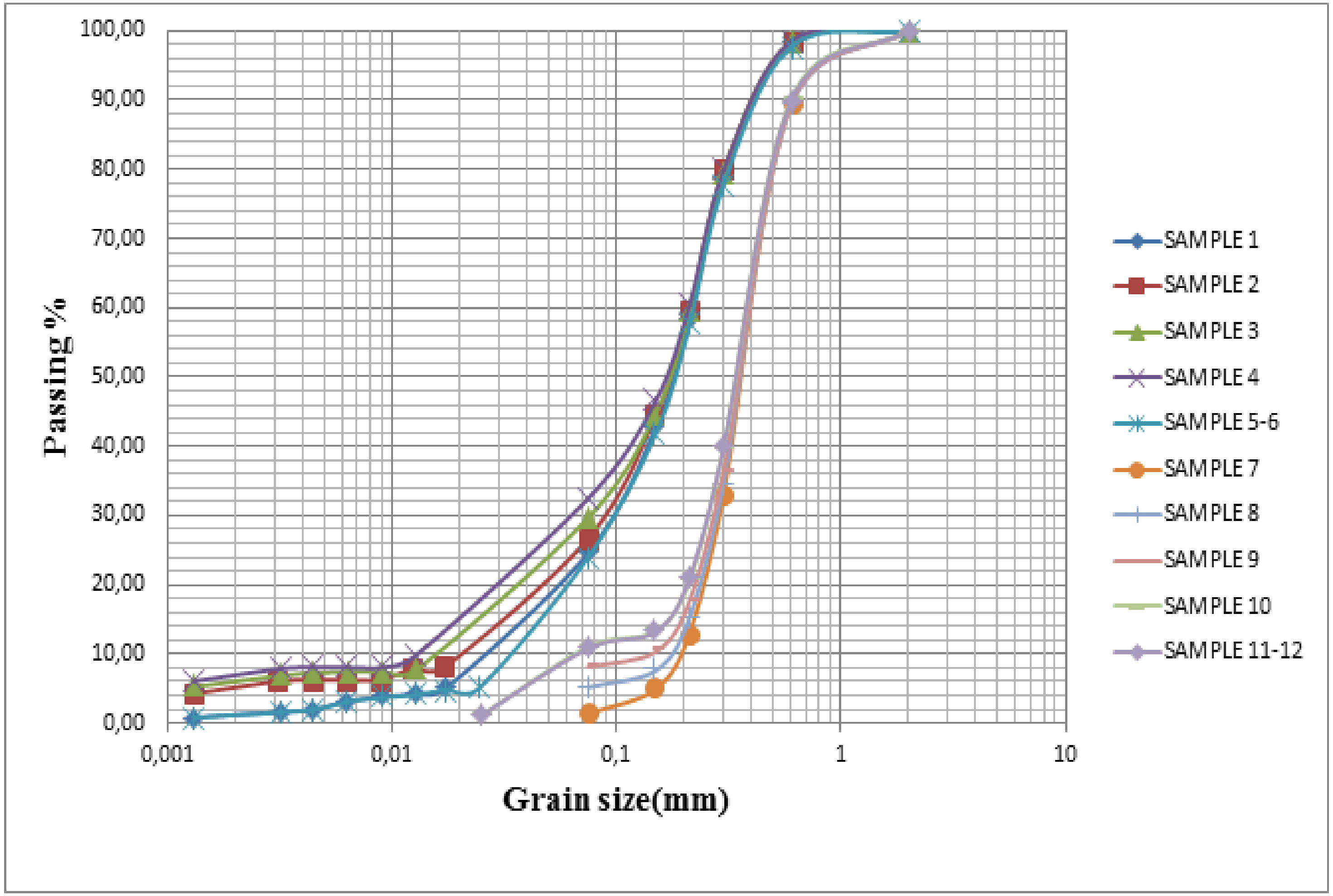


Figure 3.8 Gradation curves of mixtures used

Table 3.8 Soil Classification of Mixtures

Sample No	Mixture	Soil Classification
1	100 % Green Sand	SC
2	97 % Green Sand +3 %Bentonite	SC
3	94 % Green Sand +6 %Bentonite	SC
4	91 % Green Sand+9%Bentonite	SC
5	88% Green Sand +9% Bentonite+ 3% Pulverized Rubber	SC
6	88% Green Sand +9% Bentonite+ 3% Strip Rubber	SC
7	100 % Resin Bonded Sand	SP-SM
8	97 % Resin Bonded Sand +3 %Bentonite	SP-SM
9	94 % Resin Bonded Sand +6 %Bentonite	SP-SM
10	91 % Resin Bonded Sand+9%Bentonite	SP-SC
11	88% Resin Bonded Sand +9% Bentonite+ 3% Pulverized Rubber	SP-SC
12	88% Resin Bonded Sand +9% Bentonite+ 3% Strip Rubber	SP-SC

Table 3.9 Specific Gravity values of the mixtures used

Mixture	Specific Gravity
100 % Green Sand	2.695
97 % Green Sand +3 %Bentonite	2.631
94 % Green Sand +6 %Bentonite	2.629
91 % Green Sand+9%Bentonite	2.628
88% Green Sand +9% Bentonite+ 3% Pulverized Rubber	2.542
100 % Resin Bonded Sand	2.701
97 % Resin Bonded Sand +3 %Bentonite	2.692
94 % Resin Bonded Sand +6 %Bentonite	2.663
91 % Resin Bonded Sand+9%Bentonite	2.657
88% Resin Bonded Sand +9% Bentonite+ 3% Pulverized Rubber	2.556

Index of Soils.

All samples were cured at optimum moisture content in humidity room for one week in order to activate the bentonite content in mixture. Besides, in order to control swelling potential of bentonite in mixture due to the reactions of bentonite with water, the water content in mixture was checked daily.

Due to the smaller plasticity of green sand and resin bonded sand, the plasticity was observed for higher bentonite content. No plasticity was observed for the resin bonded sand up to the bentonite content 9 % and no plasticity was observed for the green sand up to the bentonite content 3 %. The results are tabulated in Table 3.9.

3.4 Compaction Characteristics of the Mixture Used

The water content dry density relations were determined by using standard proctor test according to the ASTM D-698, compacting the samples in 3 layer by using 25 strokes to each of three layers by using a 2.5 kg rammer falling freely from 30 cm vertical distance.

The optimum water content versus dry density relation is tabulated in Table 3.10 and the compaction curve for each mixture is given in Appendix A.

As a consequence of these results, increasing the bentonite and rubber content generally results in workable material which was easy to compact and mix during the test.

3.5 Engineering Properties of the Mixtures Used

3.5.1 Test Procedure for the Split Tensile Strength Test

It is the indirect method also called Brazilian test. In order to perform this test, cylindrical specimen is used by placing its axis horizontally between two

Table 3.10 Consistency limits of mixtures used

Mixture	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
97 % Green Sand +3 %Bentonite	26	14	12
94 % Green Sand +6 %Bentonite	35	15	20
91 % Green Sand+9%Bentonite	47	14	33
88% Green Sand +9% Bentonite+ 3% Pulverized Rubber	48	13	35
88% Green Sand +9% Bentonite+ 3% Strip Rubber	51	15	36
91 % Resin Bonded Sand+9%Bentonite	26	16	10
88% Resin Bonded Sand +9% Bentonite+ 3% Pulverized Rubber	28	17	11
88% Resin Bonded Sand +9% Bentonite+ 3% Strip Rubber	31	18	13

Table 3.11 Compaction characteristics of mixtures used

Mixture	Maximum dry density (Mg/m^3)	Optimum water content %
100 %Green Sand	1.947	12.40
97 % Green Sand +3 %Bentonite	1.905	12.83
94 % Green Sand +6 %Bentonite	1.850	13.18
91 % Green Sand+9%Bentonite	1.831	13.38
88% Green Sand +9% Bentonite+ 3% Pulverized Rubber	1.806	13.05
88% Green Sand +9% Bentonite+ 3% Strip Rubber	1.812	12.87
100 % Resin Bonded Sand	1.726	12.10
97 % Resin Bonded Sand +3 %Bentonite	1.747	12.13
94 % Resin Bonded Sand +6 %Bentonite	1.757	13.26
91 % Resin Bonded Sand+9%Bentonite	1.778	13.41
88% Resin Bonded Sand +9% Bentonite+ 3% Pulverized Rubber	1.807	12.46
88% Resin Bonded Sand +9% Bentonite+ 3% Strip Rubber	1,809	12.38

horizontal platens of compression test machine and failure is observed along vertical diameter due to the tension. (Neville 1981, cited in Yılmaz 2000).

These tests were performed for one week cured samples using strain controlled application of the axial load. Specimens were compacted at 95 % of optimum dry density and 95 % of optimum water content in static compaction. The mold used in compaction has a dimension of 72 mm in height and 36 mm in diameter. The specimens were compacted into a mold and separated from mold carefully. The specimens were also cured for 1 week in order to activate bentonite content inside specimens.

The tensile strength Ŗ corresponding to the load applied along the length of the specimen can be calculated from:

Ŗ= 2P/´ DL

Where

D=Cylindirical Specimen Diameter

L=Length of the cylinder

P=Compressive Load on Cylinder

The mold, suitable for ASTM C-496, consists of 3 main pieces: 2 platens, strips which have 5.28 mm width and 74 mm length over the platens and the author for the 36x72 mm cylindrical specimens. A picture of mold is given in Figure 3.9. Unconfined compression strength machine was used for this test with 0.5 mm/min rate of strain.

It is required to great attention for placing the cylindrical specimen between the strips to provide alignment of the specimen. To do this, a line passing through diameter on each of the specimen was drawn.

In order to perform this experiment, 2 specimens were prepared and the average of two failure dial gage readings due to the splitting along the vertical

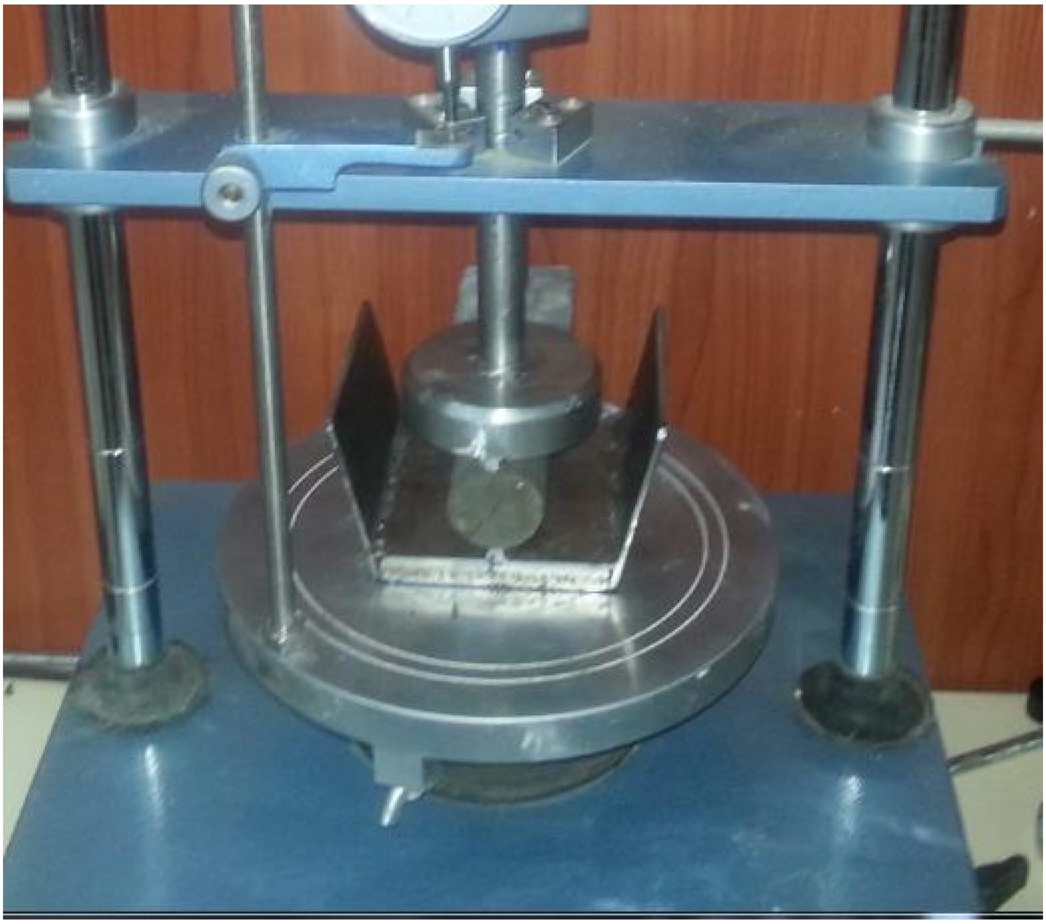


Figure 3.9 Mold of split tensile strength

diameter was taken if the results are coherent. If not the tests were repeated and the average of coherent values were taken.

3.5.2 Test Procedure for Direct Shear Test

The shear strength characteristics of sand can be determined from the results of either direct shear tests or drained triaxial tests depending on the types of the soil. Direct shear test was chosen for resin bonded sand because unconfined compression test could not be performed for the resin bonded sand. It did not remain standing for bentonite content up to 6%. Besides, direct shear test were performed for green sand in order to compare all mixtures with the same conditions.

Drained consolidated tests were performed in order to understand the behavior of the sands precisely. All specimens were cured for 1 week to activate the bentonite content in mixture and 95 % of maximum dry density corresponding to optimum water content was used. Specimens were consolidated for 1 day and drainage was permitted for all tests by using a shearing rate of 0.5 mm/min. The molds having dimension of 63.5 mm diameter and 19 mm height were used for these tests. 3 different weights were used for applying normal pressure 100,200 and 400 kPa . The tests continued until the failure of the specimens. Therefore the residual and peak values were determined for each specimen. All tests were performed according to the ASTM D-3080.

3.5.3 Test Procedure for Constant Head Test

The hydraulic conductivity tests were performed with a rigid-wall constant head permeability apparatus according to ASTM D-243, it is a standard proctor mold shaped permeability apparatus with 116 mm height and 101.7 diameter.

The hydraulic conductivity tests were tried to be performed on specimens having 95 % of maximum dry density corresponding to optimum water content. A filter paper was placed at the bottom by using water soaked container it was fixed in position then water was permitted to flow with keeping the air vent open for enough time.

However, this method was not performed for the green sand mixtures. Because, there was no water outflow observed on the valve placed on top of the mold during 3 months for 3 attempts each of which has a duration of 1 months despite using vacuum and carbon dioxide. Therefore the saturation was not satisfied completely and it was not possible to take any measurement from this system. It might be related to the congestion of the porous stone of apparatus due to the gradation of the foundry sand. Besides, evaporation is faster than the outflow. This method also was not used for resin bonded sand mixtures for comparing mixtures in same condition.

3.5.4 Test Procedure for Flexible Wall Permeability Test

Permeability Test can be used to measure the permeability of low permeable soil by using triaxial cell.

In order to perform this test the specimens were prepared and put into a triaxial machine. The back pressure and cell pressure were adjusted with using dial gauges. Carbon dioxide and vacuum were used for satisfying saturation. Hydraulic gradient is adjusted around 1 and the pressure difference between cell and back pressure is adjusted as 40 kPa with 0.95 B value.

This test also performed only for one mixture (Mixture 1) with duration 4 weeks with 0.90 B value, however the saturation degree were not satisfied for other mixtures despite 4 attempts each of which has a duration of 3 weeks and performed on 700-630 kPa cell and back pressure respectively. The B values was calculated as 60-65 % after 3 weeks. Besides, hydraulic gradient could be a problem for this test, because the hydraulic gradient reached 100 using these pressures.

3.5.5 Test Procedure for Oedometer Test

Oedometer test was used for determining the compressibility characteristics and hydraulic conductivity of the mixtures. The specimens were compacted using static compaction method in consolidation ring having a diameter of 50 mm and height of 20 mm at 95% of maximum dry density corresponding to moisture content and cured for 1 week in order to activate the bentonite content. The schematic representation of test is given in Figure 3.10.

Consolidation pressure was selected as 25 to 1600 kPa in loading stage and 400, 100, 25 kPa were chosen as consolidation pressure in unloading stage. Each loading took 24 hours and loadings were changed successfully. After replacing new loading, the readings were taken for 144 minutes to calculate permeability and the compression and unloading data were recorded for each pressure.

Minimum 4 specimens were used for permeability calculation. Hydraulic conductivity was calculated by taking the average of 4 or 5 readings if the results were consistent with each other. If not, 2 or 3 closest values were taken for hydraulic conductivity. The hydraulic conductivity was calculated for each loading interval and permeability versus pressure graph was constructed for each mixture.

3.5.6 Test Procedure for Swell Pressure Test

This swell pressure test, called no volume change swelling pressure test because of keeping the height constant during the test during the loading on sample, were performed in accordance with the ASTM D-4546 Method C.

Specimens were compacted at 95 % of maximum dry density and water content corresponding to maximum dry density value. The specimens were submerged into water then started swelling, a small pressure increment was applied to prevent swelling of specimen. At the end, no swelling was observed under the applied load and this value could be taken as swelling pressure. This test took approximately 1-1.5 day because of the low swelling potential of the mixtures.

Figure 3.10 The oedometer test

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Direct Shear Strength

Direct shear tests were performed on one specimen for each mixture considering the consistency of the normal-shear stress graph drawn for 100, 200, 400 kPa normal stress. If the consistency was not satisfied, the experiment was repeated. The results including residual and peak strength parameters of each material are presented in Table 4.1.

The relationships between internal friction angles versus green sand and resin bonded sand mixtures are presented in Figures 4.1 and 4.2, respectively. The relationships between cohesion values versus foundry sand and resin bonded sand mixtures are presented in Figure 4.3and 4.4 for peak and residual values respectively.

For green sand and resin bonded sand, named as mixture 1 and mixture 7, peak internal friction angles were calculated as 33^0 and 35.5^0 respectively. Resin bonded sand has higher internal friction angle than foundry sand convenient with gradation. Besides, these internal friction angles are convenient with literature values obtained for loose and medium sands.

While observed from Figure 4.1 and 4.2, the internal friction angle decreases as bentonite content increases due to the low internal friction angle of bentonite. Moreover, the cohesion increases as bentonite content increases due to the cohesive structure of bentonite observed from Figure 4.3 and 4.4. However, there is no considerable change observed due to the low bentonite % additives inside the mixtures. These changes can not affect the type of the classification of the mixtures directly. It is important to emphasize the effect of rubber in mixtures.

Table 4.1 Residual and Peak Strength Parameters of Mixtures

Sample No	Mixture	Internal Friction Angle-Φ' (degree)		Cohesion-c' (kPa)	
		Peak	Residual	Peak	Residual
1	100 % Green Sand	33	31	0.2	0.9
2	97 % Green Sand +3 %Bentonite	32	30.5	0.2	1.3
3	94 % Green Sand +6 %Bentonite	30.5	30.3	0.3	2.0
4	91 % Green Sand+9%Bentonite	30.4	30.2	0.4	2.7
5	88% Green Sand +9% Bentonite+ 3% Pulverized Rubber	31.5	31	0.5	3.5
6	88% Green Sand +9% Bentonite+ 3% Strip Rubber	31.4	31	0.4	3.2
7	100 % Resin Bonded Sand	35.5	33.5	0	0.1
8	97 % Resin Bonded Sand +3 %Bentonite	34	32.5	0	0.2
9	94 % Resin Bonded Sand +6 %Bentonite	33	32	0.2	0.4
10	91 % Resin Bonded Sand+9%Bentonite	32.5	30	0.2	0.5
11	88% Resin Bonded Sand +9% Bentonite+ 3% Pulverized Rubber	35	33	0.4	0.9
12	88% Resin Bonded Sand +9% Bentonite+ 3% Strip Rubber	34.6	32.6	0.3	0.8

