PARAMETERS AFFECTING THE PERMEABILITY OF BENTONITE-GRANULAR SOIL MIXTURES

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ABSTRACT

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Clay is the natural material which is very effective when used as a liner for waste disposal because of its extremely low permeability. As the clay is used to prevent the leakage of hazardous wastes by minimizing the flow of liquids through it, its most significant feature in this scope is its permeability. It is well known that addition of clay in high permeable soils decreases the permeability of final mixture. In this study, parameters affecting the permeability of bentonite-ganular soil mixtures have been investigated. Tests have been conducted on different aggregate compositions in order to determine the particle size distribution providing minimum void ratio. Series of hydraulic conductivity tests have been conducted on two different bentonite–aggregate compositions. For enhancing hydraulic conductivity performance of bentonite-aggregate mixtures, a water soluble polymer, namely Shore Pac was added and effects of polymer on permeability were investigated. Test results showed that addition of small amount of polymer extremely decreased the permeability of bentonite-granular soil mixtures. It is noted in the literature that there is an inverse relationship between viscosity of permeant and hydraulic conductivity. Viscosity determination tests have been conducted to determine effects of polymer on viscosity. Tests revealed that viscosity of polymer-water solution dramatically increased with the increase in polymer amount. Changes in viscosity and hydraulic conductivity values due to polymer addition were compared and it was concluded that reduction in hydraulic conductivity mainly caused by the increase in viscosity.

ÖZET

BENTONİT-GRANÜLER ZEMİN KARIŞIMLARININ PERMEABİLİTESİNİ ETKİLEYEN PARAMETRELER

Kil, son derece düşük permeabiliteye sahip doğal bir malzeme olması nedeniyle, atık sahalarında geçirimsiz tabaka oluşturmada oldukça etkilidir. Kil, sıvı akışını minimize ederek tehlikeli atıkların sızması önlemek üzere kullanıldığından, bu bağlamda en önemli özelliği hidrolik geçirgenliğidir. Bu çalışmada, bentonit-granüler zemin karışımlarının permeabilitesini etkileyen parametreler araştırılmıştır. Minimum boşluk oranını sağlayan tane dağılımını belirlemek için, farklı agrega kompozisyonları üzerinde deneyler yapılmıştır. İki farklı bentonit-agrega karışımı üzerinde hidrolik geçirgenlik deneyleri uygulanmıştır. Bentonit-agrega karışımlarının hidrolik geçirgenlik performansını artırmak için, ticari adı Shore Pac olan, suda çözülebilen tipte bir polimer malzeme karışıma eklenmiş ve permeabilite üzerindeki etkileri araştırılmıştır. Test sonuçları çok düşük oranda polimer eklenmesinin bentonit- agrega karışımlarının permeabilitesini ciddi şekilde düşürdüğünü göstermiştir. Literatürde, zemin içinden geçen sıvının viskozitesi ile hidrolik geçirgenlik arasında ters orantı olduğu belirtilmektedir. Polimer malzemenin viskozite üzerindeki etkisini belirlemek için viskozite deneyleri yapılmıştır. Deney sonuçları polimer-su çözeltisinin viskozitesinin polimer miktarının artması ile birlikte yüksek oranda arttığını ortaya koymuştur. Polimer eklenmesine bağlı olarak viskozite ve hidrolik geçirgenlikte meydana gelen değişimler karşılaştırılmış olup, hidrolik geçirgenlikte meydana gelen azalmaya viskozitenin artışının neden olduğu sonucuna varılmıştır.

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a	Area of the stand pipe
A	Soil sample area
D	Diameter
e	Void ratio
F_g	Weight of particle
F_s	Particle surface force
G	Specific gravity
γ_d	Dry unit weight
h_1	Water level at $t = t_1$
h_2	Water level at $t = t_2$
i	Hydraulic gradient
k	Hydraulic conductivity
L	Soil sample length
q	Volume of flow rate
T	Time difference between t_1 and t_2
t_1	Time at the beginning of the test
t_2	Time at the end of the test
v	Rate of flow of water
w	Water content
w_{opt}	Optimum water content

1. INTRODUCTION

Landfills are waste disposal sites used all around the world, designed to minimize the impact of solid wastes on environment and human health. Solid wastes are in either solid or semisolid form, containing significant amount of leachate, that is consisting of water and water soluble compounds and is the greatest threat to ground water and environment. Modern landfill design focuses on completely isolating waste from ground water systems. To isolate leachate, modern landfills are constructed with a number of safeguards, including clay or plastic lining. Different types of solid wastes are generated by community, exposing different threats to human health and environmet. Diversity of solid wastes, cause the design and construction of disposal sites to be different considering the properties of solid waste and leachate.

Because of its extremely low hydraulic conductivity, clay is widely used as a natural liner material for waste disposal. Bentonite, a highly plastic, swelling clay which is consisted mostly of montmorillonite, is the most common type of clay used for permeability lowering applications. There are different types of bentonites and their names depend on the dominant elements, such as potassium (K), sodium (Na), calcium (Ca), and aluminum (Al). Sodium bentonite is known as the most effective type against flow of liquids through its body.

Geosynthetic clay liners (GCL) are woven fabric like isolating materials, used for lining of landfills. They are composed of geomembrane and geosynthetic integrated with bentonite. They are effectively used as leakage preventers world wide. Although their effective impact against liquid seepage, due to high costs, alternative liner materials have been investigated. Bentonite-sand mixtures are tested by many investigators and researches have shown that they are effective in providing very low hydraulic conductivity values.

Polymers have been used for many years to enhance the performance of bentonite used in drilling industry. But their use for soil barrier applications has had minimal acceptance. Haug et al. (1994) conducted a rheological and triaxial permeability/volume change study and found that the low hydraulic conductivity characteristic of a marginal bentonite could be significantly improved with the addition of a small amount of polymer. Haug et. al.

(1994) found that viscosity increased, as the percentage of polymer is increased from zero to two per cent.

In this study, the performance of aggregate - bentonite mixtures with the addition of polymer has been investigated against hydraulic conductivity. In order to get a low cost liner, the amount of bentonite needed to be minimized. For this purpose, as bentonite would fill in the voids between aggregate particles, aggregate with a minimum void ratio tried to be obtained. Particle sizes in the aggregate mixture have been changed in order to obtain aggregate composition with minimum void ratio. Two different aggregate mixtures with low void ratios have been chosen and hydraulic conductivity tests have been conducted on these specimens.

Previous studies have shown that small amount of polymer addition dramatically reduced hydraulic conductivity of bentonite. In order to get desired low hydraulic conductivity values, different amounts of polymer was added to aggregate-bentonite mixtures. The polymer used in the tests was Shore Pac. This water soluble polymer have been extensively used for years as drilling mud additive. The effects of polymer addition on hydraulic conductivity of aggregate-bentonite mixtures have been investigated in detail through a series of experiments conducted. In each of the experiments, various levels of water soluble polymer was added in order to assess the level of impact on the hydraulic conductivity of the mixture. Falling head method has been used in the determination of hydraulic conductivity values of the mixtures. Significant increase in the viscosity due to polymer addition was observed. Viscosity determination tests have been conducted to assess the impact of viscosity changes due to polymer addition on the hydraulic conductivity.

2. SOIL COMPOSITION

Most soils are heterogeneous accumulation of mineral grains that are not cemented together. However, the term "soil" as used in engineering includes virtually every type of uncemented or partially cemented inorganic and organic material in the ground. Gravel and sand have essentially the same basic engineering properties, differing mainly in degree. When devoid of fines, coarse-grained soils are pervious and easy to compact. Although particle shape, angularity, gradation, and size affect the engineering properties of coarse-grained soils, gravels are generally more pervious and more stable than sands. When sand becomes finer and more uniform, its permeability decreases. In soils, small amounts of fines may have important effects on engineering properties. As little as 10 percent of particles smaller than the 75 μm sieve size in sand and gravel may make the soil virtually impervious, especially when the coarse grains are well graded. Clays are cohesive, plastic fines. Clays are virtually impervious, difficult to compact when wet, and impossible to drain by ordinary means. Due to changes in water content, large expansion and contraction occurs (Das, 2008). Textural and other characteristics of soils are summarized in Table 2.1.

Table 2.1. Textural and other characteristics of soils (Das, 2008)

Soil Name:	Gravels, Sands	Silts	Clays
Grain Size:	Coarse grained Can see individual grains by eye	Fine grained Can't see individual grains	Fine grained Can't see individual grains
Characteristics:	Cohesionless Nonplastic Granular	Cohesionless Nonplastic Granular	Cohesive Plastic -
Effect of water on engineering Behavior:	Relatively unimportant (exception: loose saturated granular materials and dynamic loadings)	Important	Very important
Effect of grain size distribution on Engineering Behavior:	Important	Relatively Unimportant	Relatively unimportant

2.1. Clay

2.1.1. Basic Definitions of Clay

Clay is a natural, earthy material primarily composed of fine-grained minerals. Due to its properties, clay has wide usage in geotechnical applications as filtering, waterproofing, foundary and absorbent material.

The term clay is generally applied to earthy materials of very fine particles size which form as a sedimentary deposit, as a residue due to weathering or by hydrothermal action. Clays are always of secondary origin and result primarily from the decomposition of other rocks, very frequently from rocks containing feldspar (Gillott, 1987).

The clay minerals in soils belong to the mineral family termed phyllosilicates, which also contains other layer silicates such as serpentine, pyrophllite, talc, mica, and chlorite. The clay minerals occur in small particle sizes, and their unit cells ordinarily have a residual negative charge that is balanced by the adsorption of cations from solution (Mitchell, 1976). The silicates are the largest and most complex group of minerals. The clay minerals are distinct from other phyllosilicates by having large percentages (often 70-90 per cent) of water trapped between silicate sheets. Much of the water within clays is not free pore-water but contained in the lattice of the clay minerals and absorbed onto their surface. To expel this water, temperatures of greater than 100^{o}C are required.

Although clay can refer to specific minerals such as kaolinite or illite, in civil engineering, clay often means a clay soil, a soil which contains some clay minerals as well as other mineral constituents, has plasticity, and is cohesive (Holtz and Kovacs, 1981). When it is moist, clay is cohesive, plastic and workable by hand. Clay shrinks when it is dried and expands when it is wetted. Plasticity is used to mean the property of the moistened material to be deformed under the application of pressure, with the deformed shape being retained when the deforming pressure is removed. Chemical analyses of clays show that they consist essentially of silica, alumina and water, occasionally with appreciable quantities of iron, alkalies and alkaline earths. The problem turns out to be that some material called clay does not meet all the above specifications. For example, the so-called flint clay has substantially no plasticity when it is mixed with water, however, it has the other attributes of clay (Grim, 1953).

There are four main groups of clay minerals:

- The Kaolinite Group: The general structure of the kaolinite group is composed of silicate sheets bonded to aluminium oxide/hydroxide layers referred to as gibbsite layers. The silicate and gibbsite layers are tightly bonded together with only weak bonding existing between the s-g paired layers.
- The Montmorillonite/Smectite Group: This group has several members which differ mostly in chemical content and the amount of water they contain. The structure of the group is composed of silicate layers sandwiching a gibbsite layer in a s-g-s stacking sequence. The varying amounts of water molecules lie between the s-g-s sandwiches.
- The Illite Group: This group is basically hydrated microscopic muscovite mica. The structure is composed of silicate layers sandwiching a gibbsite layer in a s-g-s stacking sequence. The variable amounts of water molecules would lie between the s-g-s sandwiches.
- The Chlorite Group: The structure of this group is composed of silicate layers sandwiching a brucite layer in an s-b-s stacking sequence. However, there is an extra weakly bonded brucite layer in between the s-b-s sandwiches, which gives the clay an s-b-s b s-b-s sequence. The variable amounts of water lie between the s-b-s and brucite layers (Woodward, 1995).

2.1.2. Formation

Clay minerals are formed in three ways: inheritance, neoformation and transformation. Inheritance means that a clay mineral originated from reactions that occurred in another area during a previous stage in the rock cycle and that the clay is stable enough to remain in its present environment. Origin by neoformation means that the clay has precipitated from solution or formed from reactions of amorphous materials. Transformation genesis requires that the clay has kept some of its inherited structure while undergoing chemical reactions. These reactions are typically characterized by ion exchange with the surrounding environment and/or layer transformation in which the structure of octahedral, tetrahedral, or fixed interlayer cations is modified (Mitchell and Soga, 2005).

The environment and available energy determine which of these mechanisms dominate. Inheritance dominates in the sedimentary environment because temperatures, and therefore, reaction rates, are usually low. Transformation dominates in high-temperature diagenetic, hydrothermal environments. All three mechanisms may be active in the weathering environment, but inheritance is most important in the cool, high-latitude regions, and neoformation is most important in the wet tropics (Mitchell and Soga, 2005).

2.1.3. Particle Size of Clay

Clays, which are small crystalline particles, are comprised of one or more members of a small group of minerals. Clays are mainly hydrous aluminium silicates, with magnesium or iron occupying all or part of the aluminium positions in some minerals and with alkalis (e.g., sodium potassium) or alkaline earth (e.g., calcium, magnesium) also present as essential constituents in some of them. For mineral particles in the clay-size range the upper limit of grain-size is generally taken as 2µm. ($1\mu m = 0.000001 m$)

Neither all clay minerals are finer than 2µm nor are all non-clay minerals coarser than 2µm. Consequently, the amounts of clay size and clay mineral in any soil may vary. The best way to prevent confusion is using clay size when referring to compositions in terms of clay size and clay mineral content or simply clay content when speaking of mineral compositions. A typical kaolinite clay is demonstrated in Figure 2.1.

The engineering properties of a soil mass can be significantly altered by the inclusion of even a small amount of clay minerals. The behavior of the soil is increasingly affected by the features of the clay as the clay content in the soil increases. When the clay content reaches 50 per cent, the sand and silt grains which float in a clay matrix, have little impact on the engineering behavior.

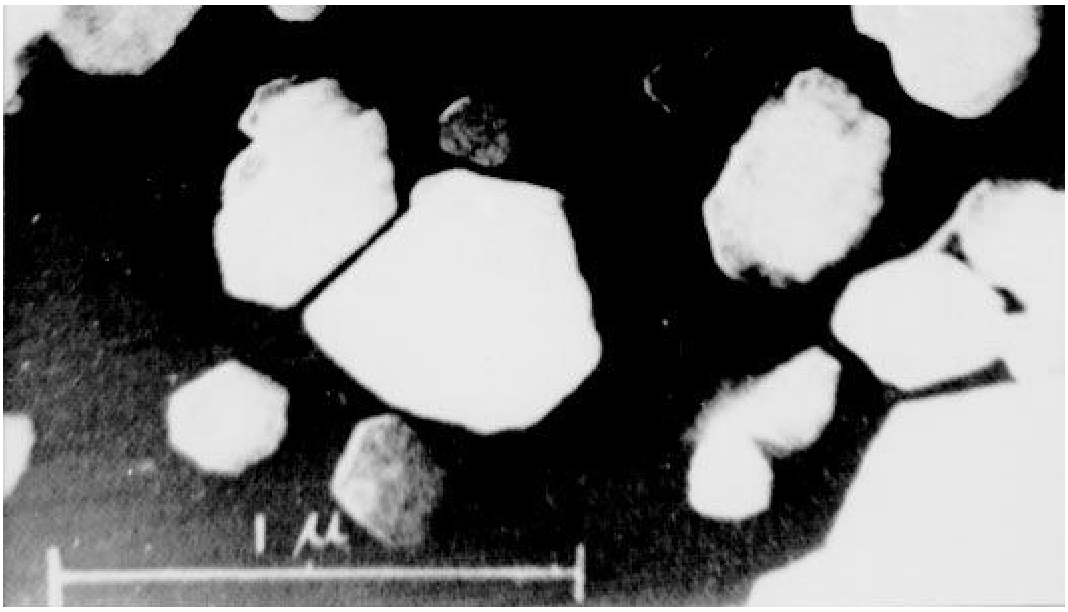


Figure 2.1. Kaolinite particles (Das, 2008)

2.1.4. Structural Characteristics

There are two major forces that affect the behavior of individual soil particles and their interaction with other particles:

- Weight of the particle F_g.
- Particle surface forces F_s.

Weight of the particle, F_g is the result of gravitational forces and is function of the volume of the particle. For example for equidimensional particles such as spheres of diameter D, the weight, F_g, is directly proportional to D^3 since volume of a sphere is a function of D^3. Particle surface forces are caused by unsatisfied electrical charges in the particle's crystalline structure. Surface forces, F_s, are directly proportional to the surface area and, hence, for equidimensional particles, to D^2.

The ratio of the weight of a particle to the particle's surface, F_g / F_s, is directly proportional to D (D^3/ D^2). Thus, for large particle sizes, which include soil particles in coarse fraction (>0.075 mm), the weight of the particle is predominant over the surface forces. As the particle diameter decreases, so does the ratio F_g / F_s; hence, , the surface forces predominate for very small values of D. This accounts for the cohesive nature of most fine-grained soils (Dunn et al., 1980).

Surface forces are very effective in the behavior of clay soils and some silts as the crystalline structure of clays forms thin platy-shaped particles that carry a net negative charge on the flat surfaces of the particles. The charged surface pulls the cations which exist in the pore water and even tends to orient water molecules into a somewhat structured arrangement. It can be very helpful to generate a basic understanding of clay particles and aqueous solution that surrounds the particles, in interpreting the engineering behavior of clays.

Clay minerals in soils belong to the mineral family termed phyllosilicates, which also contains other layersilicates such as serpentine, pyrophyllite, talc, mica, and chlorite. Clay minerals occur in small particle sizes, and their unit cells ordinarily have a residual negative charge that is balanced by the adsorption of cations from solution. The structures of the common layer silicates are made up of combinations of two simple structural units, the silicon tetrahedron represented in Figure 2.2 and the aluminum or magnesium octahedron represented in Figure 2.3. Different clay mineral groups are characterized by the stacking arrangements of sheets (sometimes chains) of these units and the manner in which two successive two- or three-sheet layers are held together. Differences among minerals within clay mineral groups result primarily from differences in the type and amount of isomorphous substitution within the crystal structure. Possible substitutions are nearly endless in number, and the crystal structure arrangement may range from very poor to nearly perfect (Mitchell and Soga, 2005).

2.1.4.1. Silica Sheet.

In clay mineral structures, the silica tetrahedra are interconnected in a sheet structure. Three of the four oxygens in each tetrahedron are shared to form a hexagonal net, as shown in Figure 2.2 b. The bases of the tetrahedra are all in the same plane, and the tips all point in the same direction. The structure has the composition $(Si_4O_{10})_4$ and can repeat indefinitely. Electrical neutrality can be obtained by replacement of four oxygens by hydroxyls or by union with a sheet of different composition that is positively charged. The oxygen-to-oxygen distance is 2.55 angstroms (A°), the space available for the silicon ion is 0.55 A°, and the thickness of the sheet in clay mineral structures is 4.63 A° (Grim, 1968).

In some of the less common clay minerals, silica tetrahedra are arranged in bands made of double chains of composition $(Si_4O_{11})_6$. Electrical neutrality is achieved and the bands are bound together by aluminum and/or magnesium ions. A diagrammatic sketch of this structure is shown in Figure 2.4. Minerals in this group resemble the amphiboles in structure.

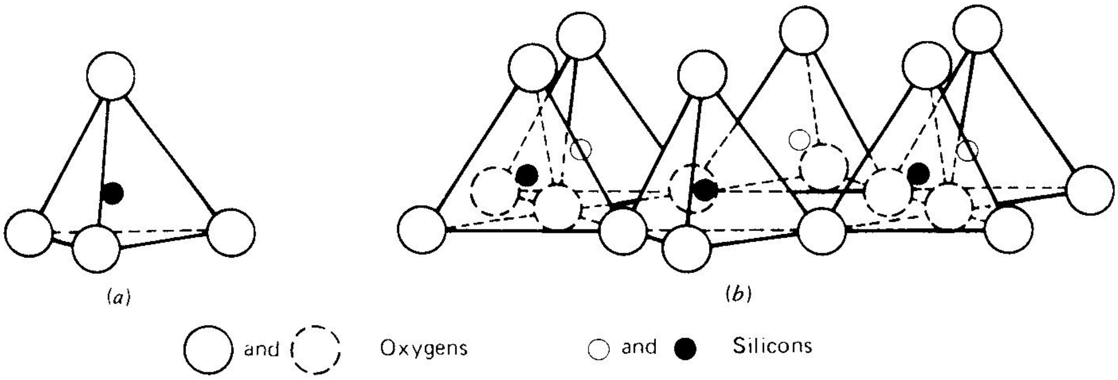


Figure 2.2. Silicon tetrahedron and silica tetrahedra arranged in a hexagonal network (Mitchell and Soga, 2005)

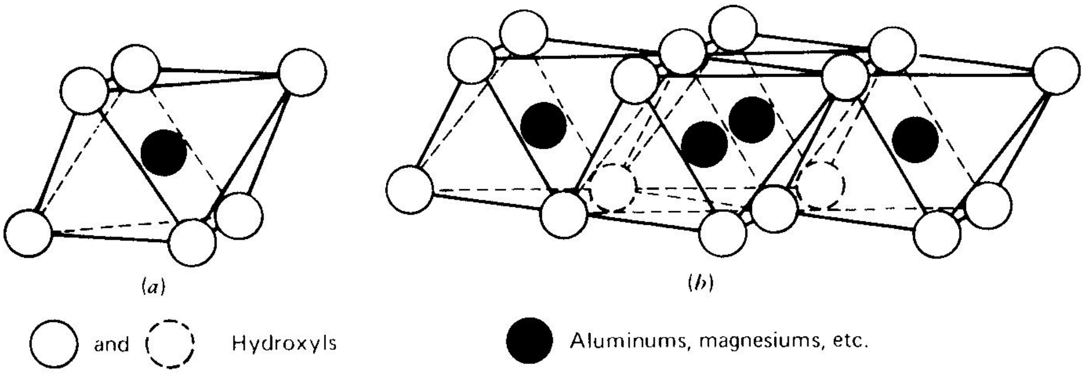
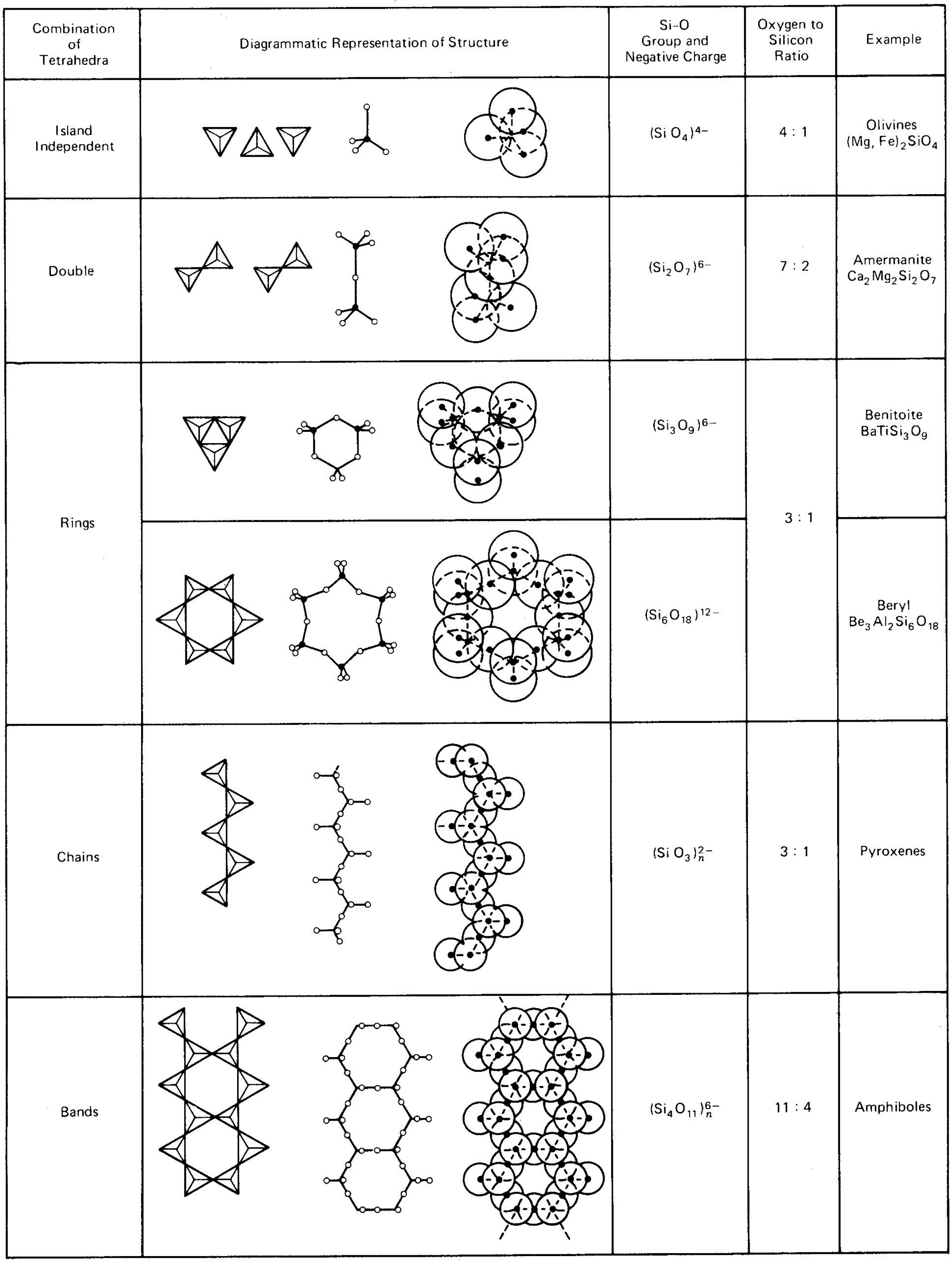


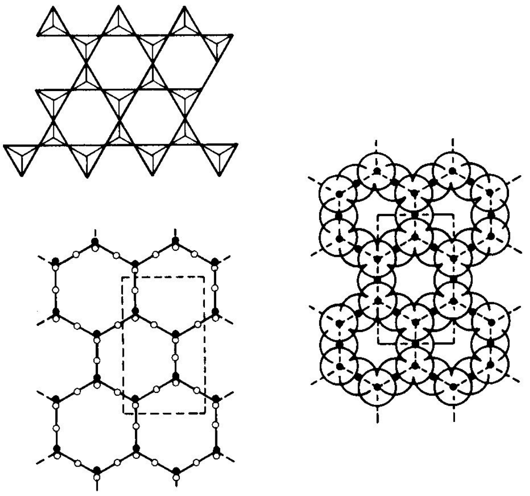
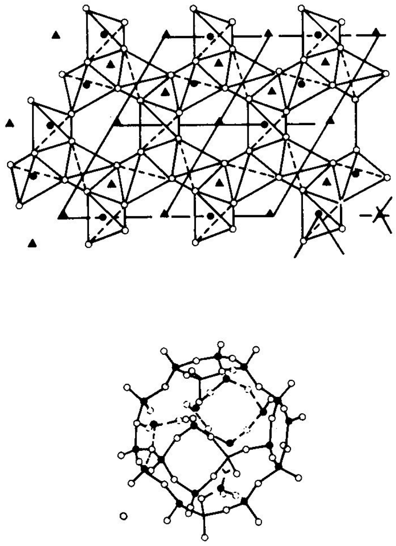
Figure 2.3. Octahedral unit and sheet structure of octahedral units (Mitchell and Soga, 2005)



Combination of Tetrahedra	Diagrammatic Representation of Structure	Si-O Group and Negative Charge	Oxygen to Silicon Ratio	Example
Island Independent		$(SiO_4)^{4-}$	4 : 1	Olivines $(Mg, Fe)_2SiO_4$
Double		$(Si_2O_7)^{6-}$	7 : 2	Amermanite $Ca_2Mg_2Si_2O_7$
Rings		$(Si_3O_9)^{6-}$	3 : 1	Benitoite $BaTiSi_3O_9$
		$(Si_6O_{18})^{12-}$		Beryl $Be_3Al_2Si_6O_{18}$
Chains		$(SiO_3)_n^{2-}$	3 : 1	Pyroxenes
Bands		$(Si_4O_{11})_n^{6-}$	11 : 4	Amphiboles

(*a*)

Figure 2.4. Silica tetrahedral arrangements in different silicate mineral structures (Gillott, 1968)

Combination of Tetrahedra	Diagrammatic Representation of Structure	Si-O Group and Negative Charge	Oxygen to Silicon Ratio	Example
Sheets		$(Si_4O_{10})_n^{4-}$	5 : 2	Micas
Frameworks		$(Si\,O_2)_n^0$	2 : 1	Quartz SiO_2 Also feldspars, for example, orthoclase, $KAlSi_3O_8$

(*b*)

Figure 2.4. continued

<u>2.1.4.2. Octahedral Sheet.</u> This sheet structure is composed of magnesium or aluminum in octahedral coordination with oxygens or hydroxyls. In some cases, other cations are present in place of Al_3 and Mg_2 , such as Fe_2, Fe_3, Mn_2, Ti_4, Ni_2, Cr_3, and Li. Figure 2.3 b is a schematic diagram of such a sheet structure. The oxygen-to oxygen distance is 2.60 A°, and the space available for the octahedrally coordinated cation is 0.61 A°. The thickness of the sheet is 5.05 A° in clays (Grim, 1968).

If the cation is trivalent, then normally only two thirds of the possible cationic spaces are filled, and the structure is termed dioctahedral. In the case of aluminum, the composition is $Al_2(OH)_6$. This composition and structure form the mineral gibbsite. When combined with silica sheets, as is the case in clay mineral structures, an aluminum octahedral sheet is referred to as a gibbsite sheet. If the octahedrally coordinated cation is divalent, then normally all possible cation sites are occupied and the structure is trioctahedral. In the case of magnesium, the composition is $Mg_3(OH)_6$, giving the mineral brucite. In clay mineral structures, a sheet of magnesium octahedra is termed a brucite sheet (Mitchell and Soga, 2005).

Isomorphous substitution is very important in the structure and properties of the clay minerals. In an ideal gibbsite sheet, only two-thirds of the octahedral positions are filled, and all of the cations are aluminum. In an ideal brucite sheet, all the octahedral spaces are filled by magnesium. In an ideal silica sheet, silicons occupy all tetrahedral spaces. In clay minerals, however, some of the tetrahedral and octahedral spaces are occupied by cations other than those in the ideal structure. Common examples are aluminum in place of silicon, magnesium instead of aluminum, and ferrous iron (Fe_2) for magnesium. This presence in an octahedral or tetrahedral position of a cation other than that normally found, without change in crystal structure, is isomorphous substitution. The actual tetrahedral and octahedral cation distributions may develop during initial formation or subsequent alteration of the mineral (Mitchell and Soga, 2005).

2.1.4.3. Intersheet and Interlayer Bonding in the Clay Minerals. A single plane of atoms that are common to both the tetrahedral and octahedral sheets forms a part of the clay mineral layers. Bonding between these sheets is of the primary valence type and is very strong. However, the bonds holding the unit layers together may be of several types, and they may be sufficiently weak that the physical and chemical behavior of the clay is influenced by the response of these bonds to changes in environmental conditions. Isomorphous substitution in all of the clay minerals, with the possible exception of those in the kaolinite group, gives clay particles a net negative charge. To preserve electrical neutrality, cations are attracted and held between the layers and on the surfaces and edges of the particles. Many of these cations are exchangeable cations because they may be replaced by cations of another type. The quantity of exchangeable cations is termed the cation exchange capacity (cec) and is usually expressed as milliequivalents (meq)3 per 100 g of dry clay (Mitchell and Soga, 2005).

Five types of interlayer bonding are possible in the layer silicates (Marshall, 1964):

- Neutral parallel layers are held by Van Der Waals forces. Bonding is weak; however, stable crystals of appreciable thickness such as the nonclay minerals of pyrophyllite and talc may form. These minerals cleave parallel to the layers.
- In some minerals (e.g., kaolinite, brucite, gibbsite), there are opposing layers of oxygens and hydroxyls or hydroxyls and hydroxyls. Hydrogen bonding then develops between the layers as well as Van Der Waals bonding. Hydrogen bonds remain stable in the presence of water.
- Neutral silicate layers that are separated by highly polar water molecules may be held together by hydrogen bonds.
- Cations needed for electrical neutrality may be in positions that control interlayer bonding. In micas, some of the silicon is replaced by aluminum in the silica sheets. The resulting charge deficiency is partly balanced by potassium ions between the unit cell layers. The potassium ion just fits into the holes formed by the bases of the silica tetrahedra. As a result, it generates a strong bond between the layers. In the chlorites, the charge deficiencies from substitutions in the octahedral sheet of the 2:1 sandwich are balanced by excess charge on the single-sheet layer interleaved between the three-sheet layers. This provides a strongly bonded structure that while exhibiting cleavage will not separate in the presence of water or other polar liquids.
- When the surface charge density is moderate, as in smectite and vermiculite, the silicate layers readily adsorb polar molecules, and also the adsorbed cations may hydrate, resulting in layer separation and expansion. The strength of the interlayer bond is low and is a strong function of charge distribution, ion hydration energy, surface ion configuration, and structure of the polar molecule. Smectite and vermiculite particles adsorb water between the unit layers and swell, whereas particles of the nonclay minerals, pyrophyllite and talc, which have comparable structures, do not. There are two possible reasons (Van Olphen, 1977):

- The interlayer cations in smectite hydrate, and the hydration energy overcomes the attractive forces between the unit layers. There are no interlayer cations in pyrophyllite; hence, no swelling.
- Water does not hydrate the cations but is adsorbed on oxygen surfaces by hydrogen bonds. There is no swelling in pyrophyllite and talc because the surface hydration energy is too small to overcome the van der Waals forces between layers, which are greater in these minerals because of a smaller interlayer distance.

Whatever the reason, the smectite minerals are the dominant source of swelling in the expansive soils that are so prevalent throughout the world.

2.1.5. Classification of the Clay Minerals

The manner in which atoms are assembled into tetrahedral and octahedral units, followed by the formation of sheets and their stacking to form layers that combine to produce the different clay mineral groups is illustrated in Figure 2.5. The basic structures shown in the bottom row of Figure 2.5 comprise the great preponderance of the clay mineral types that are found in soils. Grouping the clay minerals according to crystal structure and stacking sequence of the layers is convenient since members of the same group have generally similar engineering properties. The minerals have unit cells consisting of two, three, or four sheets. The two-sheet minerals are made up of a silica sheet and an octahedral sheet. The unit layer of the threesheet minerals is composed of either a dioctahedral or trioctahedral sheet sandwiched between two silica sheets. Unit layers may be stacked closely together or water layers may intervene. The four-sheet structure of chlorite is composed of a 2:1 layer plus an interlayer hydroxide sheet. In some soils, inorganic, claylike material is found that has no clearly identifiable crystal structure. Such material is referred to as allophane or noncrystalline clay (Mitchell and Soga, 2005).

The bottom row of Figure 2.5 shows that the 2:1 minerals differ from each other mainly in the type and amount of ‘‘glue’’ that holds the successive layers together. For example, smectite has loosely held cations between the layers, illite contains firmly fixed potassium ions, and vermiculite has somewhat organized layers of water and cations. The chlorite group represents an end member that has 2:1 layers bonded by an organized hydroxide sheet. The charge per formula unit is variable both within and among groups, and reflects the fact that the range of compositions is great owing to varying amounts of isomorphous substitution.

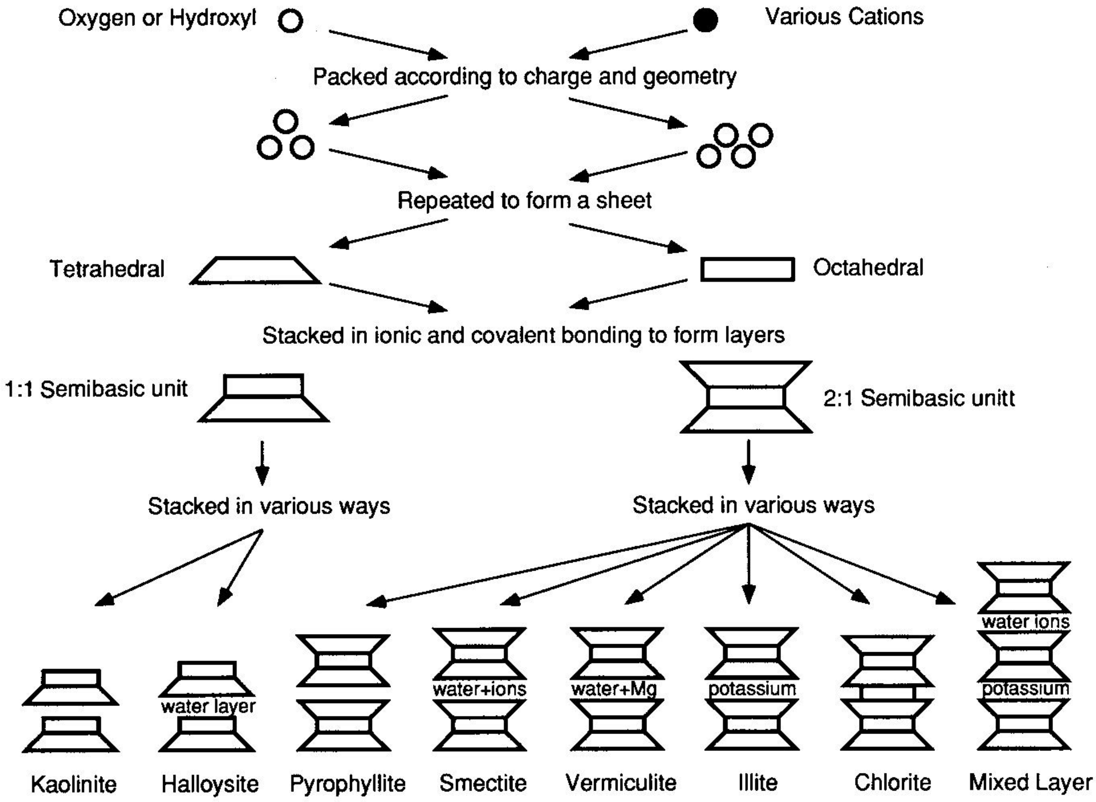


Figure 2.5. Synthesis pattern for the clay minerals (Mitchell and Soga, 2005)

<u>2.1.5.1. Smectite Clay Minerals.</u> Smectite is the name used for a group of phyllo-silicate mineral species, the most important of which are montmorillonite, beidellite, nontronite, saponite and hectorite. These and several other less common species are differentiated by variations in chemical composition involving substitutions of Al for Si in tetrahedral cation sites and Al, Fe, Mg and Li in octahedral cation sites. Smectite clays have a variable net negative charge, which is balanced by Na, Ca, Mg and, or, H adsorbed externally on interlamellar surfaces. The structure, chemical composition, exchangeable ion type and small crystal size of smectite clays are responsible for several unique properties, including a large chemically active surface area, a high cation exchange capacity, interlamellar surfaces having unusual hydration characteristics, and sometimes the ability to modify strongly the flow behaviour of liquids. In terms of major industrial and chemical uses,

natural smectite clays can be divided into three categories, Na smectites, Ca-Mg smectites and Fuller's or acid earths. Large volumes of Na smectites and Na-exchanged Ca-Mg smectites and Fuller's earth are directly used in the foundry, oil well drilling, wine, and iron ore and feed pelletizing industries, and are also used in civil engineering to impede water movement. Significant volumes of Na smectites are used for various purposes in the manufacturing of many industrial, chemical and consumer products. Large quantities of Ca-Mg smectites are used directly in iron foundries, in agricultural industries and for filtering and decolorizing various types of oils. A significant fraction of the Ca-Mg smectites used for decolorizing has been acid treated. Large volumes of Fuller's or acid earths are commercially used for preparing anirnal litter trays and oil and grease absorbents, as carriers for insecticides, and for decolorizing of oils and fats (Odom, 1984).

2.1.5.2. Properties of Smectite Clay Minerals. The smectite clay minerals have a layer lattice structure similar to micas, but they differ from micas in that the bonds between layers are weakened because of internal chemical substitutions. Only in the smectite clays are interlayer cations exchangeable and interlayer surfaces and cations hydratable. The smectite clays consist of layers of negatively charged oxygen atoms within which several types of positively charged cations are fixed in specific positions. In a two-dimensional schematic diagram of the structure shown in Figure 2.6, four layers of oxygen atoms can be seen that define upper and lower tetrahedral sheets containing tetravalent (Si) and sometimes trivalent cations (Al_3+ and Fe_3+). The apexes of the tetrahedra point toward each other, and the oxygen atoms at the apexes form part of an octahedral sheet that may containtrivalent cations, (Al, Fe), divalent cations (Fe, Mg), both divalent and trivalent cations, or divalent and monovalent (Li) cations. The presence of two tetrahedral sheets and one octahedral sheet is the basis for classifying the smectite structures as 2:1 phyllosilicates. This structural characteristic differentiates smectite clays from kaolinite clay structures containing one tetrahedral and one octahedral sheet and from chlorite clay structures that contain two tetrahedral and two octahedral sheets. Illite clay structures are similar to smectite clay structures, but in illite adjacent tetrahedral sheets are bonded by K+ ions which are not exchangeable.

Electron micrographs showing the natural textures and crystal size variations of smectite clay minerals all of which formed from the hydrolysis of volcanic glass are shown in Figure 2.7.

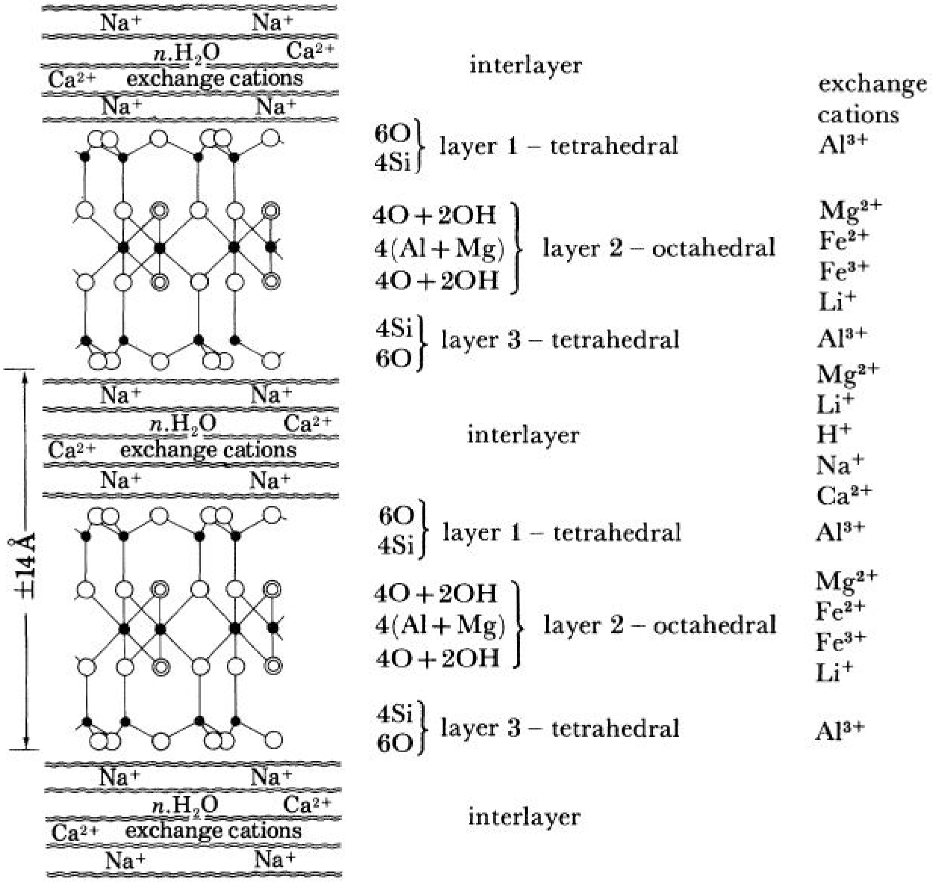


Figure 2.6. Structure of smectite clay minerals. The chemical composition shown is that of montmorillonite. Various ions that may be present in other smectite clay species are shown in column on right (Mitchell and Soga, 2005)

2.1.5.3. Bentonite. Bentonite is a highly plastic, swelling clay material widely used for a variety of purposes, ranging from drilling mud and slurry walls to clarification of beer and wine. The bentonite familiar to most geoengineers is a highly colloidal, expansive alteration product of volcanic ash. It has a liquid limit of 500 percent or more. It is widely used as a backfill during the construction of slurry trench walls, as a soil admixture for construction of seepage barriers, as a grout material, as a sealant for piezometer installations, and for other special applications (Mitchell and Soga, 2005).

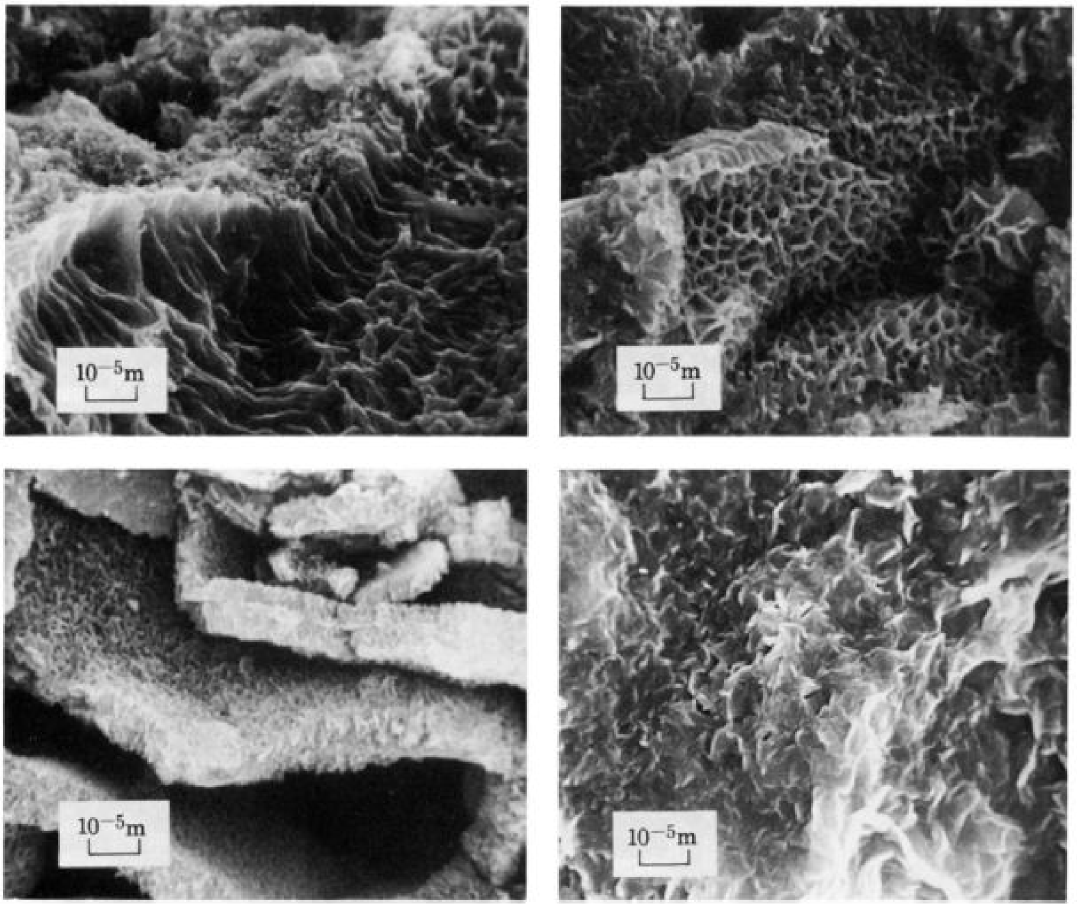


Figure 2.7. Electron micrographs showing the natural textures and crystal size variations of smectite clay minerals all of which formed from the hydrolysis of volcanic glass. The top two photographs are of Ca smectites; the bottom two photographs are Na smectites. Bar = 10 μm (Mitchell and Soga, 2005)

Bentonite is an absorbent aluminium phyllosilicate. It is consisted mostly of montmorillonite. There are different types of bentonites and their names depend on the dominant elements, such as potassium (K), sodium (Na), calcium (Ca), and aluminum (Al). Bentonite usually forms from weathering of volcanic ash, most often in the presence of water. For industrial purposes, two main classes of bentonite exist: sodium and calcium bentonite.

Sodium bentonite expands when wet, possibly absorbing several times its dry mass in water. Because of its excellent colloidal properties it is often used in drilling mud for oil and gas wells and for geotechnical and environmental investigations.

The property of swelling also makes sodium bentonite useful as a sealant, especially for the sealing of subsurface disposal systems for spent nuclear fuel and for quarantining metal pollutants of groundwater. Similar uses include making slurry walls, waterproofing of below-grade walls and forming other impermeable barriers: e.g., to seal off the annulus of a water well, to plug old wells, or as a liner in the base of landfills to prevent migration of leachate.

Sodium bentonite can also be "sandwiched" between synthetic materials to create geosynthetic clay liners. This technique allows for more convenient transport and installation and it greatly reduces the volume of sodium bentonite required. Various surface modifications to sodium bentonite improve some rheological or sealing performance in geoenviromental applications, for example the addition of polymers.

Mesri and Olson (1971) found that, at the same void ratio, a sodium-dominated (Na) smectite was about 1000 times less permeable than a calcium-dominated (Ca) smectite. Calcium bentonite has a smaller swelling capacity and a higher hyraulic conductivity to water than sodium bentonite.

Calcium bentonite is widely used in industry and well known for its adsorption property. Gleason et al. (1997) conducted tests to investigate hydraulic conductivity conductivity of calcium and sodium bentonite in bentonite sand mixtures. Calcium bentonite was investigated on the hypothesis that it might be more hydraulically stable than sodium bentonite when exposed to chemical constituents in permeating fluids. When the bentonites were hydrated with distilled water, sodium bentonite had a much larger liquid limit and plasticity index than calcium bentonite. In the study the Atterberg limits were also measured by mixing the bentonites with NaCl and $CaCl_2$ solutions. When mixed with a strong $CaCl_2$ solution, sodium bentonite and calcium bentonite had approximately the same liquid limit and plasticity index. According to test results, calcium and sodium bentonite, when mixed with sand and comapcted, approximately three times more calcium bentonite was needed, compared to sodium bentonite to lower the hydraulic conductivity of the sand to less than $1x10^{-7}$ cm/s for tap water. Drained direct shear tests on bentonite hydrated in distilled water showed that calcium bentonite has a shear strength that is approximately twice that of sodium bentonite. Gleason et al. (1997) concluded that, calcium bentonite offered no significant advantage over sodium bentonite. The only advantage of calcium bentonite over sodium bentonite was a greater shear stregth. Properties of sodium and calcium bentonite used by Gleason et al. (1997) are summurized in Table 2.2.

Table 2.2. Properties of Sodium and Calcium Bentonite (Gleason et al., 1997)

Index property	Sodium Bentonite	Calcium Bentonite
Liquid limit (%)	603	124
Plasticity index (%)	567	98
Specific gravity of solids	2,76	2,94
Cation exchange capacity (meq/100g)	100-110	91-107
Smectite composition (%)	92	75-80
Inert material (%)	8	20-25

2.1.5.4. Use of bentonite for lowering permeability. Bentonite's unique rheological properties, make its use possible for many geotechnical applications. Relatively small quantities of bentonite suspended in water form a viscous, shear thinning material. Bentonite suspensions are also thixotropic. At high enough concentrations (~5 % bentonite in the suspension), bentonite suspensions begin to take on the characteristics of a gel. The ionic surface of bentonite has a useful property in making a sticky coating on sand grains.

Exposure of bentonite powder to water, or even water vapour, results initially in surface hydration due to the attraction of water molecules to the clay surfaces. This is primarily an interlayer process due to the relative amounts of interlayer and external surface. Water uptake beyond that needed to give an interlayer separation of about 1.2 μm (3-4 layers of water) results from diffuse double layer forces between the hydrated montmorillonite unit layers (Yong, 1999a). In a sodium montmorillonite unrestrained double layer swelling can result in the dispersion of the unit layers and the formation of a gel phase, where the plate-like unit layers form a “house-of-cards” structure which, on a macroscale, is a homogeneous system with some rigidity and elasticity (Woodward, 1995). However, complete dispersion of lamellae is sometimes prevented by the formation of tactoids (possibly due to Van der Waals forces or edge-face bonding of occasional non-aligned layers), which are stable regions where the lamellae are orientated essentially parallel to one another at a distance of about 100Å. When swelling is constrained, the density of the bentonite varies spatially in a manner that suggests that some aspects of the cluster structure are preserved after swelling (Pusch and Schomburg, 1999). However, stacks of lamellae can become exfoliated from the expanding clusters and reorganise to form gels that can invade the macroporosity (Alonso et al., 1999). Thus, Pusch and Schomburg (1999) proposed that swollen bentonite can be conceptualised as consisting of stacks of individual 10Å montmorillonite lamellae (hydrated unit particles), stack aggregates (particle clusters), and non-montmorillonite grains (as bentonite is not pure montmorillonite), and gel-filled and unfilled voids. Gens and Alonso (1992) related different aspects of the mechanical behaviour of swollen bentonite to the behaviour of structural elements at two different scales; the microstructural level at which swelling of active minerals takes place, and the macrostructural level at which major structural changes take place. Similarly, Graham et al. (1992) suggested that in a dense state bentonite supports applied loading both by direct contact between the clusters of hydrated unit particles and by diffuse double layer phenomena in the pore spaces between the clusters.

Studds et al. (1998) reported the behaviour of air-dried bentonite powder (SPV200 Wyoming bentonite supplied by Volclay) swelling one-dimensionally against a surcharge. Relationship between void ratio and vertical effective stres is shown in Fgure 2.8. At vertical effective stresses below about 200 kPa the bentonite void ratio is very sensitive to the applied stress, decreasing approximately linearly with the logarithm of vertical stress.

Above about 200 kPa the void ratio is less sensitive to changes in stress, but still appears to decrease linearly with the logarithm of vertical stress.

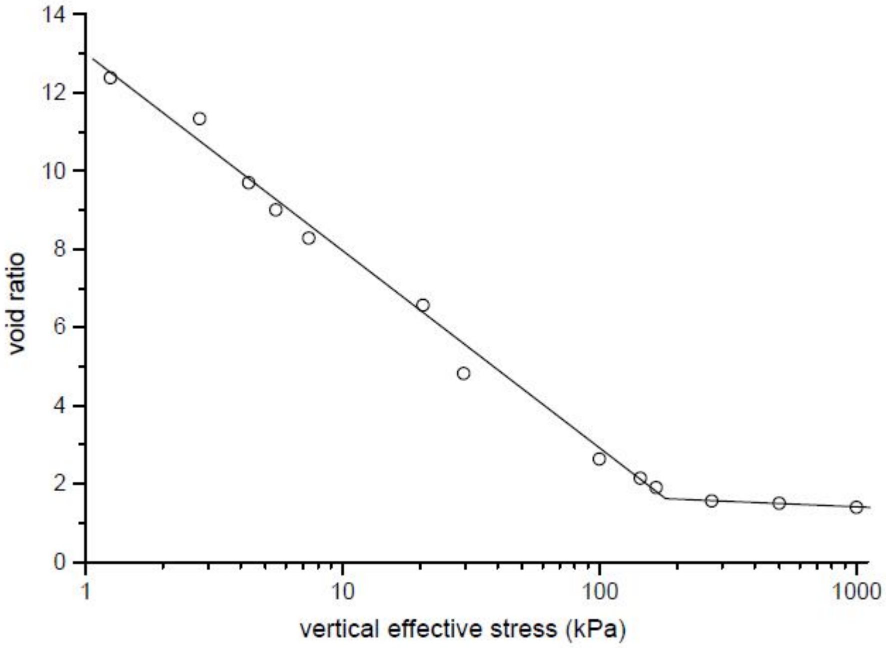


Figure 2.8. One-dimensional swelling behaviour of SPV200 bentonite in distilled water (Studds et al., 1998)

Studds et al. (1998) also reported similar tests where the same air-dried bentonite was allowed to swell with various chloride salt solutions. The tests reported by Studds et al. (1998) were conducted for periods of up to 45 days, and were not ended until all swelling had ceased. Malusis and Shackelford (2002) measured the rate of aqueous potassium chloride diffusion through a geosynthetic clay liner containing bentonite. Their specimens had a similar thickness to those used by Studds et al (1998). Malusis and Shackelford (2002) found that it took about 2 days to establish steady state diffusion of the conservative Cl^- specie, but between 10 and 30 days to establish steady state diffusion of the K^+.

Studds et al. (1998) found that at surcharges less than 200 kPa the amount of swelling in the salt solutions decreased with increasing solution concentration, and for each concentration the void ratio decreased approximately linearly with increasing vertical stres. Relationship between void ratio and vertical effective stres is shown in Figure 2.9. Studds et al. (1998) reported that in salt concentrations of 0.01M and 0.1M the amount of bentonite swelling decreased with increasing valance of the solution cation, but in 1M salt solutions the amount of swelling increased slightly with the valance of the solution cation. The trend in the 0.01M and 0.1M solutions is predicted by diffuse double layer theory, whereas the trend in the 1M solutions suggests that such a concentration is sufficient to suppress the diffuse double layer, and that the amount of swelling is related to the hydrated radius of the solution cation. Interestingly, the relatively small differences in swelling at a given solution concentration suggests that cation type does not have a significant influence on cluster-based microstructure of the bentonite when it swells against a surcharge from a dry state.

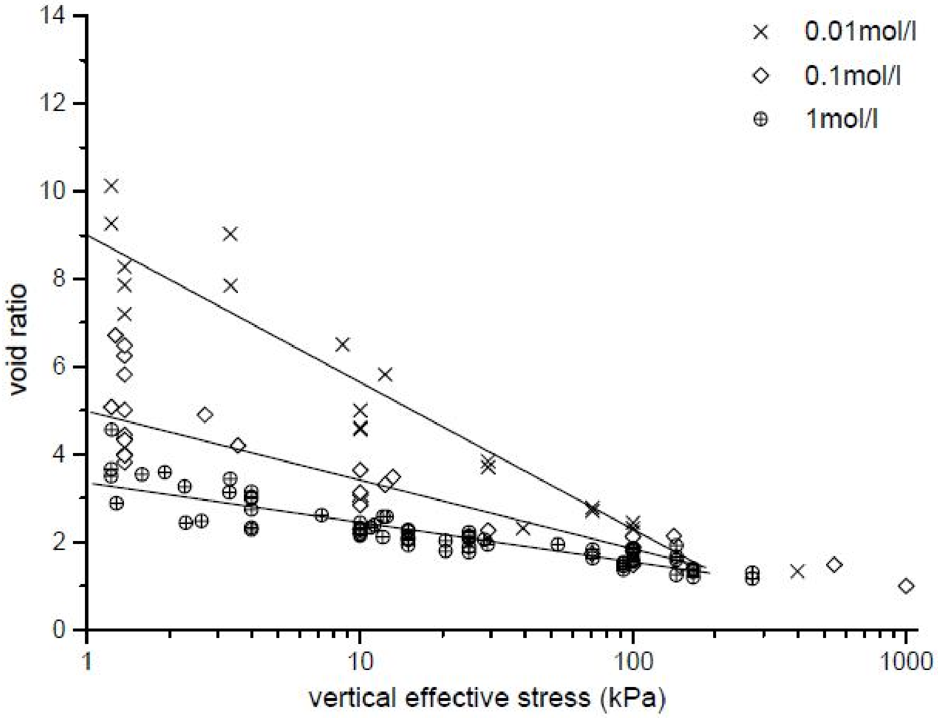


Figure 2.9. One-dimensional swelling behaviour of SPV200 bentonite in (b) various chloride salt solutions (Studds et al., 1998)

The insensitivity of bentonite void ratio to the pore solution composition and concentration above a stress of 200 kPa suggests that void ratio is not controlled by diffuse double layer interactions in this range.

Bentonite specimens that were prepared from powder will consist of clusters of hydrated unit particles separated by gel-filled and unfilled macropores, and it is suggested that an applied stress of about 200 kPa is sufficient to produce a network of particle clusters in close contact. Compression of such a network must involve deformation of the particle clusters. Thus it is suggested that, when bentonite powder swells one-dimensionally from an air-dried state, there is a change in the dominant process at an applied stress of about 200 kPa. At lower stresses the dominant process is diffuse double layer interaction between particle clusters, which will eventually produce a fabric of isolated clusters separated by gel. At higher stresses the clusters are in close contact, and volume change involves deformation of the clusters. Mollins (1996) determined the one-dimensional swelling behaviour of air-dried bentonite powder (Conquest Wyoming bentonite supplied by Colin Stewart MinChem) placed in an oedometer and allowed access to water, and compared it with the one-dimensional consolidation behaviour of the same bentonite mixed with water at a moisture content just above its liquid limit (LL) of 407%. Results are shown in Figure 2.10. It can be observed that the swelling behaviour of initially air-dried Conquest bentonite is very similar to that of SPV200 under the same conditions. During consolidation the void ratio of the LL specimen was significantly above the trendline for swelling. Mollins (1996) reported that an initially air-dried specimen that had swollen against a small surcharge exhibited very similar behaviour to the LL specimen upon subsequent consolidation. On unloading the expansion index of the LL specimen was significantly smaller than the compression index, indicating that the consolidation results in a change in bentonite fabric. It is suggested that the fabric of specimens prepared as air-dried powders (randomly orientated clusters of aligned unit particles) is only preserved during swelling if the bentonite is confined, and the structure becomes dispersed (i.e. essentially a system of hydrated unit particles) if sufficient swelling is permitted (either by mixing at the LL or if the confining stress during swelling is sufficiently small). Subsequent consolidation results in realignment of the bentonite unit particles, but not the formation of particle clusters.