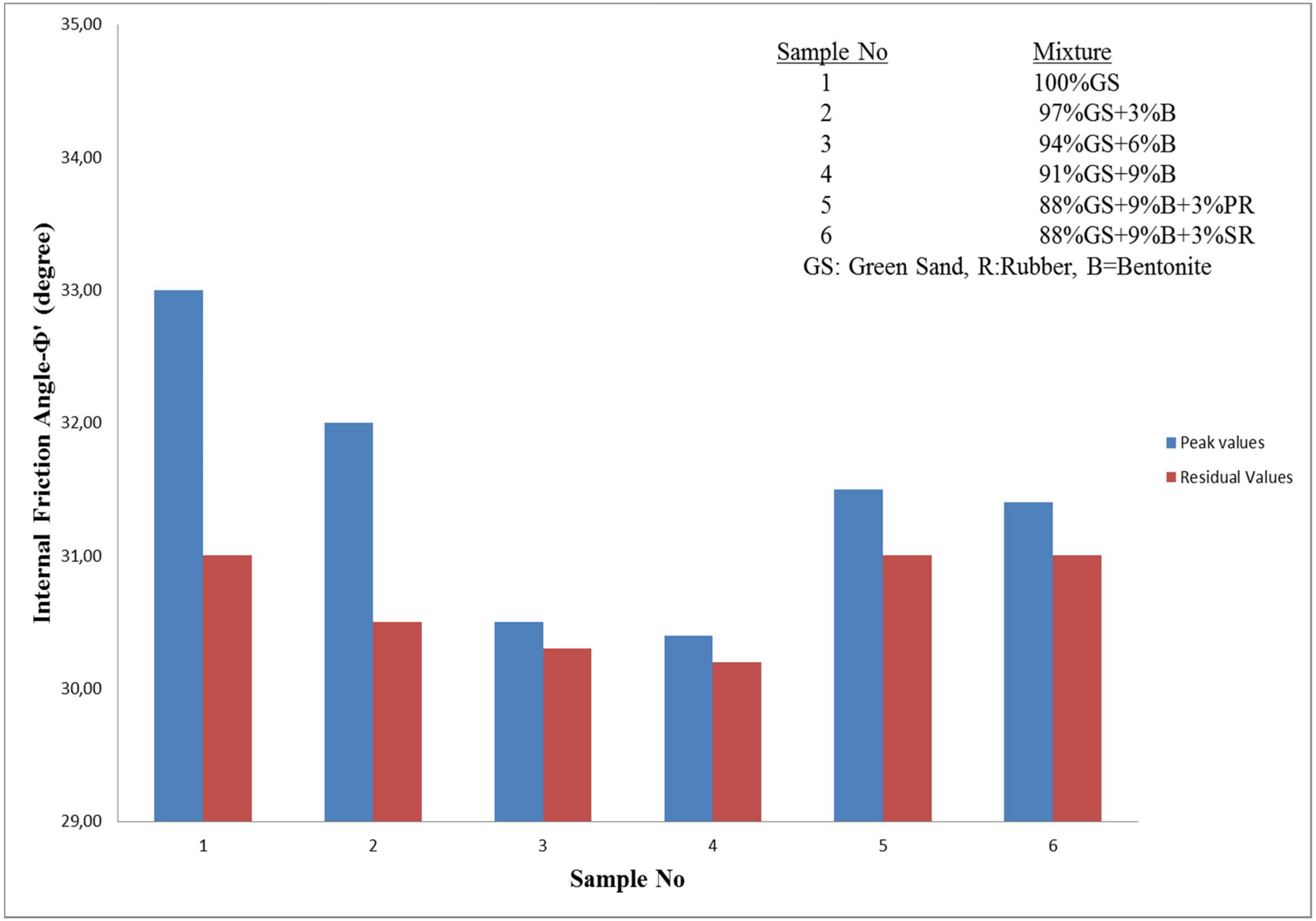


Figure 4.1Internal friction angle relationship for green sand mixtures

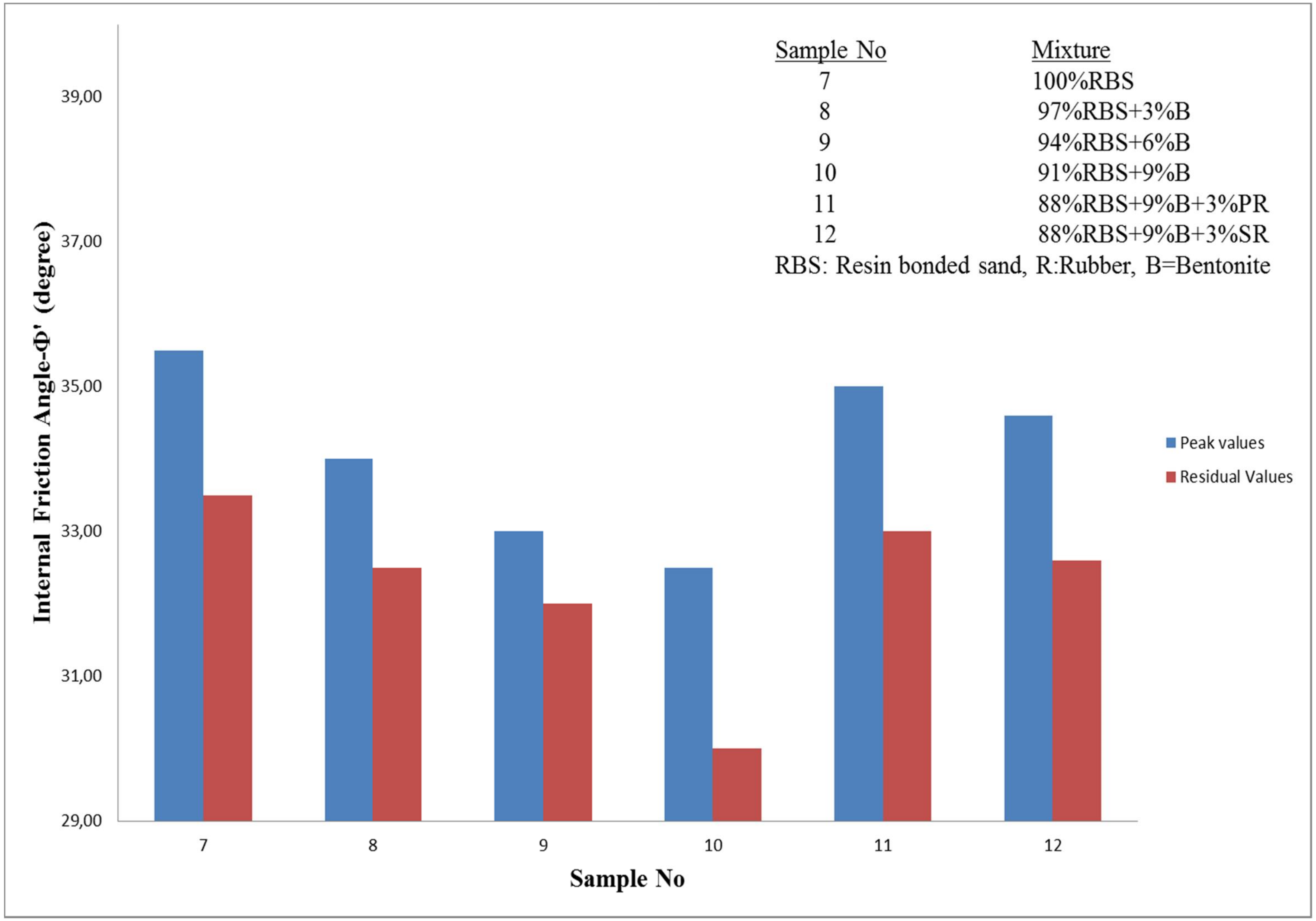


Figure 4.2Internal friction angle relationship for resin bonded sand mixtures

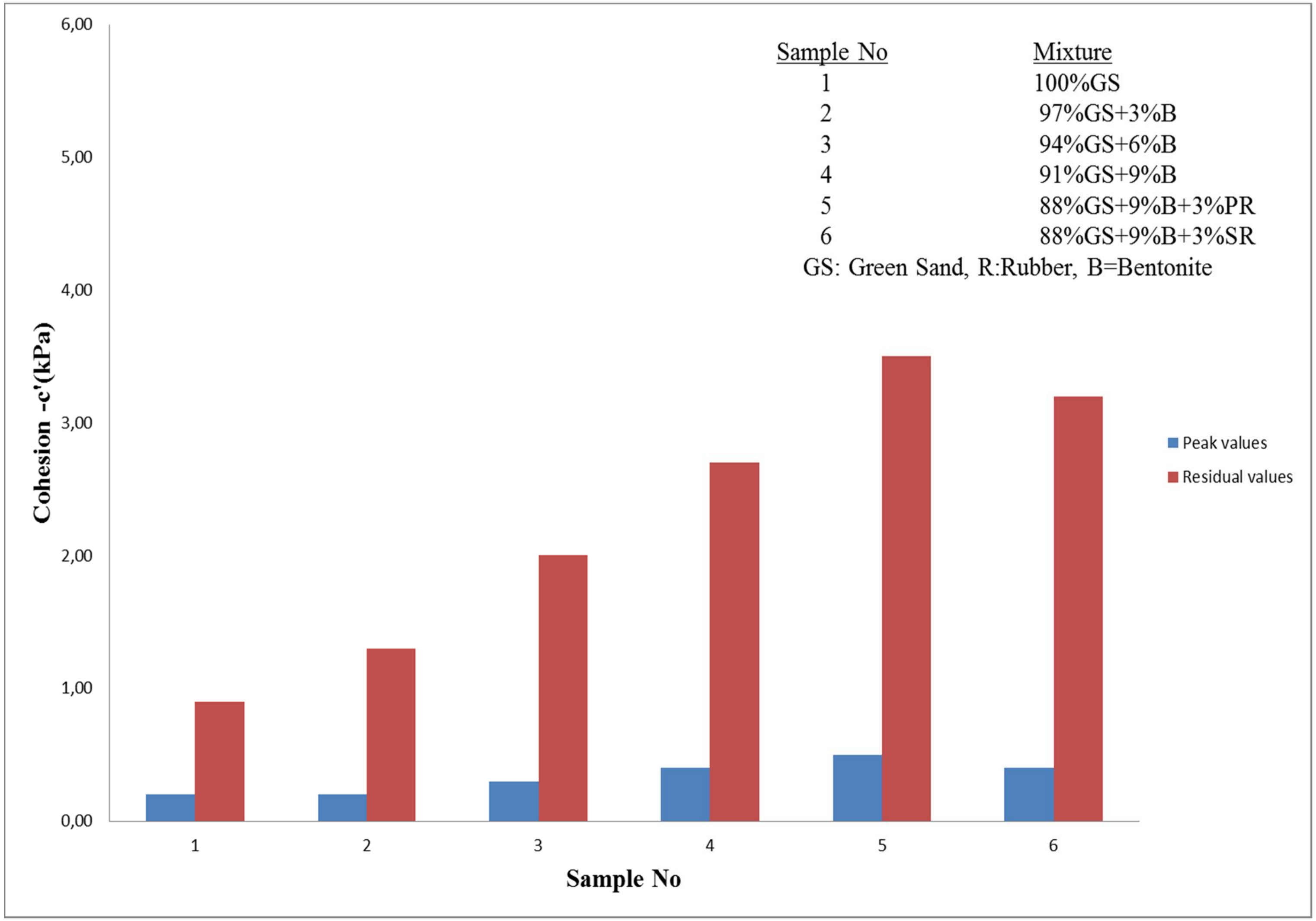


Figure 4.3 Green sand mixtures cohesion relationship

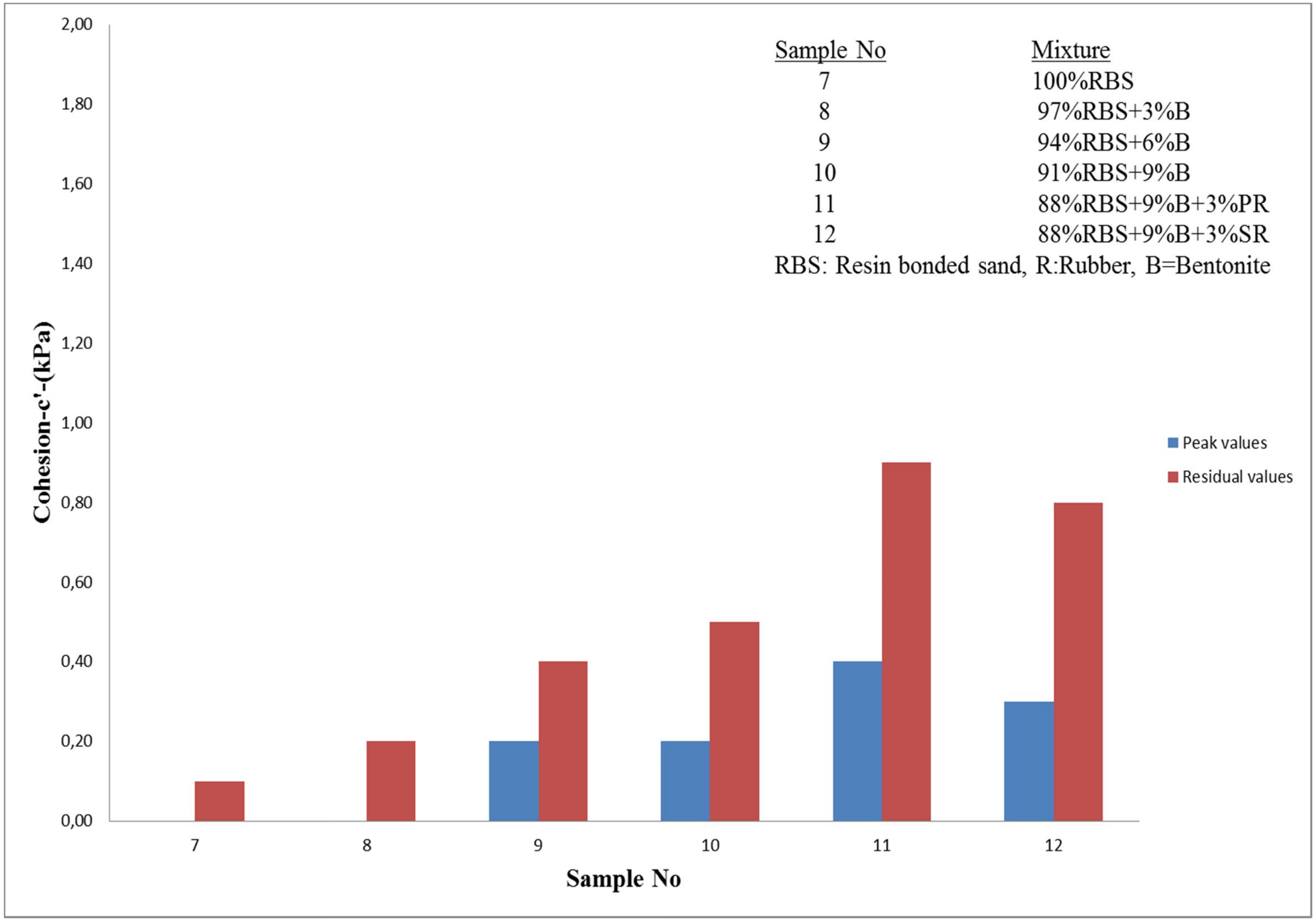


Figure 4.4 Resin bonded sand mixtures cohesion relationship

Rubber increases the internal friction angle considerably and the cohesion slightly and increases the strength. However, the type of rubber used in mixture does not affect the strength of mixture.

Strip and pulverized rubber give approximately the same effect on mixture. It proves that 2 types of rubber used in mixtures increase the strength .

4.2 Split Tensile Strength

Split tensile strength tests were performed on 7 days cured two specimen and as compacted samples. These results are tabulated in Table 4.2.

It is pointed out that this test could not be performed for resin bonded sand having bentonite content up to 6 %. Because specimens could not maintain its molded shape due to the gradation of resin bonded sand which doesn¢t have enough silt and clay particles.

The split tensile strength test results of green sand and resin bonded sand are given in Figure 4.5 and Figure 4.6, respectively. It is clearly seen that the split tensile strength increases while bentonite content increases. Drastic change was observed for the resin bonded sand. For instance, tensile strength rises from 0.47 kPa to 2.68 kPa as bentonite changes from 6% to 9 %. There is also considerable change in the tensile strength with increasing bentonite content in the green sand.

The effects of rubber on the green sand and the resin bonded sand are approximately the same. The rubber causes an increase in the tensile strength moderately depending on the type of sand. Besides, the strip rubber increases the tensile strength more than pulverized rubber due to the shape of the strip rubber which prevents the shear failure as it is expected. The increase in shear strength ratio is 12-39 % for green sand and 16-70 % resin bonded sand, respectively. It is concluded that the rubber shows more significant effect on resin bonded sand rather than green sand. Splitting test performed on rubber percent revealed that although large cracks were observed on vertical side in failure the rubber maintains the specimen as one piece. It is shown in Figure 4.7. It means the behavior of rubber particles resemble as

Table 4.2 Split Tensile Strength values of mixtures used

Mixture	**Tensile Strength (kPa)**
100 %Green Sand	14.49
97 % Green Sand +3 %Bentonite	16.59
94 % Green Sand +6 %Bentonite	21.27
91 % Green Sand+9%Bentonite	23.84
88% Green Sand +9% Bentonite+ 3% Pulverized Rubber	26.88
88% Green Sand +9% Bentonite+ 3% Strip Rubber	33.19
100 % Resin Bonded Sand	0
97 % Resin Bonded Sand +3 %Bentonite	0
94 % Resin Bonded Sand +6 %Bentonite	0.47
91 % Resin Bonded Sand+9%Bentonite	2.68
88% Resin Bonded Sand +9% Bentonite+ 3% Pulverized Rubber	3.13
88% Resin Bonded Sand +9% Bentonite+ 3% Strip Rubber	4.56

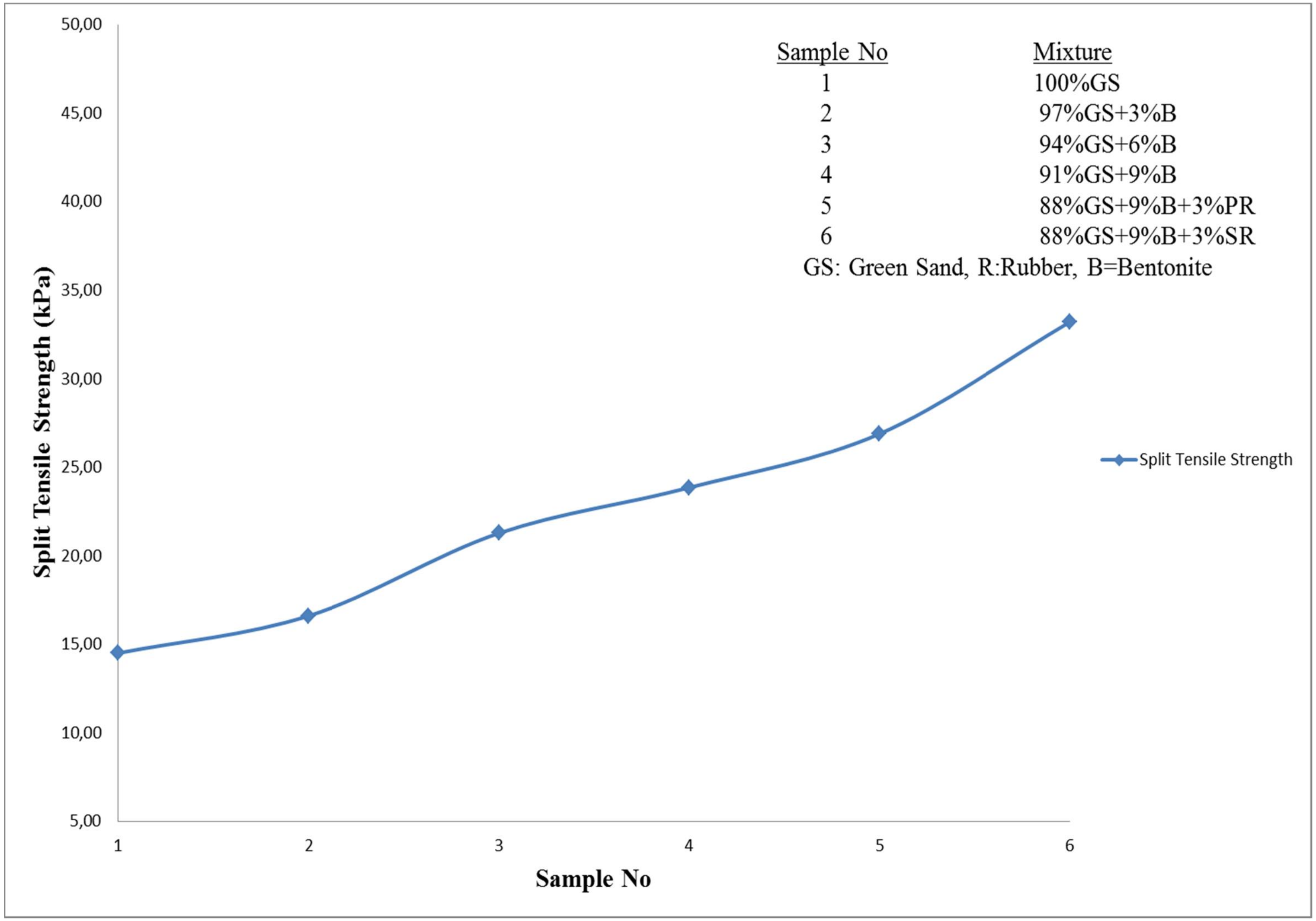


Figure 4.5 Green sand mixtures split tensile strength relationship

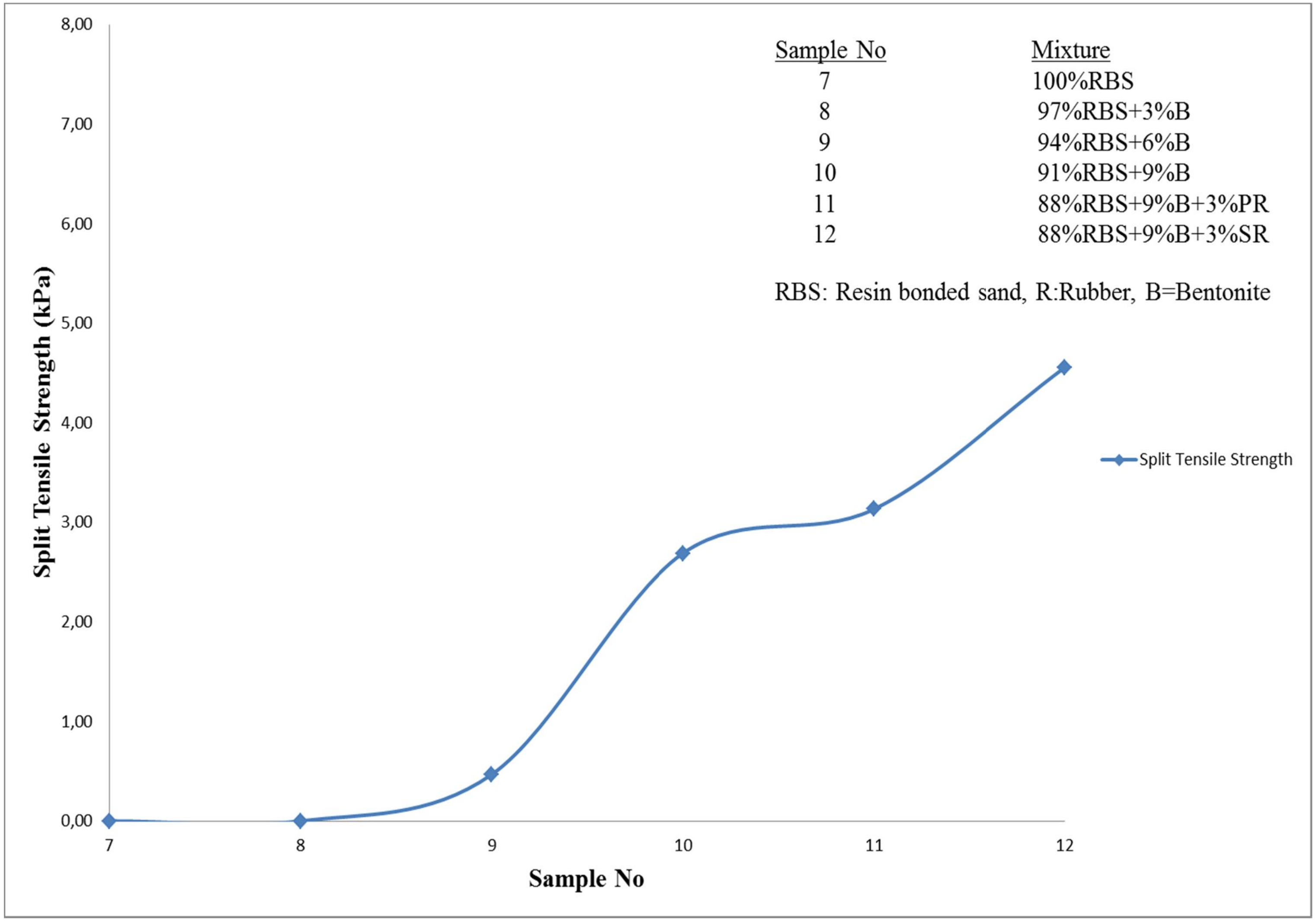


Figure 4.6 Resin bonded sand mixtures split tensile strength relationship

Figure 4.7 The line with shear strength cracking

spring behavior. Besides, it proves that the rubber increased the ductility of the mixtures apparently by increasing the failure time. Finally, it is concluded that there is significant difference in tensile strength of green sand mixture and resin bonded sand. It is presented in Figure 4.8.

4.3 Swell Pressure

Swelling characteristics of the mixtures, referred by swell pressure, might be crucial due to the swelling potential of bentonite.

Compacted samples were used for the swelling potential calculation. The results of swelling pressure of as compacted samples were tabulated in Table 4.3. The results of swelling pressure are presented in Figure 4.9 and 4.10. These figures points out that while bentonite content incases, the swelling potential also increases. However, by adding rubber in mixtures results in decreasing swelling potential as it is expected due to the lacking of contribution of rubber with swelling.

The changes in swell pressures also states that there is sharp changes in resin bonded sand rather than green sand due to the initial bentonite content of green sand.

Consequently, the swell pressures of two sands are very low and swelling problem cannot be expected.

4.4 Compressibility Characteristics

Oedometer test was used for determining compressibility characteristics of samples.

Evaluation of the results is performed according to the void ratio-log effective stress curves of the samples. They are presented in Appendix B. Dry weights of specimens were used for calculation of void ratios after the each pressure increment period. The shape of the e-log pressure curves varies with bentonite content of the soil. The results show that while increasing bentonite content, initial void ratio of foundry sand mixtures increases whereas no comment can be made for resin bonded sand. Besides, the initial void ratio decreases slightly while rubber content increases.

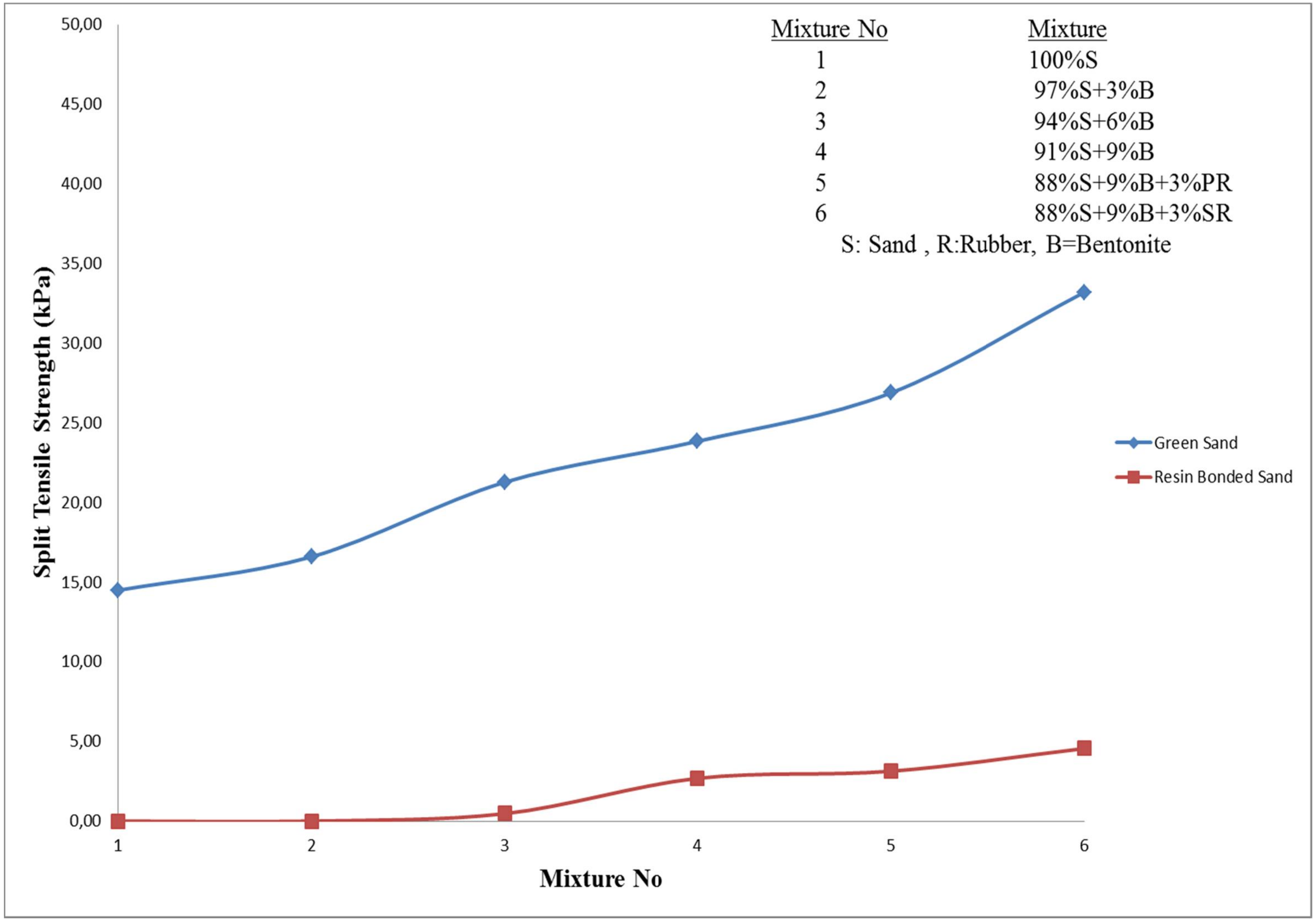


Figure 4.8 Comparison of Split Tensile Strength of Green sand and Resin Bonded Sand

Table 4.3 Swell Pressure of Mixtures

Mixture	Swell Pressure (kPa)
100 % Green Sand	14
97 % Green Sand +3 %Bentonite	25
94 % Green Sand +6 %Bentonite	30
91 % Green Sand+9%Bentonite	33
88% Green Sand +9% Bentonite+ 3% Pulverized Rubber	18
88% Green Sand +9% Bentonite+ 3% Strip Rubber	21
100 % Resin Bonded Sand	5
97 % Resin Bonded Sand +3 %Bentonite	15
94 % Resin Bonded Sand +6 %Bentonite	17
91 % Resin Bonded Sand+9%Bentonite	19
88% Resin Bonded Sand +9% Bentonite+ 3% Pulverized Rubber	10
88% Resin Bonded Sand +9% Bentonite+ 3% Strip Rubber	10

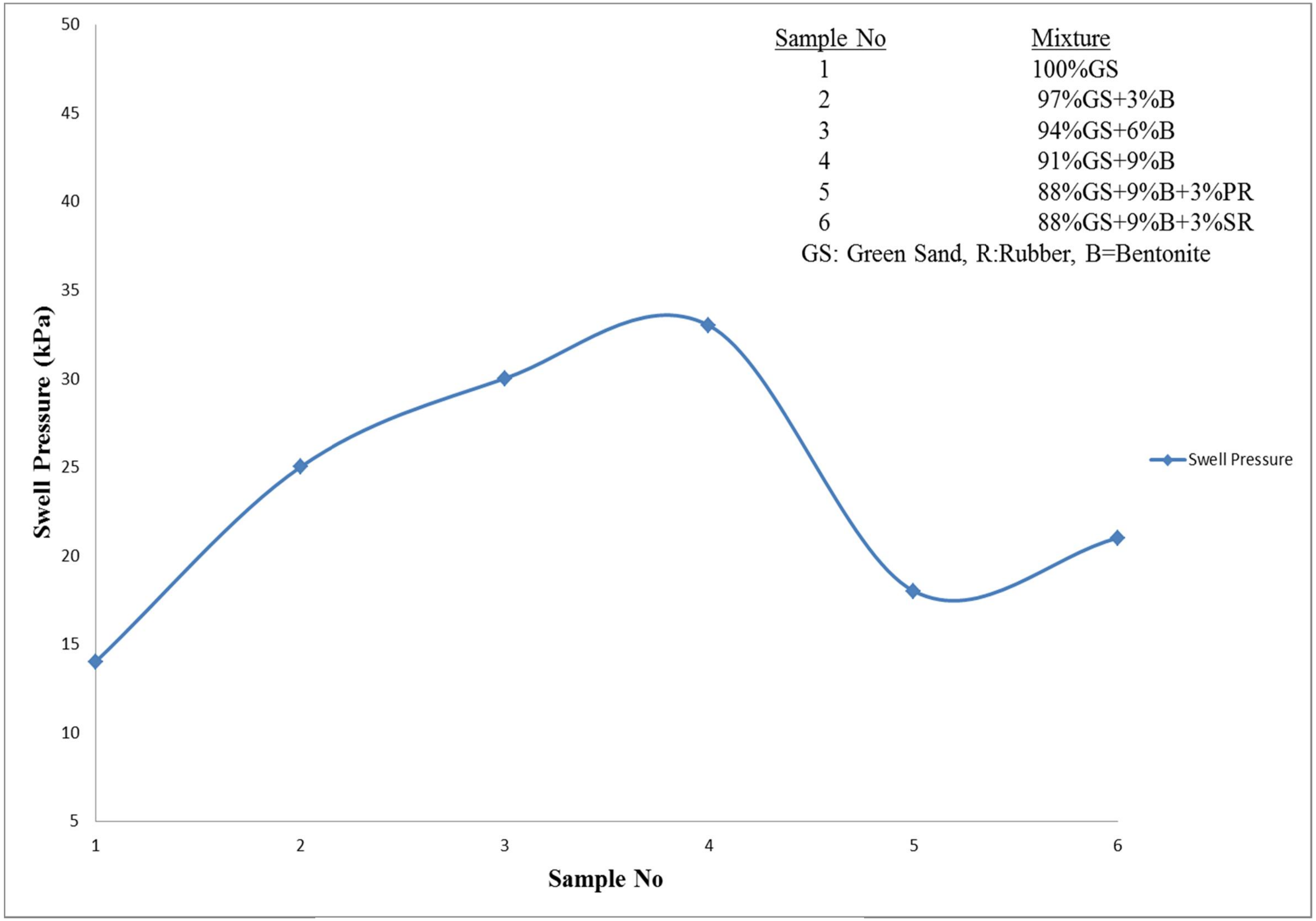


Figure 4.9 Swell Pressure Graph for Green Sand

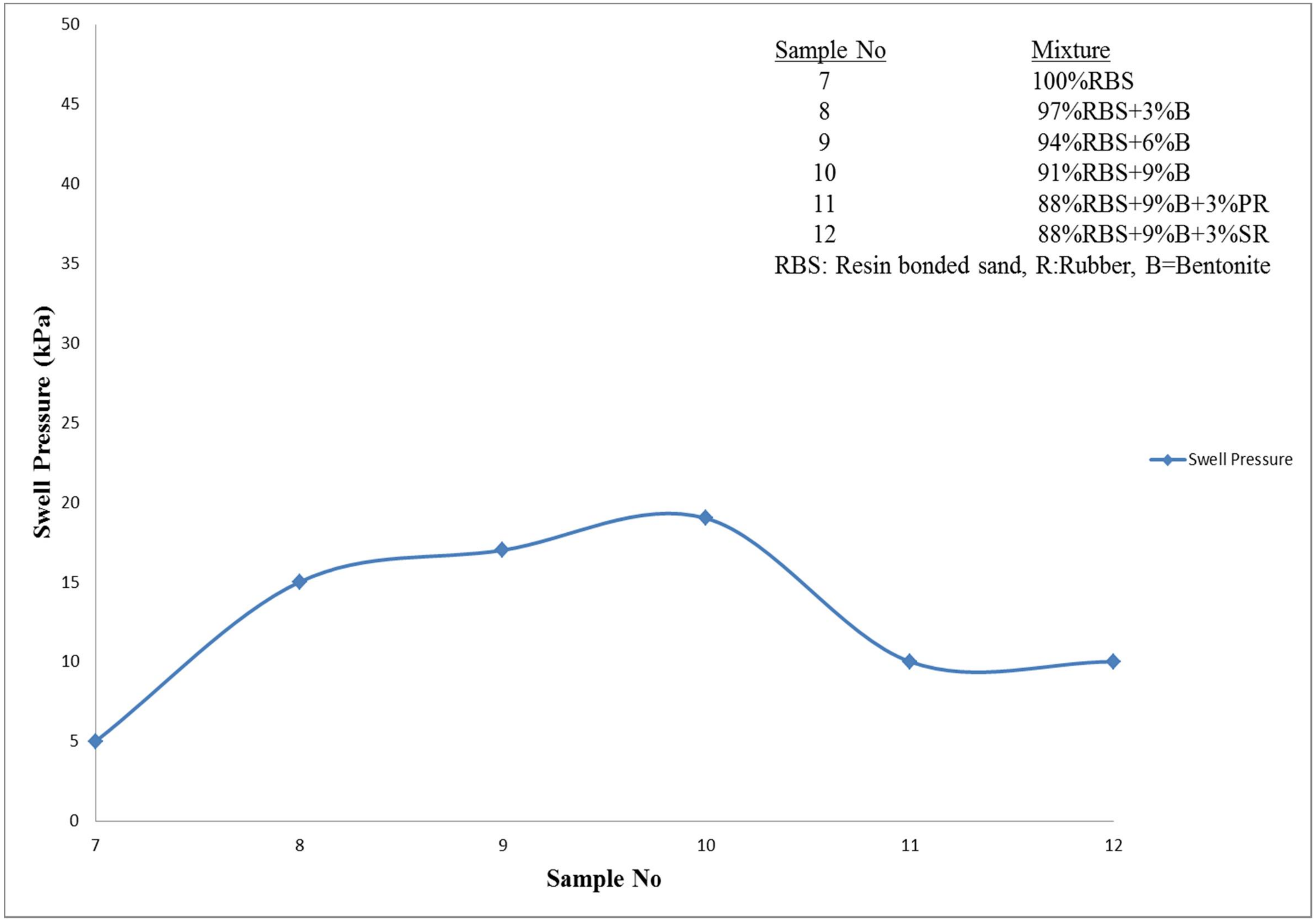


Figure 4.10 Swell Pressure Graph for Resin Bonded Sand

The initial void ratio ranges between 0.4 and 0.6 roughly. This range corresponds to the well graded loose sand with angular particles 0.65 and 0.45 respectively. (Das,2010). This change can be observed in pulverized rubber better than strip rubber.

The coefficient of volume change (m_v) values were calculated for each pressure range from 25 to 1600 kPa by considering the usage of cap layer material. The average values of coefficient of volume change are graphed in Figure 4.11 and 4.12 orderly. The general trend is that while the bentonite content increases, m_v values decreases. Besides, increase in rubber content causes an increase in m_v.

The constrained modulus values have been calculated for the determination of the soil characteristics. The constrained modulus was preferred instead of Modulus of elasticity, because it was not possible to perform enough triaxial test in order to determine the modulus of elasticity due to the reasons explained in section 3.5.4. The average constrained modulus of foundry sand and resin bonded sand for each pressure increment is presented in Figures 4.13 and 4.14 respectively.

The hydraulic conductivity values were calculated for 1 week cured samples from oedometer test results by using coefficient of consolidation obtained from the root time method (due to Taylor) with determination of t_{90} (completion time of 90% of consolidation) which is obtained from time-compression data. The hydraulic conductivity versus mixtures graph for green sand and resin bonded sand are presented in Figure 4.15 and Figure 4.16, respectively. The hydraulic conductivity graph of all mixtures corresponding to pressure increment is presented in Appendix C. Figure 4.15 and Figure 4.16 states that the hydraulic conductivity decreases with increasing bentonite content whereas hydraulic conductivity increases with increasing rubber content.

It is important to emphasize that only one triaxial permeability test could be performed for Mixture 1 (100% green sand) due to the reasons explained in Section 3.5.4. The hydraulic conductivity for Mixture 1 was found as $k=8.19x10^{-7}$ cm/sec whereas it was found as $k=13.7x10^{-7}$ by using oedometer result. It is concluded that

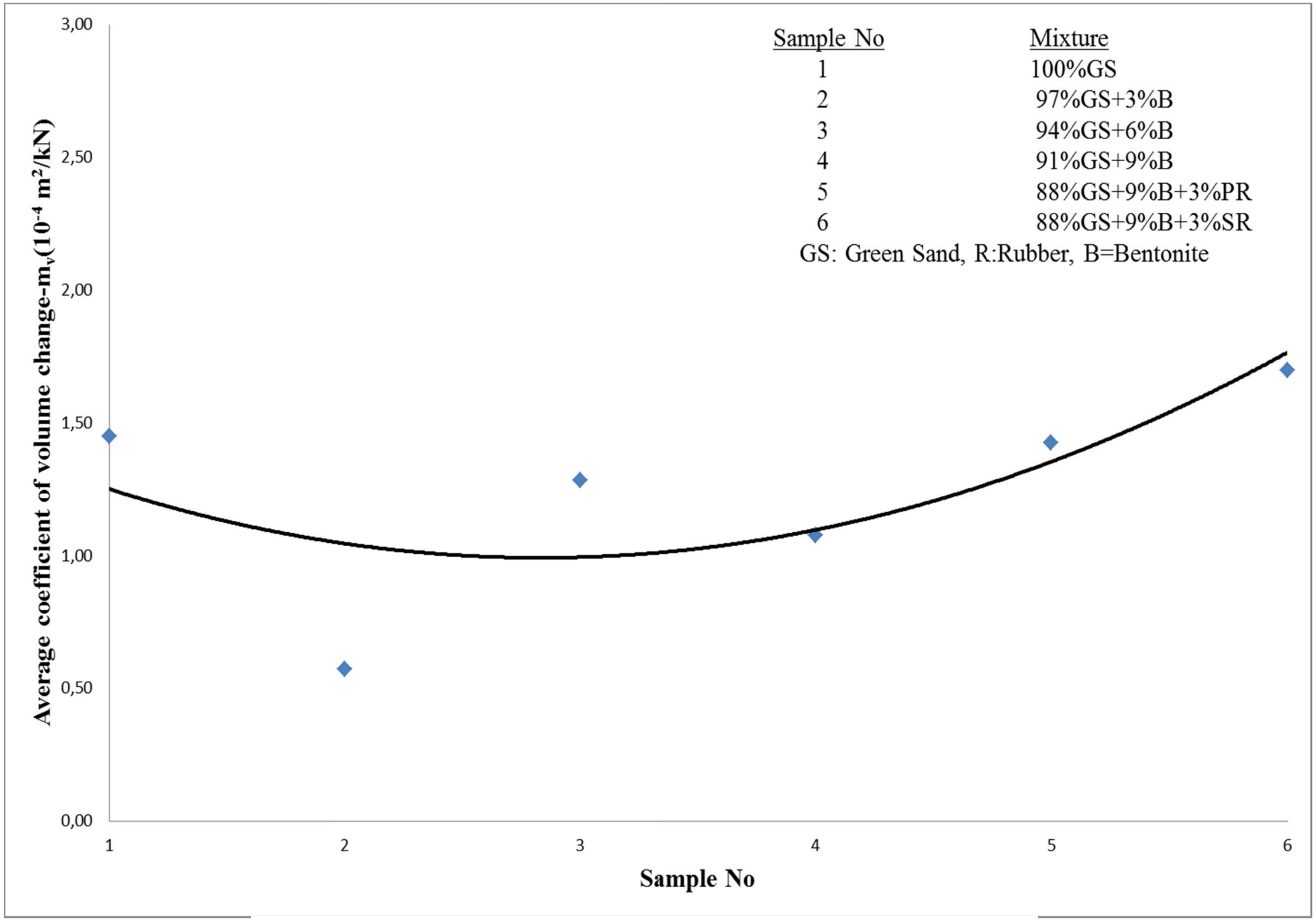


Figure 4.11 Average coefficient of volume change of green sand mixtures

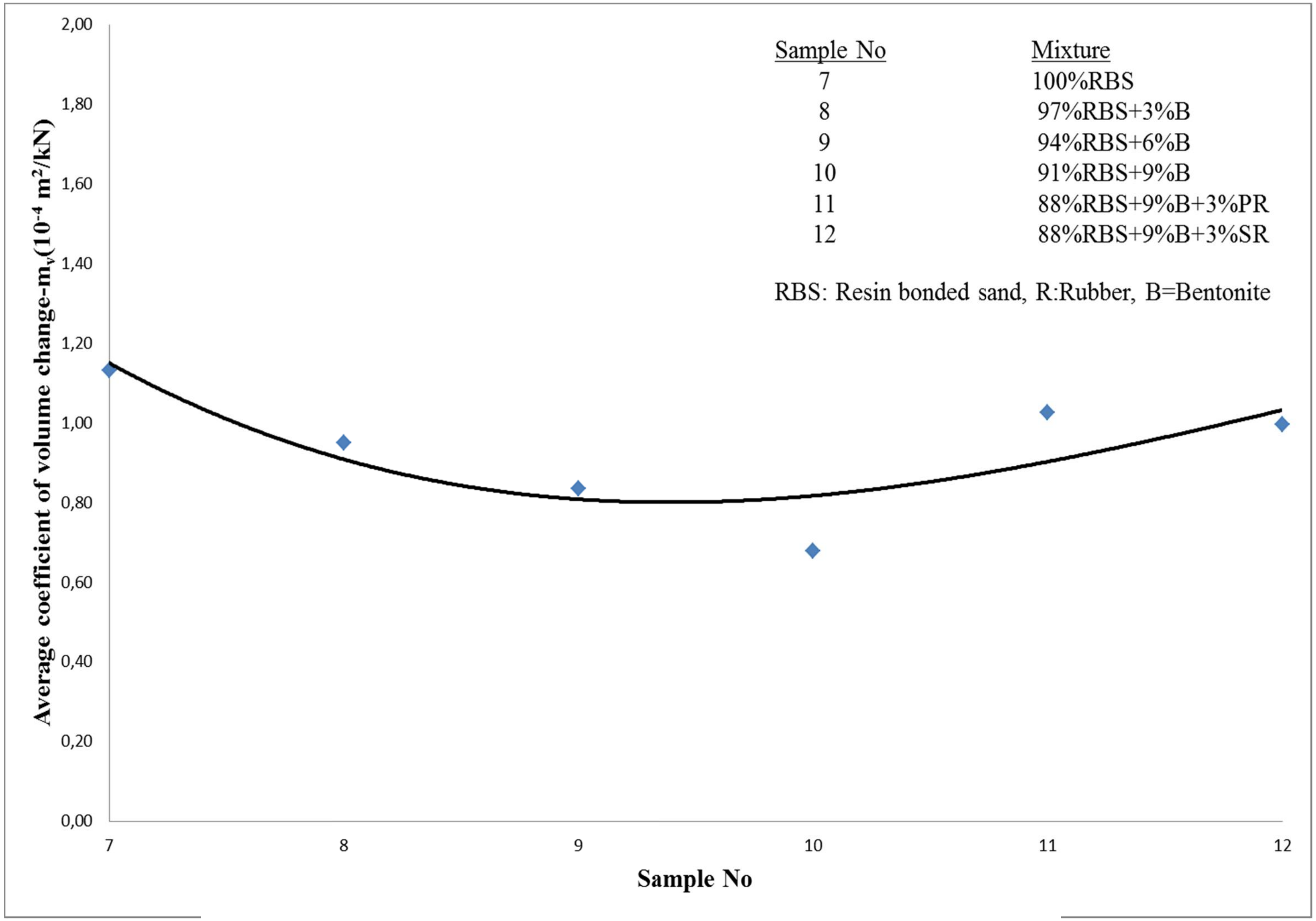
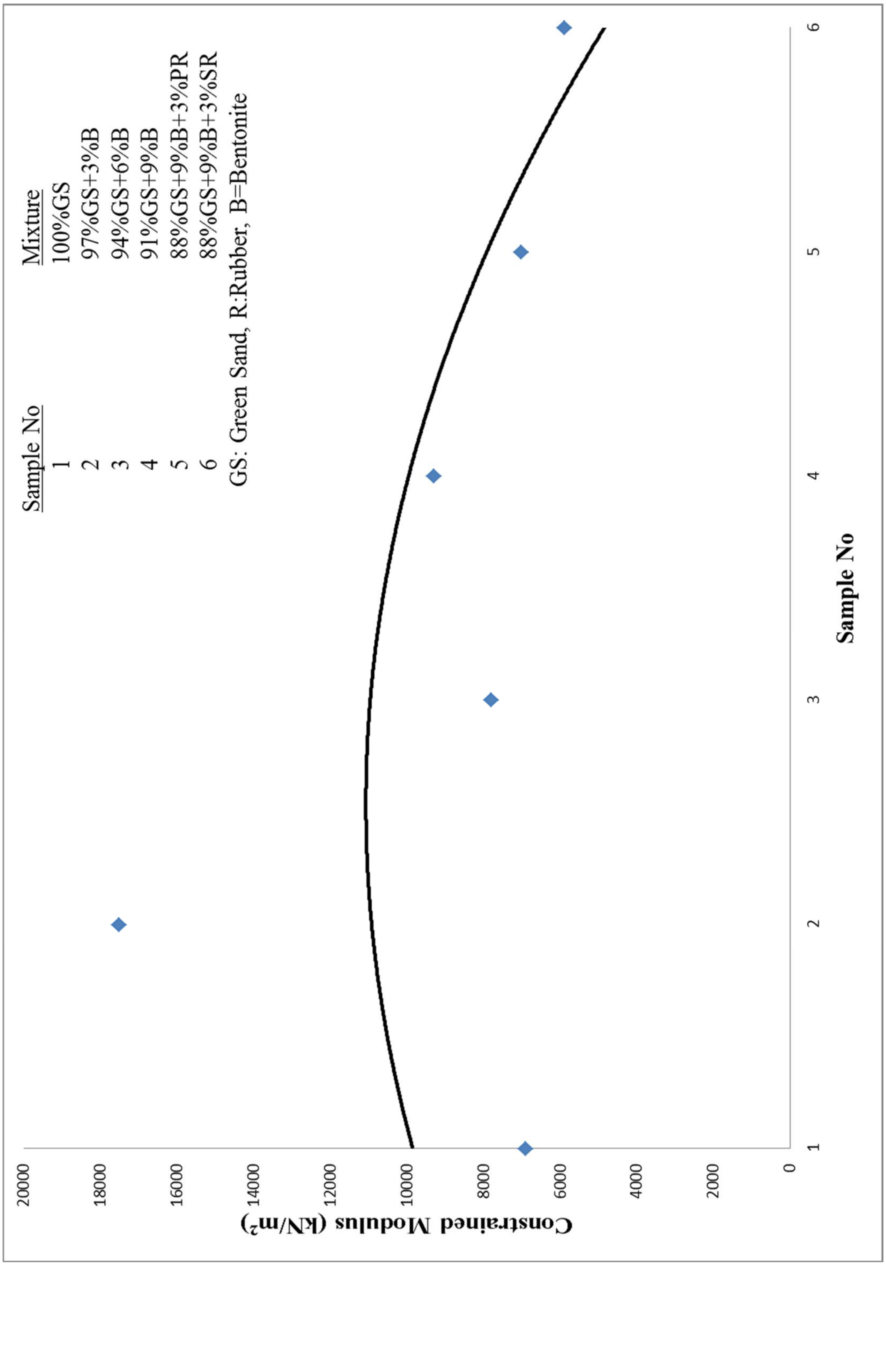


Figure 4.12 Average coefficient of volume change of resin bonded sand mixtures


Sample No
1
2
3
4
5
6
Mixture
100%GS
97%GS+3%B
94%GS+6%B
91%GS+9%B
88%GS+9%B+3%PR
88%GS+9%B+3%SR
GS: Green Sand, R:Rubber, B=Bentonite
Constrained Modulus (kN/m²)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Sample No
1
2
3
4
5
6

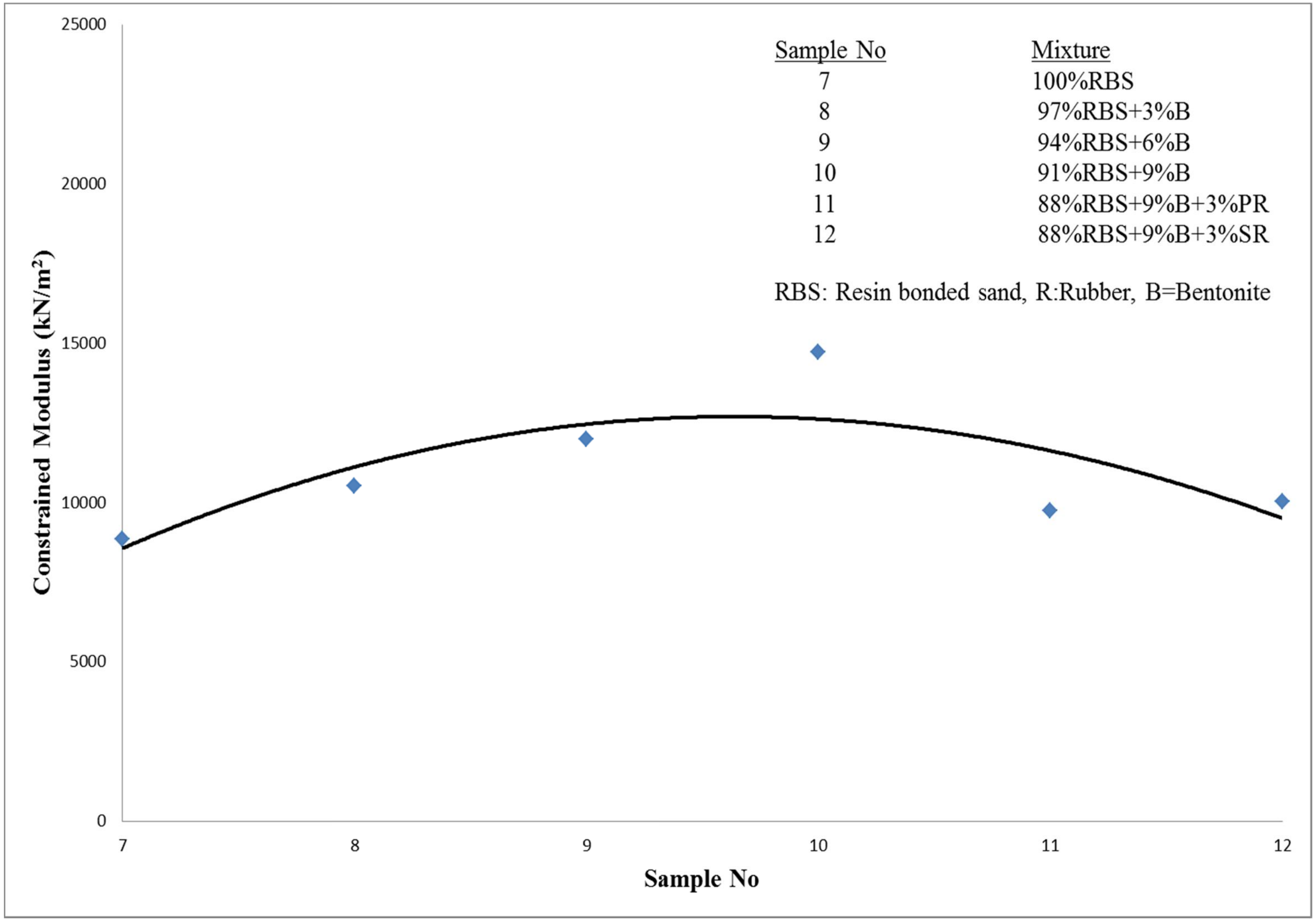


Figure 4.14 Average constrained of resin bonded sand mixtures

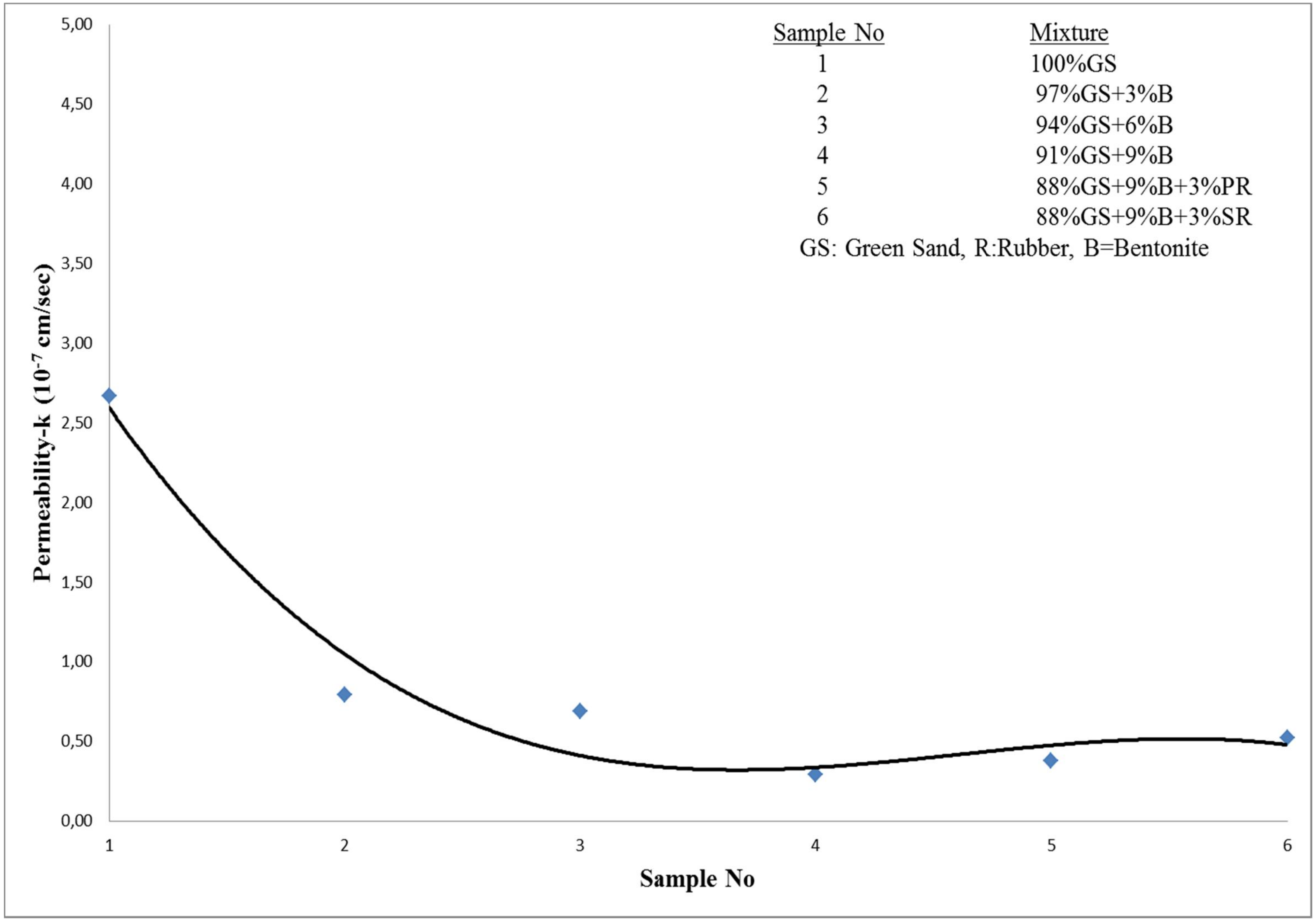


Figure 4.15 Average permeability values of green sand mixtures

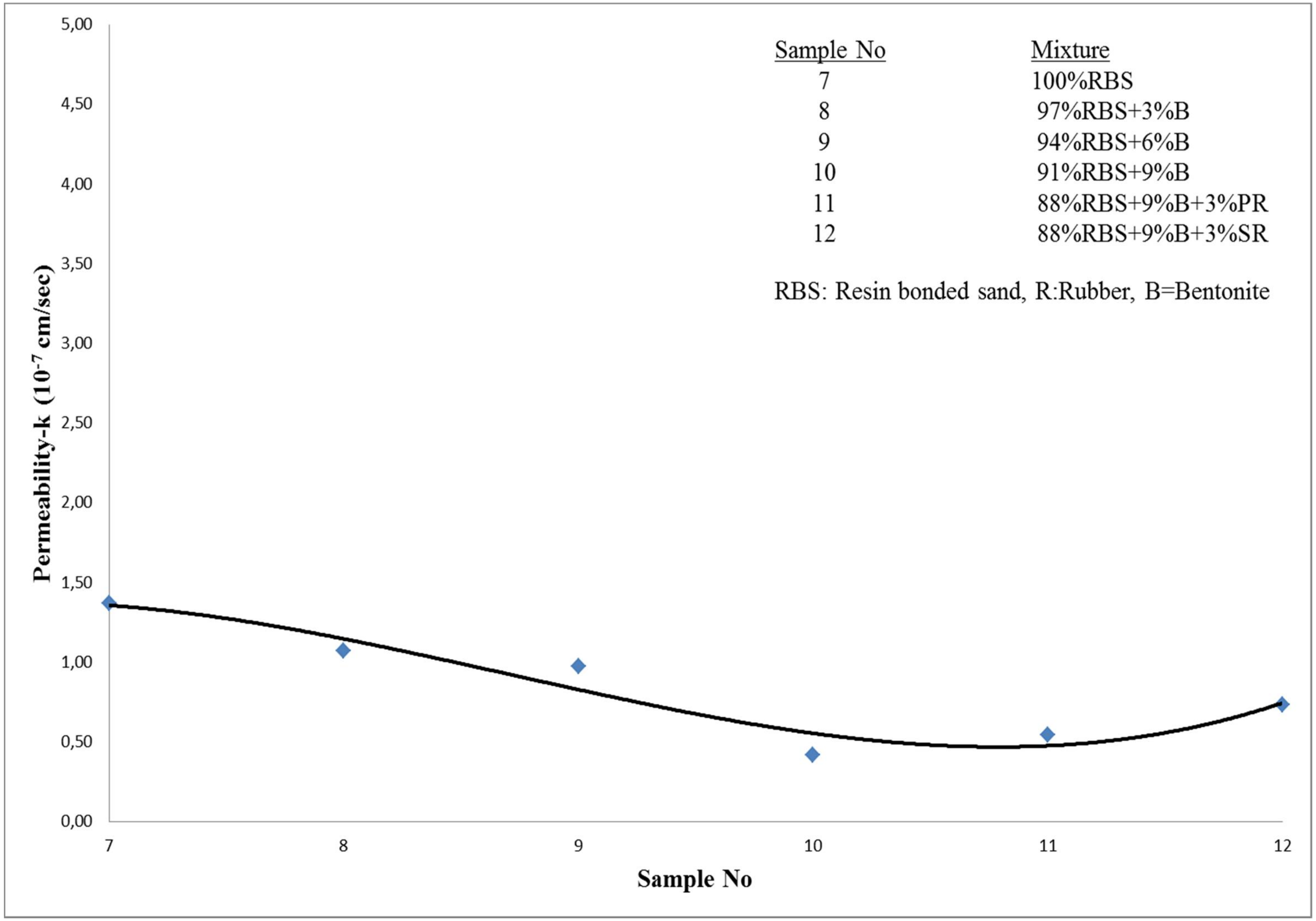


Figure 4.16 Average permeability values of resin bonded sand mixtures

the hydraulic conductivity obtained from oedometer test is approximately the same as the one obtained from triaxial permeability test.