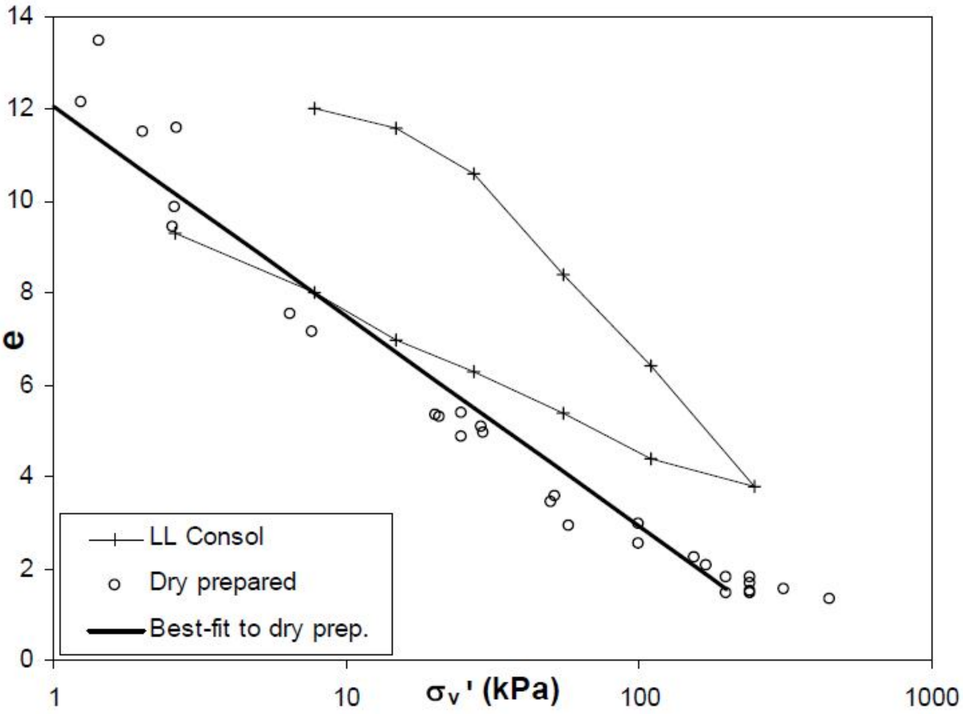


Figure 2.10. Comparison between the one-dimensional swelling behaviour and consolidation behaviour of Conquest Wyoming bentonite (Mollins, 1996)

Studds et al. (1998) measured the hydraulic conductivity to various chloride salt solutions of bentonite specimens that were initially prepared in an air-dry state, then allowed to swell in the selected solution against a surcharge stres. Hydraulic conductivity vs. void ratio graph is shown in Figure 2.11. For each strength of solution, there is a linear trend between the logarithm of hydraulic conductivity and the logarithm of void ratio. Also, at a given void ratio, the hydraulic conductivity of the bentonite increases as the solution strength increases. This later trend probably results from the influence of the permeant on the effective porosity. Dixon et al (1985) suggested that the effective porosity of a clay is less than would be expected considering the total pore space per unit volume because some of the pore space is occupied by bound water which has a greater viscosity than free water. Diffuse double layer theory predicts that the diffuse double layer thickness decreases with increasing pore-solution concentration. Therefore, at a given void ratio the effective porosity of the bentonite will increase as the solution strength increases.

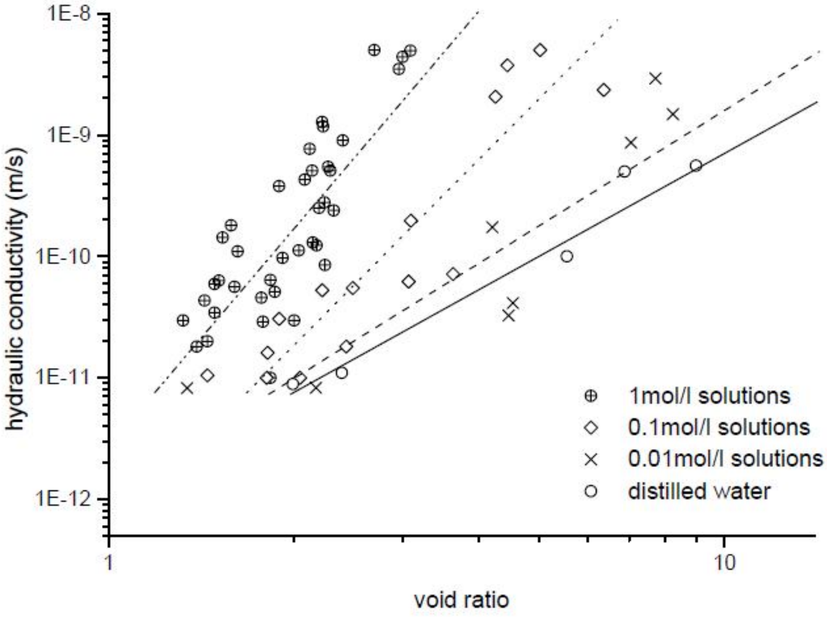


Figure 2.11. Hydraulic conductivity of SPV200 bentonite prepared in an air-dry state with distilled water and various chloride salt solutions (Studds et al., 1998)

3. LINERS FOR WASTE CONTAINMENT

Landfills are solid waste containment systems, designed to minimize the negative impacts on human health and environment. The main purpose of a landfill is isolating the waste from the soil by a liner system in order to protect the ground water and soil from the pollution caused by leachate. In an effort to inhibit the flow of liquid contaminants into the environment, soil is often used in parts of containment systems in waste disposal activities. Leachate consisting of water and water-soluble compounds, accumulate through soil by the gravitational forces. Landfill liners are designed and constructed to create a barrier between the waste and the environment and to drain the leachate to collection and treatment facilities. The liners are incorporated into an overall design philosophy of containment in which leachate is removed from a landfill for treatment to reduce static fluid pressure on a liner (Finno and Schubert, 1986).

Different types of solid wastes are generated by people, bringing out different threats to human health and environment. Diversity of solid wastes, cause the design and construction of disposal sites to be different considering the properties of solid waste and leachate. Kerry et al. (2010) suggested that liners might be grouped in three: single, composite and double liners.

Single liners are cheaper to build and maintain. They consist of a clay liner, a geosynthetic clay liner, or a geomembrane. Single liners are sometimes used in landfills designed to hold construction and demolition debris. A typical single liner is demonstrated in Figure 3.1.

Composite liners consist of a geomembrane and a clay liner. They are more effective in minimizig the leachate flow than single liners. In municipal solid waste landfills single liners are not adequate and composite liners are required. These liners are not for use against hazardous wastes. A typical composite liner is demonstrated in Figure 3.2.

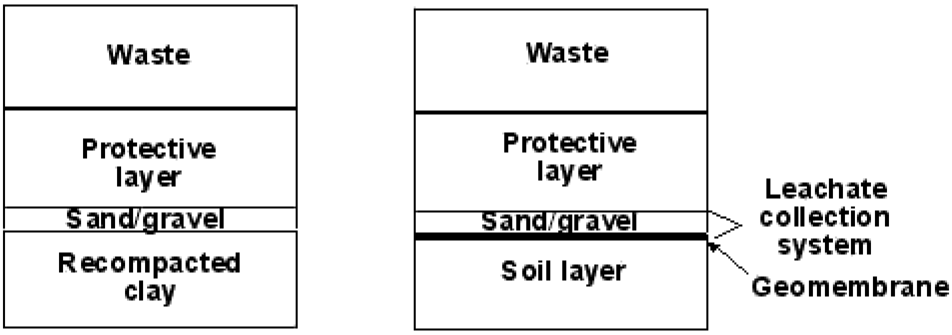


Figure 3.1. Typical single liner systems (Kerry et al., 2010)

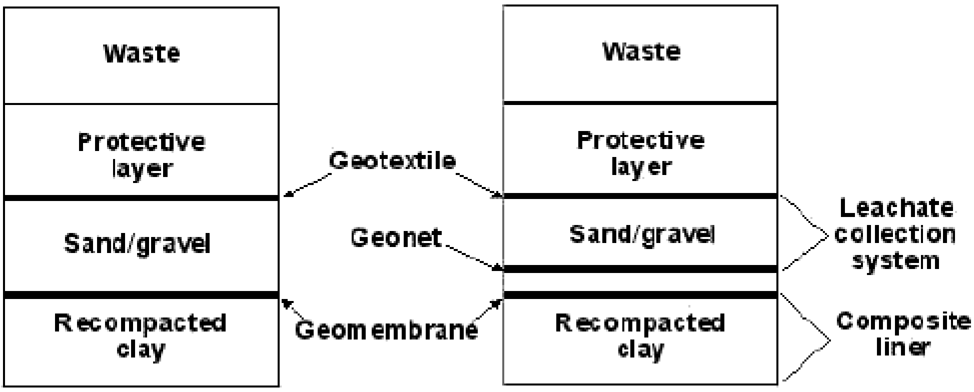


Figure 3.2. Typical composite liner systems (Kerry et al., 2010)

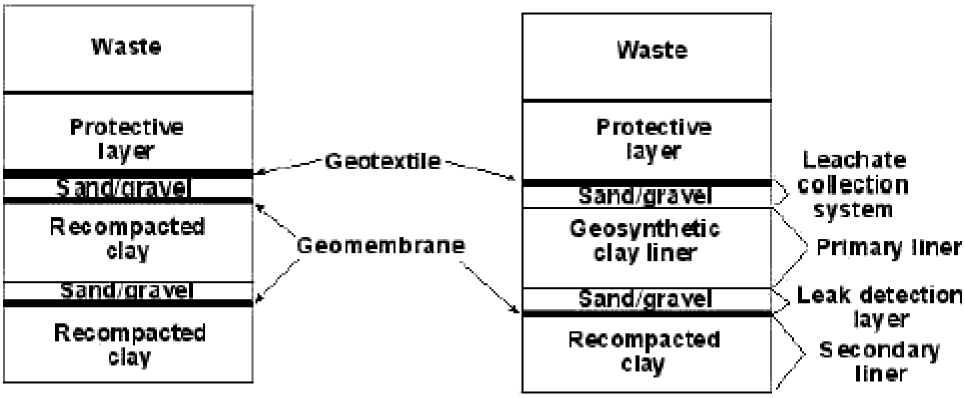


Figure 3.3. Typical double liner systems (Kerry et al., 2010)

A double liner consists of either two single liners, two composite liners, or a single and a composite liner. The upper liner usually functions to collect the leachate, while the lower liner acts as a leak-detection system and backup to the primary liner. Double-liner systems are used in some municipal solid waste landfills and in all hazardous waste landfills. A typical double liner is demonstrated in Figure 3.3.

3.1. Clay Liners

Pollution of the environment due to leakage from waste repositories is a well-known and wide spread problem. The choice of liner depends on the design of the waste deposit and its water balance. Water balance is the most important factor when it comes to determining the necessary hydraulic conductivity and the thickness of the barrier. Many different barrier materials exist, for example, plastic membranes, geotextiles, bentonite, compacted clay, cement stabilised products, and several different waste products (Goran and Lena, 2002). Clay liners are widely used as hydraulic barriers in waste-containment facilities. To be effective, they should have low hydraulic conductivity, which in many cases is considered to be less than $1x10^{-6}$ mm/s. In recent years, guidelines have been compiled for selecting appropriate soil properties and compaction methods that are likely to result in low hydraulic conductivity (Lambe, 1955). These guidelines are typically based on experience and generally include minimum values or acceptable ranges for properties that describe composition of soil, recommendations for selection criteria and compaction machinery.

Factors affecting the hydraulic conductivity of soil liners have been examined by Elsbury et al. (1990) and Benson et al. (1990). The factors can be decomposed into groups within the three preoperational stages in the life of a liner; design, construction and post-construction. These factors are grouped in Table 3.1.

3.1.1. Workability

Clay that is used in liner construction should be easy to work with. Highly plastic materials are sticky when the soil is wet and form hard clods when the soil is dry. Hence, highly plastic soils can be difficult to work with in the field. Although poor workability does not necessarily prevent the use of soil for a liner, soils that are difficult to work require more effort to process and compact into low hydraulic conductivity liners (Elsbury et al., 1990).

3.1.2. Atterberg Limits

The Atterberg limits are indices of the quantity of clay-size particles and their mineralogical composition. Higher liquid limit and plasticity index are associated with soils which have greater quantity of clay particles or clay particles having greater surface activity (Mitchell, 1976). In particular, all other factors being equal, more plastic clays should have lower hydraulic conductivity (Benson et al., 1990). Mesri and Olson (1971) found out an inverse trend of decreasing hydraulic conductivity with increasing plasticity. They investigated how the hydraulic conductivity of clays were related to clay type, void ratio, and permeant chemistry. They have tested three specimens; kaolinite, illite and montmorillonite. The specimens had placticity indices of approximately 20, 60 and 500.When permeated with water they measured the hydraulic conductivities: $1,5 \times 10^{-6}$ cm/s for kaolinite, 2×10^{-9} cm/s for illite and $1 \text{x} 10^{-11}$ cm/s for montmorillonite. They explained that the clays with a higher plasticity index had smaller particles, less aggregation, and thicker double layers. These factors combined to yield lower hydraulic conductivity.

Activity is an index of the surface activity of clay fraction. Hydraulic conductivity should decrease with increasing activity as clay minerals with greater activity are likely to consist of smaller particles having larger specific surfaces and thicker double layers. Figure 3.5. demonstrates the relationship between activity and hydraulic conductivity (Benson et al., 1990).

3.1.3. Particle-Size Distribution

The particle-size distribution of compacted clay affects hydraulic conductivity because of voids conducting flow is affected by the relative proportions of large and small particle sizes. Low hydraulic conductivity is likely to be achieved when the soil is well graded and the clay fraction governs the hydraulic behavior of the matrix (Benson et al., 1990). The soil must have sufficient clay to enable it to produce a low hydraulic conductivity (Elsbury et al., 1990).

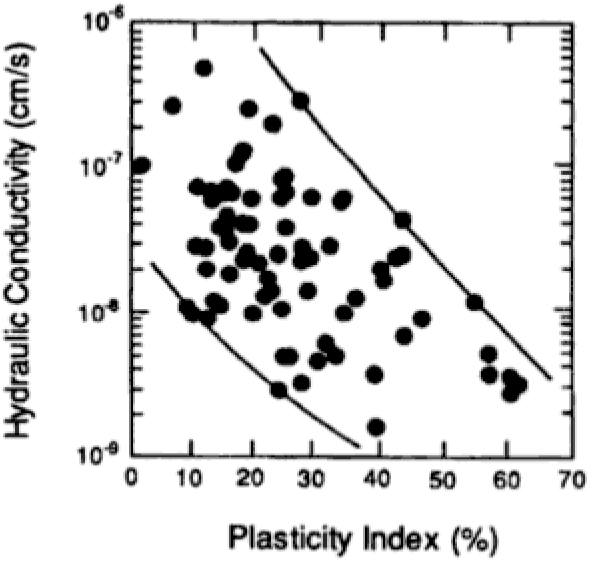


Figure 3.4. Relationship between hydraulic conductivity and plasticity index (Studds et al., 1998)

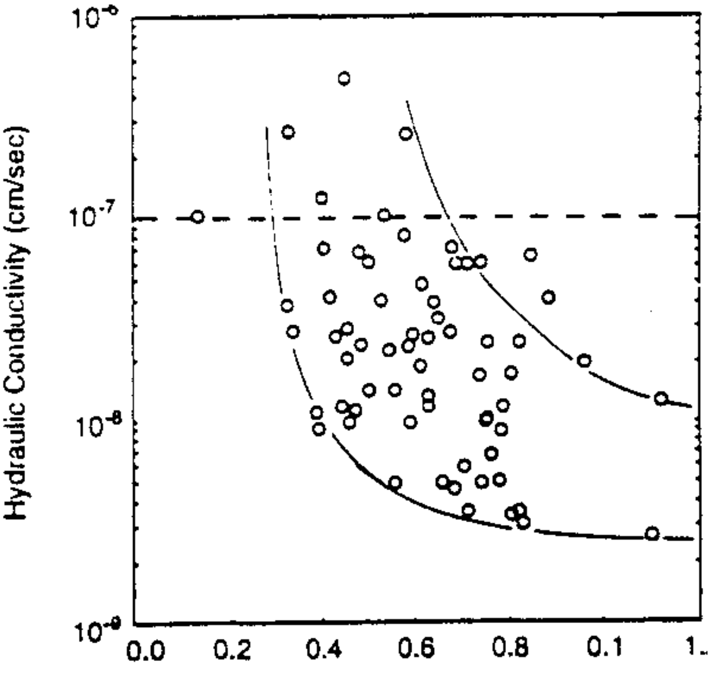


Figure 3.5. Hydraulic conductivity versus activity (Benson et al., 1990)

Table 3.1. Key factors that influence hydraulic conductivity of compacted clay liners (Elsbury et al., 1990)

Principal group(1)	Key factors (2)
(a) Design Stage	
Soil type	Workability Gradation Swell potential
Other considerations	Overburden stress Liner thickness Foundation stability
(b)Construction Stage	
Basic compaction objectives	Destruction of clods Interlift bonding
Essential choices (to achieve The basic compaction objectives)	Lift thickness Water content of the soil Type and weight of the roller Number of passes and coverages Size of clods
Supporting elements(that are İncluded in or subsidiary to Essential choices)	Dry density Degree of saturation
Other considerations	Soil preparation Compaction quallity assurance
(c)Postconstruction Stage	
Environmental influences	Desiccation Freezing

The ability of a soil to produce a low hydraulic conductivity liner can be evaluated either indirectly by plasticity index and percentage of fines, or by laboratory hydraulic conductivity tests. Presence of excessive quantities of gravel and coarse sand can result in segregation of the soil into interconnected pockets or channels that do not have enough fines.

Daniel (1987) found that hydraulic conductivty decreased significantly as the percentage of bentonite was increased from 0 per cent to 8 per cent. Kenney et al. (1992) compacted and permeated sand bentonite mixtures at various water contents and observed that for water contents wet of optimum, hydraulic conductivity was very sensitive to bentonite content when the bentonite content was less than 12 per cent and insensitive for bentonite contents exceeding 12 per cent. The low hydraulic conductivities achieved at bentonite contents 8-12 per cent occured because clay size particles filled voids between the sand particles and controlled the hydraulic behaviour of the soil. Effectively, the soil was behaving hydraulically as a clay even though it was principally composed of sand particles. This behavioor is consistent with findings of Seed et al. (1964) who found that mixtures of sand-bentonite changed from nonplastic to plastic at bentonite contents near 10 per cent.

3.1.4. Swell and Shrinkage Potential

The swell behavior of expansive soils may be desirable as in many hydraulic containment applications or unfavourable and may cause major deterioration and distress in may geotechnical applications such as highways and shallow foundations on expensive formations. Expansive soil in its natural and compacted state undergoes increase in volume upon wetting. This volume change often defined as swell, may be desirable as in many hydraulic containment applications such as soil barriers in land fill liner and cover systems. Elsbury et al. (1990) suspect that unconfined swelling can enlarge existing cracks and introduce visible structure, which will increase hydraulic conductivity.

Clay liners are typically placed and compacted wet compared to optimum water content. This practice minimizes hydraulic conductivity of the compacted clay at the time of construction. As the molding water content of a compacted clay is increased, the shrinkage potential of the soil increases as well. At relatively arid areas or sites where the clay could be subjected to seasonal drying, the liner will eventually desiccate. Large cracks can occur in wet compacted clays that are allowed to dry (Daniel and Wu, 1993).

Boynton and Daniel (1985) tested the hydraulic conductivity of samples with and without desiccation cracks. They found that hydraulic conductivity was sensitive to the effective confining stress, which was sequentially increased after each permeation stage.

Due to their low hydraulic conductivity, compacted clay liners are commonly used in modern waste disposal facilities to minimize advective flow of leachate from landfills (Rowe et al., 2004). When placed, these liners are unsaturated. The biodegradation of organic matter in the waste body can cause the temperature at the top of the landfill liner to increase up to 65°C, although increases up to 40°C are more common. A change in liner temperature causes a change in soil properties. Under non-isothermal conditions, water vapor moves from areas of higher temperature toward areas of lower temperature due to vapor diffusion, while liquid water moves from higher capillary pressure toward lower capillary pressure. In addition, air moves from zones of higher air pressure to those of lower air pressure. This air flow can increase or decrease vapor transport due to advection. The combined effect of liquid water, vapor water, and air flow is a redistribution of water in the liner system; this redistribution has the potential to cause desiccation of clay liners. Desiccation may cause a reduction in void ratio, deformations, and crack initiation and propagation. A significant temperature increase has the potential to cause sufficient decrease in water content to induce cracks that could substantially increase the hydraulic conductivity of the cracked liner (Zhou and Rowe., 2005). An example of crack in a clay liner is shown in Figure 3.6.

Desiccation also has a severe impact on the hydraulic conductivity of compacted clay by inducing shrinkage and cracking (Albrecht, 1996). Large-scale tests conducted by Drumm et al. (1997) have shown that shrinkage cracks in clay resulted in preferential flow paths and substantial increases in hydraulic conductivity.

Albrecht (1996) investigated how soil properties affect shrinkage during drying and the hydraulic conductivity of compacted clays after wetting and drying. He found that shrinkage and changes in hydraulic conductivity are minimized by compacting clay close to optimum water content. Albrecht (1996) also showed that shrinkage, cracking, and increases in hydraulic conductivity caused by desiccation are larger in more plastic clays. The results of these findings are exhibited in Figure 3.7.

Figure 3.6. Crack in a compacted clay barrier in a landfill cover in southern Wisconsin, USA (Albrecht, 1996)

3.1.5. Freeze and Thaw

Studies have shown that freeze/thaw effects can increase permeability of clay liners one to two orders of magnitude. The increase in permeability is caused by the formation and expansion of ice in the soil. When the soil thaws, cracks are left creating pathways for water movement.

Freeze and thaw is a practical problem in two cases. One involves construction of a landfill liner that is exposed to freezing temperatures before the liner can be covered with enough waste material to prevent liner from freezing. The second consideration is for cover systems. Molding water content was found to be the single most important variable that affected the tendency of compacted specimens to undergo an increase in hydraulic conductivity as a result of freeze and thaw (Kim and Daniel, 1992).

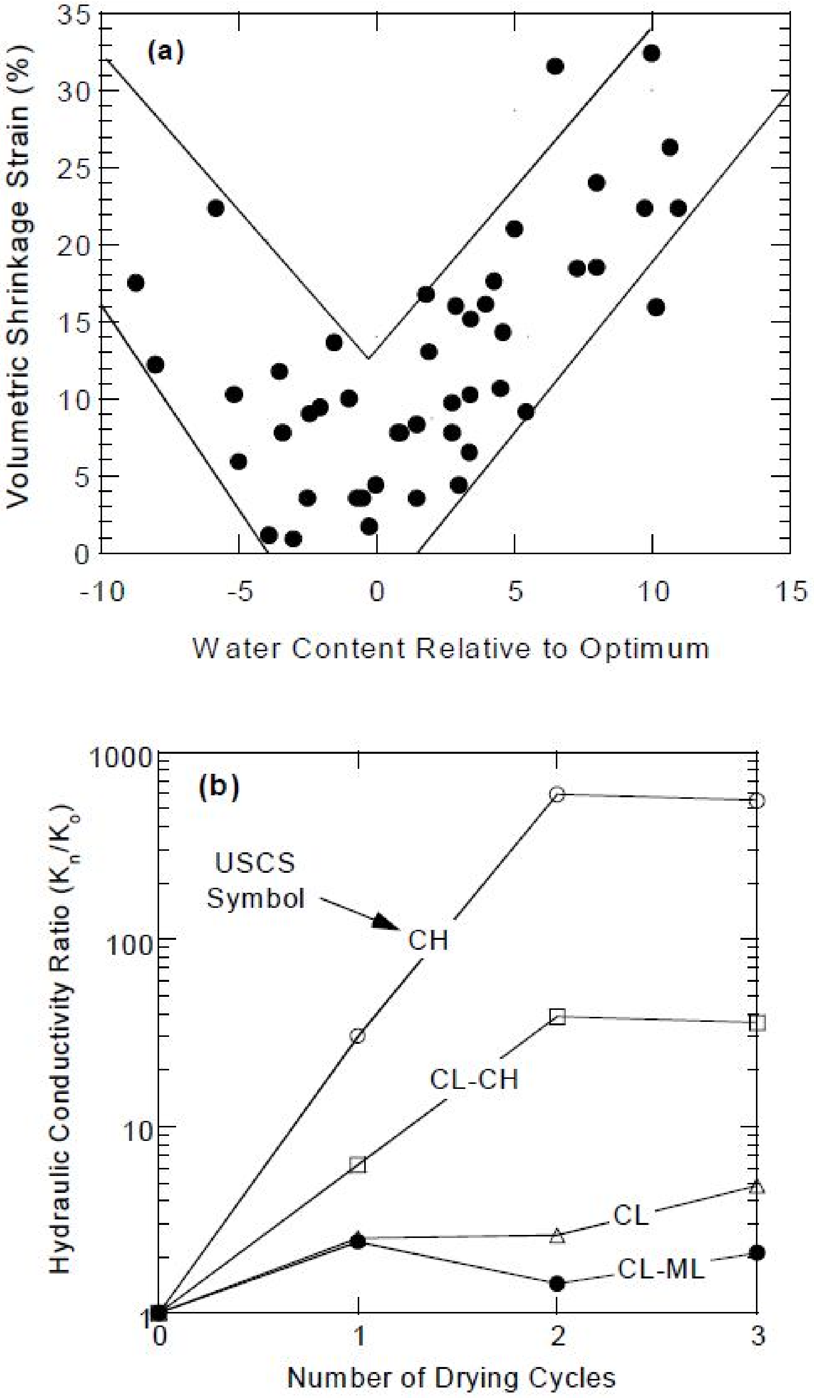


Figure 3.7. Volumetric shrinkage strain vs. compaction water content (a) and hydraulic conductivity ratio vs. number of wet-dry cycles (b) Hydraulic conductivity ratio is hydraulic conductivity after a specified number of wet-dry cycles (K_n) divided by the initial hydraulic conductivity (K_o). Volumetric shrinkage strain vs. compaction water content (a) and hydraulic conductivity ratio vs. number of wet-dry cycles (Kerry et al., 2010)

Frost-related damage to compacted clay barriers is caused by desiccation induced as the freezing front moves downward and by the formation of ice lenses (Albrecht, 1996). Hydraulic gradients driving flow to the growing lenses cause desiccation of the underlying clay, which results in vertically oriented shrinkage cracks. Horizontal cracks are created as ice lenses form. The horizontal and vertical cracks form a permeable network responsible for the increase in hydraulic conductivity. An example of cracks formed by ice lenses is shown in Figure 3.8. This photograph was taken by backlighting a frozen thin section trimmed from a larger frozen specimen. Ice lenses are the thin white features that are nearly horizontal (Benson, 2000).

Laboratory and field testing have shown that most of the damage caused by frost occurs within three to five freeze-thaw cycles (Figure 3.9.). The magnitude of these changes can be predicted reasonably well using the standard laboratory methods. Benson (2000), observed that the field and laboratory hydraulic conductivities were similar for freze/thaw effect.

3.1.6. Overburden Stress

Significant effects may be observed on the hydraulic conductivity of clay liners with the vertical stress on it. The range of overburden pressures induced on compacted clay barriers beneath landfills, surface impoundments was documented by Peirce et al. Results indicated that maximum overburden pressures for hazardous waste landfill facilities varied considerably, but were generally in the range of 160 to 360 kPa for hazardous landfill sites and 22 kPa to 115 kPa for sanitary landfills.

3.1.7. Thickness of Liner

Although definitions of performance vary, adequate performance requires that a soil liner be physically stable (foundation and side slopes), have relatively long time before leakage first occurs, and have a small flux subsequent to the commencement of leakage. No consensus has been formed, however, regarding a minimum thickness that satisfies these performance criteria. The lack of concensus is evident in wide variation in minimum thickness, 60-360 cm (Benson and Daniel, 1994).

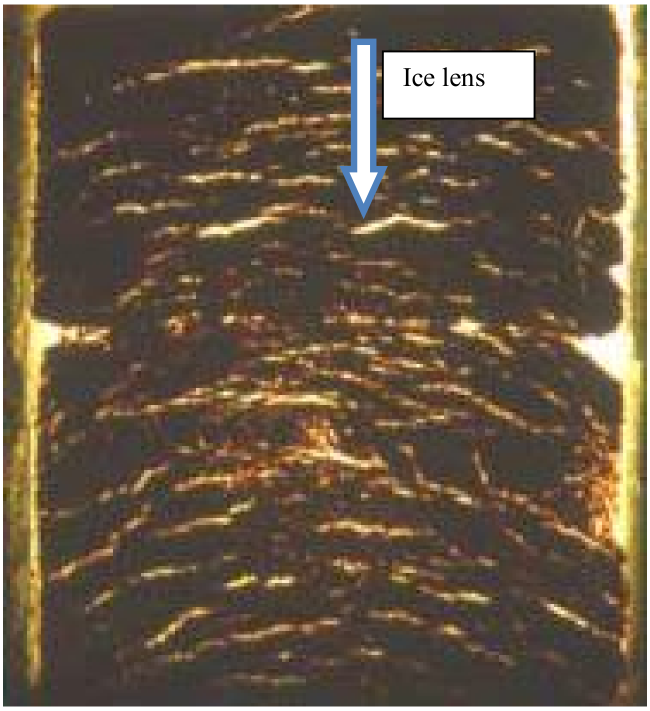


Figure 3.8. Ice lenses in a compacted clay (Benson, 2000)

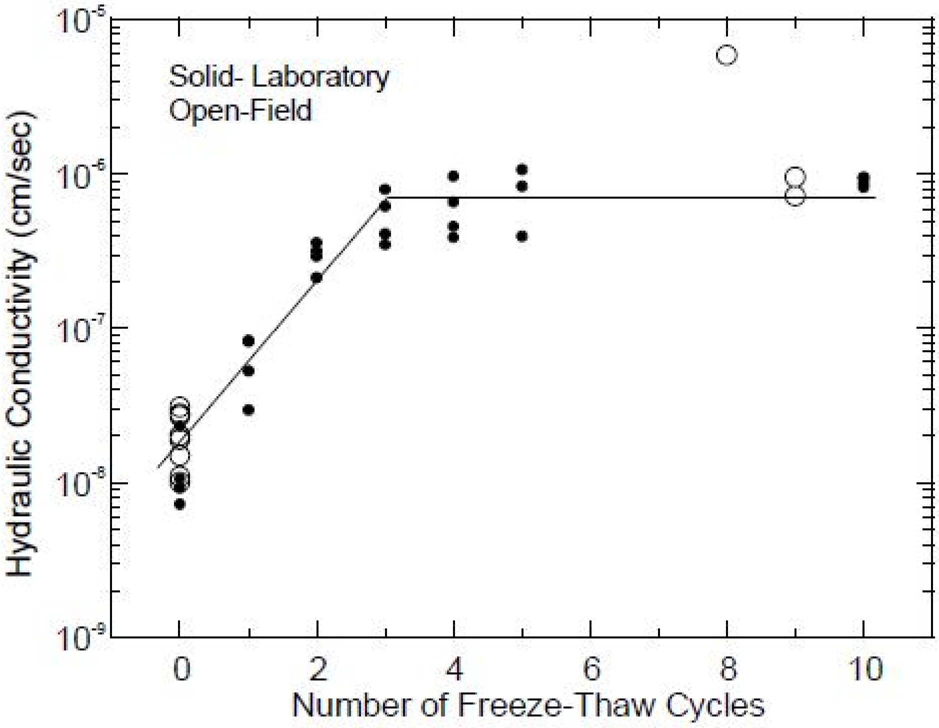


Figure 3.9. Hydraulic conductivity of compacted clay as a function of number of freeze-thaw cycles (Benson, 2000)

The thickness of the liner affects the overburden stress and the length of the seepage paths. Thicker liners will lead to an increase in overburden stress and this will cause lower permeability (Elsbury et al., 1990).

3.1.8. Effects of Compaction

The negative consequences of excessively high field conductivity prompted research into mechanisms controlling field hydraulic conductivity and how specifications can be written to ensure that low field hydraulic conductivity can be obtained. Benson and Boutwell (2000) found that the key factor influencing the field hydraulic conductivity is the compaction condition relative to the line of optimums. Clay liners compacted wet of the line of optimums typically are comprised of microscale pores and are devoid of interconnected macropores (Figure 3.10.). As a result, the field hydraulic conductivity (K_F) of clay liners compacted wet of the line of optimums is typically low and comparable to the hydraulic conductivity measured on small laboratory-scale (76 mm diameter) specimens (K_L). In contrast, clay liners compacted dry of the line of optimums typically contain numerous macropores that are not captured in small laboratory-scale specimens. As a result $K_F >> K_L$ for clay liners compacted dry of the line of optimums (Benson, 2000).

Mitchell et al. (1965) published the most extensive study illustrating how molding water content and dry unit weight influence the hydraulic conductivity of compacted clay and concluded that lowest hydraulic conductivity values are obtained with compaction at a water content slightly wet of the optimum water content. In other words, the permeability of compacted clay is minimum on the wet side of the optimum moisture content, w_{opt}, and at about maximum dry unit weight, γ_{dmax} (Figure 3.11.). This means that permeability can be minimized by compacting the clay to the appropriate moisture content and dry unit weight.

There are two theories about why compaction wet of optimum produces low hydraulic conductivity. Benson and Daniel (1990) named two theories as the particle-orientation theory and the clod theory. The particle-orientation theory was proposed by Lambe (1958a) and relates the hydraulic conductivity of compacted soils to the orientation of the soil particles. Lambe (1958b) concluded that comparisons show a much higher permeability for a soil compacted dry of optimum than for the soil compacted wet of optimum. Since the sample compacted dry of optimum has more random orientation (flocculated), it has larger pores than does the sample with more nearly parallel arrangement (dispersed) obtained from wet-side compaction. The larger the individual pores for any given total pore area, the greater is the flow, since the permeability varies as a power function of opening size. Thus according to the particle orientation theory, the arrangement of individual particles, which is influenced by molding water content, controls the hydraulic conductivity (Figure 3.12).

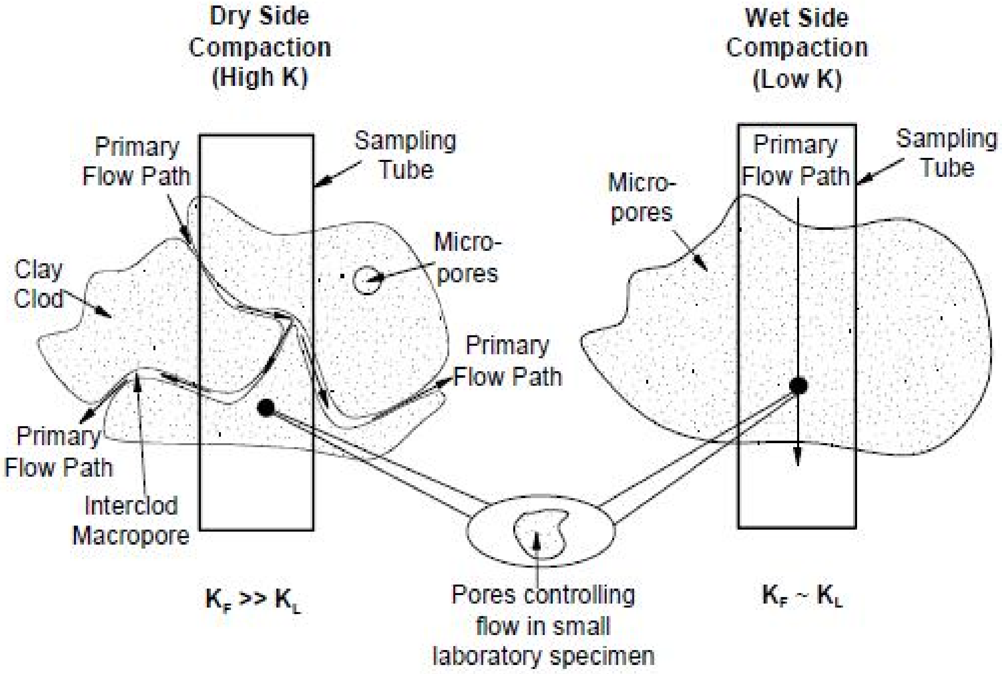


Figure 3.10. Schematic diagram showing size of pores conducting flow relative to the size of a typical thin-wall sampling tube (Benson, 2000)

The second theory seems to have developed gradually. The influence of cluster (the uncompacted soil consists of aggregates of soil particles, called clusters), but Mitchel et al. (1965) implied that they were of microscopic size (Figure 3.13.). He referred to both flocculated structure and also to visible clusters and aggregates as the explanation for the higher permeability of clays compacted dry of optimum. Barden and Sides (1970) clearly concluded from studies involving laboratory tests and scanning electron microscopy that 'macropeds' and the resulting 'macropores' not the arrangement of individual clay particles, are the principle cause of higher permeability in compacted clays. And lately Elsbury et. al. (1990) stated after examination of laboratory-compacted soils that the fate of clods and the interclod pores had a major influence on permeability.

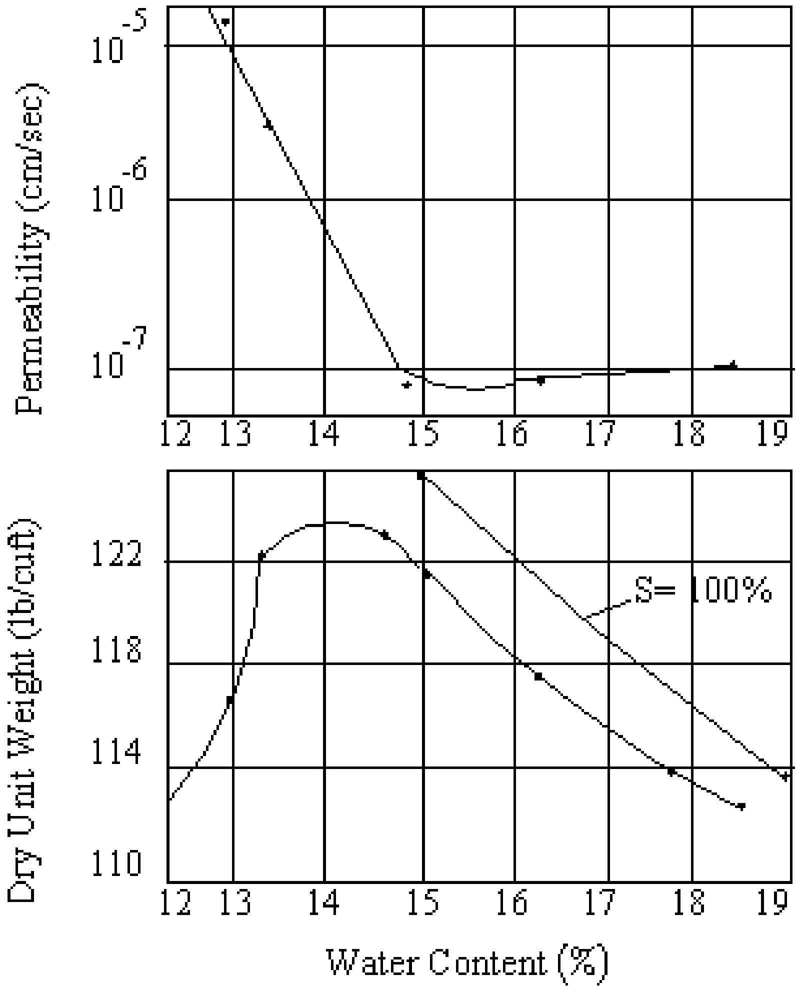


Figure 3.11. Relationship of permeability to dry density and water content. Compaction-permeability tests on Jamaica sandy clay (Mitchell et al., 1965)

In addition to the effect of moisture content and type of compaction, the amount of compactive effort also influence the moisture density relationship and therefore, the hydraulic conductivity (Figure 3.15.). Permeability at constant compactive effort decreases with increasing water content and reaches a minimum at about the optimum. If the compactive effort is increased, the coefficient of permeability decreases because the void ratio decreases (increasing dry unit weight). This change in permeability with molding water content is shown in Figure 3.11, where it can be seen that the permeability is about an order of magnitude higher when this soil is compacted dry of optimum than when it is compacted wet of optimum.

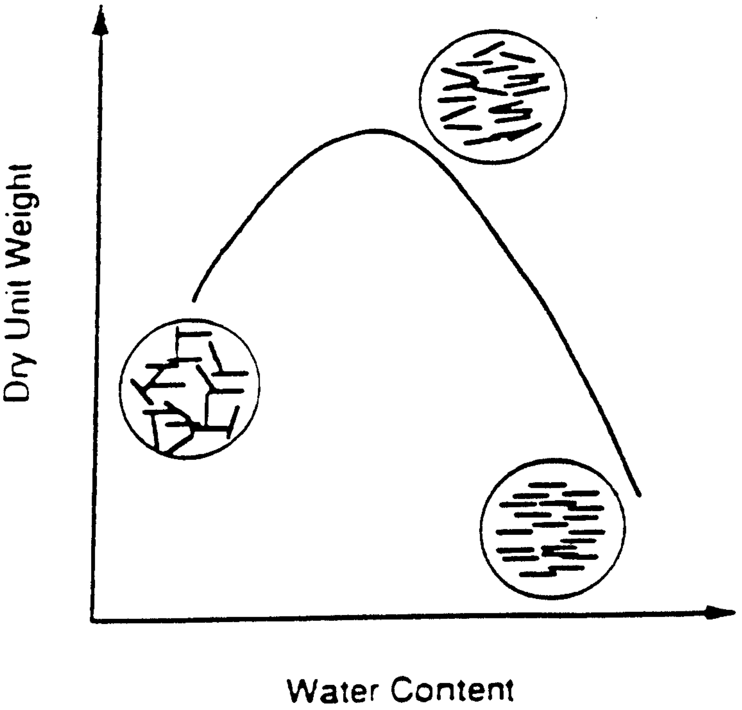


Figure 3.12. Arrangement of soil particles (Lambe, 1958a)

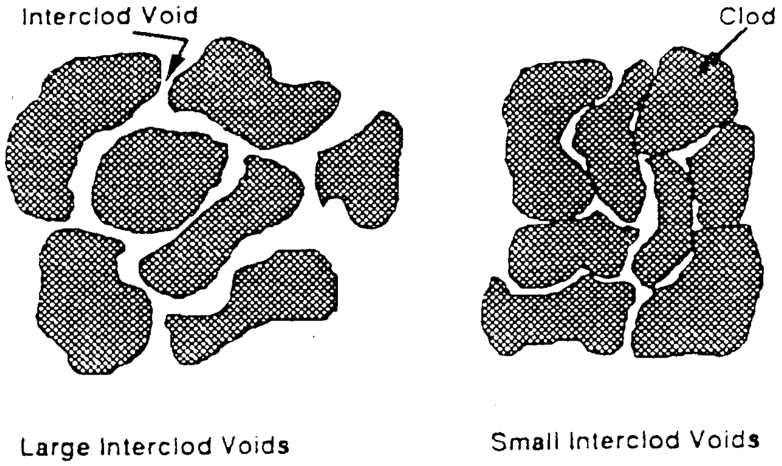
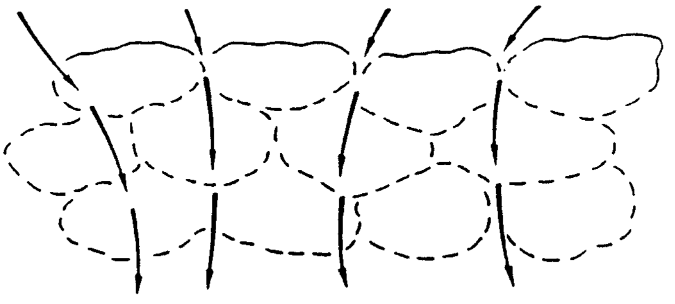
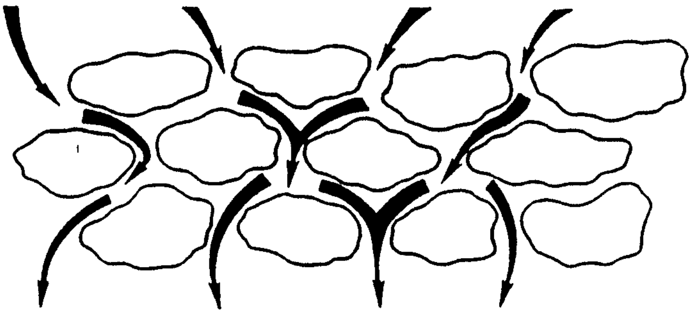


Figure 3.13. Flow of water through relatively large pores between clods of soil (Elsbury et al., 1990)



REMOLDED CLODS



UNBONDED CLODS

Figure 3.14. Influence of remolding of soil clods on permeability of compacted clay (Elsbury et al., 1990)

3.1.9. Chemical Effects on the Hydraulic Conductivity of Clay

Organic and inorganic chemicals affect the hydraulic conductivity of clay liners. Inorganic chemicals affect the fabric and pore spaces of the clays. The effects of inorganic chemicals on hydraulic conductivity are consistent with: their effect on double layer and inter-particle forces that promote flocculation, dispersion, shrinkage and swelling; their effects on surface and edge charges on flocculation and deflocculation; the effects of high and low pH. Hydraulic conductivity values changes because of changes in ion concentrations, ion exchange, anion absorption, and dissolution. Strongly acidic and strongly basic liquids can dissolve clay minerals. When the clay minerals are dissolved this process causes loss of mass and thus increases the effective pore space increasing the hydraulic conductivity at the same time. Soil organic interactions are usually by absorption, intercalation and cation exchange. Absorption is the most effective one on hydraulic conductivity. Organic acids can cause dissolution of clay minerals by effecting on carbonates and iron oxides.

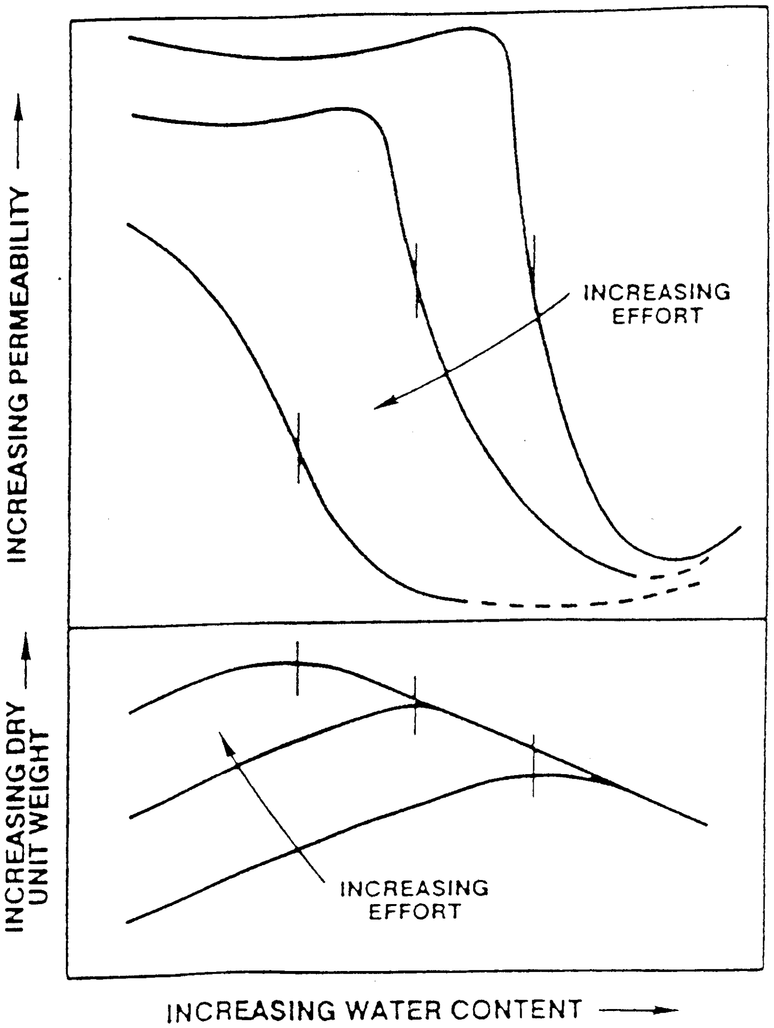


Figure 3.15. Influence of compactive effort and water content on permeability of compacted clay soils (Elsbury et al., 1990)

4. COMPACTED BENTONITE-SAND MIXTURES FOR HYDRAULIC CONTAINMENT

Bentonite-sand mixtures are widely used as barriers to control the movement of liquid from waste disposal facilities because, these mixtures combine relatively high strength and low compressibility with very low hydraulic conductivity. These properties are achieved by using a mixture that contains enough sand to ensure the stability of compacted mixture and enough bentonite to fill the voids between sand particles. Other important benefits are that bentonite-sand mixtures containing modest amounts of bentonite is fairly resistant to desiccation (Tay et al., 2001), and the bentonite in the mixture has a high chemical buffering capacity (Yong, 1999).

4.1. Factors Affecting the Hydraulic Conductivity of Sand-Bentonite Mixtures

In most cases the maximum allowable hydraulic conductivity for a barrier material is specified by the client. The base material, sand or till, is usually a local material and can be very different from place to place. The task to produce a barrier material in place, which meets the criteria given at the lowest possible cost, requires good knowledge of the different factors affecting the final hydraulic conductivity of the mixture. These factors are listed and briefly discussed below (Goran and Lena, 2002).

4.1.1. Percentage of Bentonite

This is the prime parameter and, as bentonite is a material with a very low hydraulic conductivity, it is quite obvious that the higher the percentage of bentonite, the lower the permeability. However, as the cost of bentonite is high, the main task is usually to determine the minimum percentage of bentonite necessary to fulfill the given requirements. Normally, the amount of bentonite (in a sand-bentonite mixture used as a barrier) constitutes 4-13 per cent of the dry weight of the sandy material. Greater amounts of bentonite tend to form around the sand grains, and the mixture becomes plastic and consequently difficult to compact. Further, the decrease in hydraulic conductivity becomes marginal, and will not be cost-effective in a design (Chapuis, 1990).

4.1.2. Mixture and Compaction

The procedure on site for mixing, placing and compacting the sand-bentonite mixture plays an extremely important role for the final quality of the barrier. A thorough mixture of the bentonite and the base material is important for reducing the scatter in the permeability. Equally important is to follow the outlined procedure for placing and compaction. The most effective compaction is reached when the sand-bentonite mixture has a water content close to optimum or just above (about 2 per cent) (Haug and Wong, 1992).

4.1.3. Water Content

Almost all compaction work, where density is an issue, is preceded by a laboratory compaction test. Hereby, the optimal water content is determined, which defines the water content for which the highest dry density is obtained. For clayey material, and certainly for a sand-bentonite mixture, the hydraulic conductivity of the compacted material is greatly dependent on whether compaction is made on the wet side or the dry side of optimum. Compaction on the wet side leads to good kneading and a fairly homogeneous distribution of voids within the material. Compaction on the dry side often results in a large portion of much larger pores, due to aggregation of the clay matrix, and usually results in substantially larger hydraulic conductivity (Goran and Lena, 2002).

4.1.4. Type of Bentonite

Bentonite is a brand name for fine grained swelling types of clay. Often clays with a high content of swelling clay minerals (smectites) are used. The minerals swell during uptake of water, which is absorbed into the crystalline lattice and bound through electrical charges. The electrical bindings are mediated by the cations, which are loosely connected to the crystalline lattice. The amount of cations and the ion strength of the liquid determine the magnitude of the swelling. The most common cation is calcium and sodium, where sodium has the greater ability to swell and consequently gives better sealing i.e. lower hydraulic conductivity (Mitchell and Soga, 2005).

4.1.5. Grain Size Distribution for the Base Material

The grain size distribution is one of the most important parameters used to characterise a soil material, and it has an impact on the hydraulic conductivity. A coarse grained material will have a higher hydraulic conductivity than a fine-graded material due to the distributions of the voids. Similarly, a well-graded material when compacted is likely to have a lower hydraulic conductivity than a poorly graded material (Goran and Lena, 2002).

4.1.6. Time

Time plays a very important role when it comes to the resulting hydraulic conductivity of a sand-bentonite mixture. The sand and bentonite are often mixed dry or at least in an unsaturated phase and then compacted at an optimum water content, resulting in a sample that is not fully saturated. The bentonite swells during uptake of water and, consequently, it will take a long time before the degree of saturation in the sample is homogeneous and the minimum hydraulic conductivity is obtained due, to the low hydraulic conductivity of the bentonite. For example, it can take about 2-7 days, with a gradient of five or larger to reach full hydration of a small sample of a sand-bentonite mixture and to reach steady state seepage conditions. However, reaching steady state does not necessarily mean that the specimen is fully saturated. Since the degree of saturation strongly affects the hydraulic conductivity, it is important to determine the degree of saturation at the end of each test (Chapuis, 1990).

4.2. Performance of Bentonite-Sand Mixtures

The size of the coarser fraction has a very important role in controlling the hydraulic conductivity of the bentonite-sand mixture. At low bentonite contents the hydraulic conductivity of the mixture varies depending on the size of the coarser fraction apart from clay content. At a given clay content, the hydraulic conductivity increases with an increase in the size of the coarser fraction. But when the clay content is more than that which can be accommodated within the voids of the coarser fraction, the hydraulic conductivity is controlled primarily by clay content alone (Sivapullaiah et al., 2000). Daniel (1987) found that hydraulic conductivity decreased significantly as the percentage of bentonite was increased from zero per cent to eight per cent. At higher bentonite contents, however, little further reduction in hydraulic conductivity occurred. Similar results have been observed by Kenney et al. (1992), who compacted and permeated sand-bentonite mixtures at various molding water contents. For water contents wet of optimum, hydraulic conductivity was less than 12 per cent and insensitive for bentonite contents exceeding 12 per cent.

The low hydraulic conductivities achieved at bentonite contents exceeding 8-12 per cent occurred because clay-size particles filled voids between the sand particles and controlled the hydraulic conductivity of the soil. Effectively, the soil behaves hydraulically as a clay even though it is composed of sand size particles. This behavior is consistent with findings of Seed et al. (1964), who found that mixtures of sand and bentonite changed from nonplastic to plastic at bentonite contents near 10 per cent. In Figures 4.1, 4.2, 4.3 and 4.4 the hydraulic conductivity versus void ratio relationship for bentonite and different sand mixtures are exhibited according to the tests conducted by Sivapullaiah et al. (2000). The physical properties of the soils mentioned to have been used in the tests were as follows:

Table 4.1. Physical properties of the soils used in the tests (Sivapullaiah et al., 2000)

Type of soil	Specific Gravity, G	% Sand 1.4-0.075mm	Liquid limit (%)	Plastic limit (%)	Shrinkage limit (%)
Coarse sand r	2,60	100	nonplastic	nonplastic	-
Coarse sand a	2,62	100	nonplastic	nonplastic	-
Fine sand r	2,60	100	nonplastic	nonplastic	-
Fine sand a	2,62	100	nonplastic	nonplastic	-
Bentonite	2,75	0	344	60	7,6

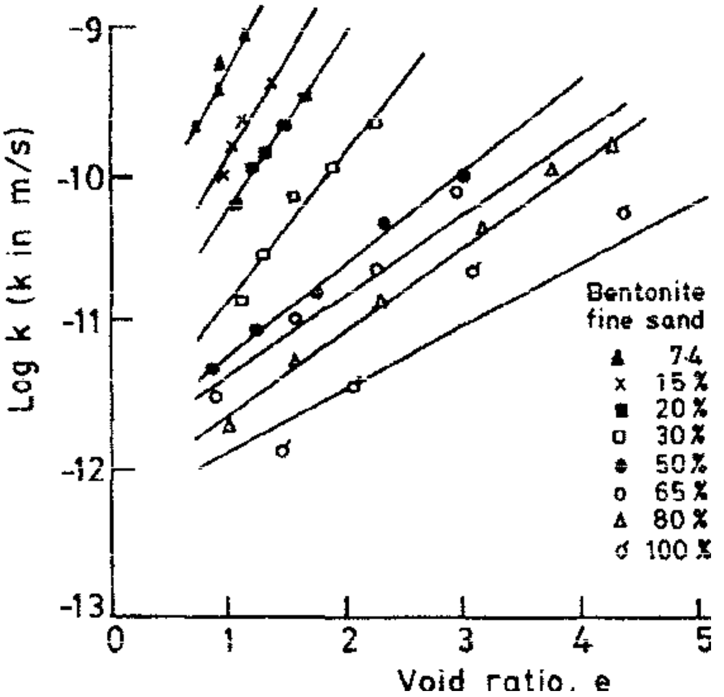


Figure 4.1. Hydraulic conductivity vs. void ratio relationship for mixtures of fine sand r and bentonite (Sivapullaiah et al., 2000)

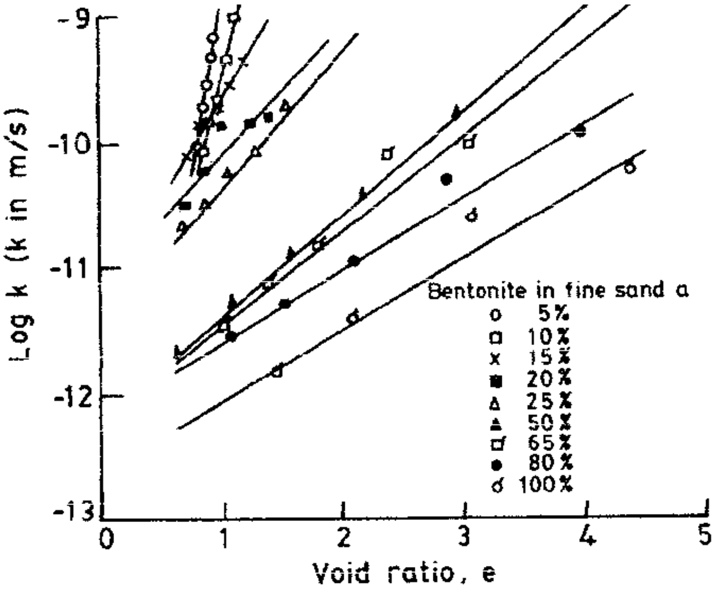


Figure 4.2. Hydraulic conductivity vs. void ratio relationship for mixtures of fine sand a and bentonite (Sivapullaiah et al., 2000)

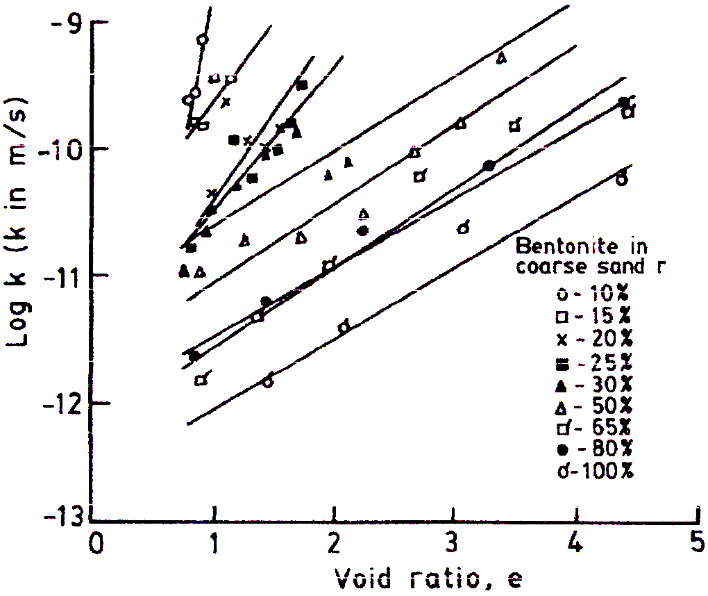


Figure 4.3. Hydraulic conductivity vs. void ratio relationship for mixtures of coarse sand r and bentonite (Sivapullaiah et al., 2000)

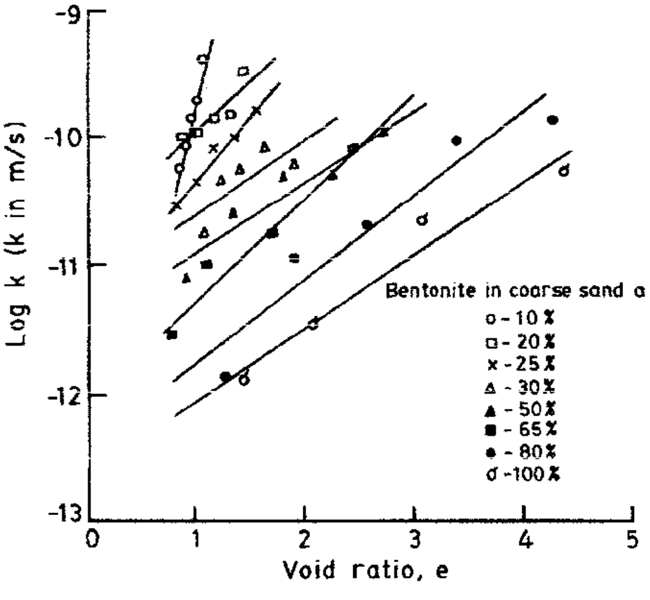


Figure 4.4. Hydraulic conductivity vs. void ratio relationship for mixtures of coarse sand a and bentonite (Sivapullaiah et al., 2000)

4.3. Polymer Additives For Reducing Hydraulic Conductivity

Drilling is one of the most common operations in hydrocarbon exploration and production (Giuliano, 1983). During drilling, fluids are permanently circulated downwards through the drilling pipe and upwards through the annulus. These fluids are complex mixtures which must meet requirements like lubrication, cooling of the bit, displacement of rock cuttings to the surface and filtration control aiming to reduce formation damage in the near-wellbore (Bourgoyneiuliano et al., 1985). Most drilling fluids are water-based dispersions containing polymer additives. Anionic polymers, such as Polyacrylates, reduce fluid loss i.e. penetration of fluid in the formation by effectively increasing viscosity. The performance of this type of polymer as filtration control agent is dependent on pH and salinity. Usually drilling fluids contain additives to ensure a high pH and a certain ionic strength intending to prevent washouts, corrosion and excessive dissolution of calcium. However, these properties can be modified by interaction with the formation or the formation water. This is particularly true in horizontal wells, where the drilling fluid can experience large changes in pH and salinity due to the extent of the borehole (Filip and Denys, 2003).

The flow properties of a bentonite-water system is related to the interactions between particle–particle and particle-water molecules of the system. The exchangeable cations that exist between the bentonite layers are the effective parameter on rheological properties. In the bentonite-water system, like many other characteristic features, the rheological properties are dependent on cation types and their quantities (Güngör and Karaolan, 2001).

The extent of polymers on clay minerals is determined by a number of parameters such as molecular weight, polymer concentration, degree of hydrolysis of polymer, functional groups of polymer and bentonite-to-water ratio, pH. Anionic polymers are effective flocculants and deflocculants for clays which normally carry negative charges in water only when the polymer also contains nonionic polar groups (such as OH^{-1}, NH_2) or if the anion is carboxyl (COO^-) (Güngör and Karaolan, 2001).

The adsorption of non-ionic or weakly ionic polymers is the consequence of physical forces (Van der Waals forces or hydrogen bonding) between adsorbent (polymer) and adsorbate (clay). The molecules adsorbed initially are taking up a flat configuration. With the continuation of adsorption, the molecules are assuming a configuration with more loops protruding out from the surface to enable more material to adsorb. This process involves the adsorption of segments.

Three possibilities can be considered for the interaction between Polyacrylate molecules and clay particles: (i) an anionic exchange between the surface hydroxyls of the mineral and the carboxylic anions of the polymer; (ii) the formation of hydrogen bonds between the surface hydroxyls and the C=O of the polymer; (iii) the establishment of bridges involving divalent ions, originating from electrostatic forces (Mitchell, 1976). Güngör and Karaolan (2001) concluded that, the rheological properties of bentonites and the formation of gel structures with water are altered by the addition of Polyacrylate and the type of bentonite and the concentration of Polyacrylate are influential factors (Güngör and Karaolan, 2001).

4.3.1. Polymer Solution Viscosity

Viscosity is a fundamental property which plays an important role in fluid transport. Viscosity is a measure of the resistance of a fluid which is being deformed by either shear stress or tensile stress. Viscosity of a polymer solution depends on concentration and size (i.e., molecular weight) of the dissolved polymer. By measuring the solution viscosity we should be able to get an idea about molecular weight. Mark-Houwink-Sakurada equation states that;

$$\text{intrinsic viscosity, } \eta = KM_r^a \qquad (4.1)$$

Where, M_r is relative molecular mass, K and a are constants, dependent on the polymer, solvent, and temperature (Muthukumar, 1981).