The relationships of plasticity index PI and liquid limit with hydraulic conductivity are presented in Figure 4.17 and 4.18 respectively. It is clearly seen that the there is a positive correlation between hydraulic conductivity and Atterberg limit within this range for all foundry sand types.

The relationship between hydraulic conductivity and %95 of maximum dry density are presented in Figures 4.19 and 4.20, respectively for green sand and resin bonded sand. It is concluded that the hydraulic conductivity decreases as dry density decreases for green sand whereas increases with increasing dry density of foundry sand.

As it can be seen from Appendix C clearly, Mixture 4 (91%Green Sand+9% Bentonite), Mixture 5 (88%Green Sand+9% Bentonite+3%Pulverized Rubber) and Mixture 10 (91%Green Sand+9% Bentonite) satisfy the hydraulic conductivity limit kÒ1x10^{-7} cm/sec. Although other mixtures satisfies the limitation for higher pressures generally, only 3 of them, mentioned above, can be preferred as cap layer material in order to be on the safe side.

Resin bonded sand shows better performance as it is expected due to the gradation. While comparing Mixture 1 (100% Green sand) and Mixture 7 (100% Resin Bonded Sand), Mixture 7 has a lower hydraulic conductivity than Mixture 1. This shows that resin provide the hydraulic impermeability to mixtures. However, rate of decrease of hydraulic conductivity decreases with increasing bentonite content which may cause the interaction between bentonite and resin in resin bonded sand mixtures.

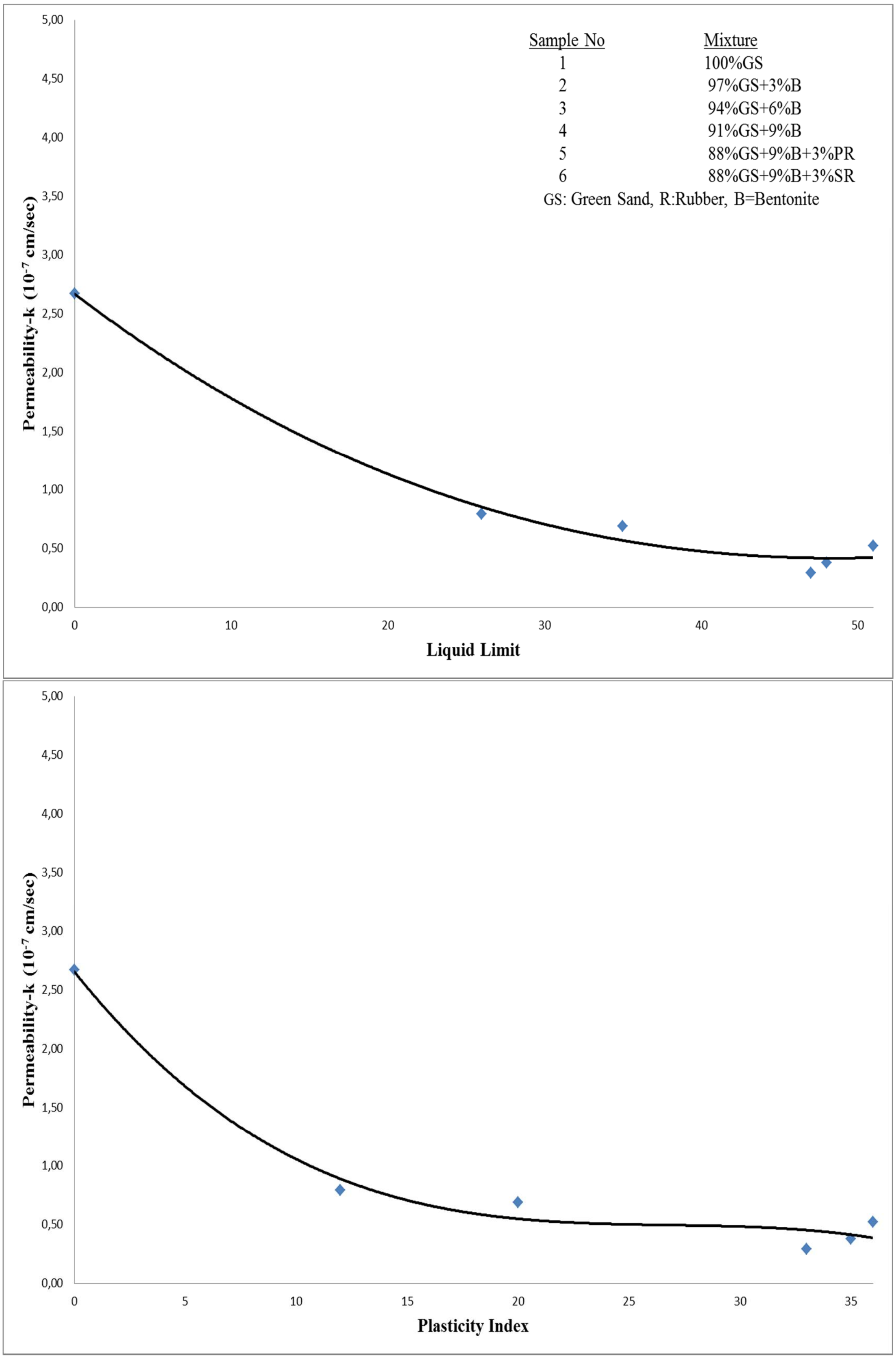
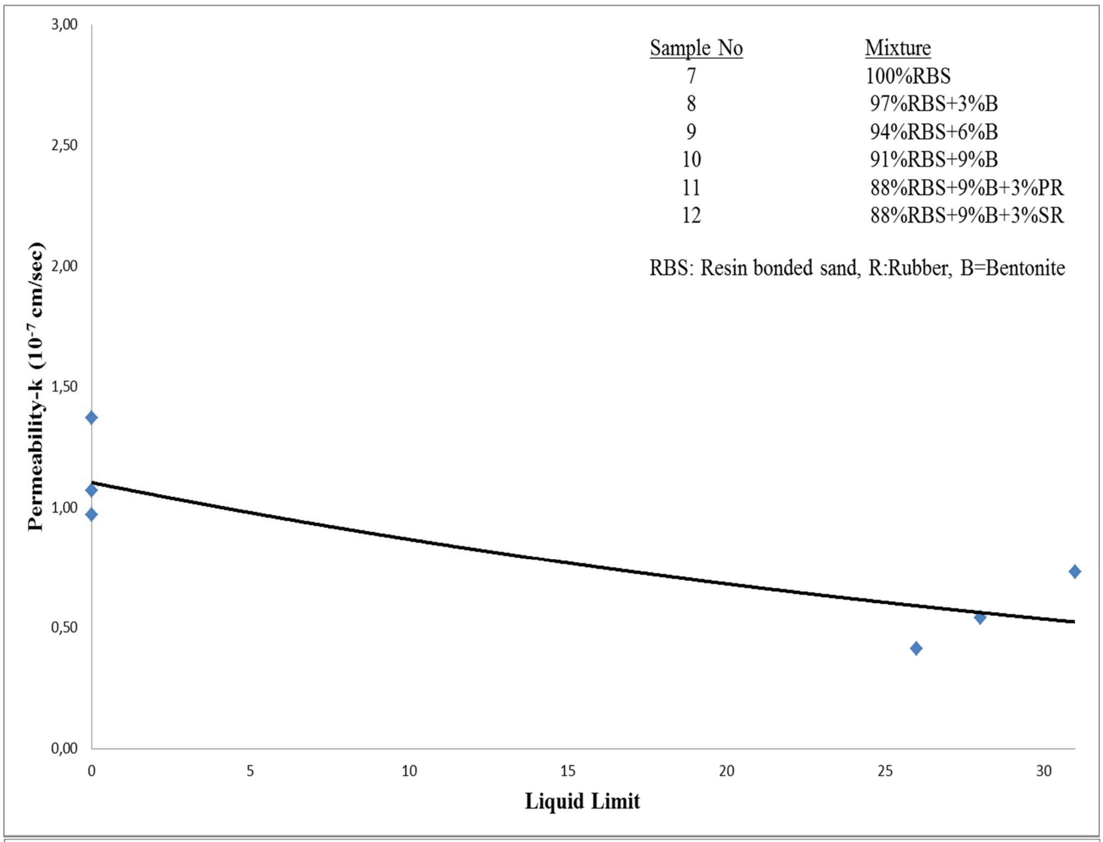


Figure 4.17 Consistency limits versus Permeability Graph for Green Sand mixtures



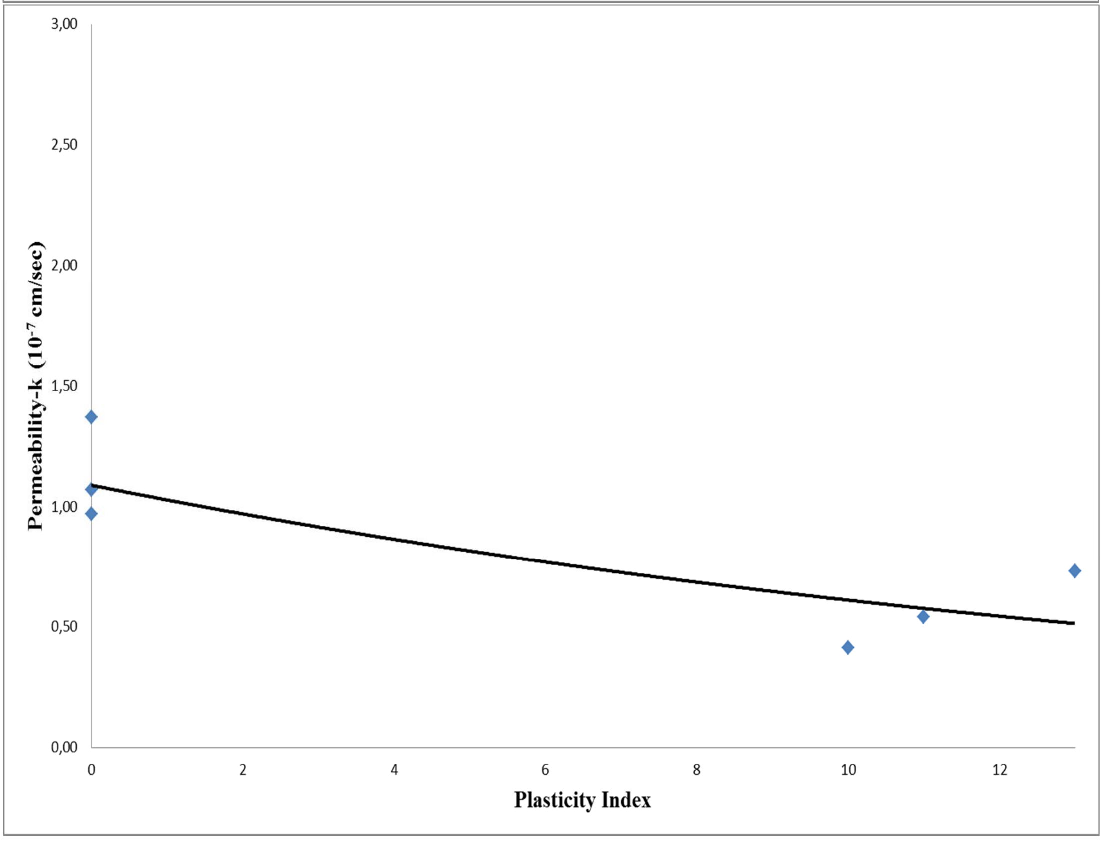


Figure 4.18 Consistency limits versus Permeability Graph for Resin Bonded sand mixtures

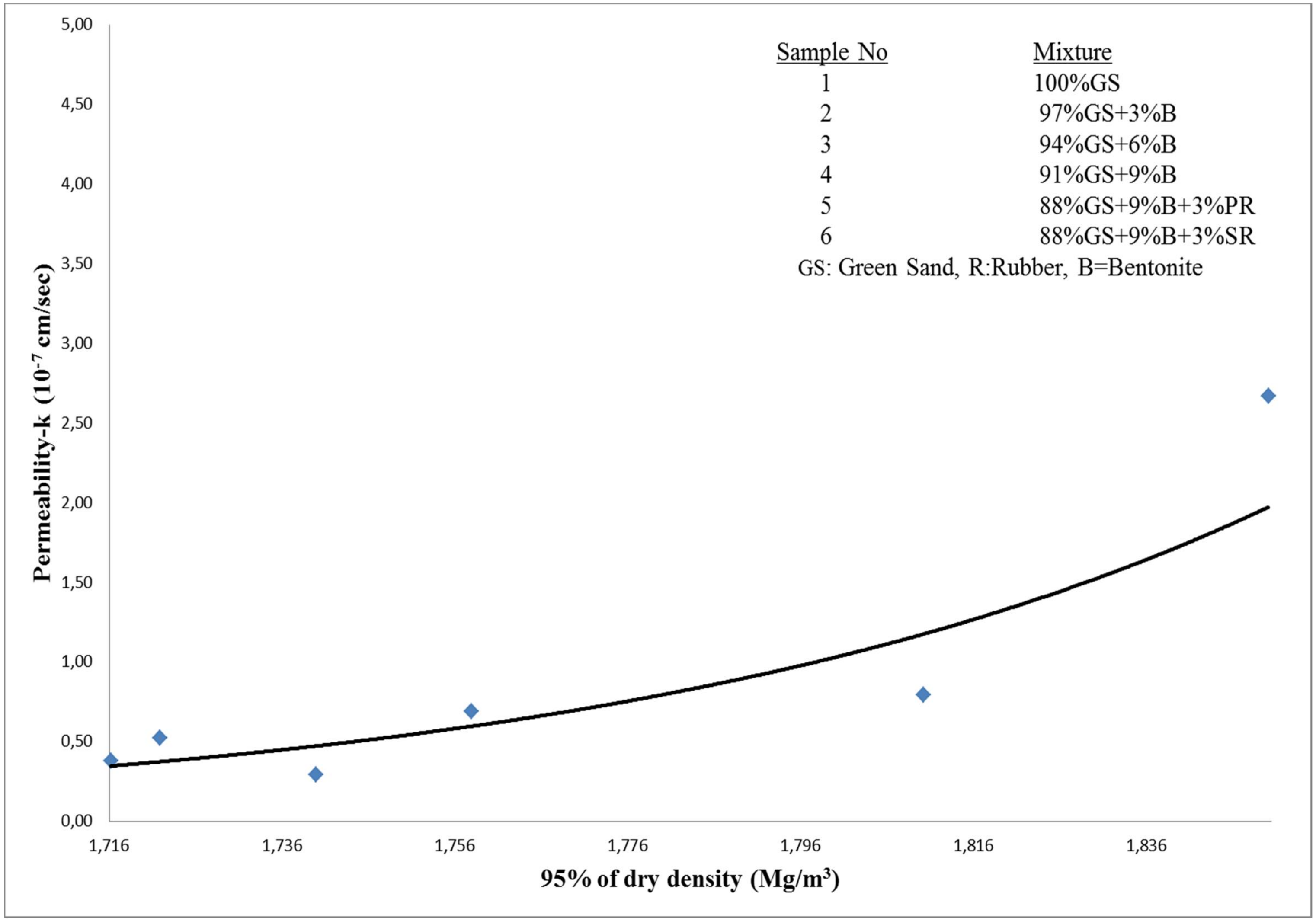


Figure 4.19 Maximum dry density average permeability relationship for green sand mixtures

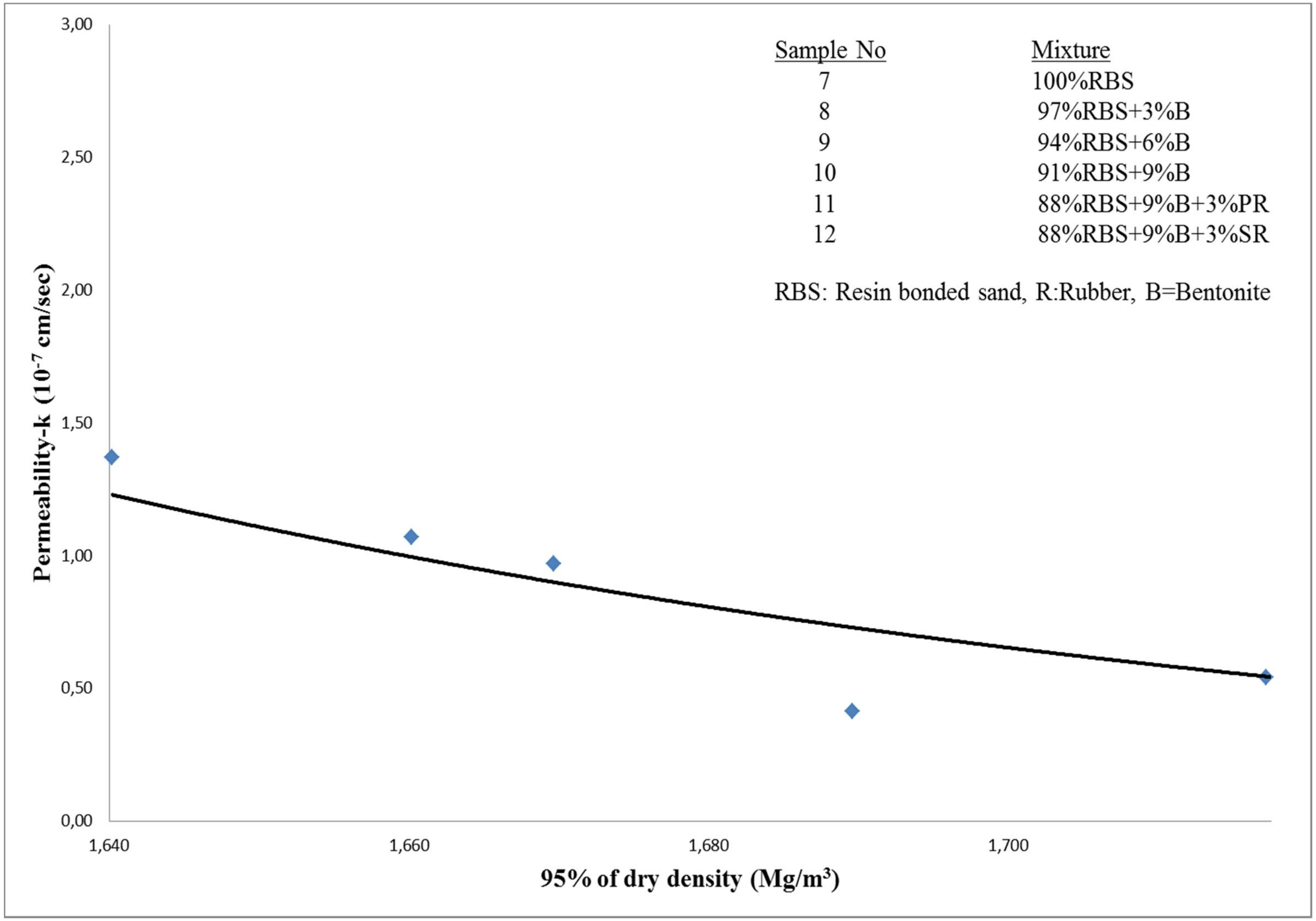


Figure 4.20 Maximum dry density average permeability relationship for resin bonded sand mixtures

CHAPTER 5

DISCUSSIONS

The conclusions mentioned below derived based on from the experimental study of direct shear test, split tensile strength, swell pressure, oedometer test performed on two different green sand mixture : green sand and resin bonded sand containing different percentages of bentonite and pulverized and strip rubber.

- Wet-dry cycling and desiccation effect were not investigated during the experiment. Because, previous studies emphasize that these effects does not change the permeability considerably.
- No problem can be expected due to the effect of the leaching of bentonite. Because, bentonite has an huge water absorption capacity.
- Grain size distribution of rubber used in study was selected as a randomly by considering the usage of rubber in market in Turkey.
- The oedometer tests were performed in an unsaturated condition. While considering the environment used in this cap layer, permeability values obtained from these tests can be acceptable.
- The rubber percent used in this study is 3%. By considering the rubber percent in this study and the uniform distribution of mixtures, any detrition problem is expected for rubber in this study. However, this effect should be investigated by further researchers.

- Leachate analysis should be performed for further studies.

- Strip rubber is more effective than pulverized rubber considering the split tensile strength for both resin bonded sand and green sand. The rubber increases the tensile strength of resin bonded sand considerably rather than green sand mixtures.

- Swelling pressures increases with bentonite content and decreases with rubber content generally. Swell pressure of green sand is quite higher than resin bonded sand. However, swelling pressures for both mixtures are low.

- Resin gives the hydraulic impermeability to the mixture less than it is expected. However due to the interaction problem with bentonite, these effect will decrease gradually with increasing bentonite content.

- The hydraulic conductivity limit for layer construction (kÒ1x10^{-7} cm/sec) is satisfied for all mixtures with different pressure range.

- Foundry sand has a large production potential in both Turkey and world. For instance, Wisconsin gray-iron foundries generate about 800,000 Mg of byproducts per year, most of which are landfilled in America (Abiechu, 2000). Besides, rubber is also produced from refusals and it is also very cheap and obtained from factories easily. Finally, bentonite is easily obtained from factories and it is also cheap material. By considering the percentages used in mixtures, it is concluded that mixtures that might be used as cap layer material are economical solution in landfill area. However, transportation cost will be examined by further researchers carefully.

CHAPTER 6

CONCLUSIONS

The conclusions mentioned below derived based on from the experimental study of direct shear test, split tensile strength, swell pressure, oedometer test performed on two different green sand mixture : green sand and resin bonded sand containing different percentages of bentonite and pulverized and strip rubber. The maximum amount of additives was kept at 12 %.

- Peak and residual internal friction angle decreases with increasing bentonite content in direct shear test whereas it decreases with increasing rubber content.

- Cohesion increases with bentonite content. However, there is slight decrease in cohesion with addition of rubber.

- Split tensile strength increases with both increasing of bentonite content and rubber content in mixtures.
- The coefficient of volume change (m_v) increases with decreasing bentonite content and increasing rubber content in mixture generally.

- Constrained modulus increases with bentonite and decreases with rubber addition to mixture.

- Hydraulic conductivity decreases with increasing bentonite content and decreasing rubber content in mixture.

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- Hydraulic conductivity decreases with decreasing 95% maximum dry density of green sand whereas increases with decreasing 95 % maximum dry density of resin bonded sand.

- The hydraulic conductivity limit for layer construction (kÒ1x10^{-7} cm/sec) is satisfied for all mixtures with different pressure range.

- Three mixtures, Mixture 4 (91%Green Sand+9% Bentonite), Mixture 5 (88% Green Sand+9% Bentonite+3%Pulverized Rubber) and Mixture 10 (91%Resin Bonded Sand+9% Bentonite) satisfy the hydraulic conductivity limit in all pressure ranges can be proposed as cap layer material by considering the regulations .