The coefficient of permeability k has the units of velocity, such as cm/s or mm/s, and is a measure of the resistance of the soil to flow of water. When the properties of water affecting the flow are included, we can express k by the relation:

$$k(\mathrm{cm/s}) = \frac{K\rho g}{\mu} \tag{4.2}$$

Where;

K = intrinsic (or absolute) permeability, cm^2
g = acceleration due to gravity, $\mathrm{cm/s}^2$
ρ= density of the fluid, $\mathrm{g/cm}^3$
μ = absolute viscosity of the fluid, poise (g/cm·s)

The quantity of K (the intrinsic permeability) depends upon the geometry of the grains skeleton only. The coefficient of permeability, k depends on several factors, most of which are listed below:

- Shape and size of the soil particles.
- Void ratio. Permeability increases with increase in void ratio.
- Degree of saturation. Permeability increases with increase in degree of saturation.
- Composition of soil particles. For sands and silts this is not important; however, for soils with clay minerals this is one of the most important factors. Permeability depends on the thickness of water held to the soil particles, which is a function of the cation exchange capacity, valence of the cations, and so forth. Other factors remaining the same, the coefficient of permeability decreases with increasing thickness of the diffuse double layer.
- Soil structure. Fine-grained soils with a flocculated structure have a higher coefficient of permeability than those with a dispersed structure.
- Viscosity of the permeant (Das, 1985).

Equations 4.1 and 4.2, when considered together, states that viscosity of a polymer solution changes with the molecular weight of polymer and coefficient of permeability is inversely proprtional with viscosity of permeant.

4.3.2. Effects of Polymer Addition in Bentonite-Sand Mixtures

Polymers have been used for many years to enhance the performance of bentonite used in drilling industry. But their use for soil barrier applications has had minimal acceptance. Haug and Boldt-Leppin (1992) conducted a rheological and triaxial permeability/volume change study and found that the low hydraulic conductivity characteristic of a marginal bentonite could be significantly improved with the addition of a small amount of polymer.

Haug and Boldt-Leppin (1992) found that both Bingham Yield and plastic viscosity increase, as the percentage of polymer is increased from zero to two per cent. The impact of polymer addition on the shear stress versus shear strain characteristics of an eight per cent marginal quality bentonite slurry is illustrated in Figure 4.5.

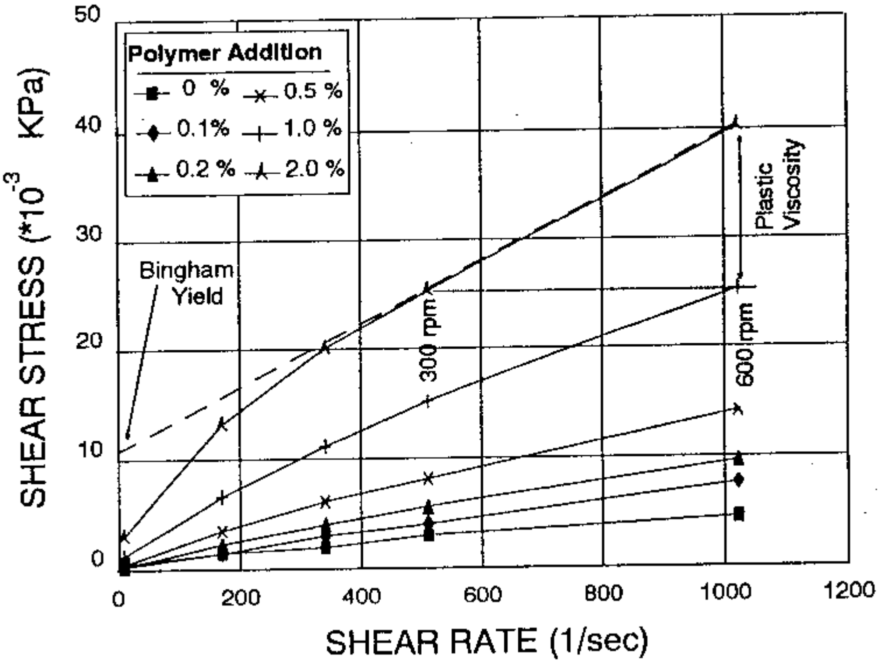


Figure 4.5. Impact of polymer addition of stress-strain characteristics of marginal quality bentonite (Haug and Boldt-Leppin, 1992)

Figure 4.6. contains a summary plot of the tests conducted by Haug and Boldt-Leppin (1992), which shows the relationship between final hydraulic conductivity and percentage of aged and non-aged polymer added to bentonite. All of these values apply to

identically prepared test specimens containing 8 per cent marginal quality bentonite, mixed, moisture conditioned and compacted with Ottawa sand. The initial dry densities of these test specimens were tightly grouped near 1.78 Mg/m^3, with all of the specimens compacted at optimum. The only variation between these specimens was the percentage of polymer added to the marginal quality bentonite. This figure shows that a small concentration of polymer has a significant impact on the hydraulic conductivity of a marginal quality bentonite. The addition of 0.5 per cent polymer resulted in a decrease in hydraulic conductivity of approximately 4 orders of magnitude (10^{-4} mm/s to 10^{-8} mm/s). The initial impact of a small quantity of polymer is considerable, however further increases in polymer had a diminishing impact on lowering hydraulic conductivity. In the tests conducted by Haug and Boldt-Leppin (1992), little decrease in hydraulic conductivity occurred with increases in polymer concentration above 0.05 percent. However, below that value, all of the test specimens eventually failed, which suggests that a threshold polymer concentration exists to prevent failure. Based on this data and for these test and material conditions, this threshold concentration appears to be near 0.05 per cent.

Figure 4.6 also shows that the hydraulic conductivity produced through polymer addition is near that for non-polymerized high quality bentonite. The pattern of change in hydraulic conductivity with time for polymerized marginal quality bentonite is also similar to that for a high quality bentonite. The sample consolidation and swelling characteristics were also similar for both the 0.5 per cent polymerized moderate quality bentonite and for the high quality bentonite.

The deterioration of polymers with time is a concern where polymers are used for long-term soil liner applications. In the test program conducted by Haug and Boldt-Leppin (1992), no significant variation was found between the shelf aged and non-aged polymer. In a three-year study of a field test cover conducted with a different polymerized bentonite-sand mixture, Haug and Boldt-Leppin (1992) found no indication of degradation.

4.3.3. Hydraulic Conductivity of Bentonite-Granular Soil Mixtures

Compacted mixtures of bentonite and sand are widely used as liners against liquid seepage while much study is not available for granular materials in gravel size to displace sand. Published studies have shown that at high aggregate contents, i.e., more than 60 per cent, the permeability of compacted soils tends to increase (Holtz and Lowitz, 1957) (Shelley and Daniel, 1991) .

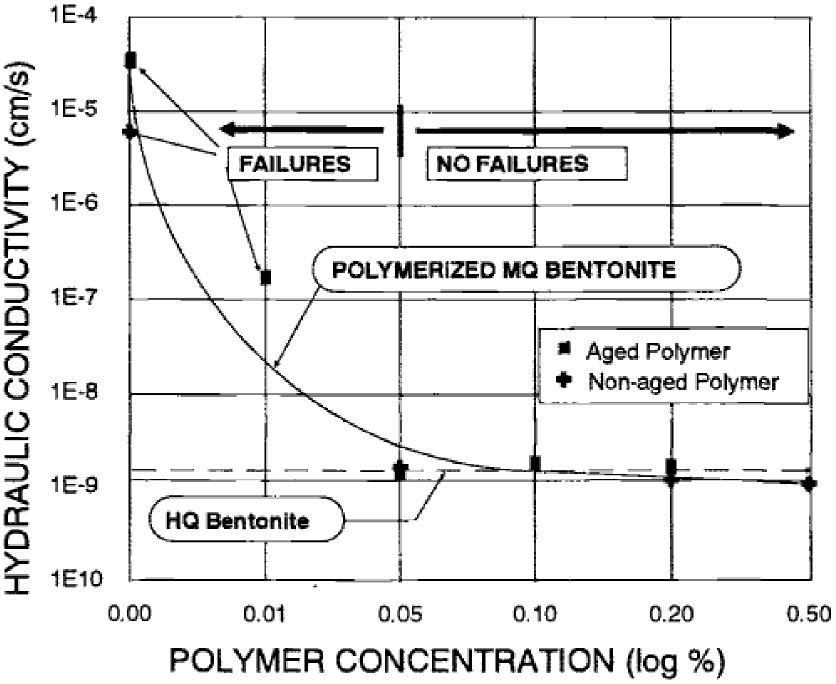


Figure 4.6. Impact of polymer addition on the final hydraulic conductivity of compacted eight per cent marginal quality bentonite Ottawa sand samples (Haug and Boldt-Leppin, 1992)

Holtz and Lowitz (1957) indicated that an increase in permeability of soils containing high aggregate content can be accredited to interference of the gravel portion on the proper compaction of the finer material. Furthermore, when the gravel portion exceeds two-thirds of the total material, there is insufficient finer material to fill the voids between the aggregate particles. These two factors result in a higher void ratio that increases the permeability of the soil. Shelley and Daniel (1991) showed how soils such as mine spoil or kaolonite mixed with gravel at contents as high as 60 per cent can achieve low hydraulic conductivities. They concluded that, beyond 60 per cent gravel content the permeability of both soil mixtures increased rapidly. It should be noted that the above mentioned studies were conducted using little or no expansive clays. The ability of expansive clays to swell, fill the void and lower the permeability of the barrier is well understood (Roberts and Shimaoka, 2008) .

Based on studies concerning the effect of aggregate content on the permeability of soils, such as the ones presented here and others, recommendations for constructing landfill soil liners indicate that the amount of gravel should remain below 30-50 per cent by unit weight of the barrier (Shelley and Daniel, 1991). It is important to indicate that these recommendations are based not on the amount of gravel content itself, but on the assumptions that: it will be very difficult to obtain a proper distribution of the gravel and the matrix material during construction of the barrier in the field; and higher gravel contents can produce segregation of the gravel causing pockets; and this is likely to occur during construction of the barrier. However, the question remains on the performance of soils with high gravel content mixed with highly expansive clay.

Roberts and Shimaoka (2008) investigated a special type of material, which is consisted of gravels coated by bentonite, to be used as a liner material for waste landfills. The concept of bentonite coated gravel (BCG), is similar to that of almonds covered with chocolate; each aggregate particle has been covered with the clayey material. A BCG is shown in Figure 4.7 a, Figure 4.7 b shows the cross-section of a typical BCG particle.

BCG was primarily designed to act as capping materials for contaminated sediments in aquatic environments. The function of the aggregate core is to act as a sinker that will deliver reactive clay components through a column of water and settle over the contaminated sediments. After settling, the clay components will swell to form a cohesive low hydraulic conductivity barrier between the contaminated sediment and the surrounding water ecosystem, allowing isolation, stabilization and/or ease removal of the contaminated sediment. However, in a landfill scenario, the function of the aggregate core will be mainly to support the vertical burdens impose by other barrier components, layers of daily refused and cover soil. In Figure 4.7 c a typical BCG particle in its dry stage is shown while Figure 4.7 d shows hydrated uncompacted particles.

The BCG used by Roberts and Shimaoka (2008) was a commercial type provided by AquaBlok, Ltd. The aggregate core represented 70 per cent of the particles weight, while the other 30 per cent represents the clay shell and moisture. The aggregate core is nominally equivalent in size gradation to ASSHTO No. 8. The shell consists mainly of bentonite clay and other polymers. X-ray diffraction plot analysis, in Figure 4.8. depicted large amounts of montmorillonite, which were mostly Na-montmorillonite and some Ca-montmorillonite.

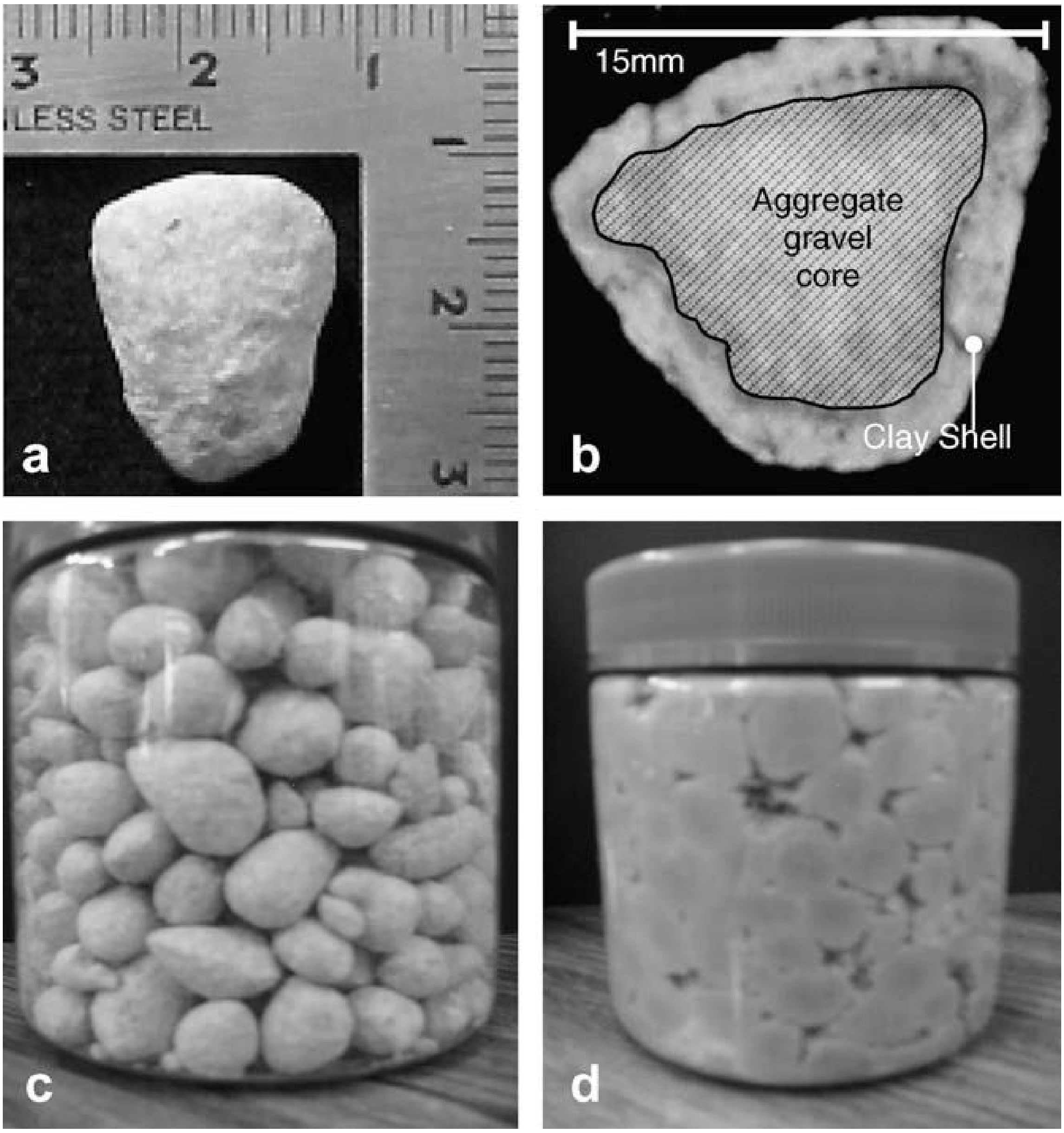


Figure 4.7. (a) Typical bentonite coated gravel particle; (b) Cross-section of a typical bentonite coated gravel particle; (c) bentonite coated gravel particles in the dry stage; (d) hydrated un-compacted bentonite coated gravel particles (Roberts and Shimaoka, 2008)

In the hydraulic conductivity tests conducted by Roberts and Shimaoka (2008), though the aggregate portion represented 70 per cent of BCG weight, extremely low hydraulic conductivities were attained, i.e. 6.10^{-10} cm/s. Results of hydraulic conductivity tests as a function of compactive effort are represented in Figure 4.9. Roberts and Shimaoka (2008) concluded that, compaction had a relatively small influence on the compressibility of BCG. The high aggregate content in BCG allowed little deformation at low or no compactive efforts. Because of the low compressibility of BCG, appropriate angles on internal friction were difficult to attain thus limiting the use of BCG on slopes. Roberts and Shimaoka (2008), also concluded that moderate compactive effort was the best for constructing a BCG barrier, by using moderate compactive efforts, very low permeability, good workability and good trafficability were easily attainable.

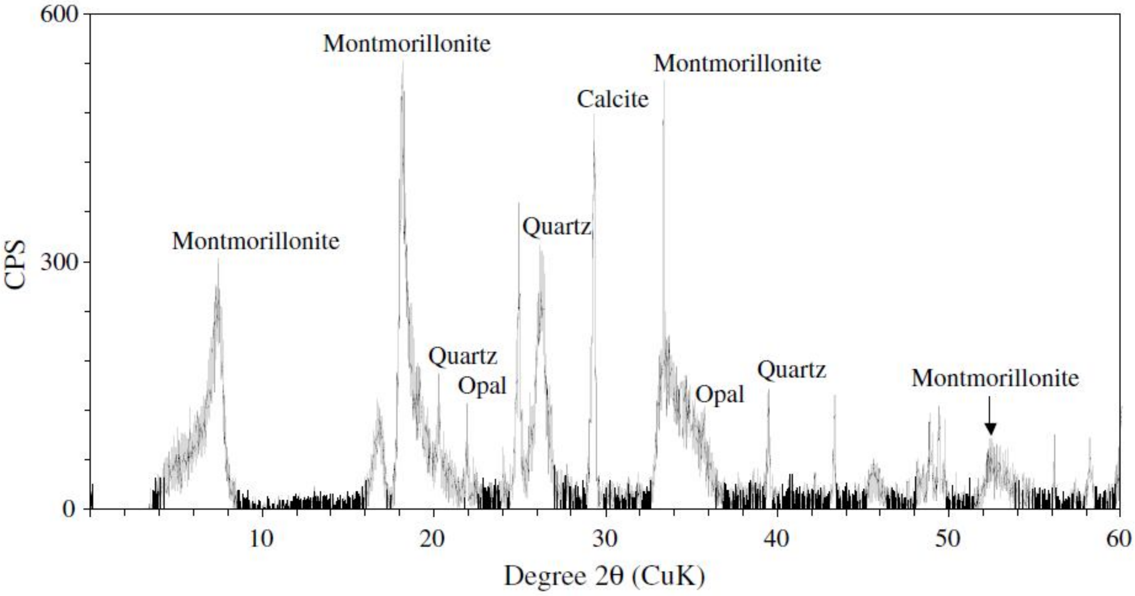


Figure 4.8. X-ray diffraction plot of the clay minerals in the bentonite coated gravel (Roberts and Shimaoka, 2008)

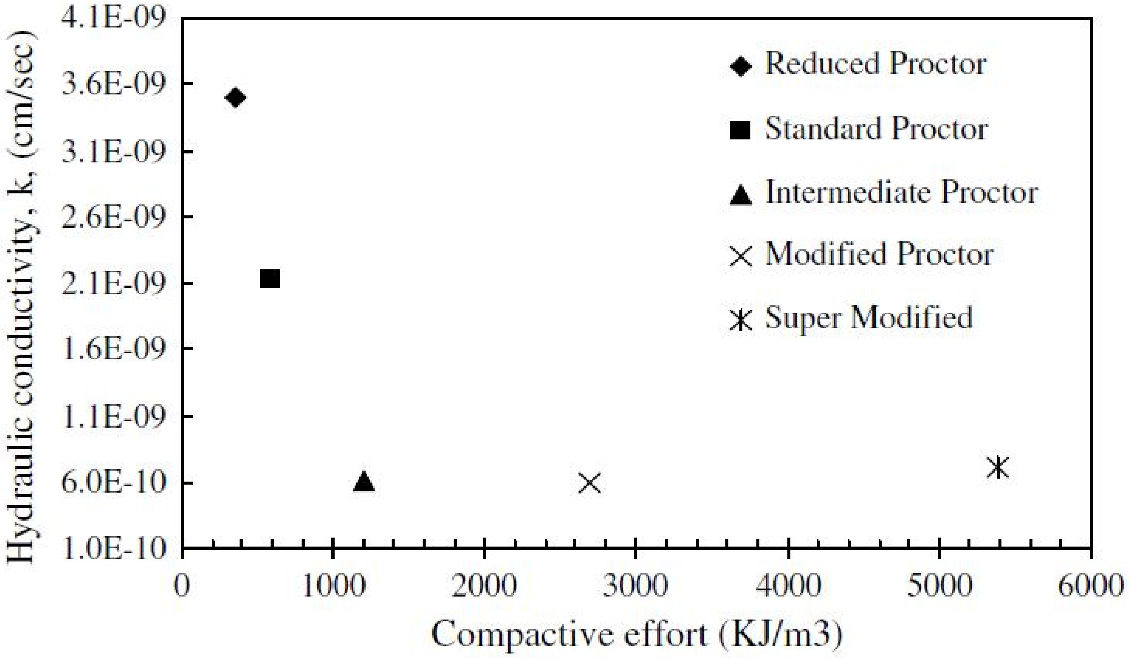


Figure 4.9. Hydraulic conductivity of bentonite coated gravel as a function of compactive effort. (Roberts and Shimaoka, 2008)

5. METHODOLOGY

5.1. Materials Used in the Tests

Tests have been conducted on different aggregate mixtures in order to find the one with minimum void ratio. After determining aggregate composition with minimum void ratio, bentonite and a viscous soil stabilizing polymer are added to aggregate mixtures and hydraulic conductivity of the final mixtures have been investigated. In the hydraulic conductivity tests two different aggregate compositions have been used; one with the minimum void ratio determined by testing and the second one was the typical aggregate composition used in the production of C20 type concrete. The aggregate composition having minimum void ratio is called “Aggregate II” in this study, while “Aggregate I” has the typical aggregate composition used in the production of C20 type concrete.

5.1.1. Bentonite

Bentonite clay that was used in the tests was a sodium bentonite provided from Karakaya Bentonit in Ankara. The chemical, rational analysis and index properties of bentonite are given in Tables 5.1 - 5.3.

Table 5.1. Chemical analysis of bentonite

SiO_2 %	61.28
Al_2O_3 %	17.79
Fe_2O_3 %	3.01
MgO %	2.10
CaO %	4.54
Na_2O %	2.70
K_2O %	1.24

Table 5.2. Rational analysis of bentonite

Smectite (mostly montmorillonite)	0.90
Micas, felspar, quartz, impurities	0.10

Table 5.3. Geotechnical properties of bentonite

Liquid Limit %	324
Plastic Limit %	39
Plasticity Index %	285

5.1.2. Aggregate

Aggregates were supplied from Ece Beton. A typical aggregate consisting of number 2 (22-12 mm) crushed stone, number 1 (12-5 mm) crushed stone, number 0 (5mm-0 mm) stone powder and sand was used in the tests.

Results of the sieve analysis of the aggregate specimens are represented in Figures 5.1, 5.2, 5.3 and 5.4.

5.1.3. Shore Pac

Shore Pac is a dry granular synthetic anionic polyacrylamide which is manufactured from co-polymerization of acrylimide and acrylic acid or its inorganic salts. Shore Pac is a very high molecular weight synthetic polymer with negative charges on the backbone. Its high molecular weight gives high viscosities to water at low concentrations.

When Shore Pac is dissolved in aqueous solution, the very long polymer chains dissolve and arrange themselves randomly within the fluid as tight coils. In fresh water, the repulsion of the negative charges on the backbone of the polymer chains causes the coils to expand and to occupy a large volume in the fluid. When the fluid is sheared, the expanded polymer chains dissipates mechanical energy and results in viscosity.

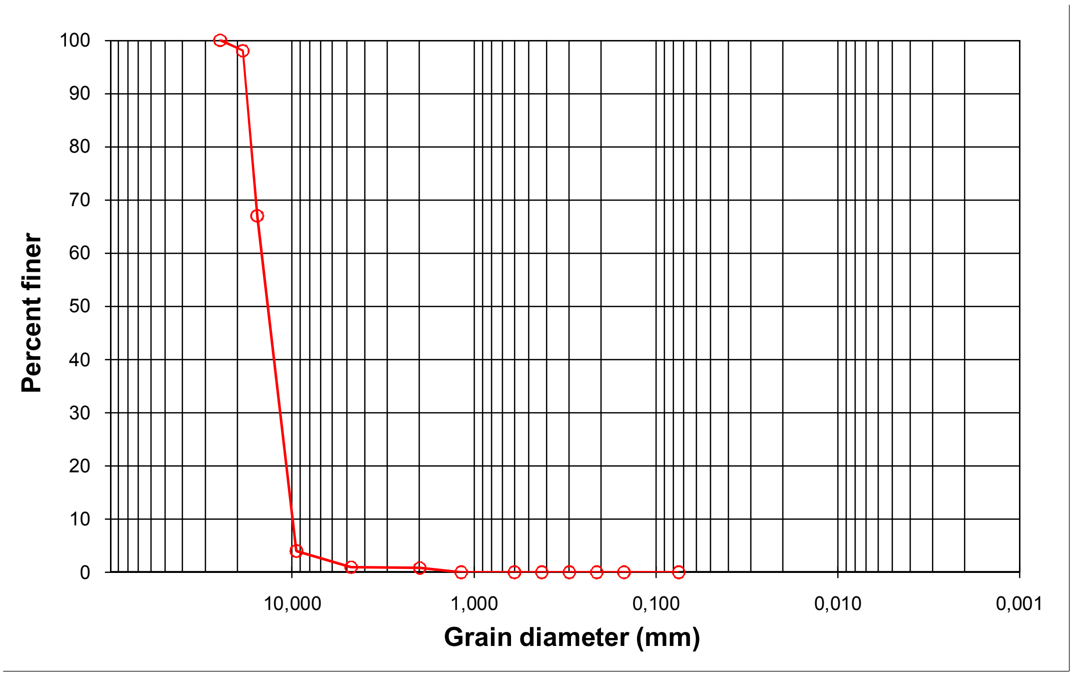


Figure 5.1. Sieve analysis for crushed stone no 2

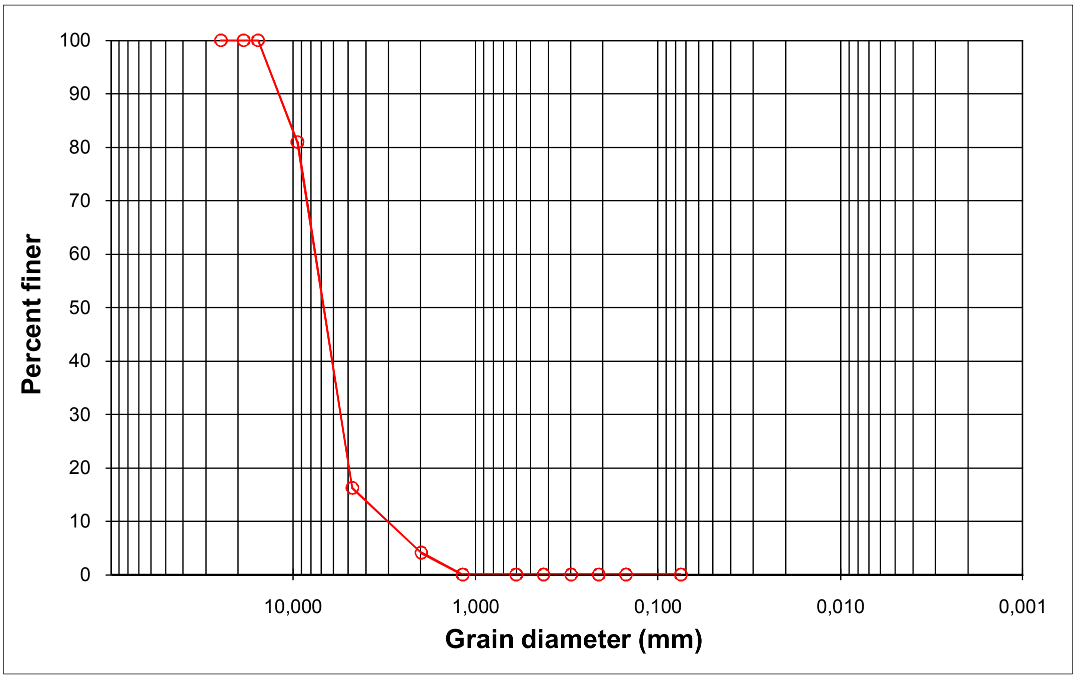


Figure 5.2. Sieve analysis for crushed stone no 1

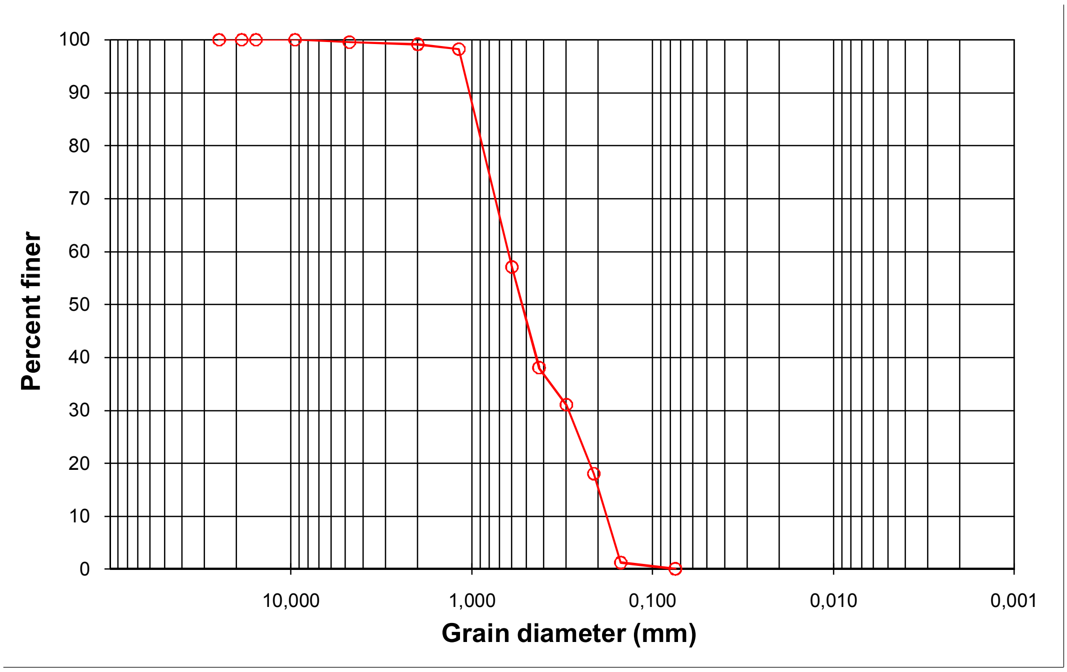


Figure 5.3. Sieve analysis for sand

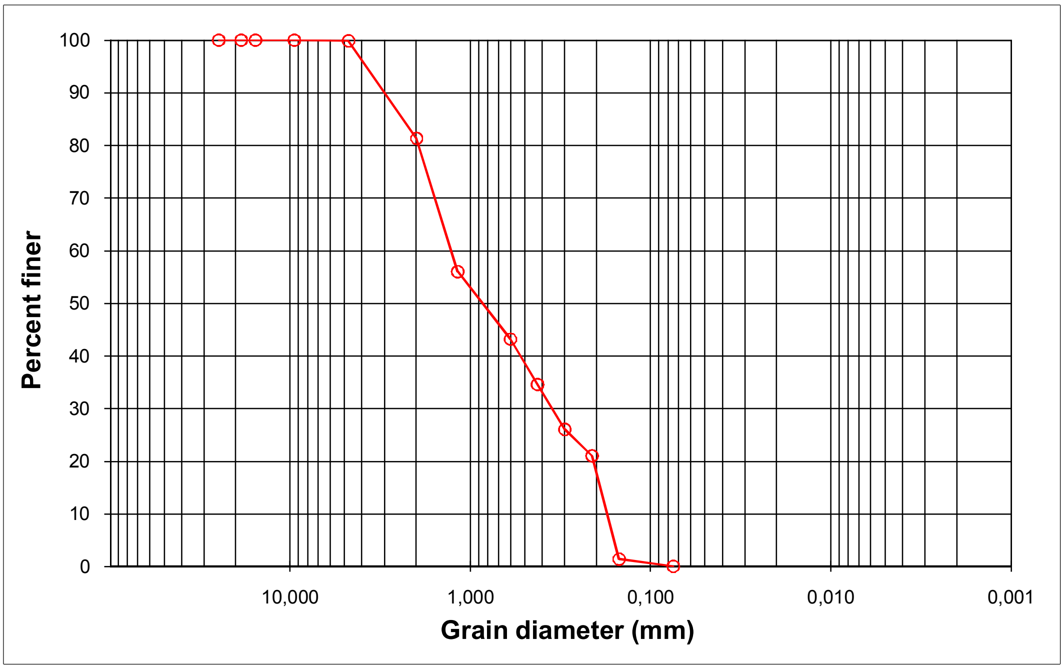


Figure 5.4. Sieve analysis for stone powder

The high molecular weight polymer chains are so long that different parts of individual polymer chains bridge different solid particles. It is this adsorption on surfaces and bridging of solid surfaces that makes Shore Pac effective in keeping solids consolidated while drilling a foundation. In addition, adsorbed layer of hydrophilic polymer on rock surfaces slows down the diffusion of water into the rock.