- Mixture 5 (88% Green Sand+9% Bentonite+3%Pulverized Rubber) can be chosen as cap layer material by considering hydraulic conductivity, split tensile strength and direct shear test results. Because the hydraulic conductivity of this mixture is always below 1x10^{-7} cm/sec in all pressure increments and the split tensile strength is the 2nd best option in mixtures and there is no considerable difference between Mixture 6 (88% Green Sand+9% Bentonite+3%Pulverized Rubber) only 6 kPa differs between two mixture. Besides, direct shear parameters are also high.

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APPENDIX A

MAXIMUM DRY DENSITY VERSUS OPTIMUM WATER CONTENT CURVES

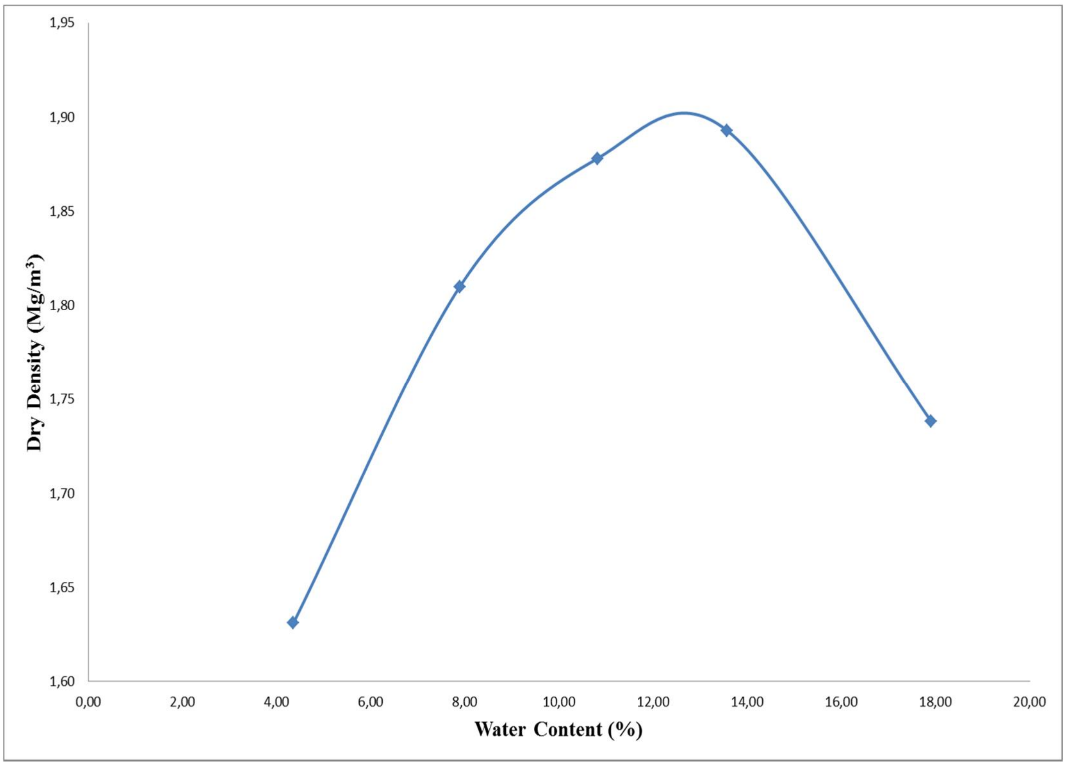

Figure A1. Compaction curve of 100%Green Sand

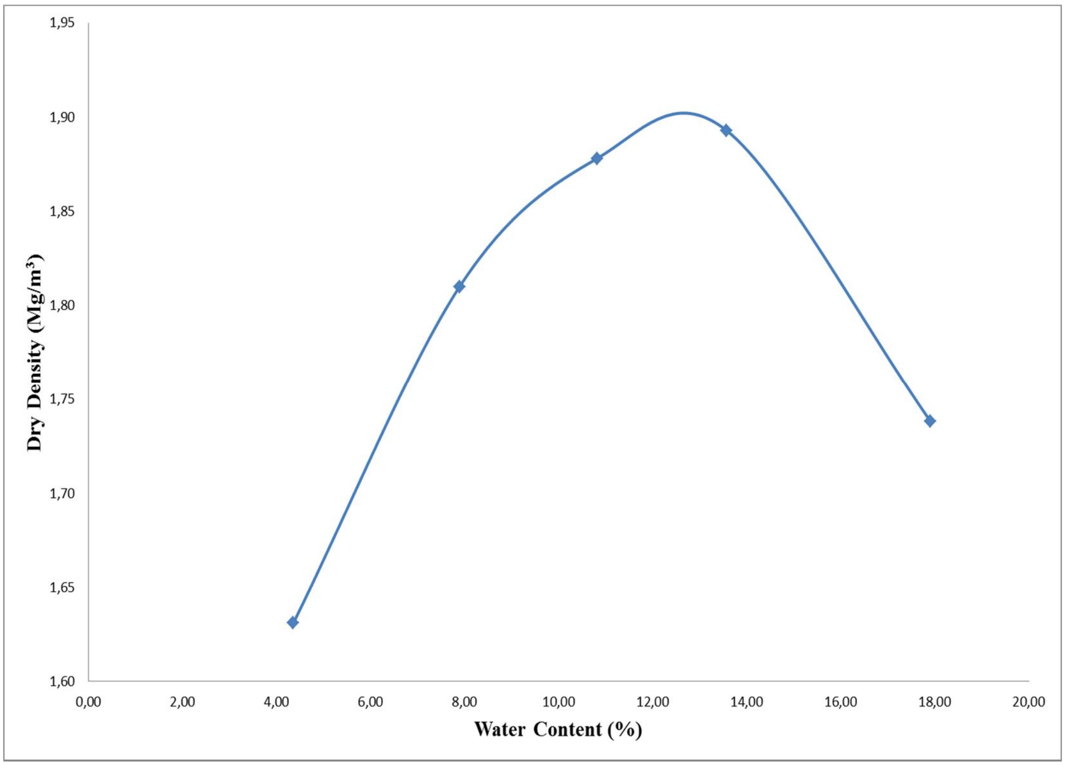

Figure A2. Compaction curve of 97%Green Sand+3%Bentonite

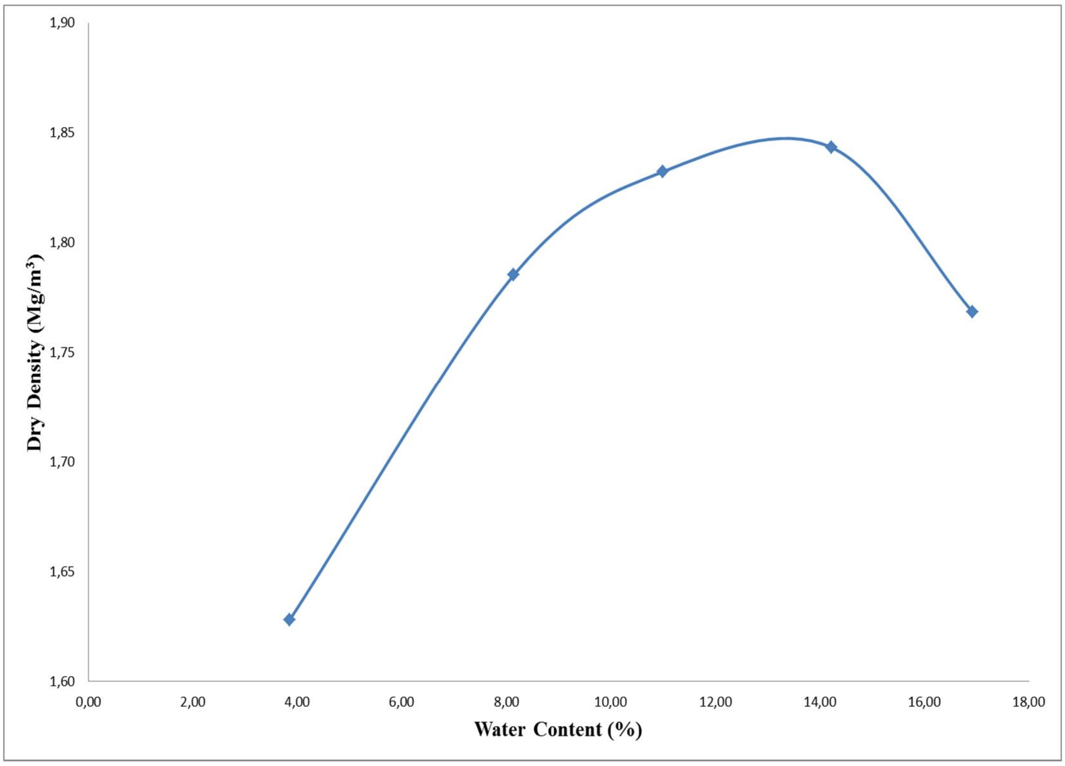

Figure A3. Compaction curve of 94%Green Sand+6%Bentonite

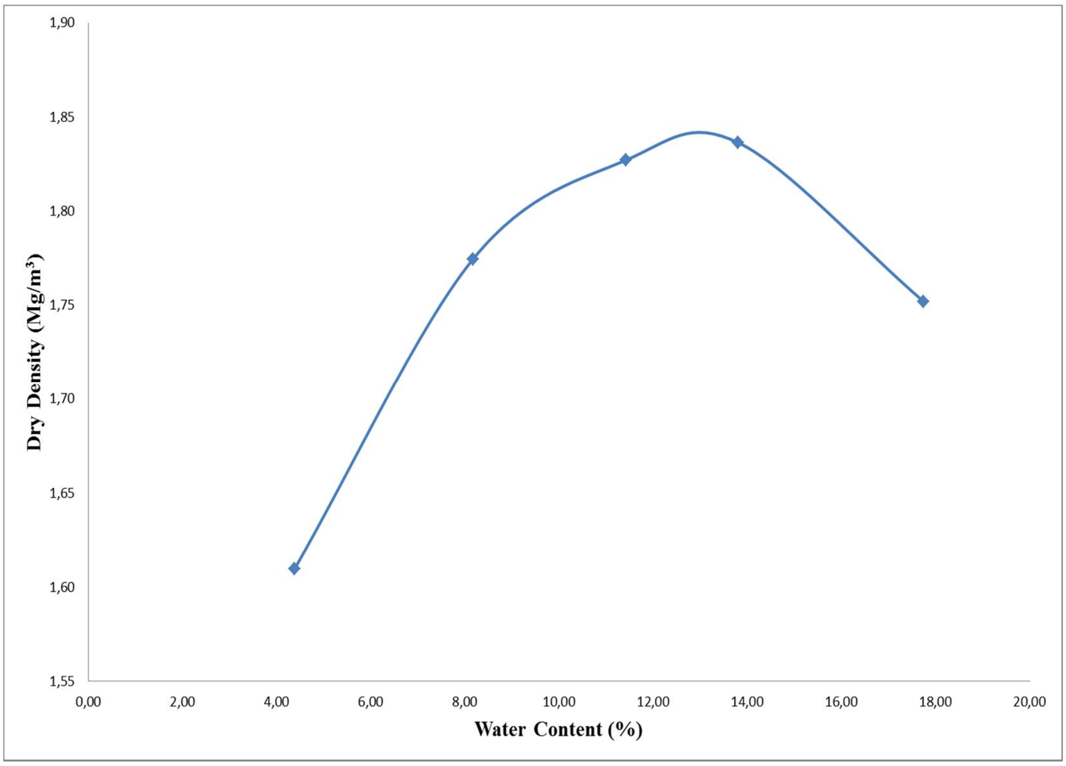

Figure A4. Compaction curve of 91%Green Sand+9%Bentonite

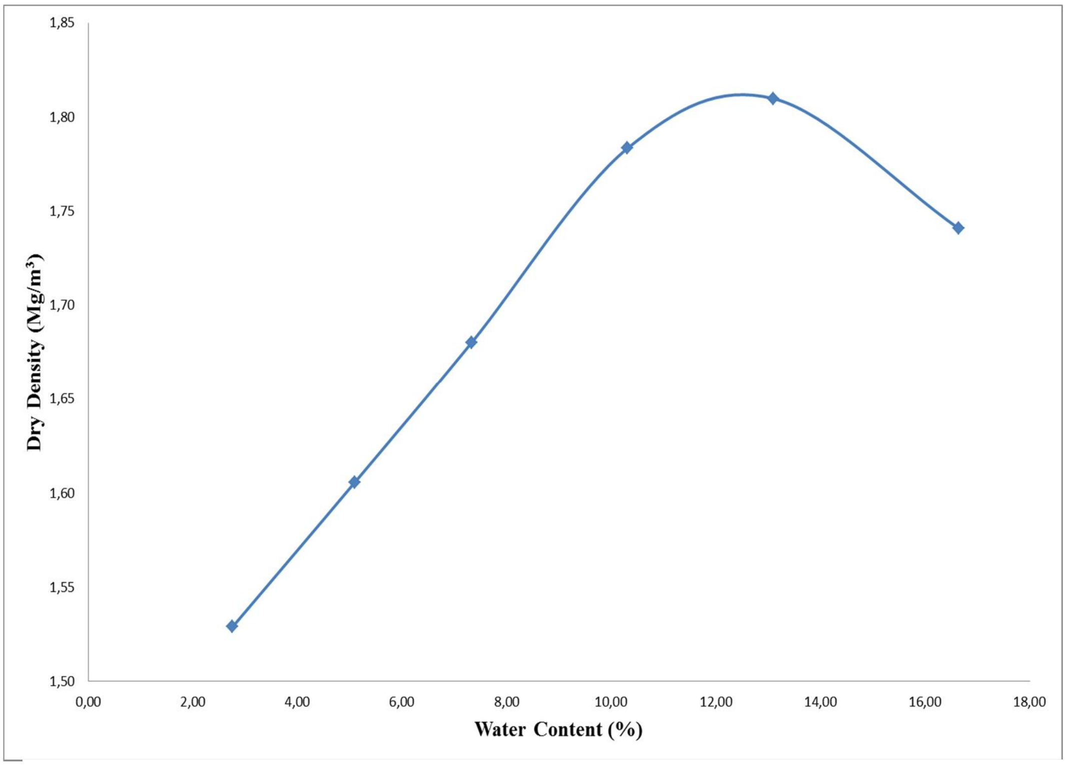

Figure A5. Compaction curve of 88%Green Sand+9%Bentonite+3%Rubber

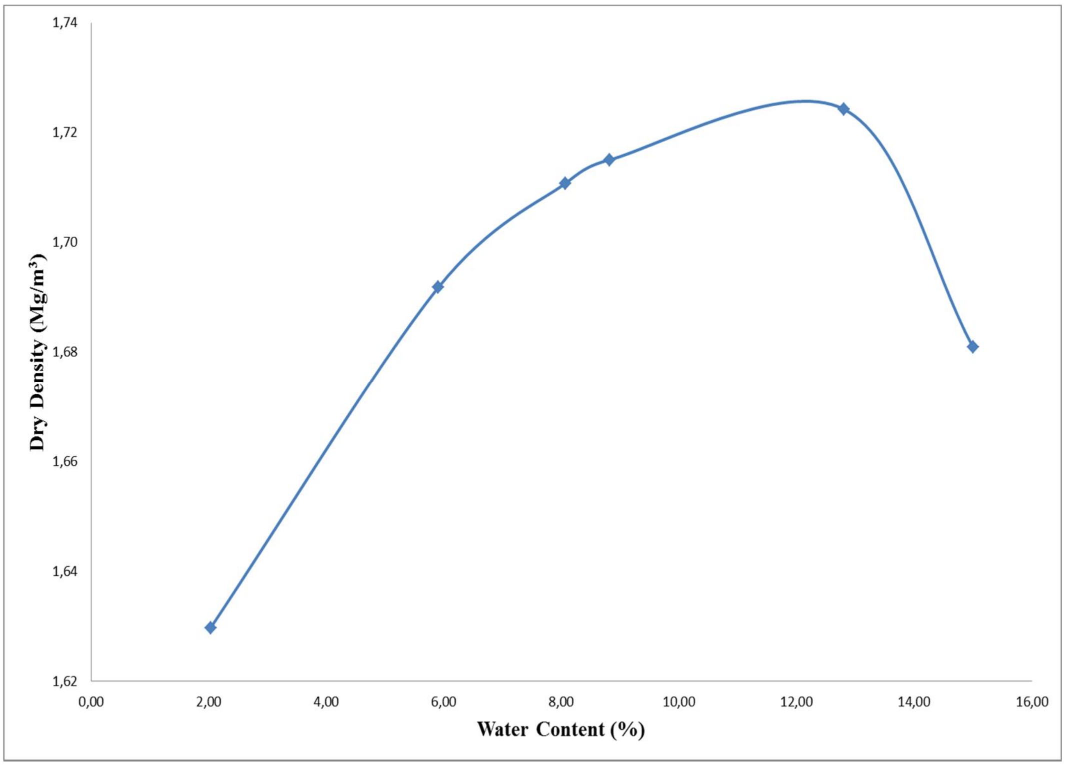