This easy mixing, water-soluble polymer is supplied as a granular powder. It is mainly designed for preparation of viscous earth-reinforcing fluids or slurries for a variety of drilling, trenching and walling applications in the geo-construction industry.

5.2. Test Method

Different amounts of aggregate, bentonite and polymer mixtures were used in the study. To determine the effects of change in the amount of bentonite and polymers on hydraulic conductivity, different amounts of Shore Pac and bentonite were added into the aggregate mixtures by weight. Hydraulic conductivity tests were conducted on final specimens, which were compacted by Standard Proctor Compaction.

Void ratios of different aggregate mixtures were found. A typical aggregate mixture, used in the production of C20 type concrete was chosen and void ratio of the specimen was calculated. This aggregate mixture was named "Aggregate I". According to void ratio tests aggregate composition with minimum void ratio has been found, this mixture was named "Aggregate II" in this study. Different amounts of bentonite, ranging from 0,1 percent to 15 percent and different amounts of polymer, ranging from 0,5 percent to 10 percent were added to Aggregate I and Aggregate II specimens and hydraulic conductivity tests have been conducted. Hydraulic conductivity tests were conducted in rigid wall compaction wall permeameters using falling head method.

Viscosity tests were conducted on polymer solutions. In this study falling-ball viscometry is used. Effects of polymer addition on the viscosity have been investigated.

Atterberg limit tests were conducted on bentonite, in order to determine liquid and plastic limit and plasticity index.

Optimum water contents and the maximum dry unit weights of the mixtures were found using Standard Proctor Compaction (ASTM D698).

5.2.1. Sample Preparation

Aggregate was sieved from No:200 sieve, then the aggregate containing no clay size particles was air dried and stored in plastic containers. Bentonite and polymer, namely Shore Pac, were also air dried and stored in plastic containers. A typical aggregate consisting of number 2 (22-12 mm) crushed stone, number 1 (12-5 mm) crushed stone, number 0 (5mm-0 mm) stone powder and sand was used in the tests. Aggregate I was composed of 29 per cent number 2 (22-12 mm) crushed stone, 29 per cent number 1 (12-5 mm) crushed stone, 24 per cent number 0 (5mm-0 mm) stone powder and 18 per cent sand by weight. Aggregate II was composed of 20 per cent number 2 (22-12 mm) crushed stone, 20 per cent number 1 (12-5 mm) crushed stone, 20 per cent number 0 (5mm-0 mm) stone powder and 40 per cent sand by weight. Figure 5.5 shows aggregate, stone powder, sand and Shore Pac used in tests.

In all hydraulic conductivity tests, predetermined amount of Shore Pac was added to the bentonite prior to the mixing with the aggregate. The elements of the aggregate mixtures were mixed air dry. Then, predetermined amount of water was added to the aggregate mixture with a spray bottle in order to avoid any pre-compaction effects and large clods as shown in Figure 5.6.

The samples were compacted at 15 per cent initial water content, at the wet side of optimum. The applied compaction energies were Standard Proctor. In Figure 5.7 cylindrical mold on compaction equipment is shown. Figure 5.8 shows the details of cylindrical mold used in the series of tests.

5.2.2. Hydraulic Conductivity Tests

Hydraulic conductivity tests were conducted on rigid wall compaction permeameters in which the specimens were prepared. An illustrative figure for a rigid wall permeameter is in Figure 5.9.

Figure 5.5. Materials used in the tests

Figure 5.6. Addition of water to the aggregate mixture with a spray bottle

Figure 5.7 Cylindrical mold on compaction equipment

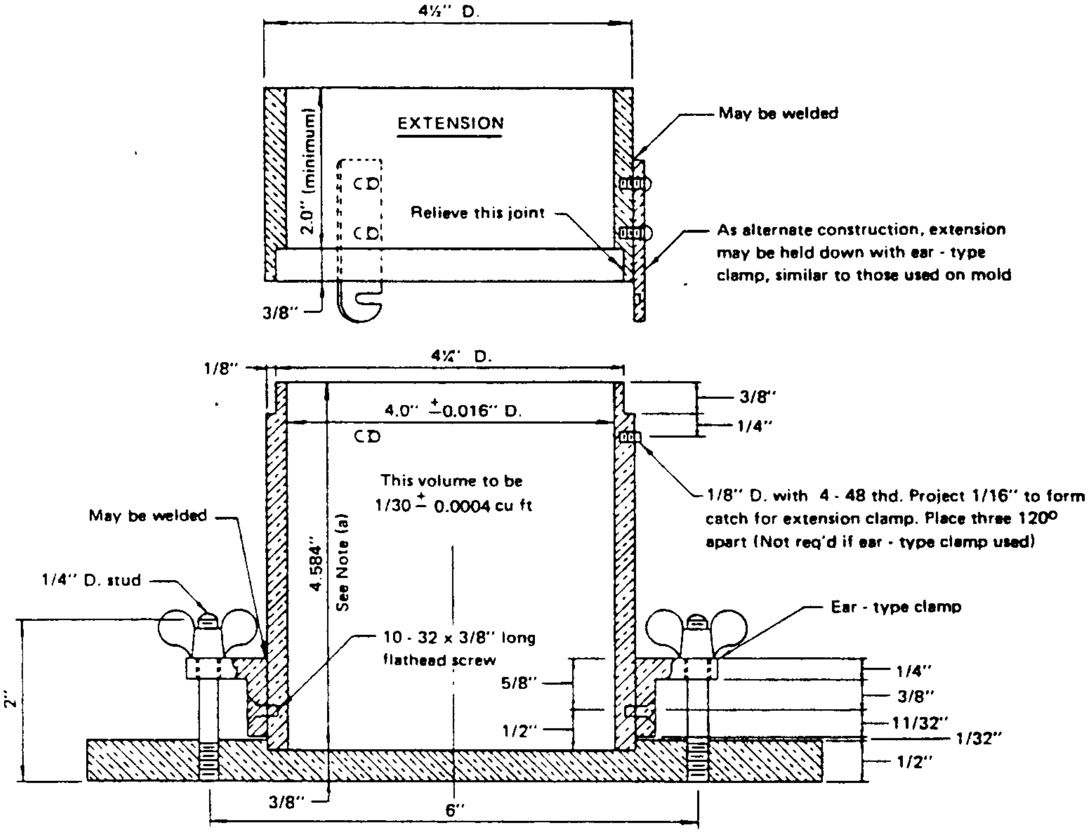


Figure 5.8. Details of cylindrical mold (Benson and Daniel, 1994)

Falling head method was used. The theory of this test is given below. The falling head test is the preferred test for measuring the hydraulic conductivity of fine grained soils. Darcy's law is used for the calculation of hydraulic conductivity. Darcy originally developed this equation for clean sands, but experiments have shown that the equation is valid for a wide range of soil types at engineering hydraulic gradients. Figure 5.10 shows details of the falling head test equipment. For this equipment, the velocity of the fall in the standpipe is,

$$v = -dh/dt \tag{5.1}$$

And the flow into the sample is found by the equation,

$$Q = -a\,dh/dt \tag{5.2}$$

Darcy's law states that,

$$v= ki \tag{5.3}$$

The second equation for flow can be written as:

$$Q= kiA = k(h/1)\ A \tag{5.4}$$

By equating the two equations for Q by continuity equation, we get,

$$-adh/dt = k\ (h/1)\ A \tag{5.5}$$

Separating the variables and integrating over the limits,

$$-\int_{h1}^{h2} dh/h = \int_{t1}^{t2} kA/Ladt \tag{5.6}$$

We obtain

$$k = \frac{aL}{At}\ln(h1/h2) \tag{5.7}$$

Where;

a= area of the standpipe,
A= soil sample area,
L= soil sample length,
t_1= time at the beginning of the test,
t_2= time at the end of the test,
h_1= water level at the beginning of the test,
h_2= water level at the end of the test.

In all tests permeant was tap water. All the tests were continued until the hydraulic conductivity values were steady.

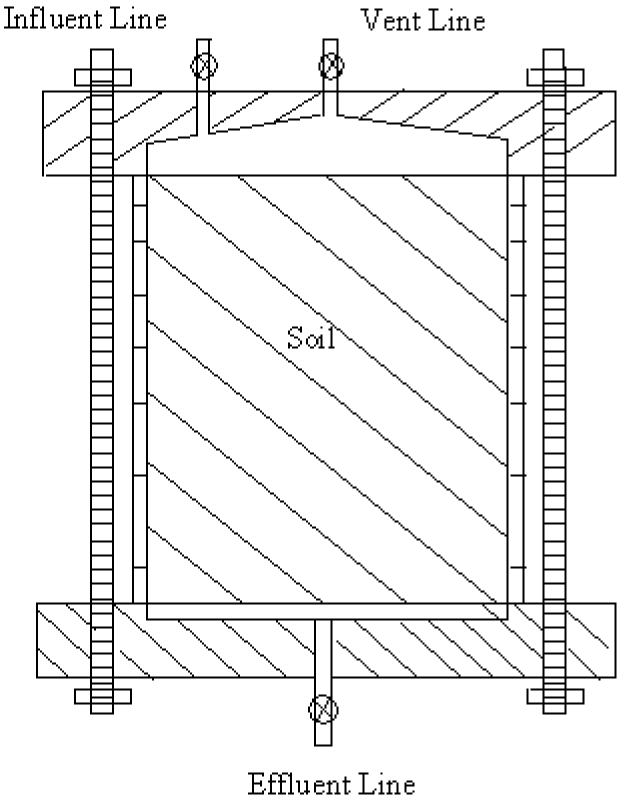


Figure 5.9. Rigid wall permeameter (Gillot, 1987)

5.2.3. Viscosity Determination Tests

Viscosity determination tests were conducted according to falling-ball viscometry in which viscosity is calculated by Stokes law.

Fluids resist a flow gradient. This resistance produces a frictional force known as a viscous force proportional to the area of contact, A, between the flowing regions and to the velocity gradient, dv/dx (Figure 5.11). The constant of proportionality is called the coefficient of viscosity, η , as given in Eq. (5.8).

There are many ways to measure viscous behavior. In this study falling-ball viscometry is used. In this method measurement of viscosity relies on Stokes Law, which relates the viscous drag on a falling object to the viscosity of the medium through which it falls. The unit of viscosity is a poise, 1 g cm^{-1} s^{-1}.

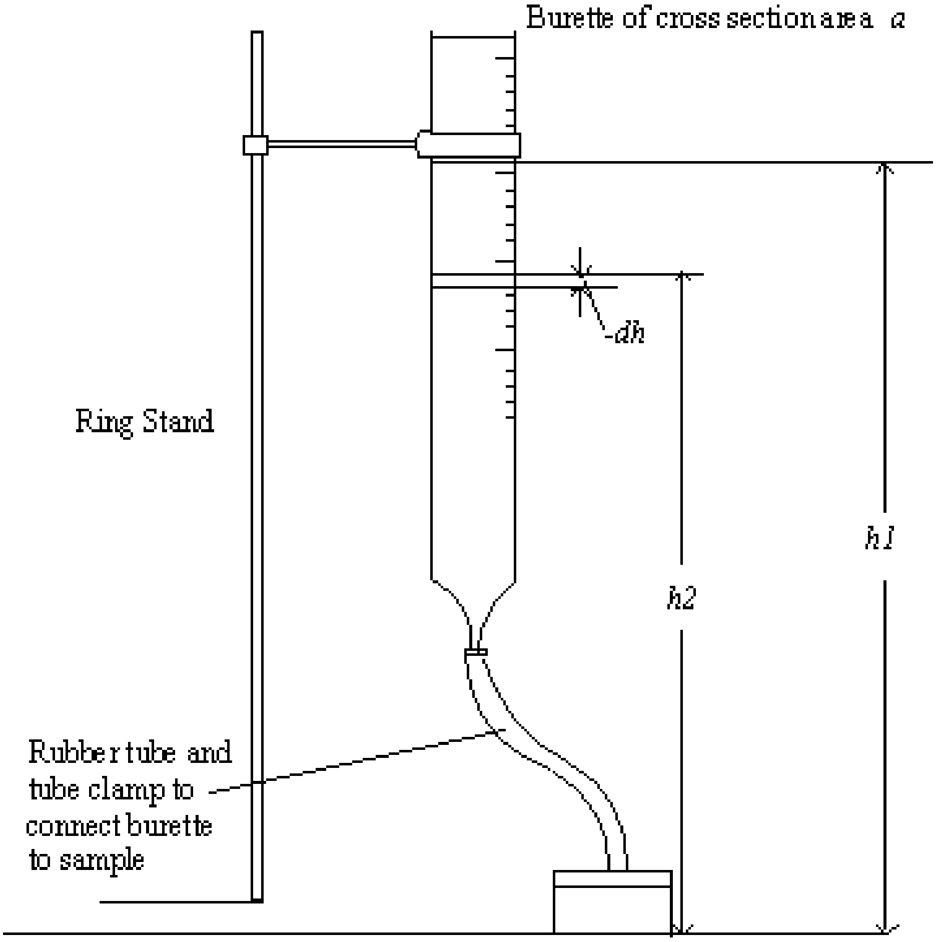


Figure 5.10. Details of apparatus for hydraulic conductivity (Benson and Boutwell, 1964)

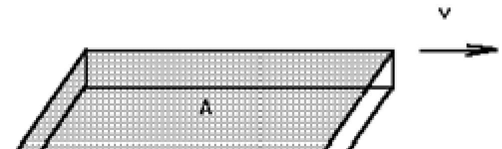


Figure 5.11 Differential flow in a system

$$F= \eta \ A \ dv/dx \tag{5.8}$$

The resistance, applied on the moving objects in liquids is directly proportional with velocity. According to Stokes law, this resistance is;

$$R = 6 \ \pi \ \mu \ r \ v \tag{5.9}$$

The force acting on the solid particle caused by gravitational force is;

$$P = 4 \pi r^3 d^1 g / 3 \tag{5.10}$$

The force acting on the solid particle caused by the lifting force of liquid is;

$$F = 4 \pi r^3 d g / 3 \tag{5.11}$$

Where;

r: Radius of the sphere
v: Equivalent fall velocity of the sphere
d^1: Density of the viscous fluid
d: Density of the sphere
g: Gravitational constant (9.81 m/s^2),

When the sum of these there forces acting on the sphere is zero, the sphere drops with a limit velocity.

$$R+F-P=0 \Longrightarrow 6 \pi \mu r v + 4 \pi r^3 d g / 3 - 4 \pi r^3 d g / 3 = 0$$

Therefore, viscosity μ,

$$\mu = 2 g r^2 (d^1-d)/9v \tag{5.12}$$

In the tests steel, glass and plastic spheres have been used. Five spheres for each sample were dropped near the center of the tubes very carefully to prevent air bubbles from forming behind the spheres and trailing in the wake. The time is recorded for the spheres to pass predetermined distance on the plexiglass tube.

5.2.4. Void Ratio Determination Tests

Void ratio determination tests were conducted on aggregate mixtures containing different particle sizes in order to find the composition with minimum void ratio. A typical aggregate mixture, used in the production of C20 type concrete was chosen and void ratio of the specimen was calculated. This mixture was called as “Aggregate I” and it was composed of 29 per cent number 2 (22-12 mm) crushed stone, 29 per cent number 1 (12-5 mm) crushed stone, 24 per cent number 0 (5mm-0 mm) stone powder and 18 per cent sand by weight. The amount of particle sizes were changed randomly and it was found that when the amount of fine particles increased, the void ratio values decreased. Tests have been conducted on the specimens containing increased amount of fine particles.

For void ratio determination, the specific gravity of the selected mixtures have been determined by using a pycnometer. Specific gravity is the ratio of the mass of unit volume of soil at a stated temperature to the mass of the same volume of gas-free distilled water at a stated temperature. ASTM D 854-00 - Standard Test for Specific Gravity of Soil Solids by Water Pycnometer has been used. Pycnometer, balance, vacuum pump, funnel and spoon have been used in the tests. Pycnometer and vacuum pump used in the tests are exhibited in Figure 5.12.

Figure 5.12 Pycnometer and vacuum pump used in the tests

In the tests, the weight of the empty and dry pycnometer, W_P was measured, 100 g of dry soil sample placed in the pycnometer. The weight of the pycnometer containing the dry soil, W_{PS} was measured. Distilled water was added to fill about half to three-fourth of the pycnometer. The sample was soaked for 10 minutes. Vacuum was applied to the contents for 10 minutes, to remove the entrapped air. After stopping the vacuum and removing the vacuum line from pycnometer, the pycnometer was filled with distilled water to the mark. The weight of the pycnometer and contents, W_B. was measured. Afterwards, the pycnometer was emptied and cleaned. Then, the pycnometer was filled with distilled water only to the mark. The weight of the pycnometer and distilled water, W_A, was measured.

The G_S was calculated as follows:

$$\text{Specific Gravity,} G_S = W_0/W_0+(W_A-W_B) \tag{5.13}$$

Where:
W_0 = weight of sample of oven-dry soil, = W_{PS} - W_P
W_A = weight of pycnometer filled with water
W_B = weight of pycnometer filled with water and soil

After calculating G_s, void ratio was calculated according to following equations:

$$e=G_s.\gamma_w/\gamma_d-1 \tag{5.14}$$

$$\gamma_d=W_s/V \tag{5 .15}$$

The aggregate sample was compacted by standard compaction energy in the mold and after compaction, the volume of the sample was determined. γ_d was obtained by dividing the weight of the soil sample by the volume of the sample. Void ratio of the sample was calculated by the Eq. 5.14.

6. RESULTS AND DISCUSSIONS

6.1. Results of Void Ratio Determination Tests

Results of void ratio determination tests are exhibited in Table 6.1. The detailed results of tests are provided in Appendix A. In the tests void ratios of different aggregate compositions are determined. In the first tests the void ratios of samples composed of only crushed stone, sand and stone powder are determined. The void ratio values decreased when the particle size of the samples decreased.

Table 6.1. Results of void ratio determination tests for different aggregate compositions.

Test No	% of No:2 Crushed Stone	% of No:1 Crushed Stone	% of No:0 Crushed Stone	% of Sand	n (Porosity)	e (Void Ratio)
1	29	29	18	24	0,25	0,33
2	100	0	0	0	0,45	0,81
3	0	100	0	0	0,41	0,68
4	0	0	0	100	0,26	0,36
5	0	0	100	0	0,17	0,21
6	25	25	25	25	0,23	0,3
7	20	20	40	20	0,17	0,21
8	40	30	10	20	0,31	0,46
9	30	30	20	20	0,25	0,33
10	36	28	18	18	0,26	0,35
11	35	35	10	20	0,28	0,4
12	30	30	10	30	0,27	0,36
13	20	25	35	20	0,19	0,23
14	15	15	60	10	0,17	0,21
15	30	30	15	25	0,26	0,35
16	25	25	40	10	0,20	0,25
17	23	23	40	14	0,19	0,24
18	25	25	35	15	0,21	0,26

The tests have been conducted on aggregate mixtures, starting with adding 25 per cent of each four aggregate components. The void ratio for aggregate mixture composed of

25 per cent no:2 crushed stone, 25 per cent no:1 crushed stone, 25 per cent no:0 stone powder and 25 per cent sand was 0,30. Tests have been conducted by changing the amounts and minimum void ratio was found as 0,21 for the sample composed of 20 per cent no:2 crushed stone, 20 per cent no:1 crushed stone, 40 per cent no:0 stone powder and 20 per cent sand. Additional increase in stone powder content did not decrease void ratio. Hydraulic conductivity tests have been conducted on the sample with minimum void ratio and on the sample that had similar content of an aggregate mixture used in the production of C20 type concrete. According to void ratio determination tests, the aggregate mixture that had similar content of aggregate to C20 type concrete, such as 29 per cent no:2 crushed stone, 29 per cent no:1 crushed stone, 18 per cent no:0 stone powder and 24 per cent sand, had 0,33 void ratio.

6.2. Results of Proctor Compaction Tests

Compaction curves of the Aggregate I – bentonite mixtures are shown in Figures 6.36 to 6.39. The detailed results of the Proctor compaction tests are provided in Appendix D.

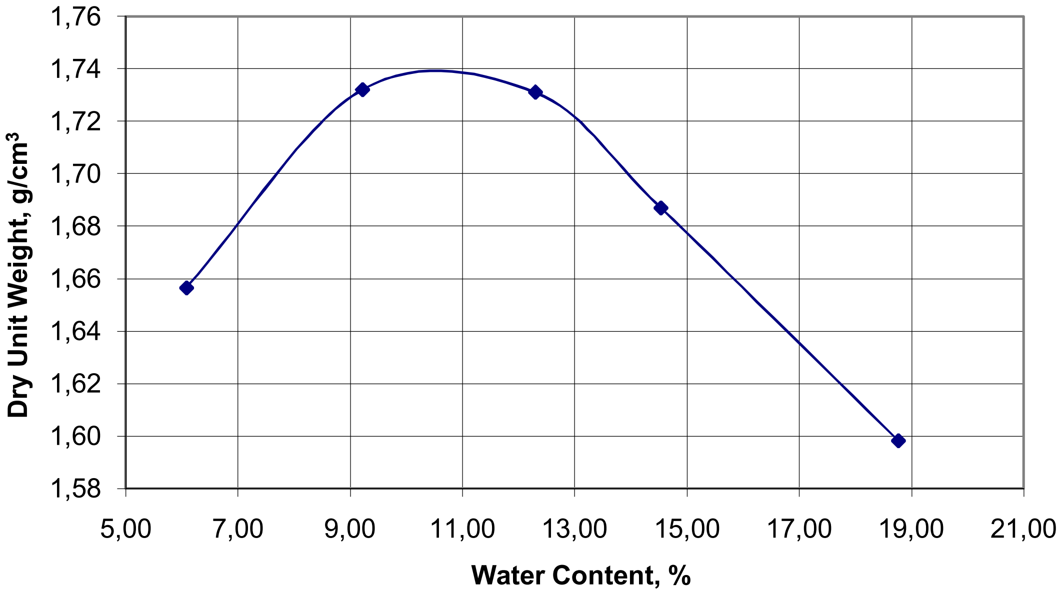


Figure 6.1. Compaction curve of standard Proctor, for Aggregate I + 8 per cent bentonite mixture

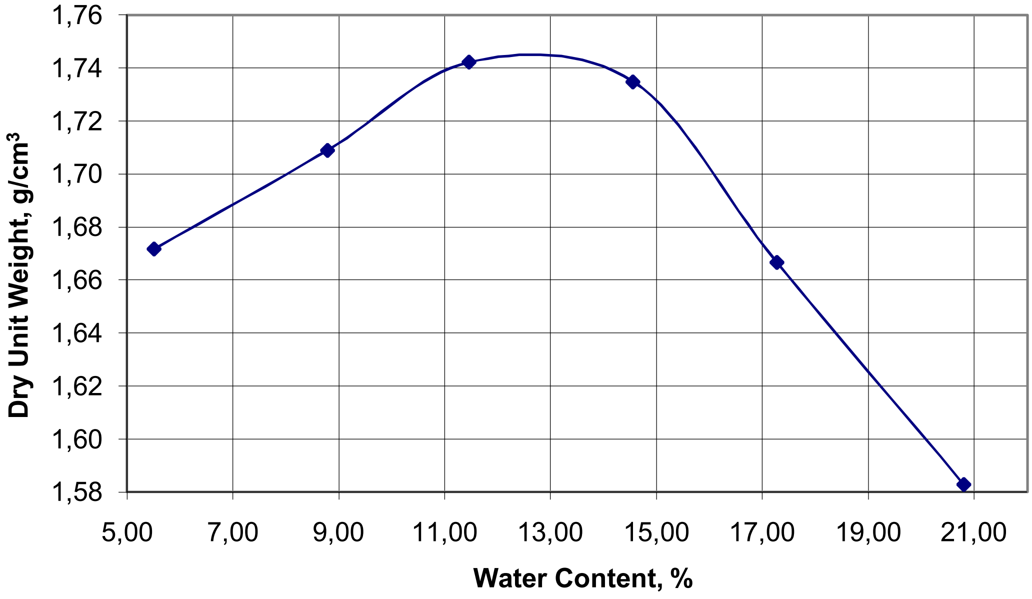


Figure 6.2. Compaction curve of standard Proctor, for Aggregate I + 10 per cent bentonite mixture

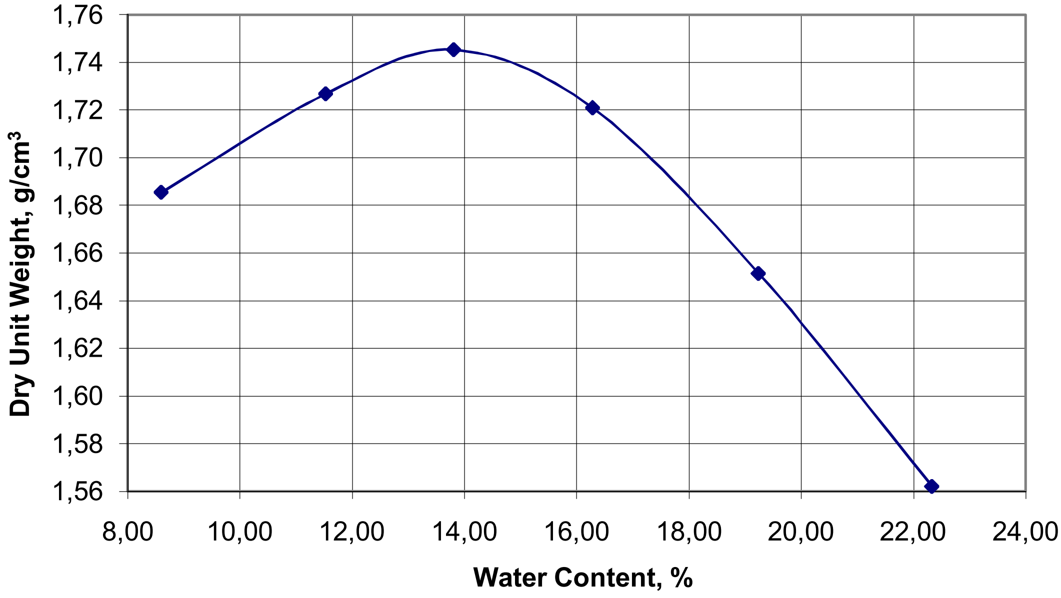


Figure 6.3. Compaction curve of standard Proctor, for Aggregate I + 12 per cent bentonite mixture

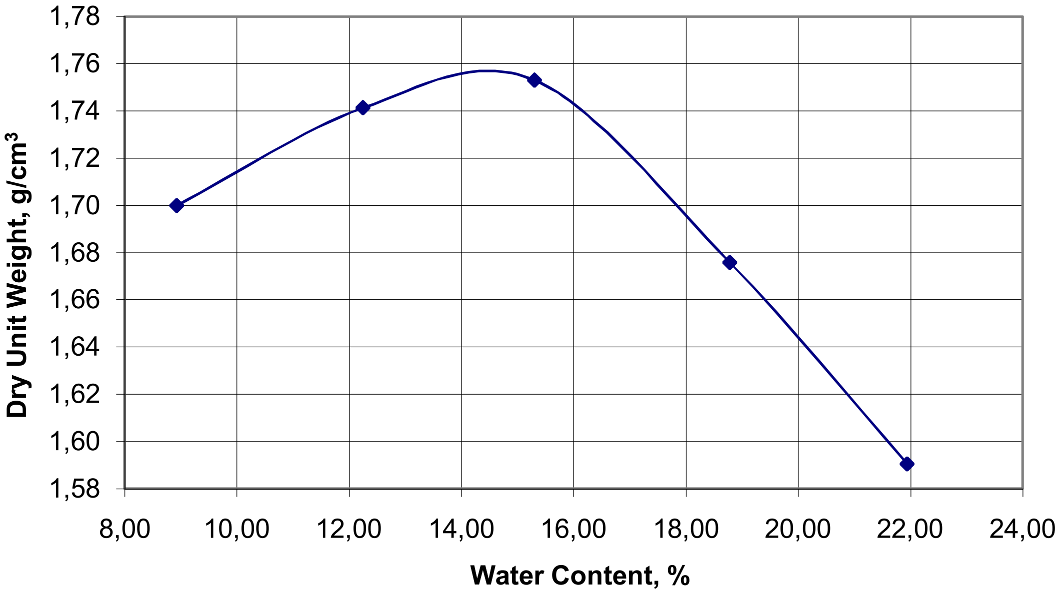


Figure 6.4. Compaction curve of standard Proctor, for Aggregate I + 15 per cent bentonite mixture

6.3. Results of Hydraulic Conductivity Tests

The results of all hydraulic conductivity tests conducted on different amounts of bentonite, aggregate and polymer mixtures are exhibited in the Figures 6.5 to 6.31. The detailed results of the experiments are provided in Appendix C.

In Figure 6.5 the effect of bentonite content on the hydraulic conductivity is represented. When there is no bentonite in the Aggregate I, the hydraulic conductivity value is 1.88E-01 cm/s. Addition of 0,1 per cent bentonite, decreases hydraulic conductivity value to 8.46E-02 cm/s while 0,2 per cent bentonite addition results in a hydraulic conductivity value of 6.74E-02 cm/s for Aggregate I. When the bentonite content is 5 per cent by weight of aggregate, hydraulic conductivity is 7.36E-05 cm/s. Hydraulic conductivity value decreases as the bentonite content increases and when the bentonite content of the bentonite-Aggregate I mixture reaches 15 per cent the hydraulic conductivity is 6.51E-07 cm/s.