Figure A6. Compaction curve of 100% Resin Bonded Sand

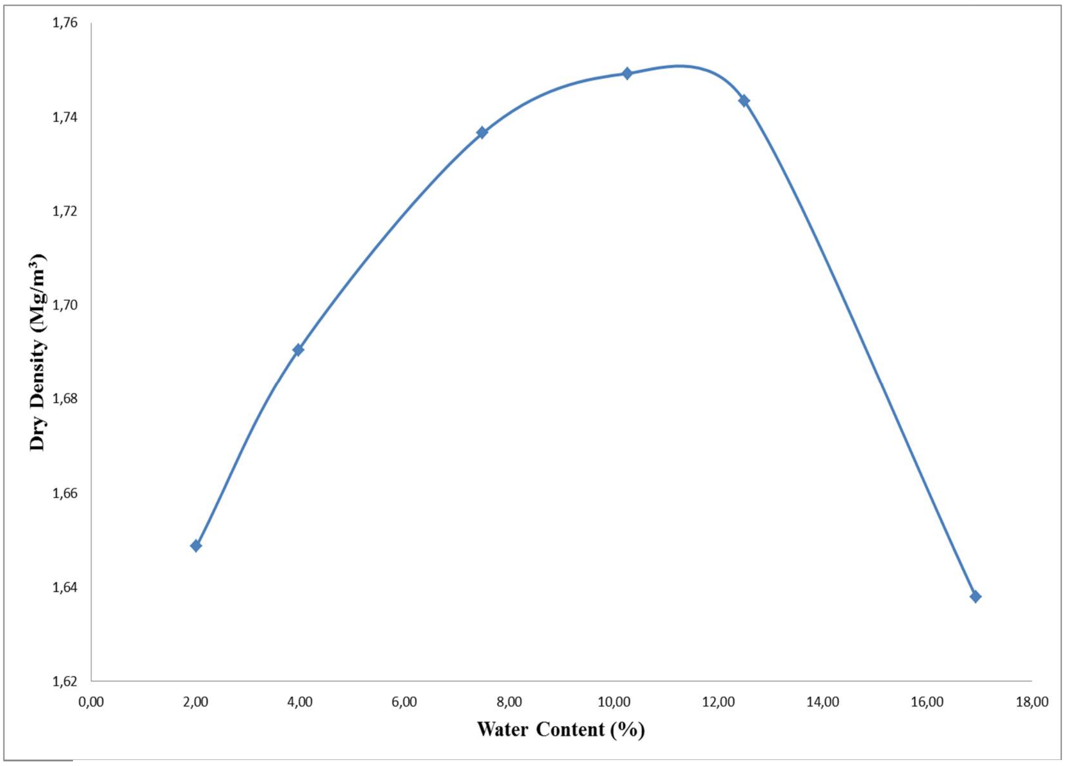

Figure A7. Compaction curve of 97%Resin Bonded Sand+3%Bentonite

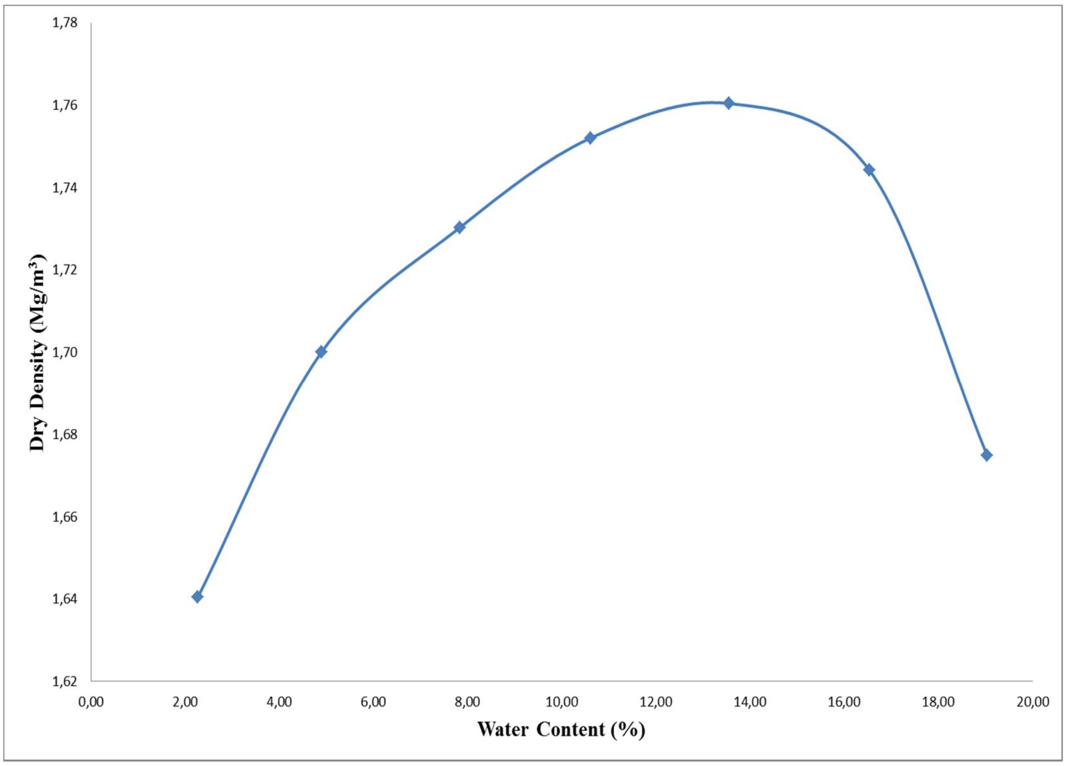

Figure A8. Compaction curve of 94%Resin Bonded Sand+6%Bentonite

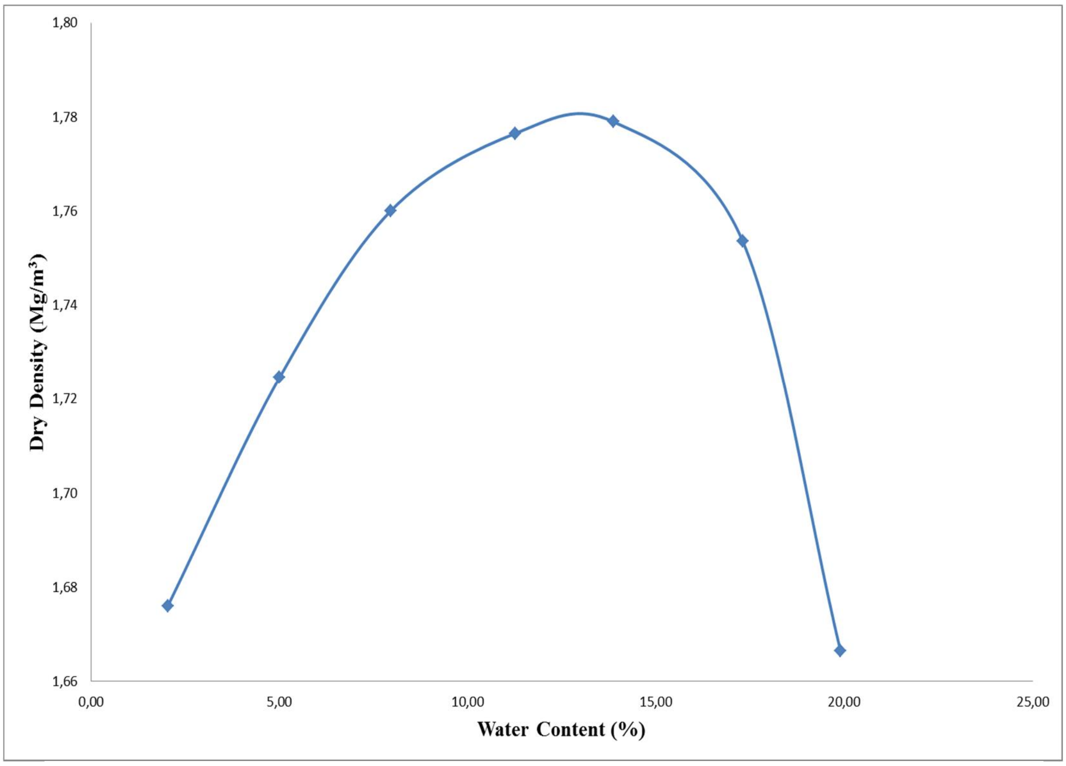

Figure A9. Compaction curve of 91%Resin Bonded Sand+9%Bentonite

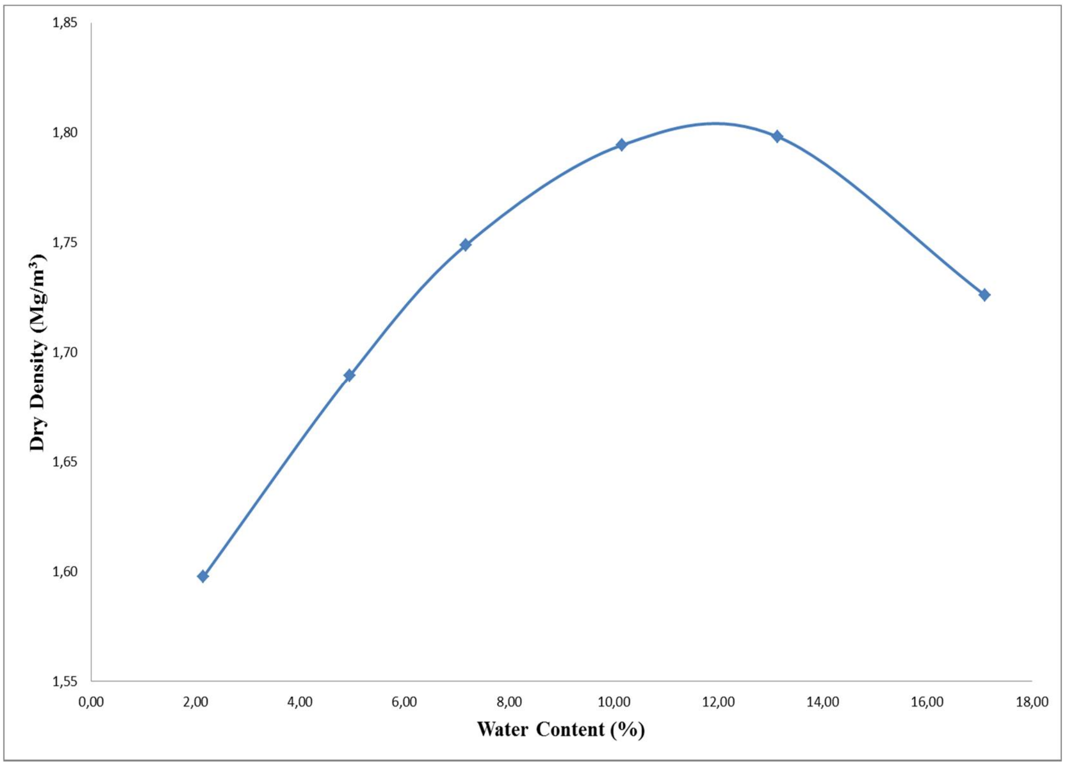

Figure A10. Compaction curve of 88%Resin Bonded Sand+9%Bentonite+3%Rubber

APPENDIX B

e-log P CURVES

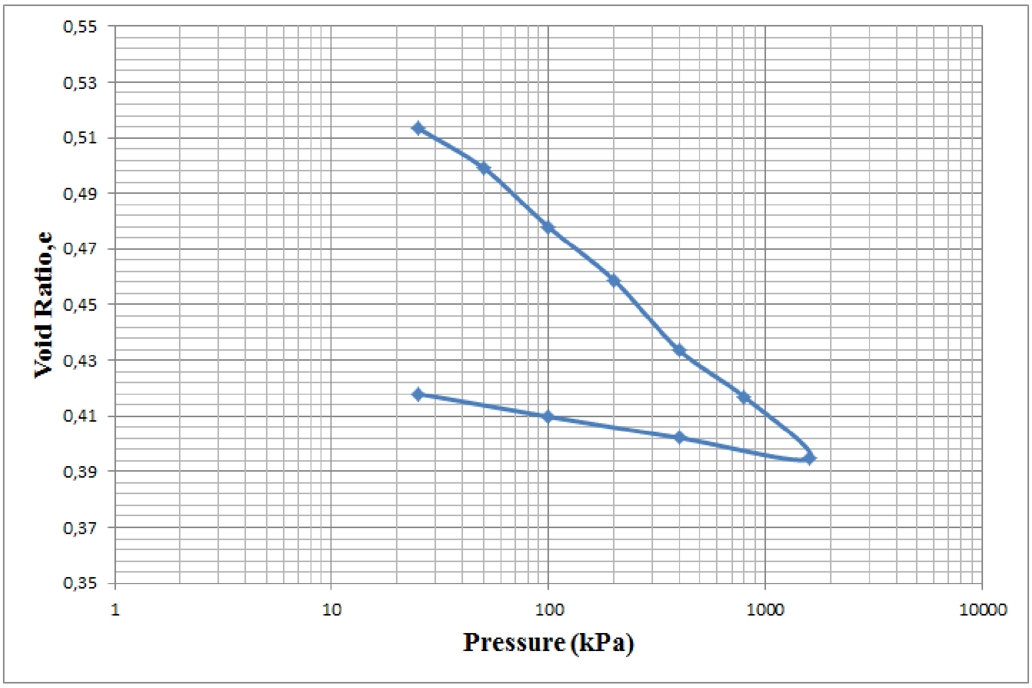

Figure B.1 e-log p curve for mixture 1

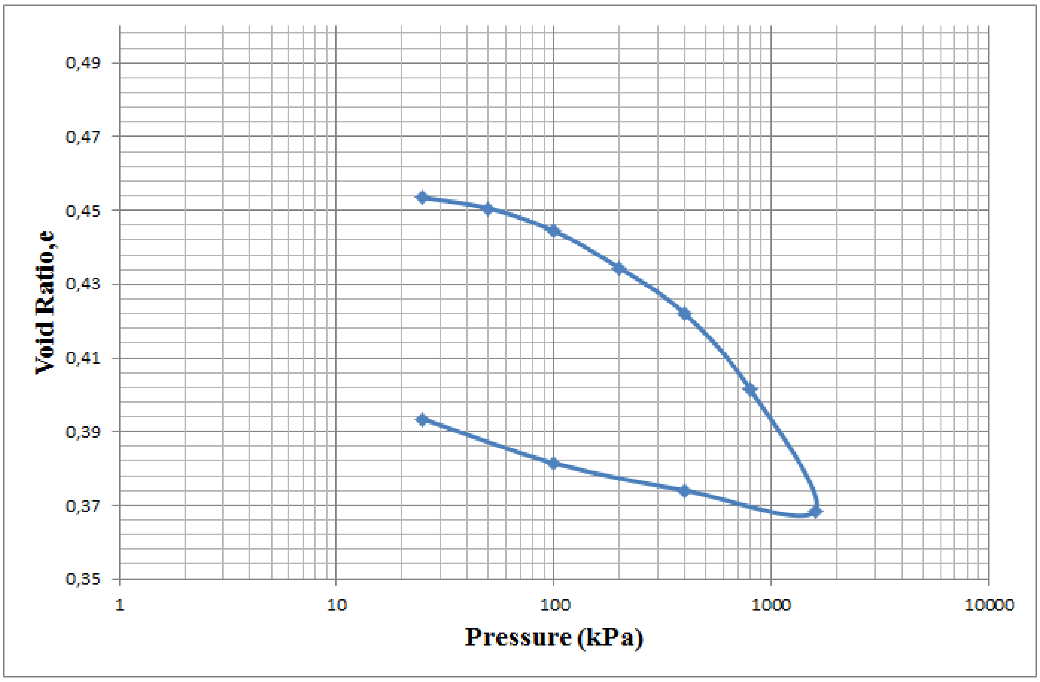

Figure B.2 e-log p curve for mixture 2

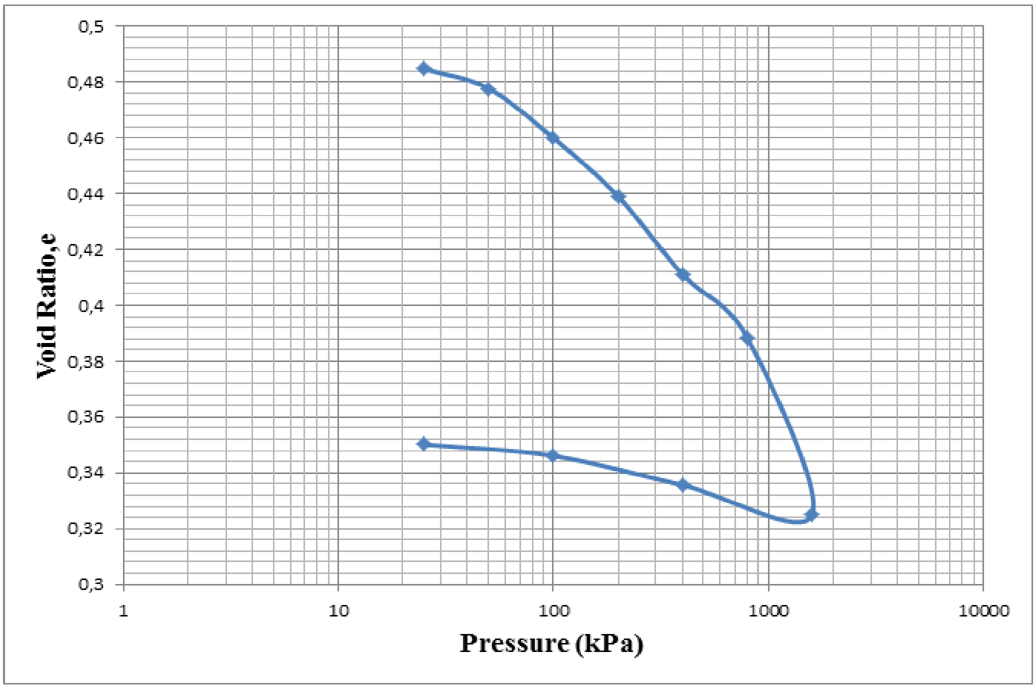

Figure B.3 e-log p curve for mixture 3

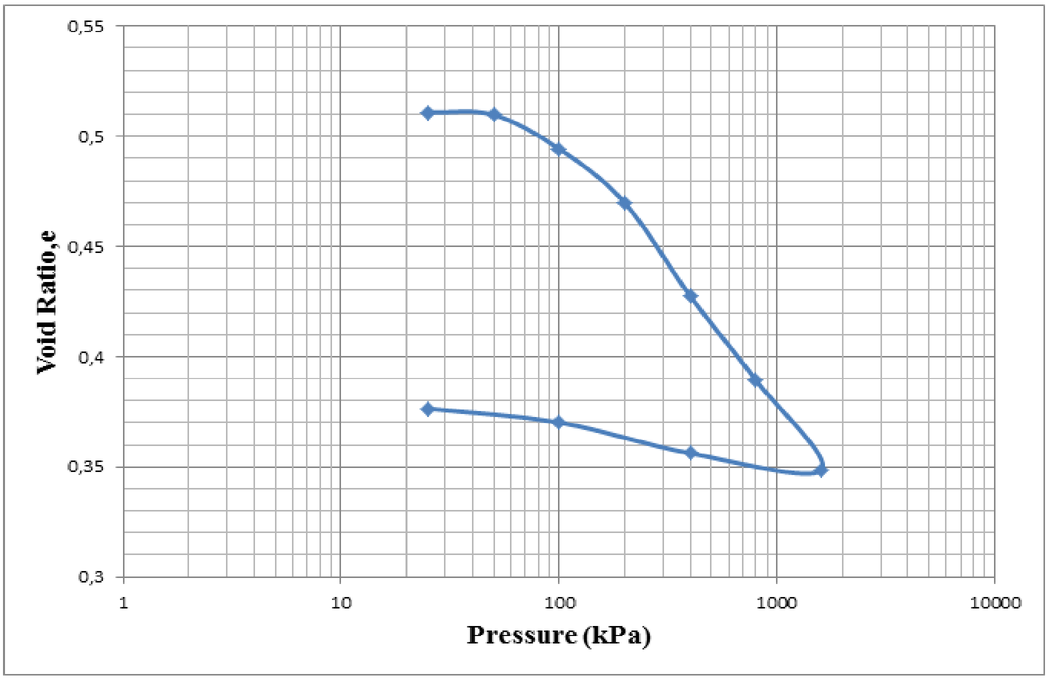

Figure B.4 e-log p curve for mixture 4

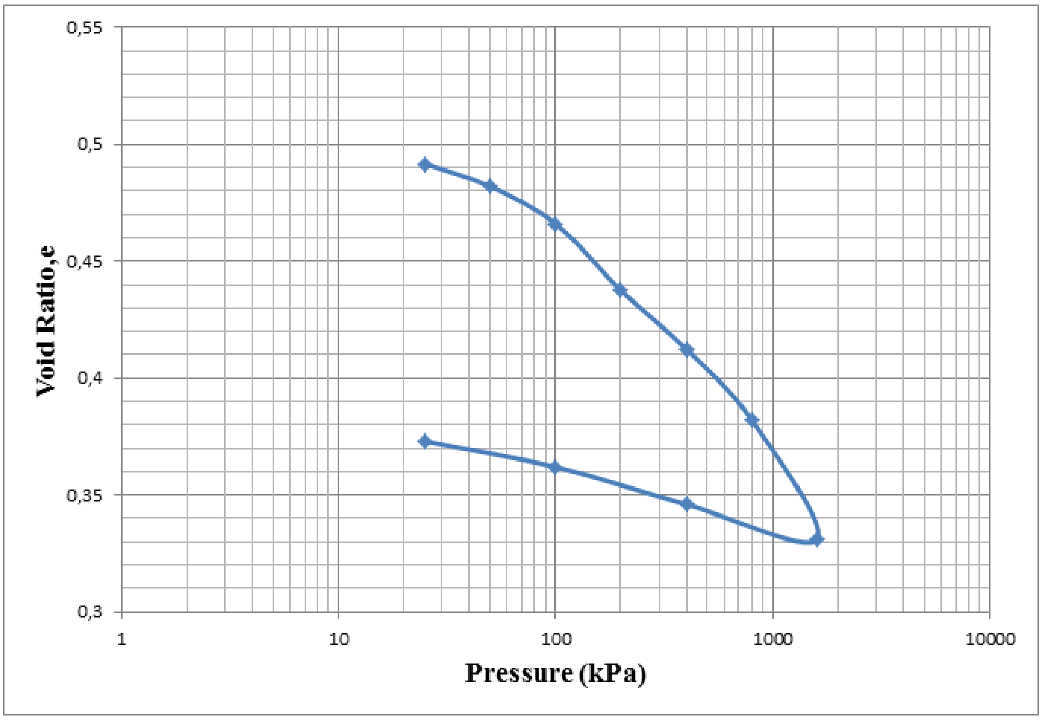

Figure B.5 e-log p curve for mixture 5

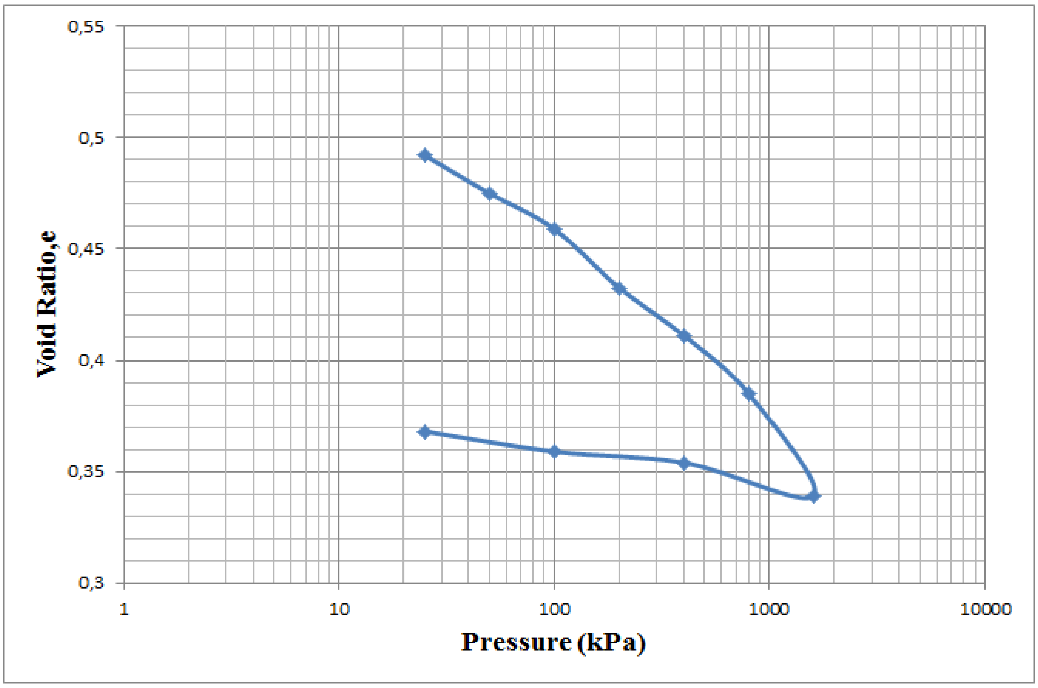

Figure B.6 e-log p curve for mixture 6

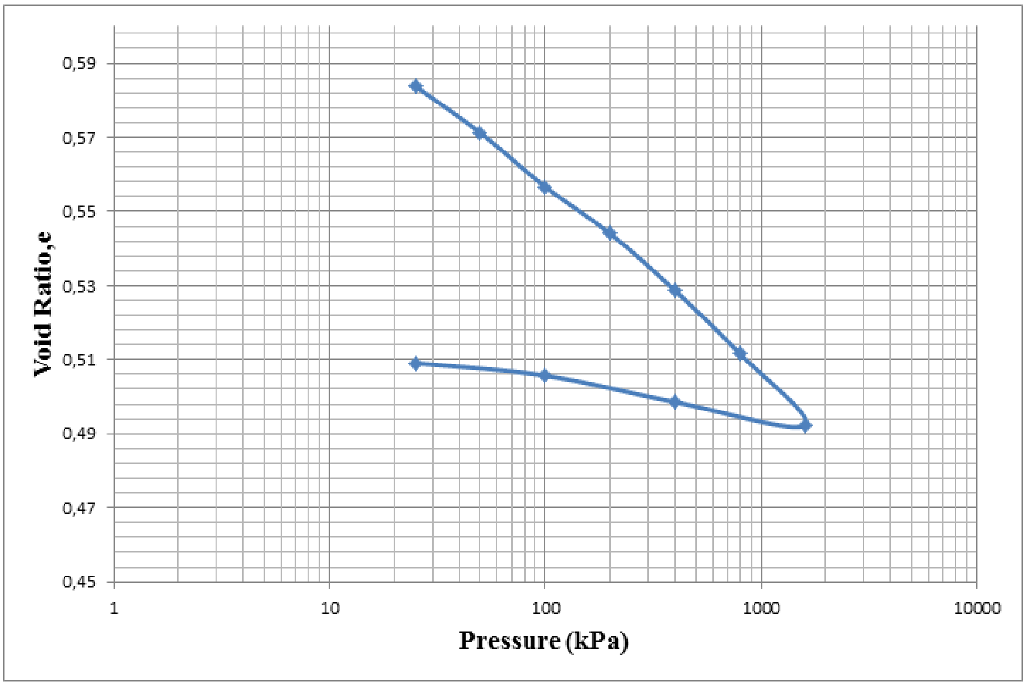

Figure B.7 e-log p curve for mixture 7

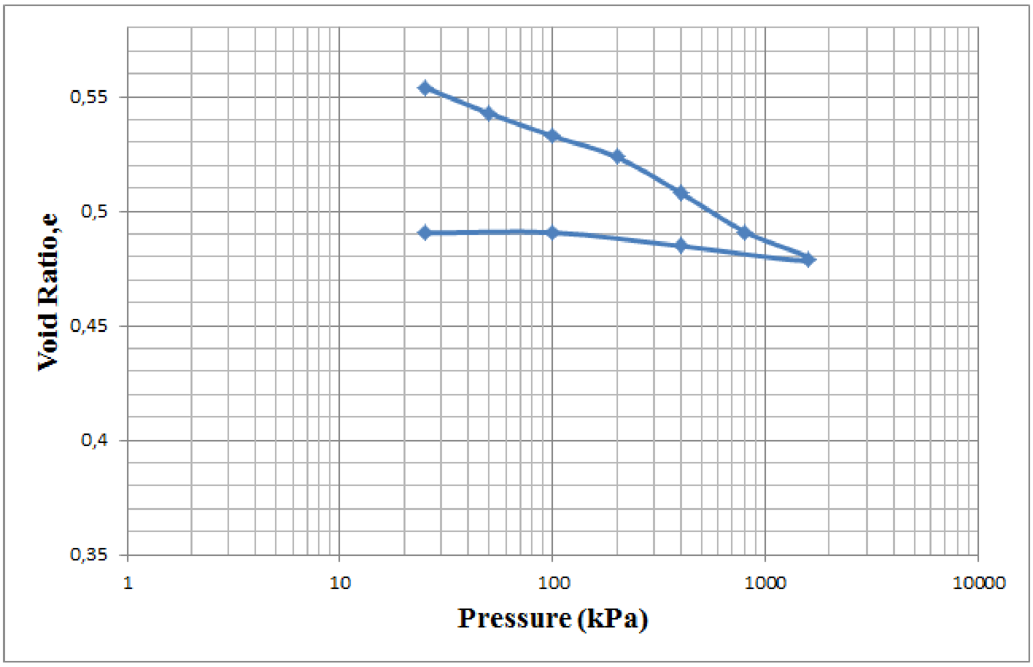

Figure B.8 e-log p curve for mixture 8

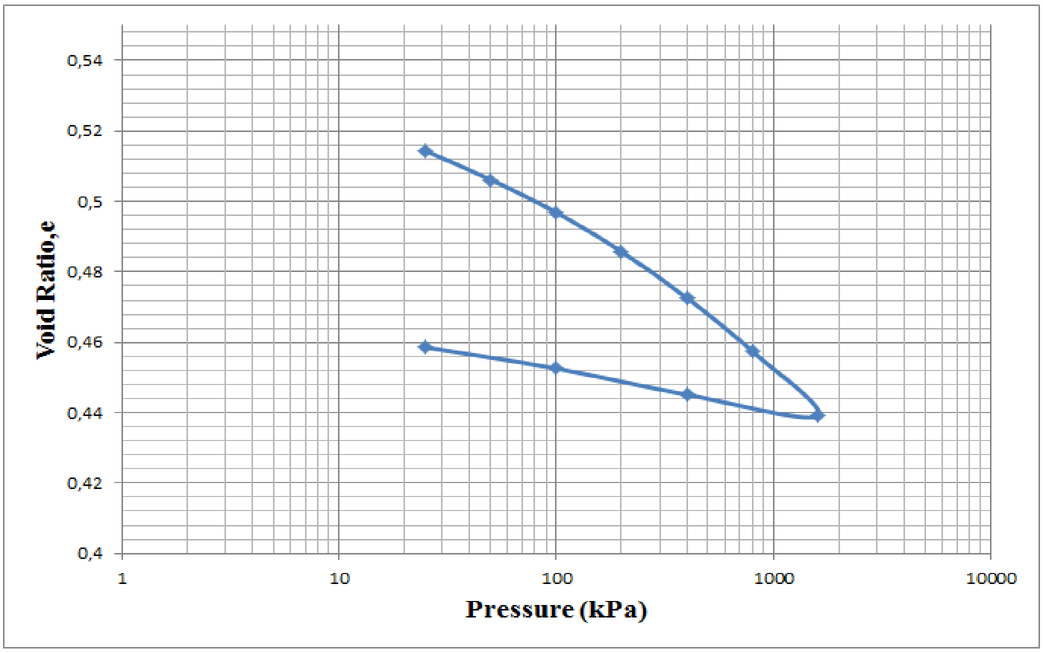

Figure B.9 e-log p curve for mixture 9

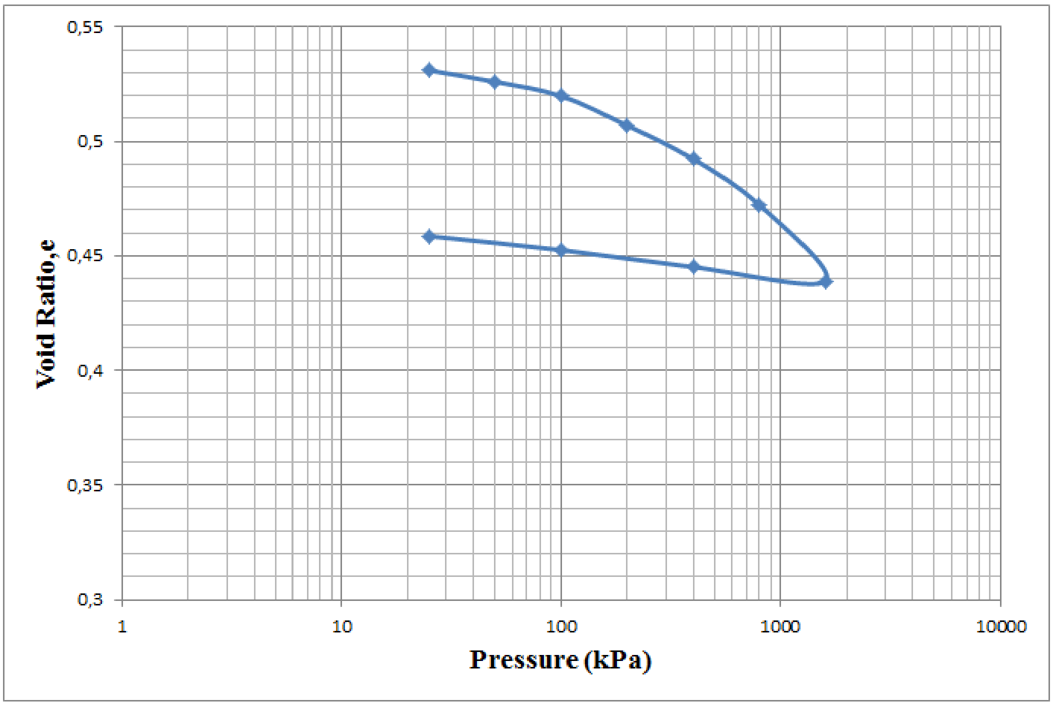

Figure B.10 e-log p curve for mixture 10

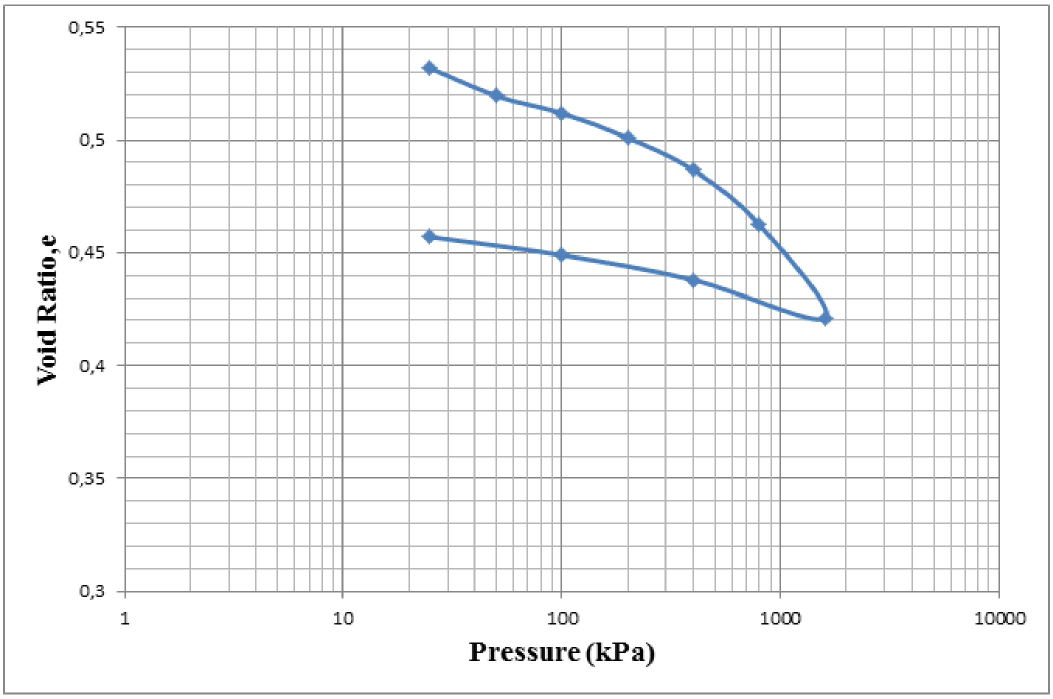

Figure B.11 e-log p curve for mixture 11

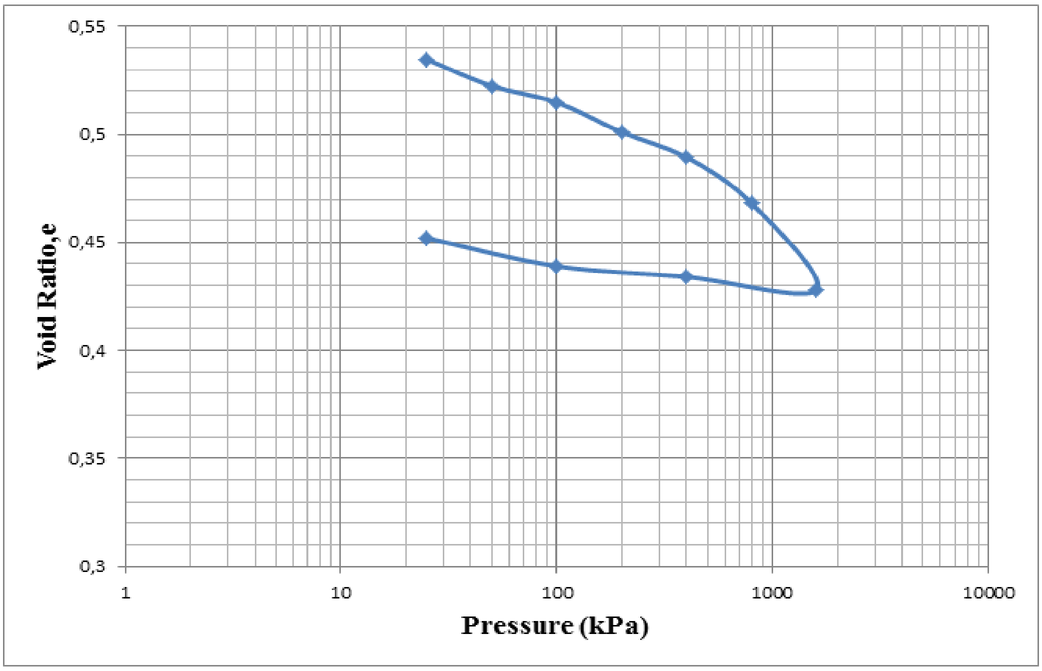

Figure B.12 e-log p curve for mixture 12

APPENDIX C

HYDRAULIC CONDUCTIVITY PRESSURE CURVES

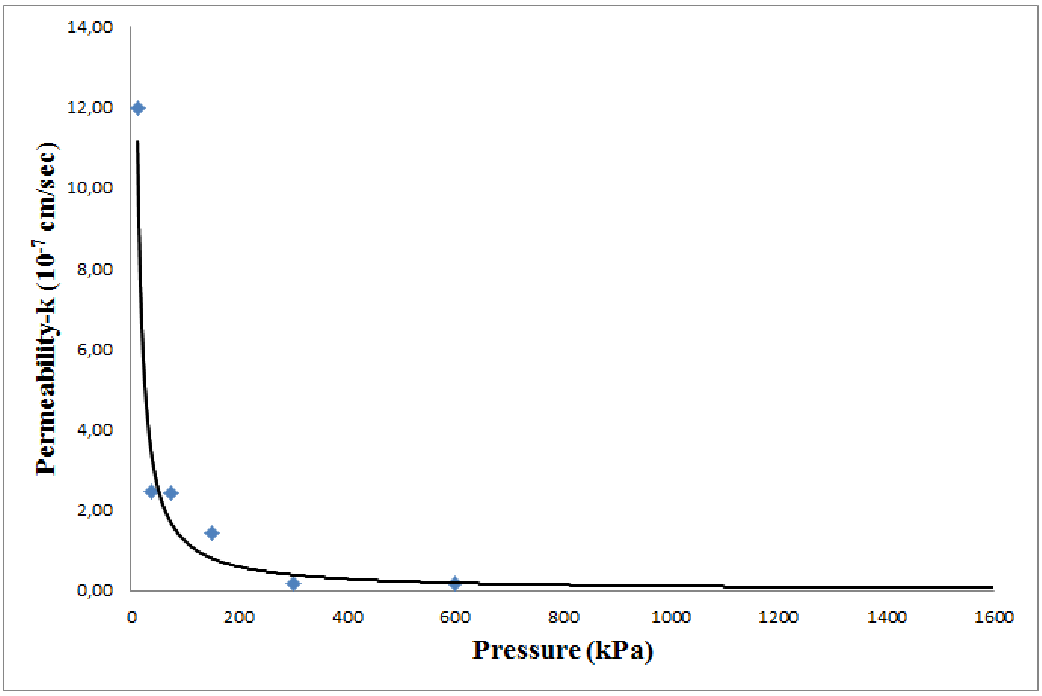

Figure C.1 Permeability-pressure curve for mixture 1

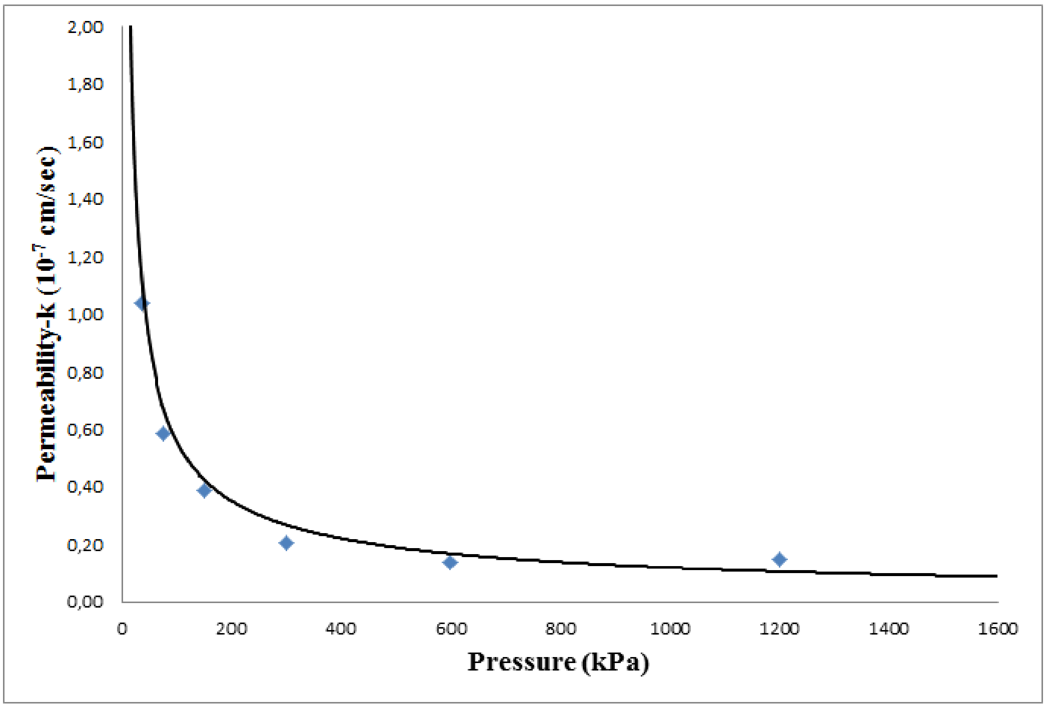

Figure C.2 Permeability-pressure curve for mixture 2

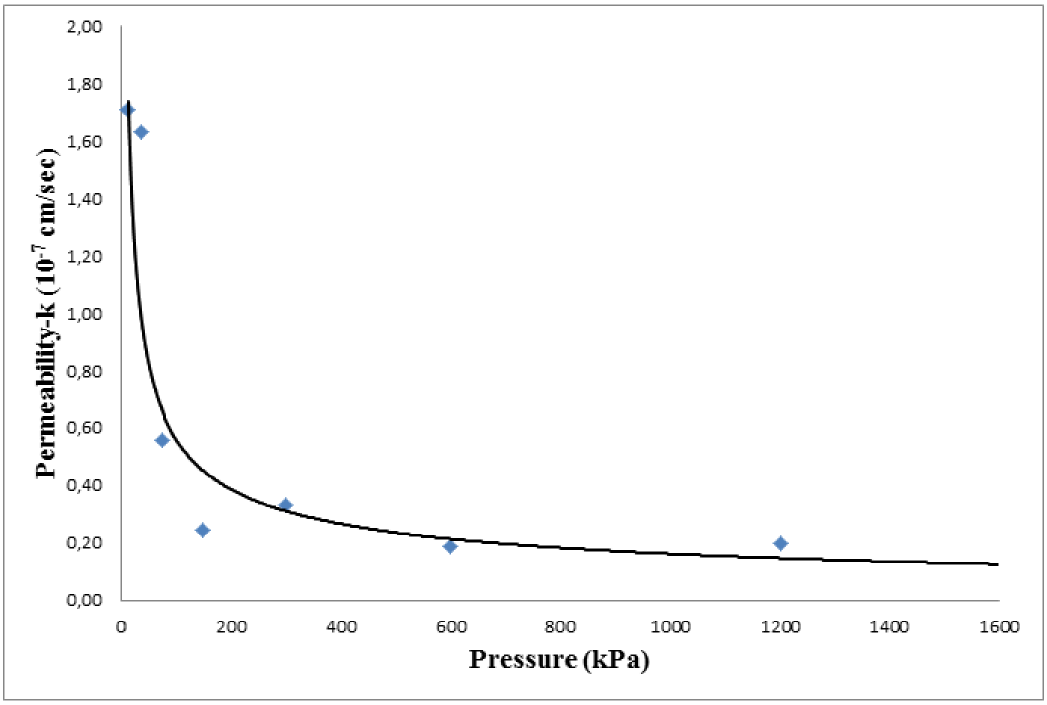

Figure C.3 Permeability-pressure curve for mixture 3

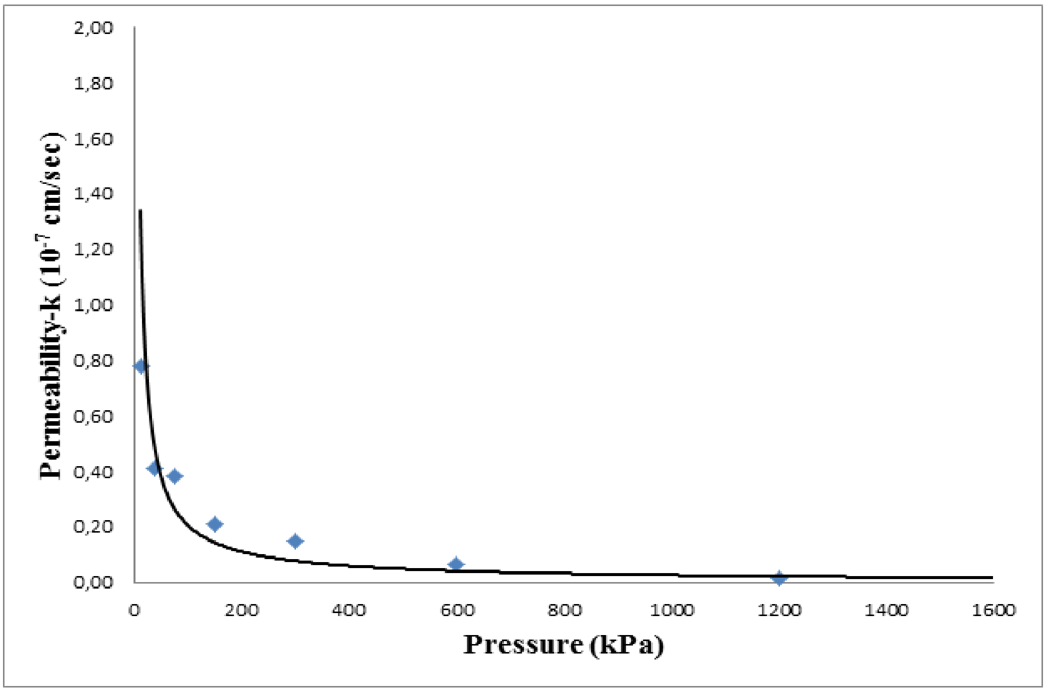

Figure C.4 Permeability-pressure curve for mixture 4

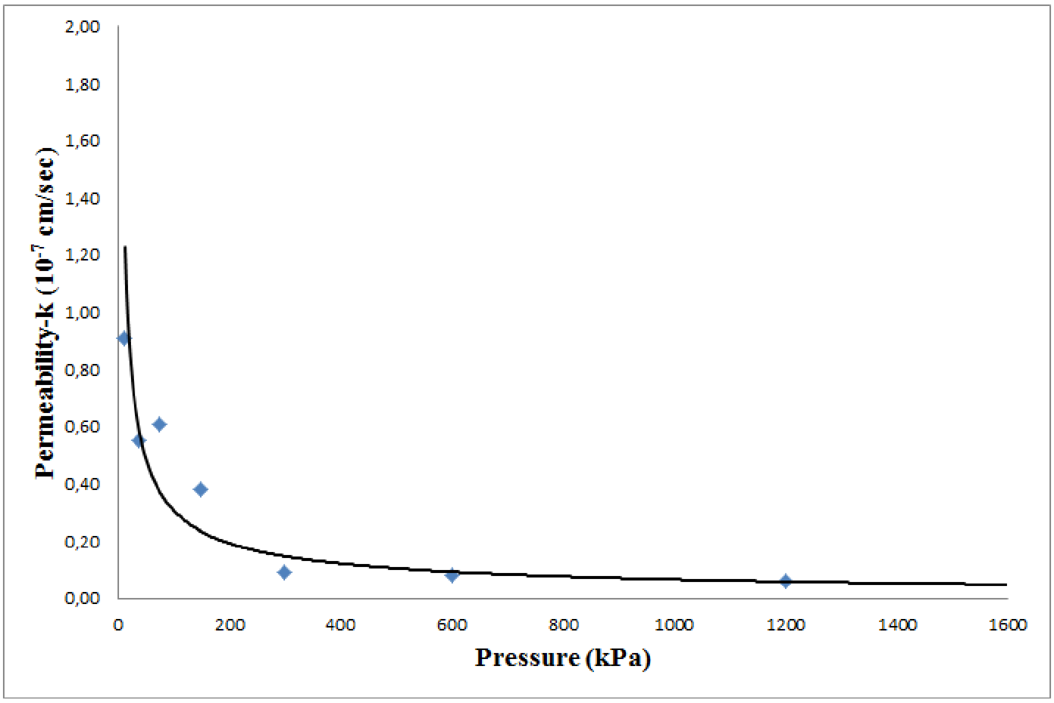

Figure C.5 Permeability-pressure curve for mixture 5

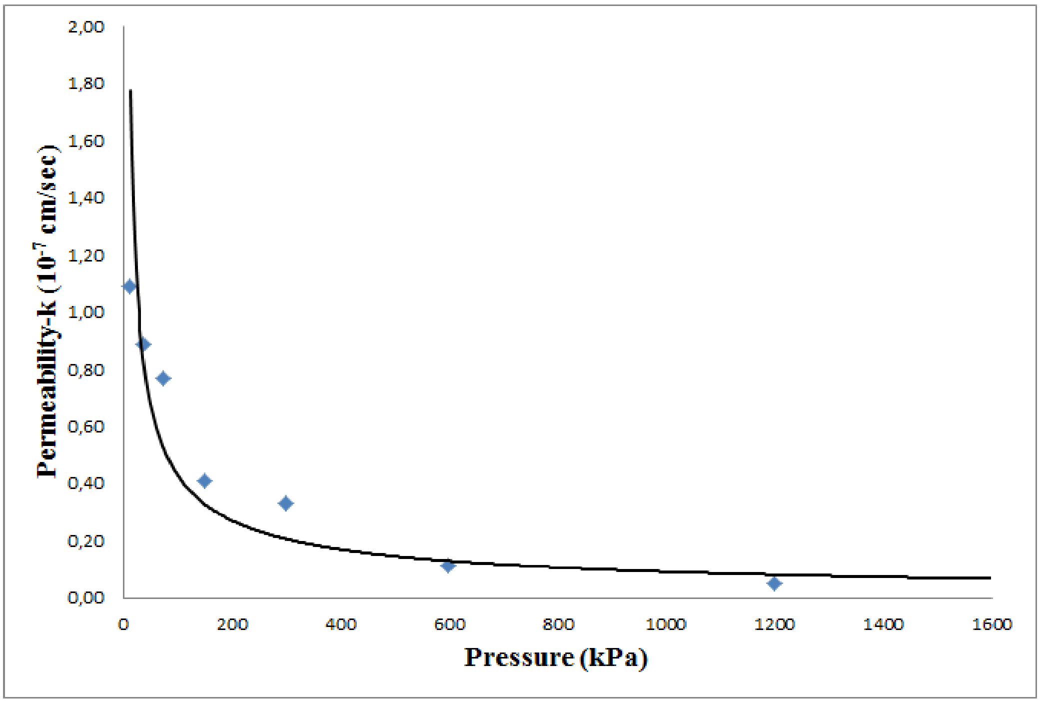

Figure C.6 Permeability-pressure curve for mixture 6

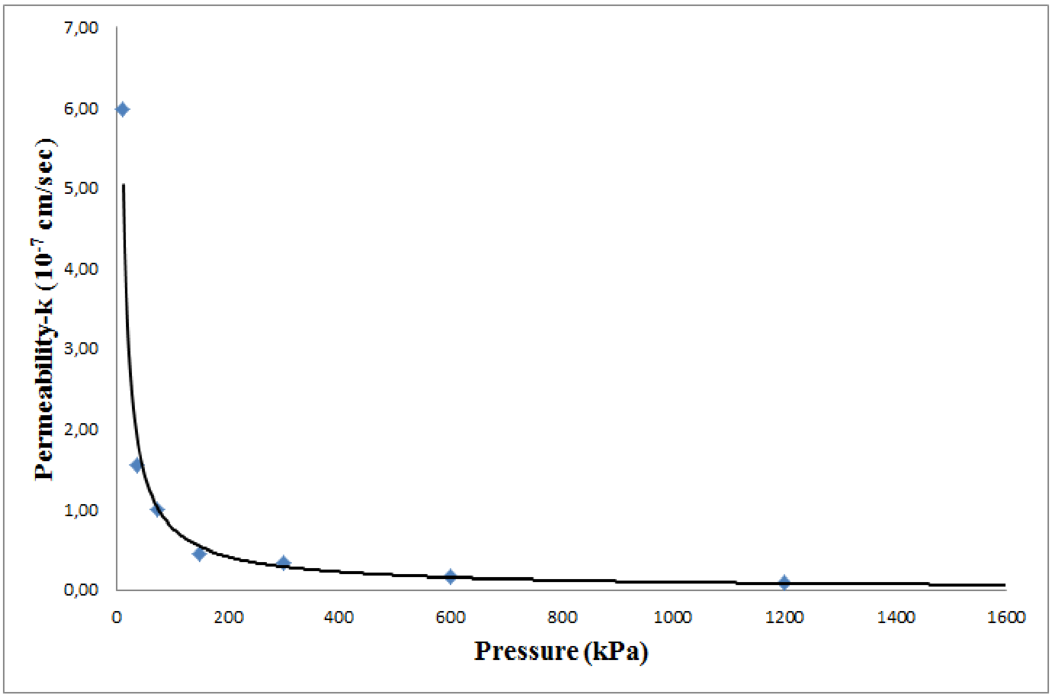

Figure C.7 Permeability-pressure curve for mixture 7

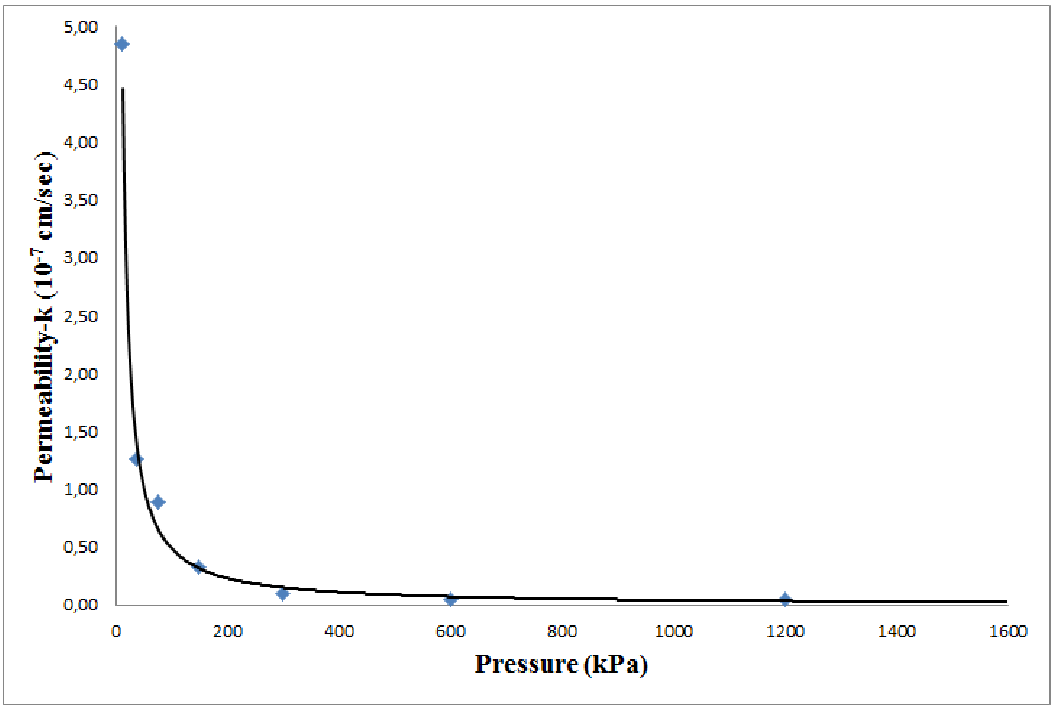

Figure C.8 Permeability-pressure curve for mixture 8

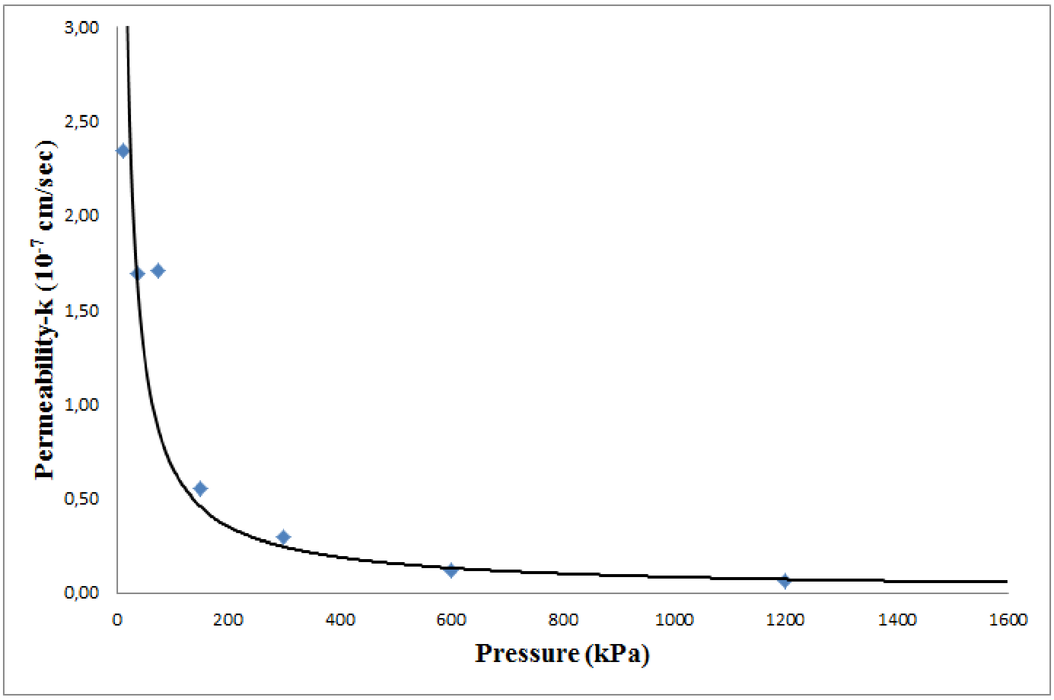

Figure C9. Permeability-pressure curve for mixture 9

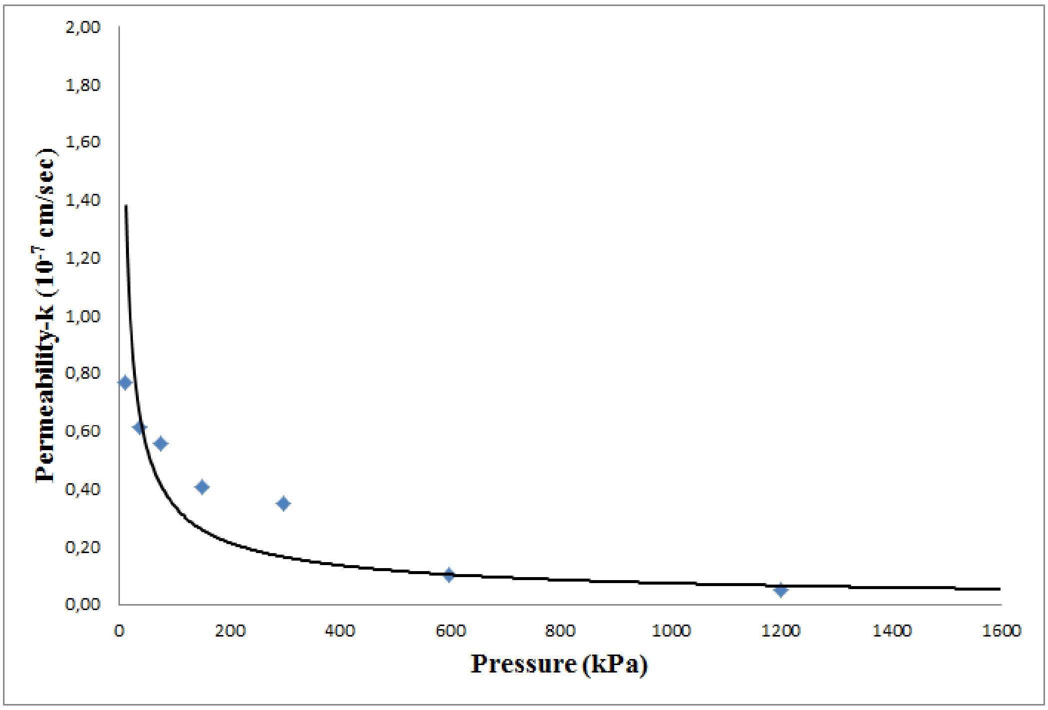