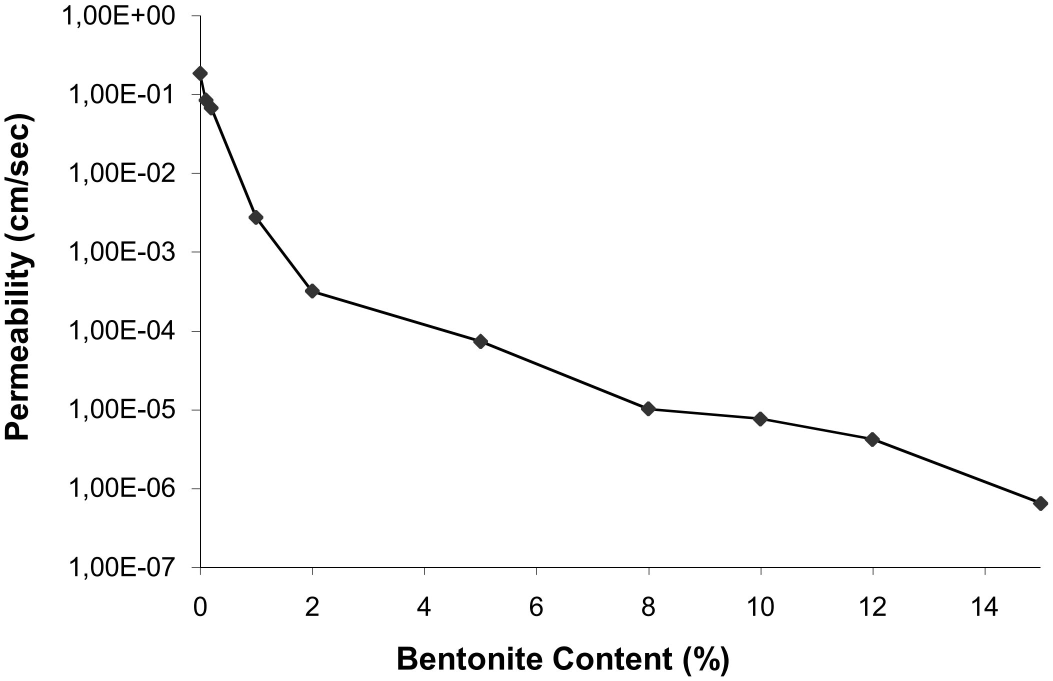


Figure 6.5. Effect of bentonite content on hydraulic conductivity of Aggregate I - bentonite mixture

From the above test results it was observed that the minimum bentonite content that satisfies the EPA regulation requiring a minimum of 10^{-7} cm/s permeability value could only be achieved with a minimum bentonite content of 8 per cent. Therefore for the tests where the effect of polymer addition was investigated the minimum bentonite content was taken as 8 per cent.

In Figure 6.6 the effect of polymer, namely Shore Pac, on hydraulic conductivity of Aggregate I + 8 per cent bentonite mixture is represented. The addition of 0.5 per cent polymer by air-dried weight of bentonite reduced the hydraulic conductivity value to 5.65E-07 cm/s from 1.03.E-05 cm/s. When the percentage of polymer was increased to 0.75 per cent the hydraulic conductivity value decreased to 4.35E-07 cm/s. Addition of one per cent polymer decreased the hydraulic conductivity value to 3.48E-07 cm/s while two per cent polymer addition decreased hydraulic conductivity value to 3.82E-08 cm/s. The decrease in hydraulic conductivity continued with the increase in the amount of polymer in the mixture.

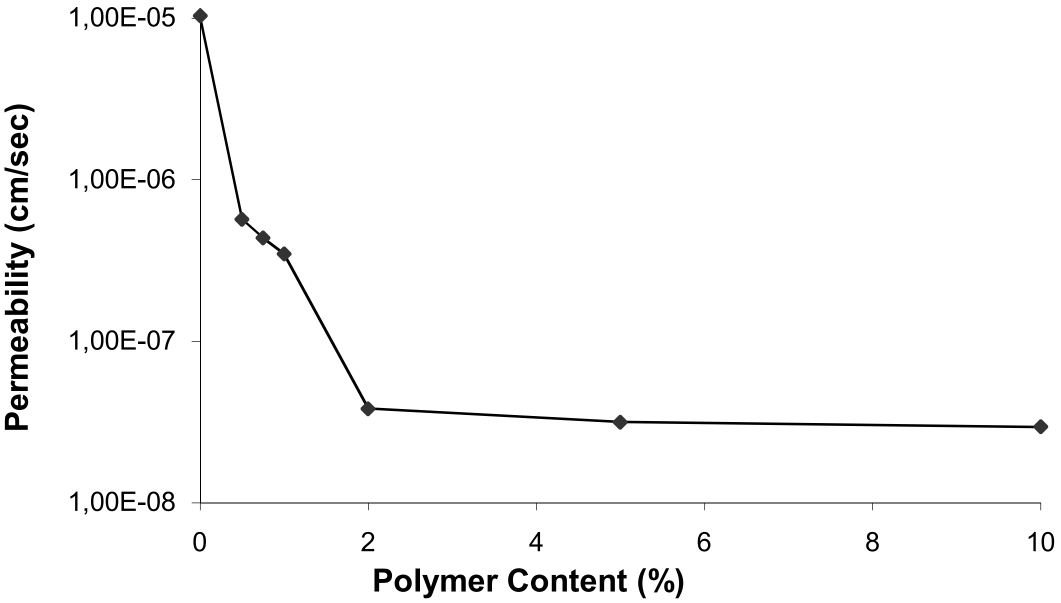


Figure 6.6. Effect of polymer content on hydraulic conductivity of Aggregate I + 8 per cent bentonite mixture

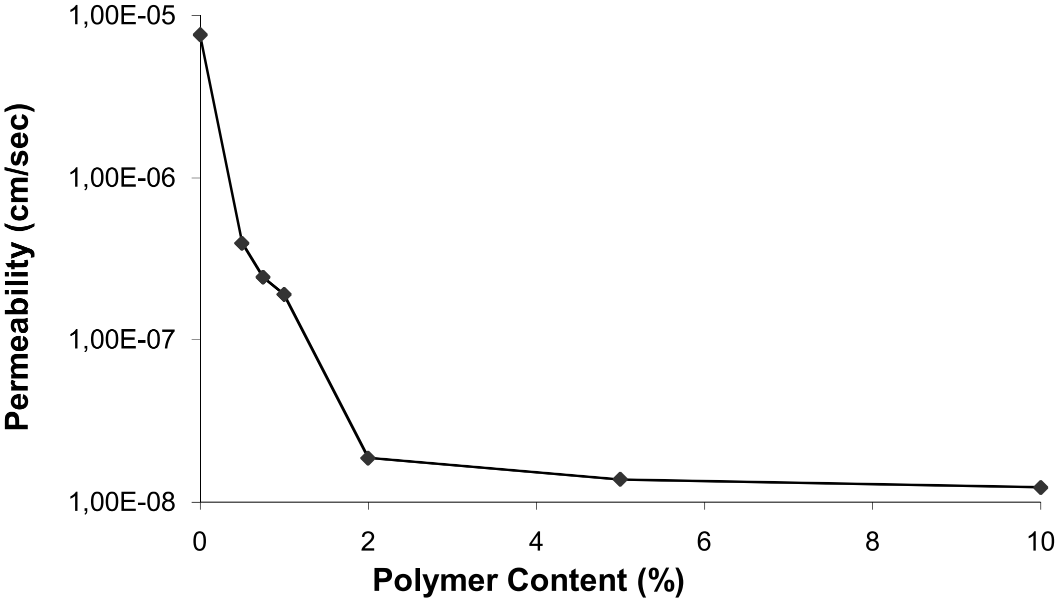


Figure 6.7. Effect of polymer content on hydraulic conductivity of Aggregate I + 10 per cent bentonite mixture

In Figure 6.7 the effect of polymer, on hydraulic conductivity of Aggregate I + 10 per cent bentonite mixture is represented. The addition of 1 per cent polymer by air-dried weight of bentonite reduced the hydraulic conductivity value to 1.92E-07 cm/s from

7.64.E-06 cm/s. When the percentage of polymer was increased to 10 per cent, the hydraulic conductivity value decreased to 1.23E-08 cm/s.

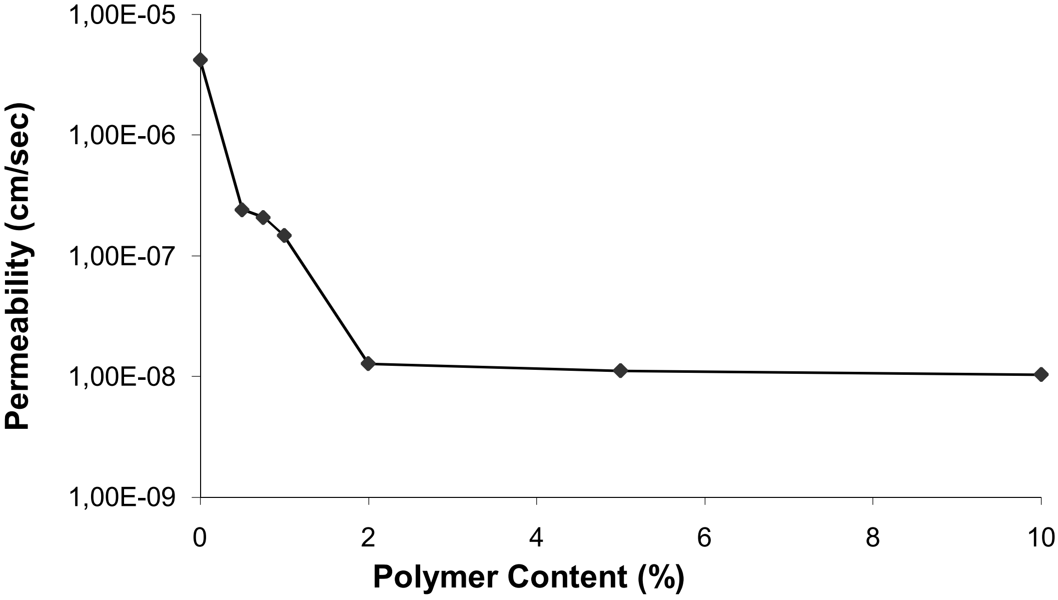


Figure 6.8. Effect of polymer content on hydraulic conductivity of Aggregate I + 12 per cent bentonite mixture

In Figure 6.8 the effect of polymer content, on hydraulic conductivity of Aggregate I + 12 per cent bentonite mixture is represented. The addition of 0,75 per cent polymer by air-dried weight of bentonite reduced the hydraulic conductivity value to 2.08E-07 cm/s from 4.23.E-06 cm/s. When the percentage of polymer was increased to 2 per cent the hydraulic conductivity value decreased to 1.28E-08 cm/s.

In Figure 6.9 the effect of polymer content, on hydraulic conductivity of Aggregate I + 15 per cent bentonite mixture is represented. The hydraulic conductivity of Aggregate I + 15 per cent bentonite mixture was 6.51E-07 cm/s. The addition of 0,75 per cent polymer by air-dried weight of bentonite decreased the hydraulic conductivity value to 2.268E-08 cm/s. When the amount of polymer was increased to 2 per cent the hydraulic conductivity value decreased to 2.01E-09 cm/s.

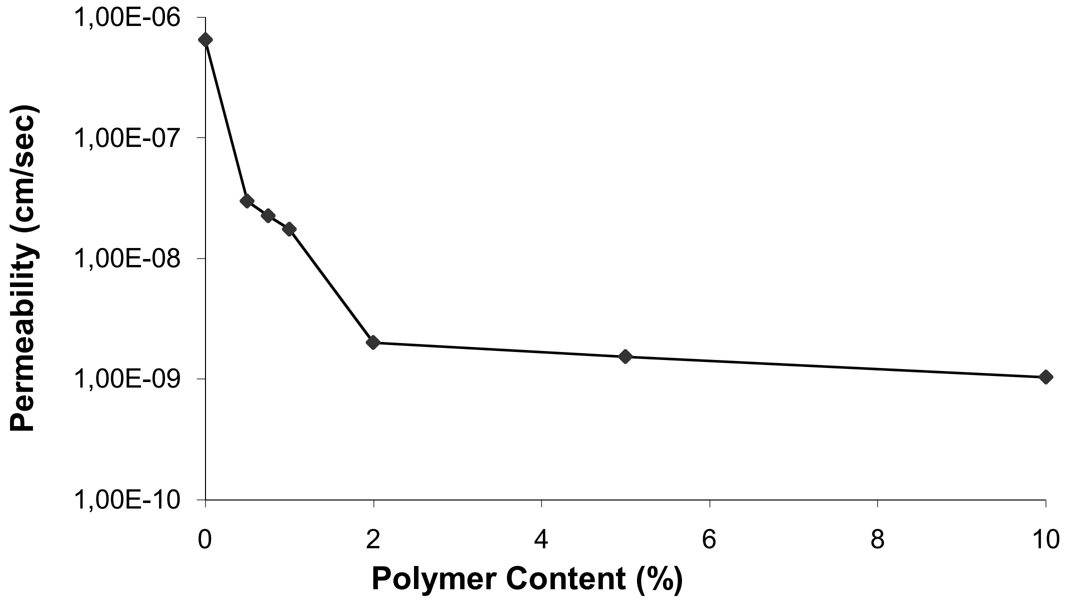


Figure 6.9. Effect of polymer content on hydraulic conductivity of Aggregate I + 15 per cent bentonite mixture

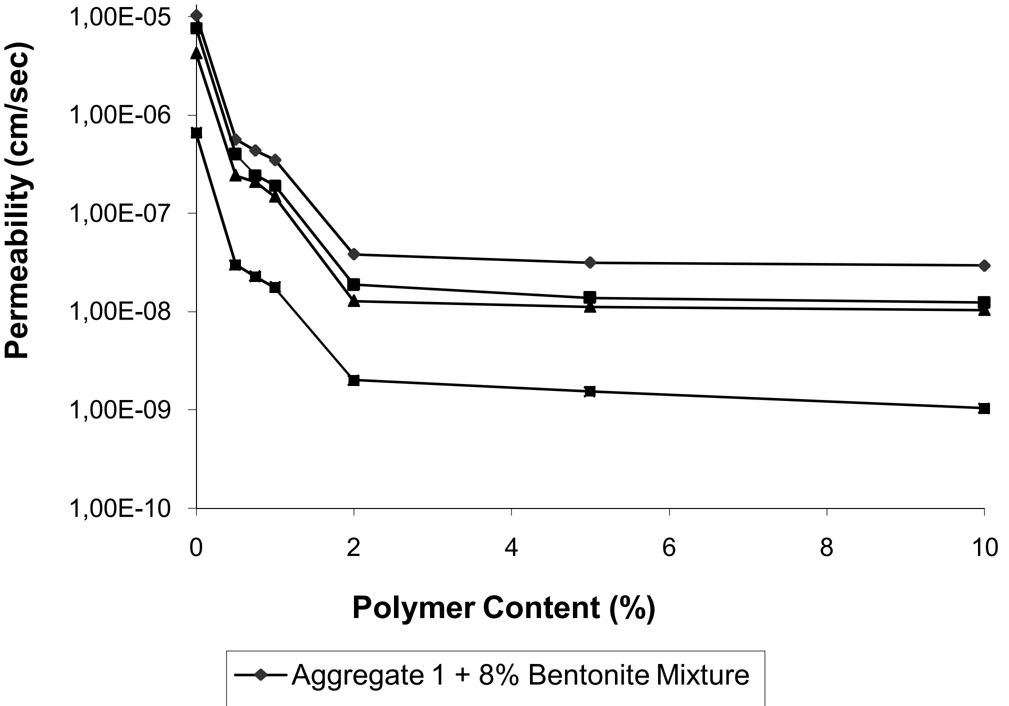


Figure 6.10. Effect of polymer content on hydraulic conductivity of Aggregate I + several bentonite mixtures

In Figure 6.10 the effect of polymer content, on hydraulic conductivity of Aggregate I + several Aggregate I - bentonite mixtures are represented. The addition of polymer, decreased hydraulic conductivity values for all specimens. The decrease in hydraulic conductivity is very high when the added amount of polymer was lower than 2 per cent. Although polymer addition resulted in lower hydraulic conductivities for the amounts more than 2 percent, the polymer content increase didn't affect much. For Aggregate I + 12 percent bentonite mixture, when the polymer content increased from 2 percent to 10 percent, the hydraulic conductivity value decreased from 1.28E-08 to 1.04E-08. However, the addition of 3 per cent bentonite in Aggregate I + 12 percent bentonite mixture, reduced the hydraulic conductivity value from 1.28E-08 to 2.01E-09

In Figures 6.11 – 6.17 the effect of bentonite addition for several aggregate - polymer mixtures are represented. Addition of bentonite resulted in similar hydraulic conductivity values for different polymer concentrations. In Figure 6.11 when the bentonite content in the mixture is 8 per cent, the hydraulic conductivity is 5.65E-07. While the amount of polymer content kept constant at 0,5 per cent, the increase of bentonite content to 15 per cent decreased hydraulic conductivity value to 2.99E-08 cm/s. In Figures 6.12-6.16, the bentonite content increase lowered hydraulic conductivities for all specimens.

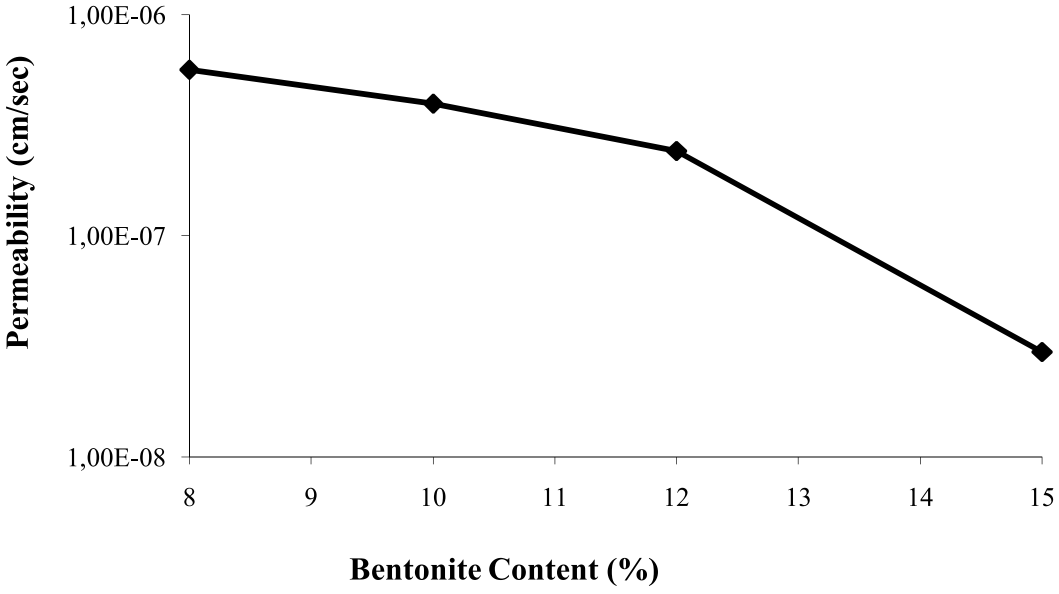


Figure 6.11. Effect of bentonite content on hydraulic conductivity of Aggregate I + 0,5 per cent polymer mixture

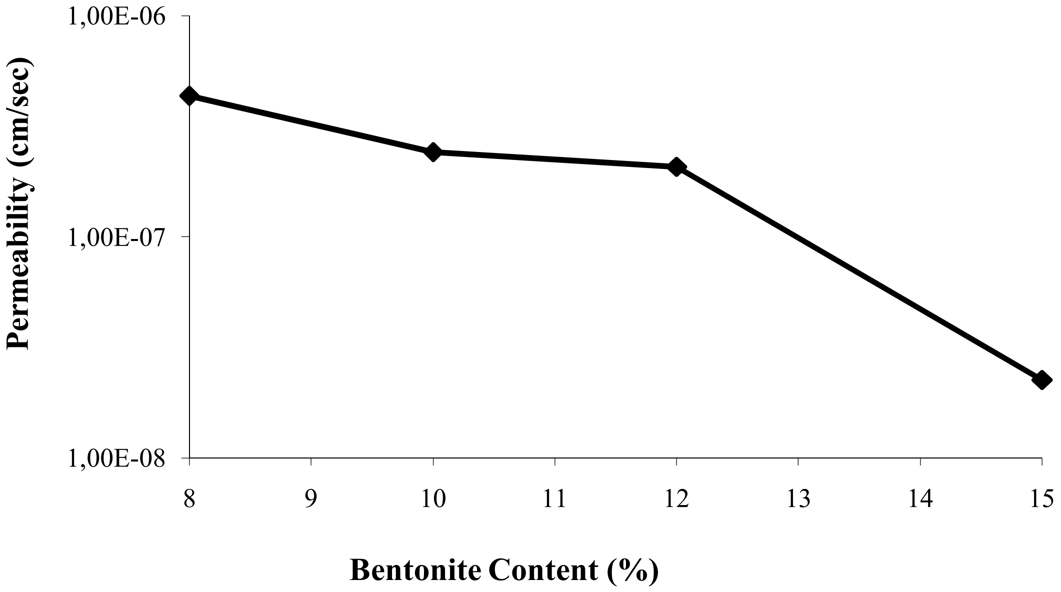


Figure 6.12. Effect of bentonite content on hydraulic conductivity of Aggregate I + 0,75 per cent polymer mixture

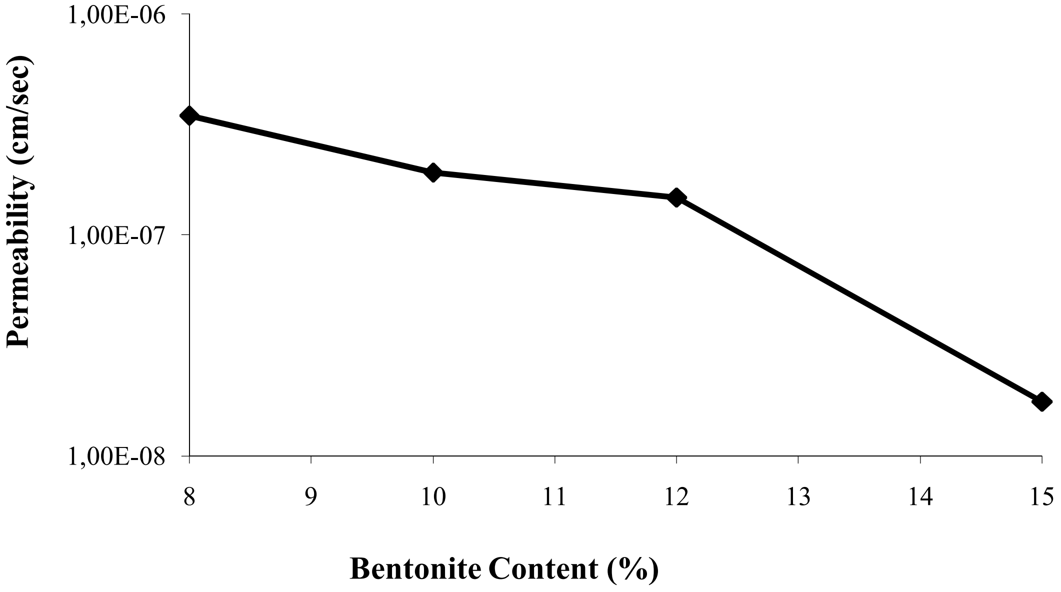


Figure 6.13. Effect of bentonite content on hydraulic conductivity of Aggregate I + 1 per cent polymer mixture

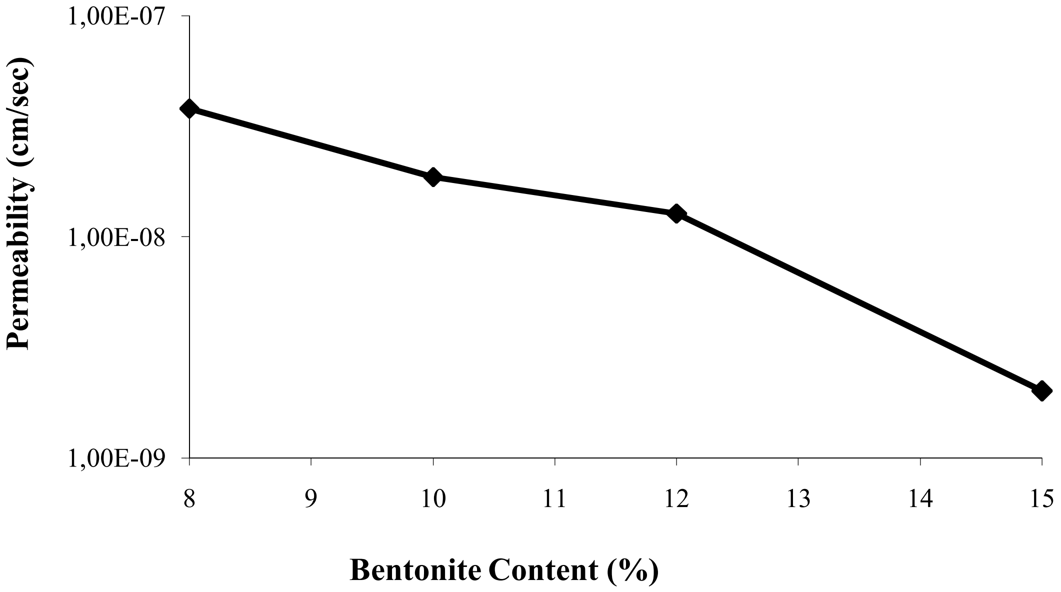


Figure 6.14. Effect of bentonite content on hydraulic conductivity of Aggregate I + 2 per cent polymer mixture

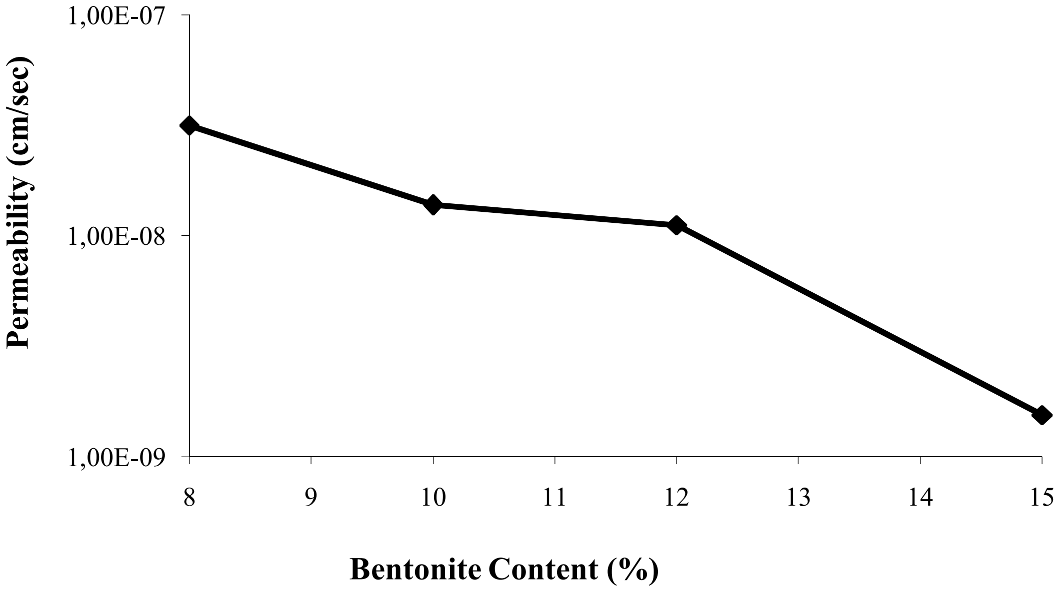


Figure 6.15. Effect of bentonite content on hydraulic conductivity of Aggregate I + 5 per cent polymer mixture

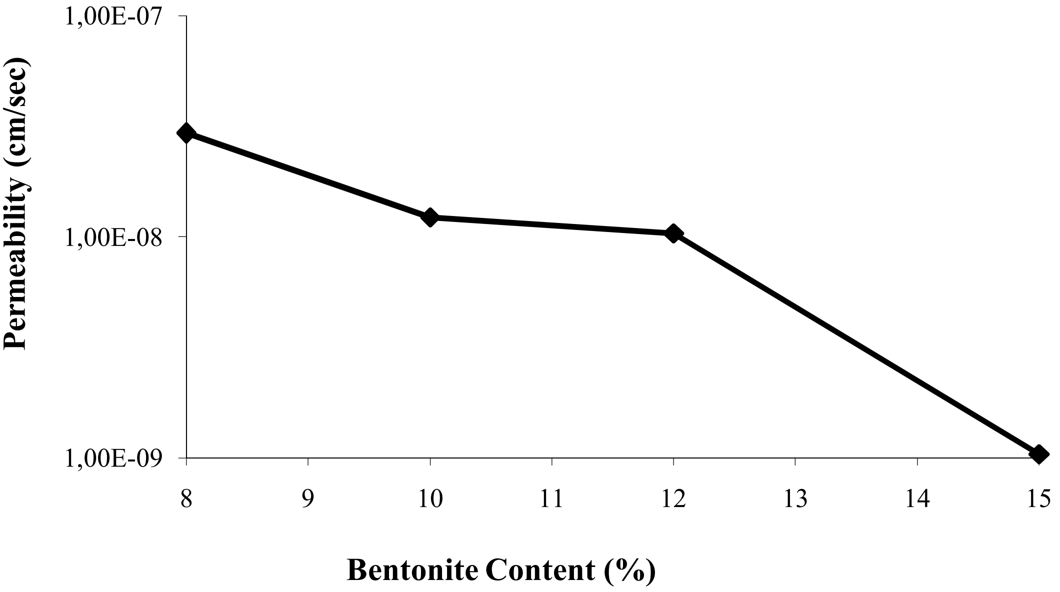


Figure 6.16. Effect of bentonite content on hydraulic conductivity of Aggregate I + 10 per cent polymer mixture

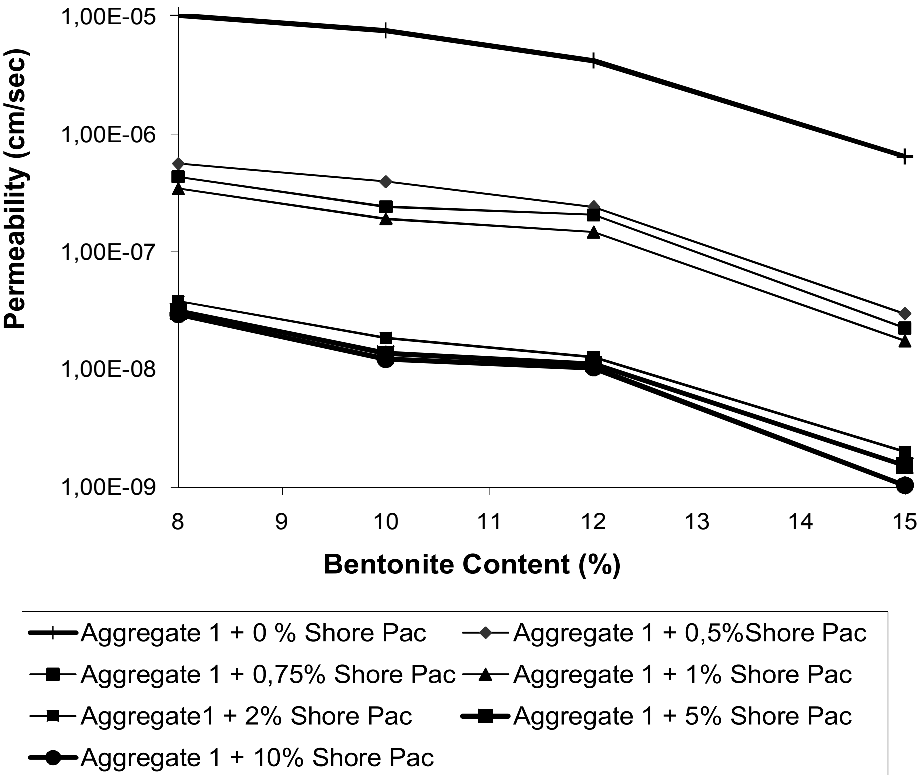


Figure 6.17. Effect of bentonite content on hydraulic conductivity of Aggregate I + several polymer mixtures

In Figure 6.17 the effect of bentonite addition for several aggregate - polymer mixtures are represented. The increase in polymer content decreased the hydraulic conductivity of all four different bentonite-aggregate mixtures. In the tests, 0.5, 0.75, 1, 2, 5 and 10 per cent polymer was added to different bentonite-aggregate mixtures. When the polymer content exceeded 2 per cent, additional increases in the polymer amount slightly affected hydraulic conductivity.