Figure C10. Permeability-pressure curve for mixture 10

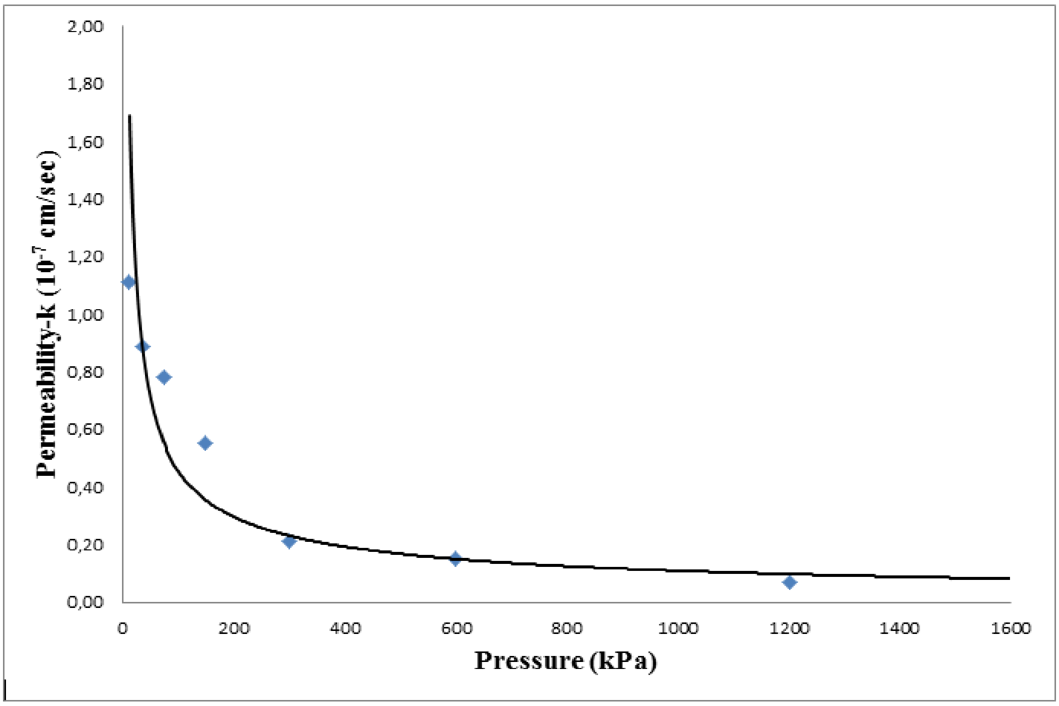

Figure C11. Permeability-pressure curve for mixture 11

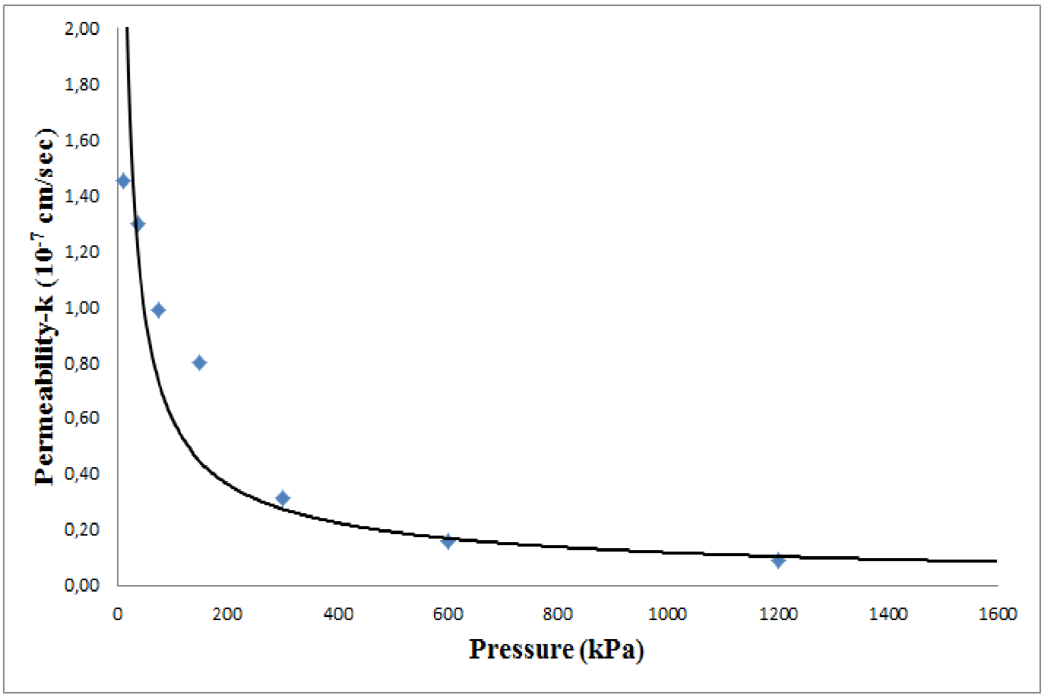

Figure C12. Permeability-pressure curve for mixture 12

APPENDIX D

MOHR COLOUMB RELATIONSHIPS

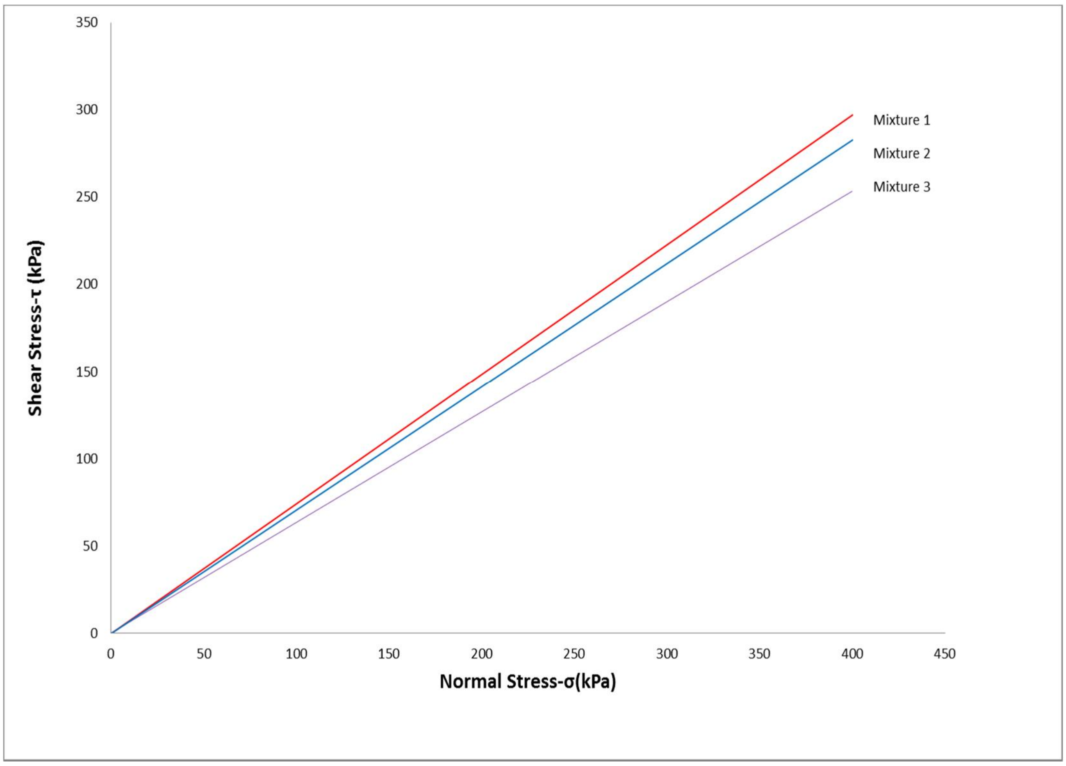

Figure D.1 Mohr -Coloumb Relationship for Peak Values for Green Sand 1

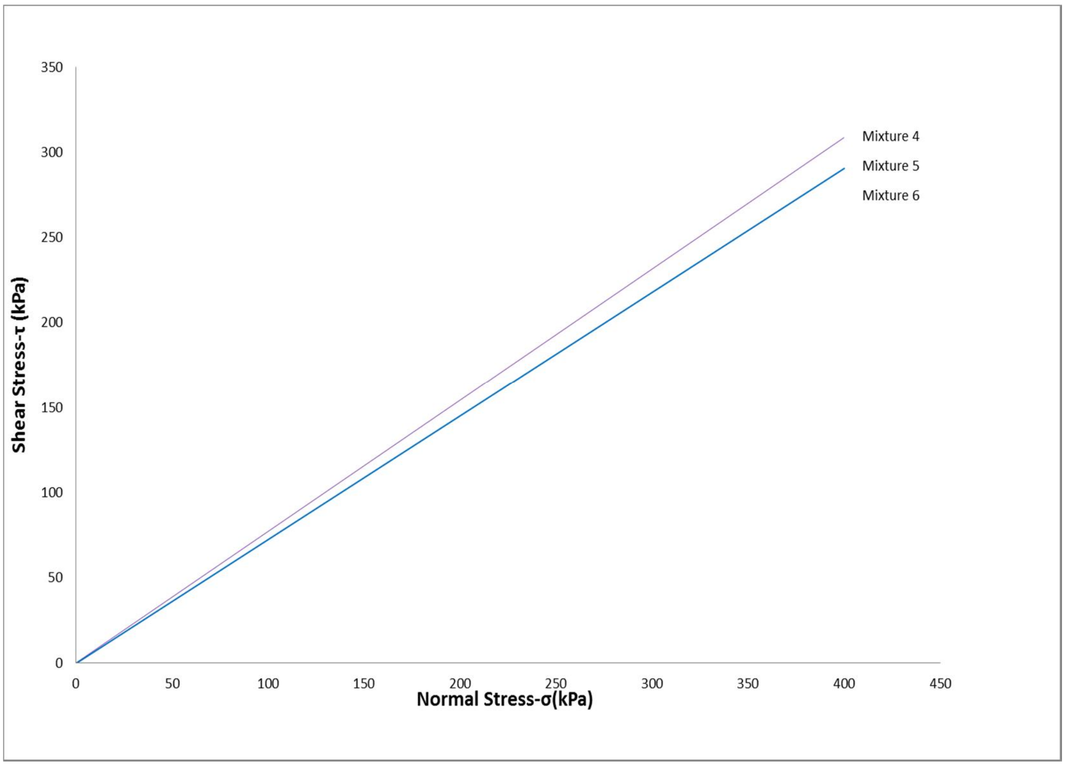

Figure D.2 Mohr Coloumb Relationship for Peak Values for Green Sand 2

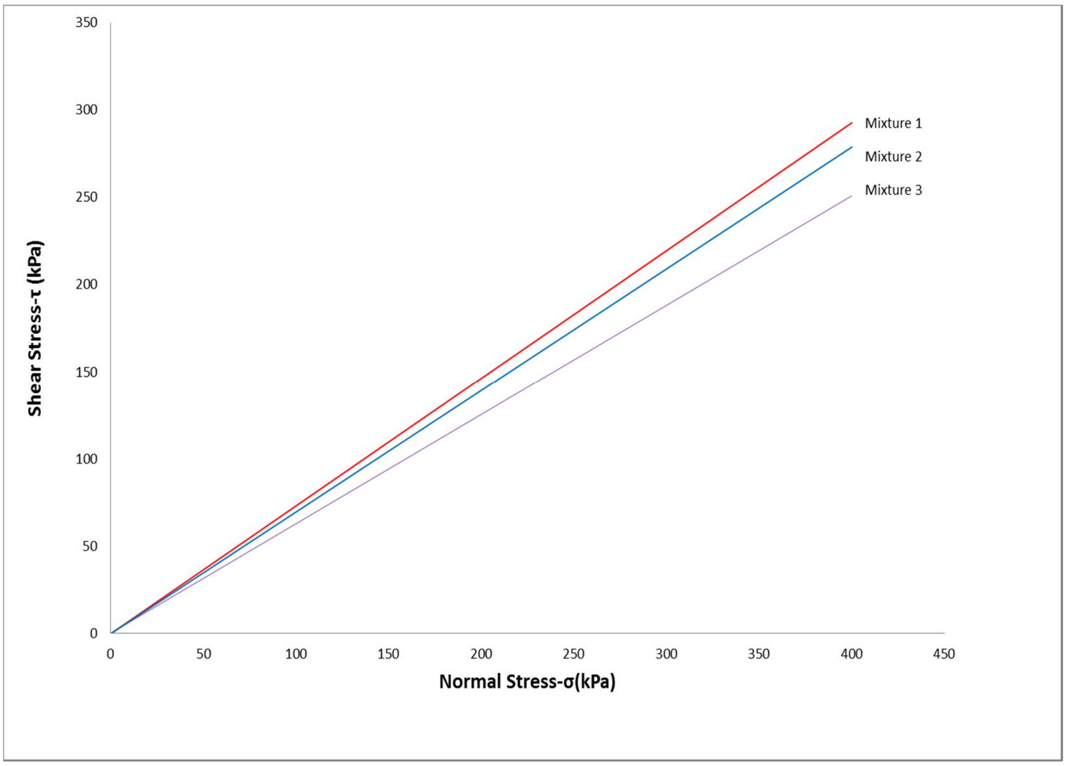

Figure D.3 Mohr Coloumb Relationship for Residual Values for Green Sand 1

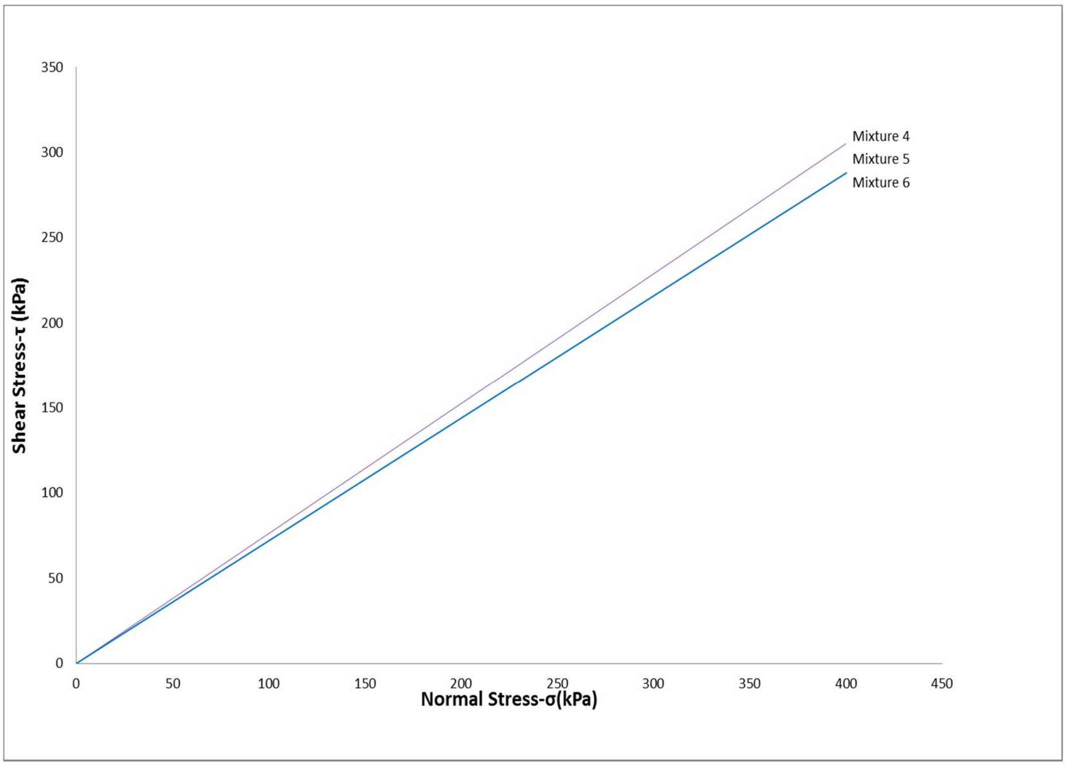

Figure D.4 Mohr Coloumb Relationship for Residual Values for Green Sand 2

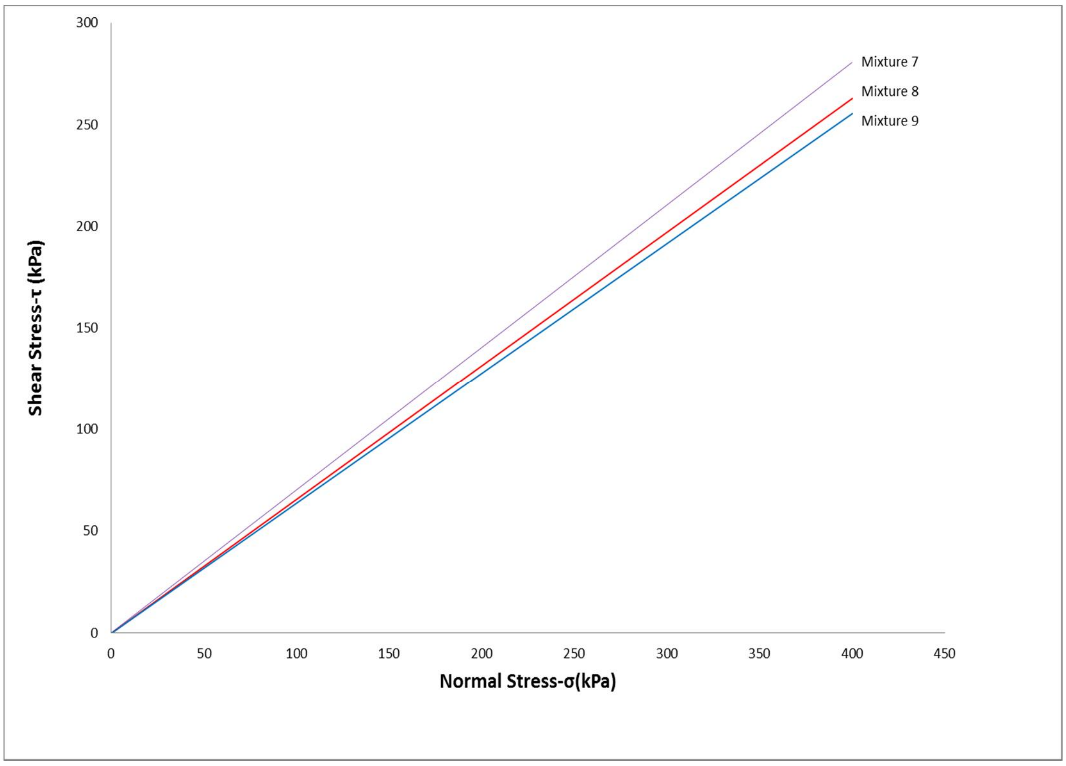

Figure D.5 Mohr -Coloumb Relationship for Peak Values for Resin Bonded Sand 1

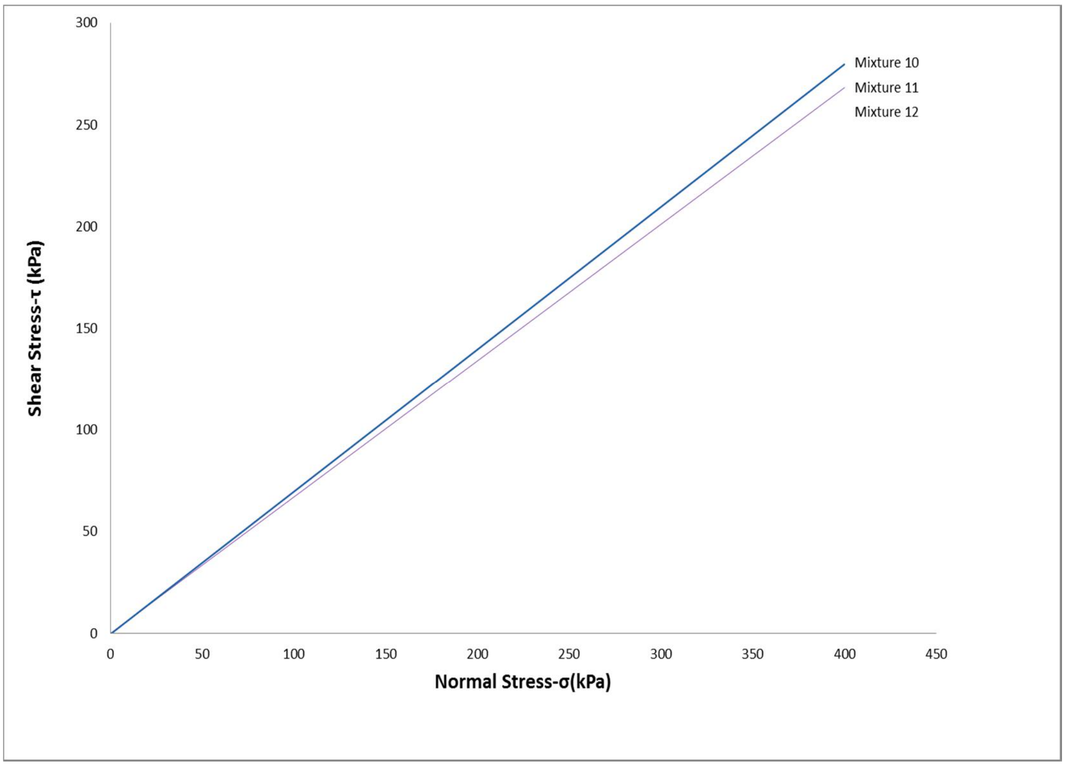

Figure D.6 Mohr -Coloumb Relationship for Peak Values for Resin Bonded Sand 2

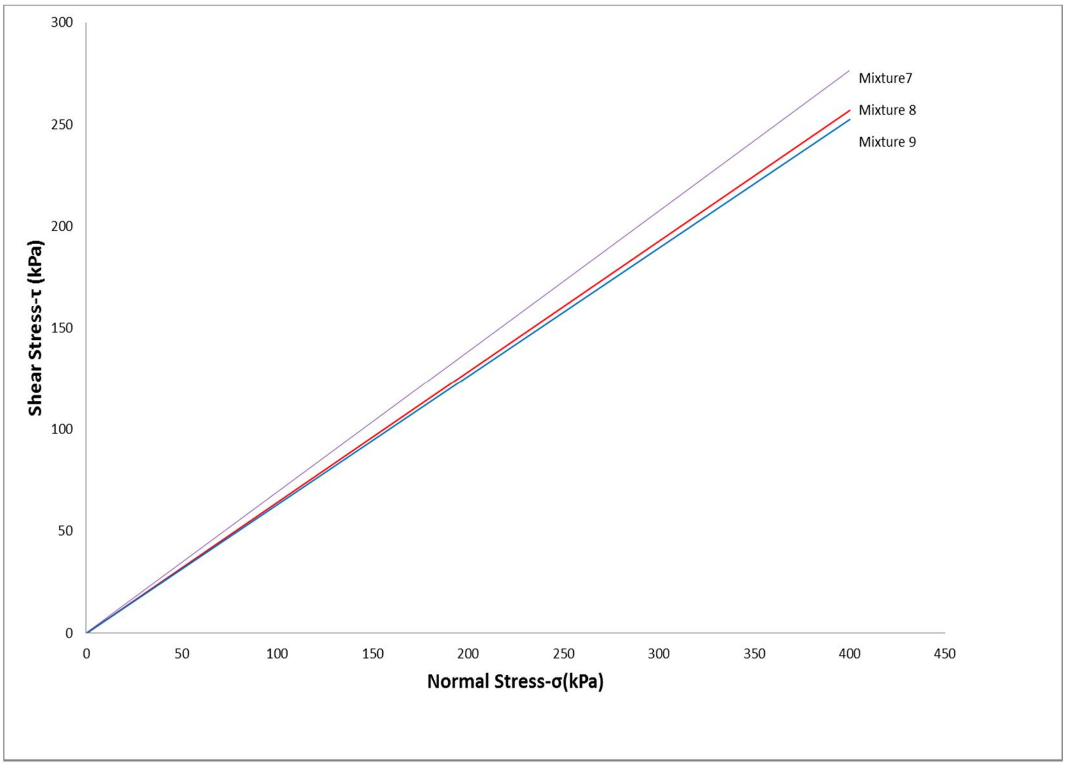

Figure D.7 Mohr -Coloumb Relationship for Residual Values for Resin Bonded Sand 1

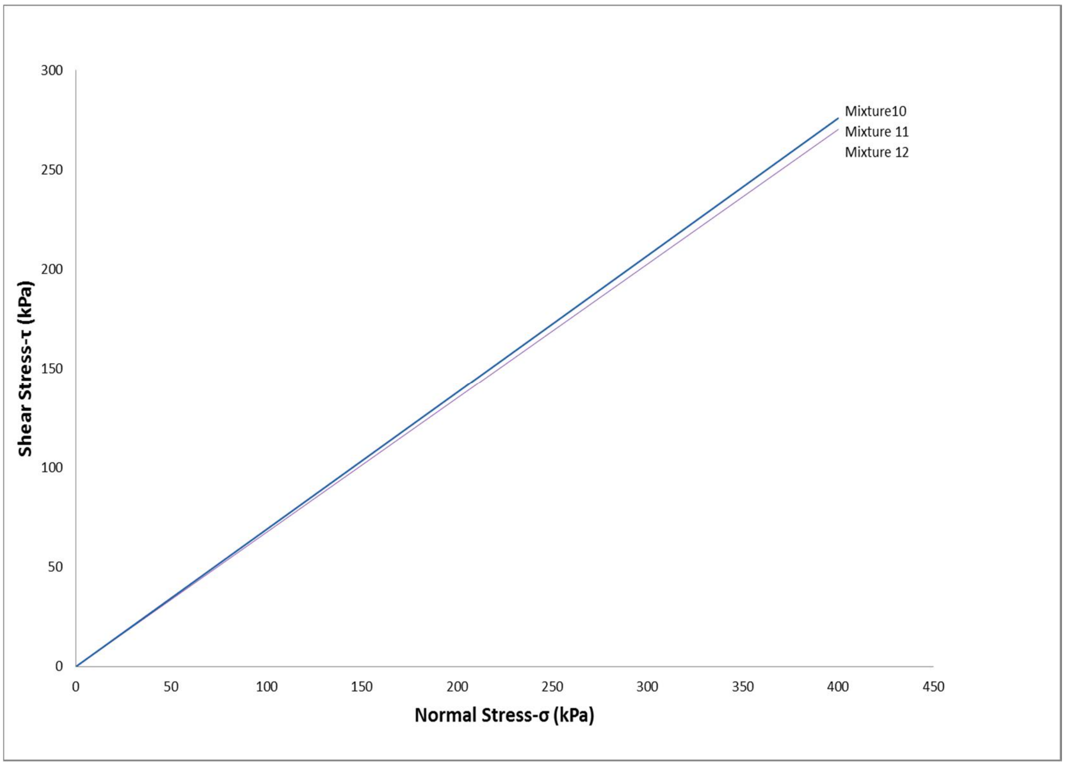

Figure D.8 Mohr -Coloumb Relationship for Residual Values for Resin Bonded Sand2