In Figures 6.18 – 6.30 hydraulic conductivity results for Aggregate II-bentonite and polymer mixtures are represented. In Figure 6.18 the effect of bentonite content on the hydraulic conductivity is represented. When there is no bentonite in the Aggregate II, the hydraulic conductivity value is 1.71E-01 cm/s. When the bentonite content is 5 per cent by weight of aggregate hydraulic conductivity is 6.08E-05 cm/s. Hydraulic conductivity value decreases as the bentonite content increases and when the bentonite content of the bentonite-Aggregate II mixture is 15 per cent the hydraulic conductivity value is 5.431E-07 cm/s.

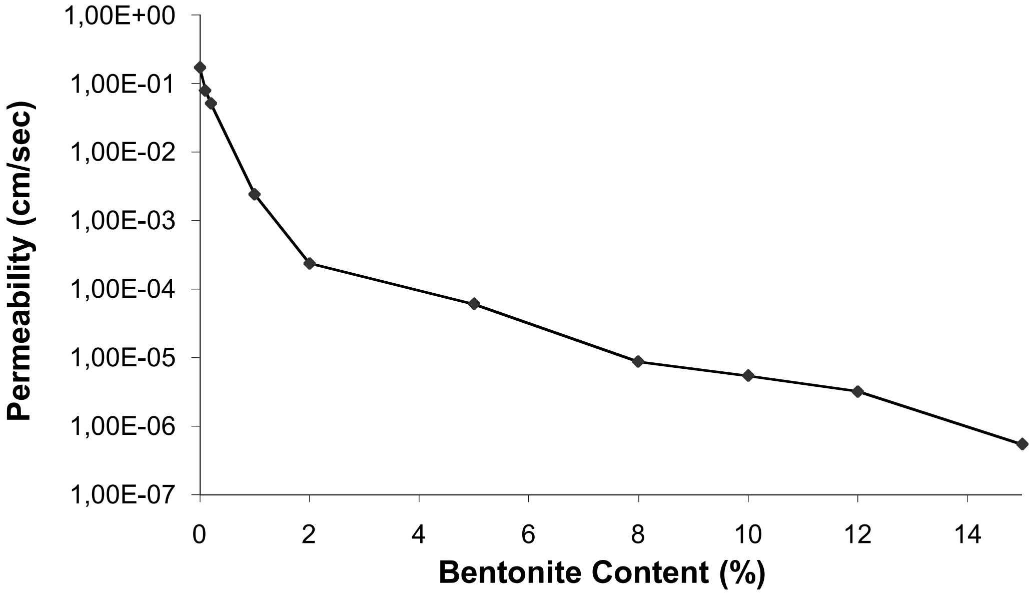


Figure 6.18. Effect of bentonite content on hydraulic conductivity of Aggregate II - bentonite mixture

In Figure 6.19 the effect of polymer, on hydraulic conductivity of Aggregate II + 8 per cent bentonite mixture is represented. The addition of 0.5 per cent polymer by air-dried weight of bentonite reduced the hydraulic conductivity value to 6.13E-07 cm/s from 8.73.E-06 cm/s. When the percentage of polymer was increased to 0.75 per cent the hydraulic conductivity value decreased to 4.28E-07 cm/s. Addition of 10 per cent polymer decreased hydraulic conductivity value to 2.38E-08 cm/s.

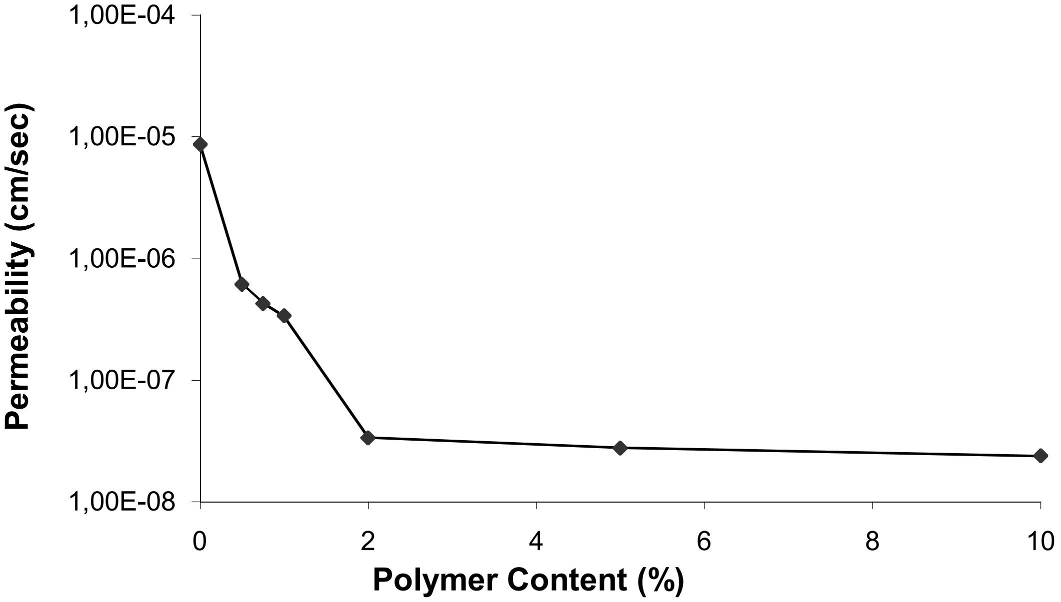


Figure 6.19. Effect of polymer content on hydraulic conductivity of Aggregate II + 8 per cent bentonite mixture

In Figure 6.20 the effect of polymer, on hydraulic conductivity of Aggregate II + 10 per cent bentonite mixture is represented. The addition of 0.5 per cent polymer by air-dried weight of bentonite reduced the hydraulic conductivity value to 3.00E-07 cm/s from 5.46E-06 cm/s. When the percentage of polymer was increased to 5 per cent the hydraulic conductivity value decreased to 1.34E-08 cm/s. Addition of 10 per cent polymer decreased hydraulic conductivity value to 1.16E-08 cm/s.

In Figure 6.21 the effect of polymer, on hydraulic conductivity of Aggregate II + 12 per cent bentonite mixture is represented. The addition of 1 per cent polymer by air-dried weight of bentonite reduced the hydraulic conductivity value to 9.02E-08 cm/s from 3.20E-06 cm/s. When the percentage of polymer was increased to 2 per cent the hydraulic conductivity value decreased to 7.96E-09 cm/s. Addition of 10 per cent polymer decreased hydraulic conductivity value to 5.29E-09 cm/s.

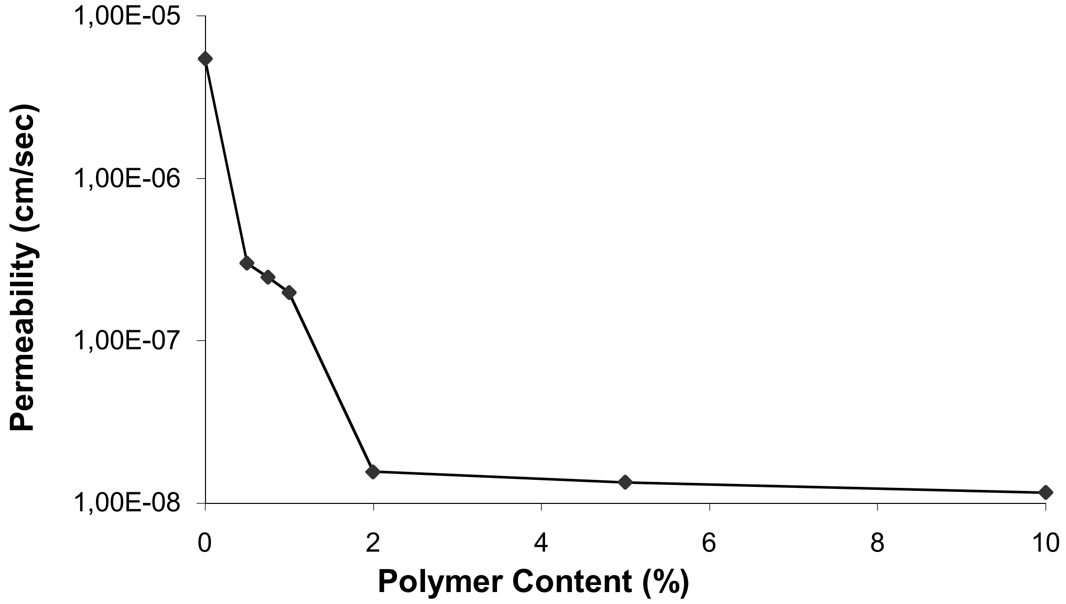


Figure 6.20. Effect of polymer content on hydraulic conductivity of Aggregate II + 10 per cent bentonite mixture

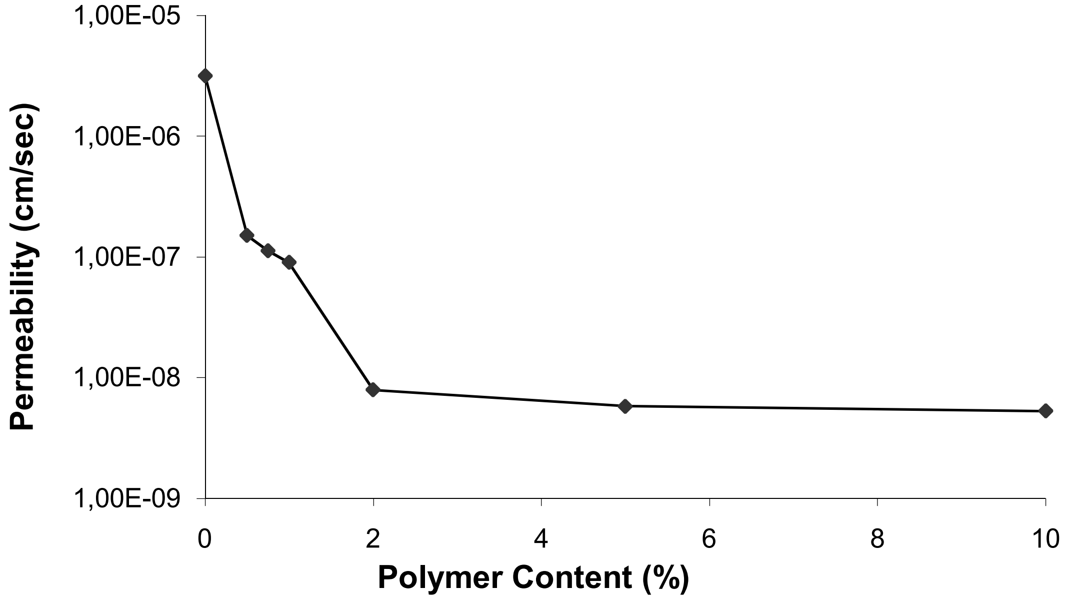


Figure 6.21. Effect of polymer content on hydraulic conductivity of Aggregate II + 12 per cent bentonite mixture

In Figure 6.22 the effect of polymer, on hydraulic conductivity of Aggregate II + 15 per cent bentonite mixture is represented. Without polymer addition, the hydraulic conductivity of Aggregate II + 15 per cent bentonite mixture was 5.43E-07 cm/s. The addition of 0,75 per cent polymer by air-dried weight of bentonite decreased the hydraulic conductivity value to 1.598E-08 cm/s. When the amount of polymer was increased to 5 per cent the hydraulic conductivity value decreased to 1.30E-09 cm/s.

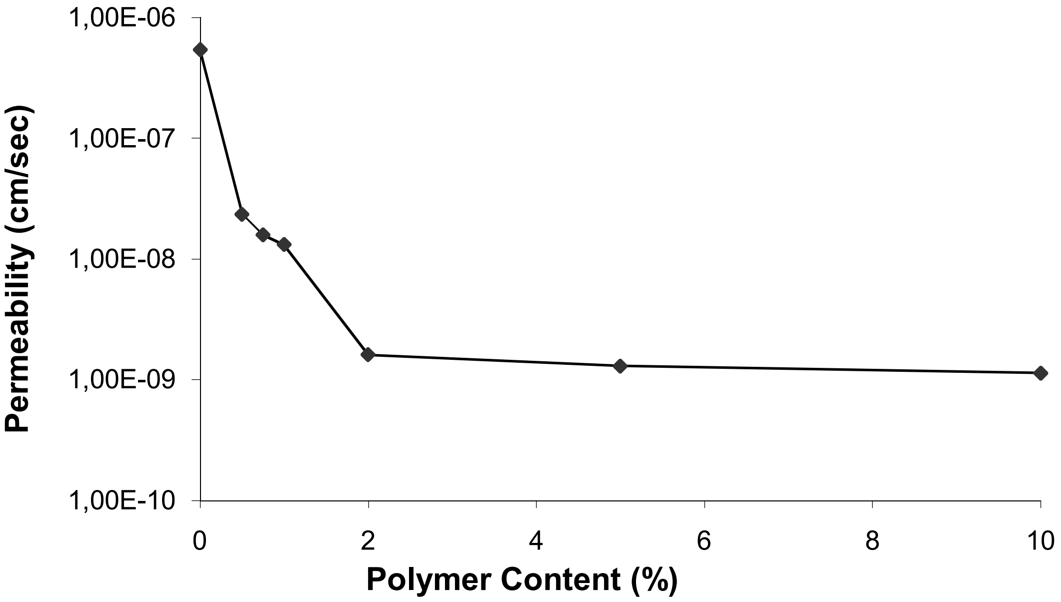


Figure 6.22. Effect of polymer content on hydraulic conductivity of Aggregate II + 15 per cent bentonite mixture

In Figure 6.23 the effect of polymer content, on hydraulic conductivity of several Aggregate II - bentonite mixtures are represented. The addition of polymer, significantly decreased hydraulic conductivity values for all specimens. Although polymer addition resulted in very low hydraulic conductivities, for the amounts more than 2 percent, the polymer content increase slightly affected hydraulic conductivity values.

In Figures 6.24 – 6.30 the effect of bentonite addition for several aggregate - polymer mixtures are represented. Addition of bentonite resulted in similar hydraulic conductivity values for different polymer concentrations. In Figure 6.24 when the bentonite content in the mixture is 8 per cent, the hydraulic conductivity is 6.13E-07 cm/s. While the amount of polymer content kept constant at 0,5 per cent, the increase of bentonite content to 15 per cent decreased hydraulic conductivity value to 2.36E-08 cm/s.

In Figure 6.25 when the bentonite content in the mixture is 10 per cent, the hydraulic conductivity is 2.46E-07 cm/s. While the amount of polymer content kept constant at 0,75 per cent, the increase of bentonite content to 12 per cent decreased hydraulic conductivity value to 1.13E-07 cm/s.

In Figure 6.26 when the bentonite content in the mixture is 8 per cent, the hydraulic conductivity is 3.38E-07 cm/s. While the amount of polymer content kept constant at 1 per cent, the increase of bentonite content to 15 per cent decreased hydraulic conductivity value to 1.32E-08 cm/s. In Figures 6.23-6.25, it is shown that, the bentonite content increase lowered hydraulic conductivity values for all specimens.

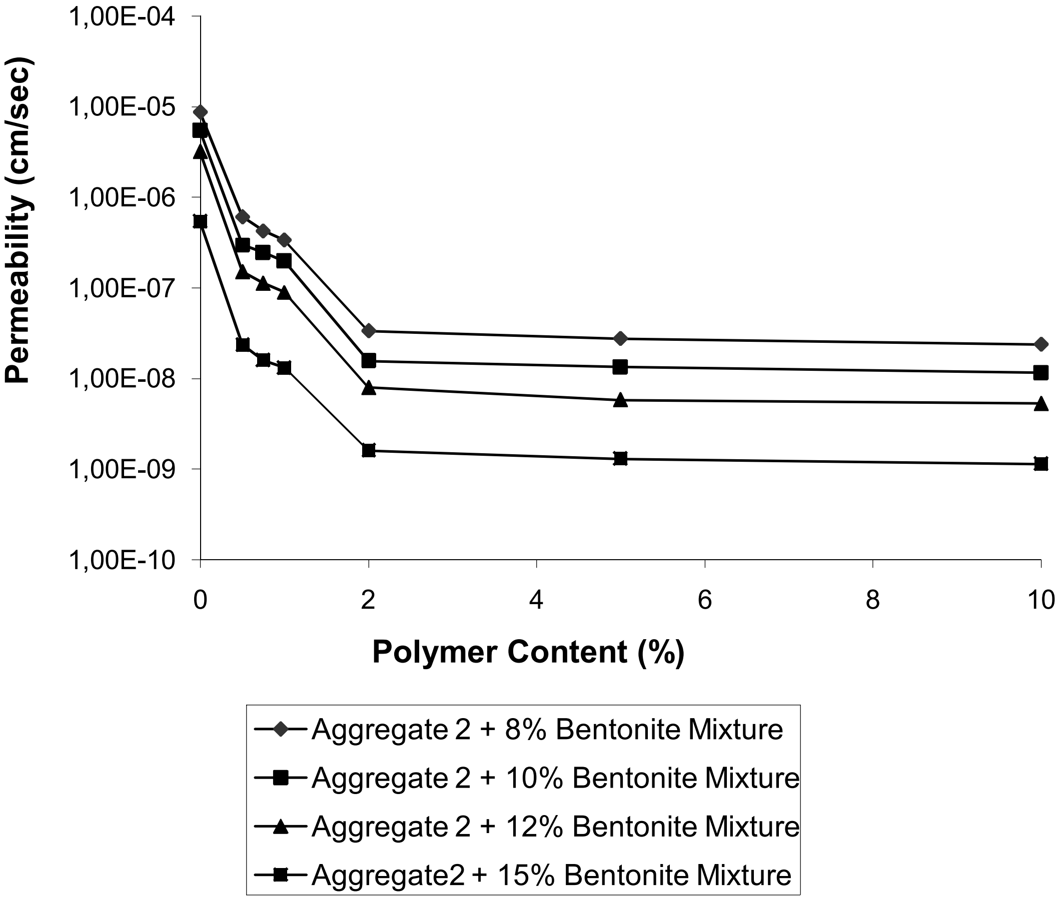


Figure 6.23. Effect of polymer content on hydraulic conductivity of Aggregate II + several bentonite mixtures

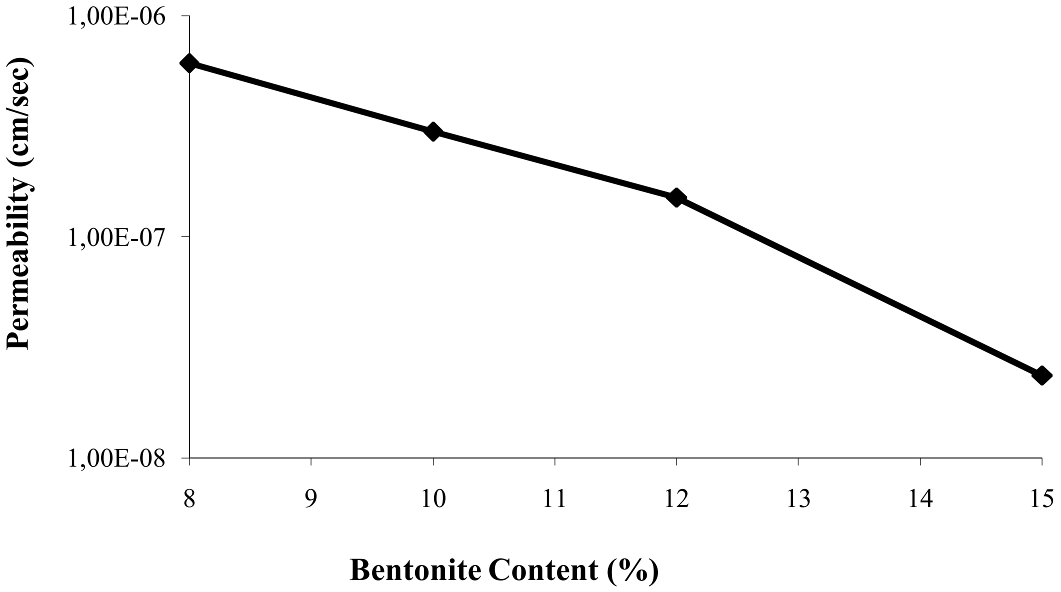


Figure 6.24. Effect of bentonite content on hydraulic conductivity of Aggregate II + 0,5 per cent polymer mixture

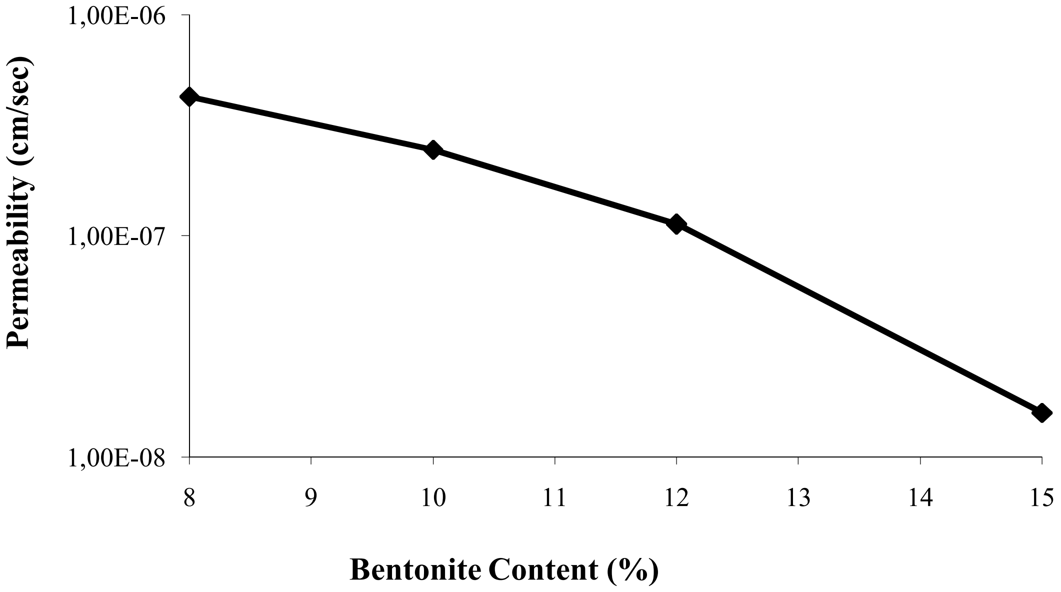


Figure 6.25. Effect of bentonite content on hydraulic conductivity of Aggregate II + 0,75 per cent polymer mixture

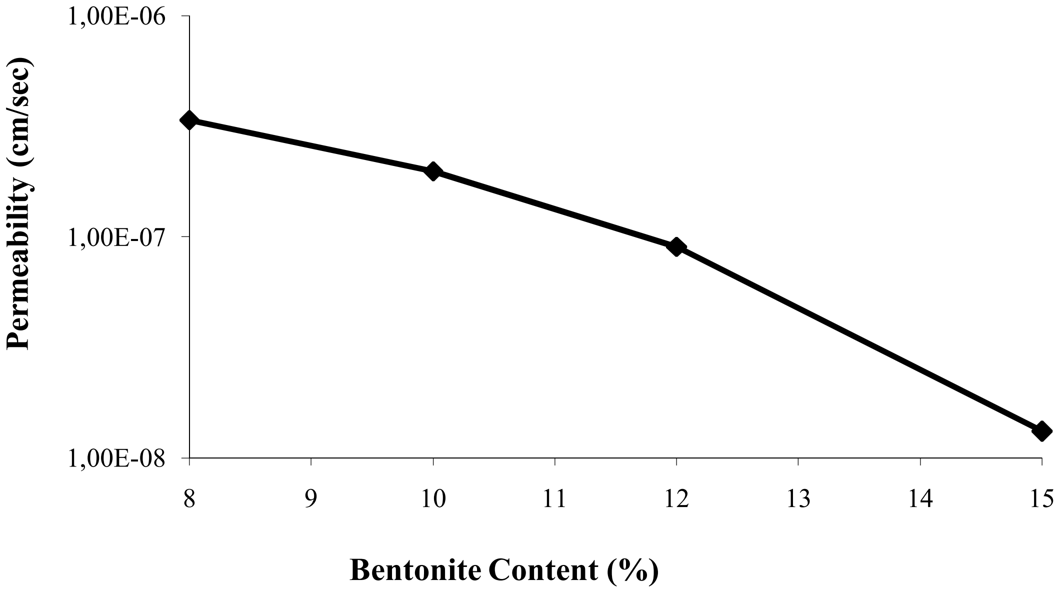


Figure 6.26. Effect of bentonite content on hydraulic conductivity of Aggregate II + 1 per cent polymer mixture

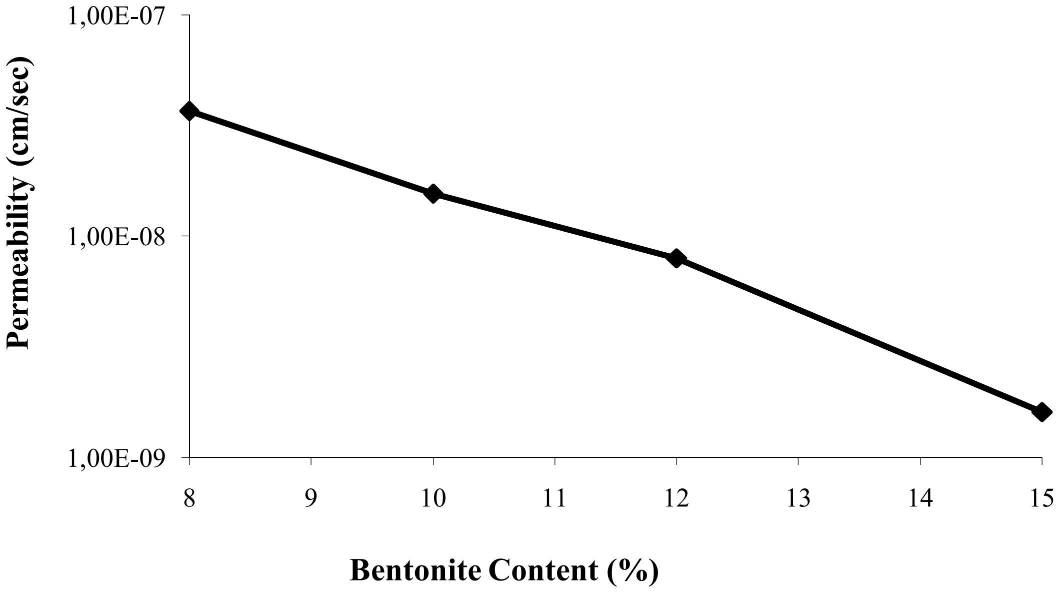


Figure 6.27. Effect of bentonite content on hydraulic conductivity of Aggregate II + 2 per cent polymer mixture

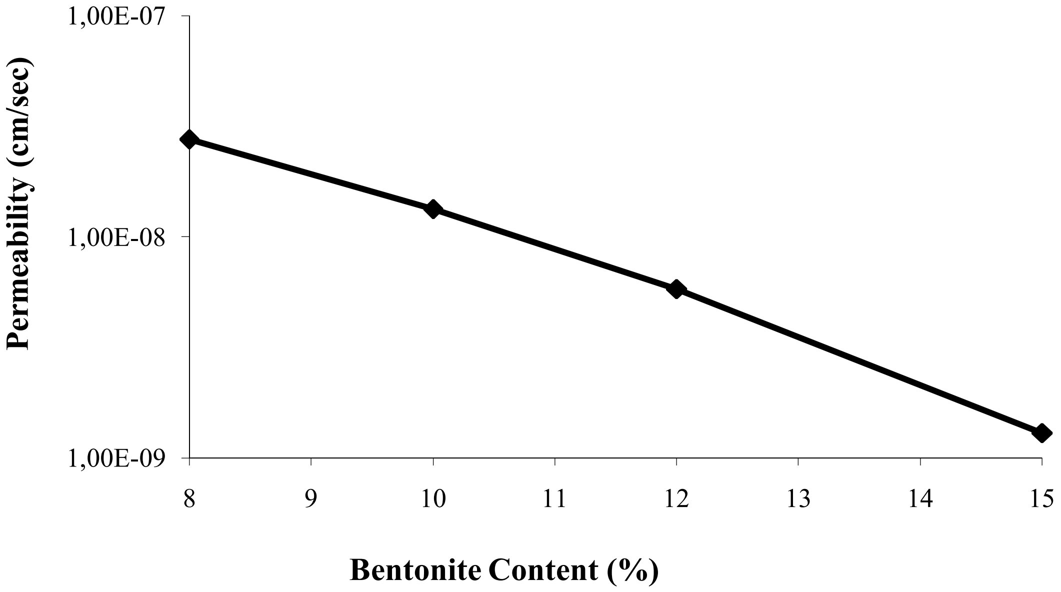


Figure 6.28. Effect of bentonite content on hydraulic conductivity of Aggregate II + 5 per cent polymer mixture

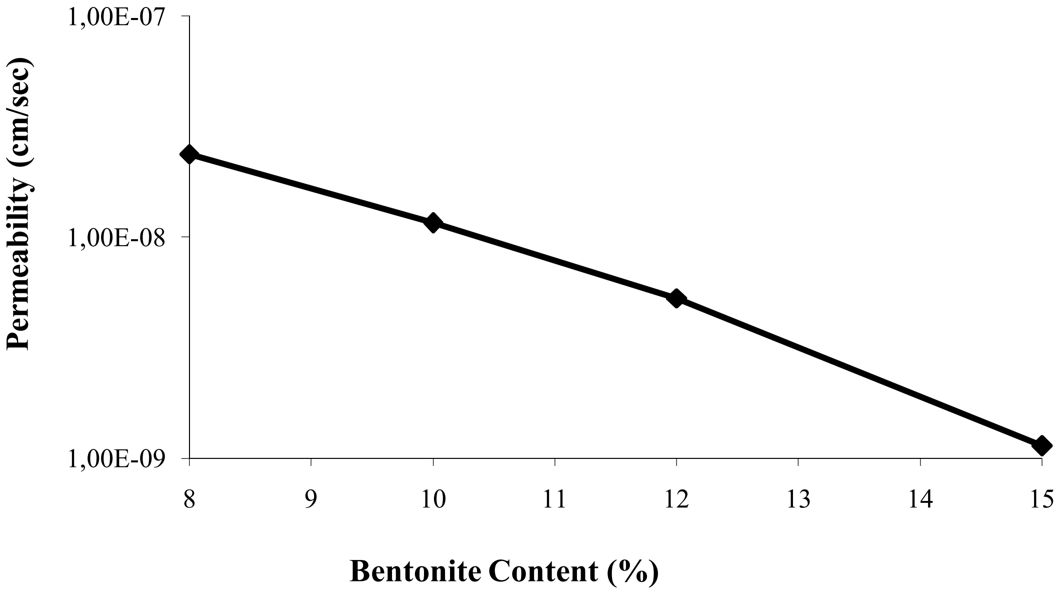


Figure 6.29. Effect of bentonite content on hydraulic conductivity of Aggregate II + 10 per cent polymer mixture

In Figure 6.30 the effect of bentonite addition for several aggregate - polymer mixtures are represented. The increase in polymer content decreased the hydraulic conductivity of all four different bentonite-aggregate mixtures. In the tests, 0.5, 0.75, 1, 2, 5 and 10 per cent polymer was added to different bentonite-aggregate mixtures. When the polymer content exceeded 2 per cent, additional increases in the polymer amount slightly affected hydraulic conductivity.

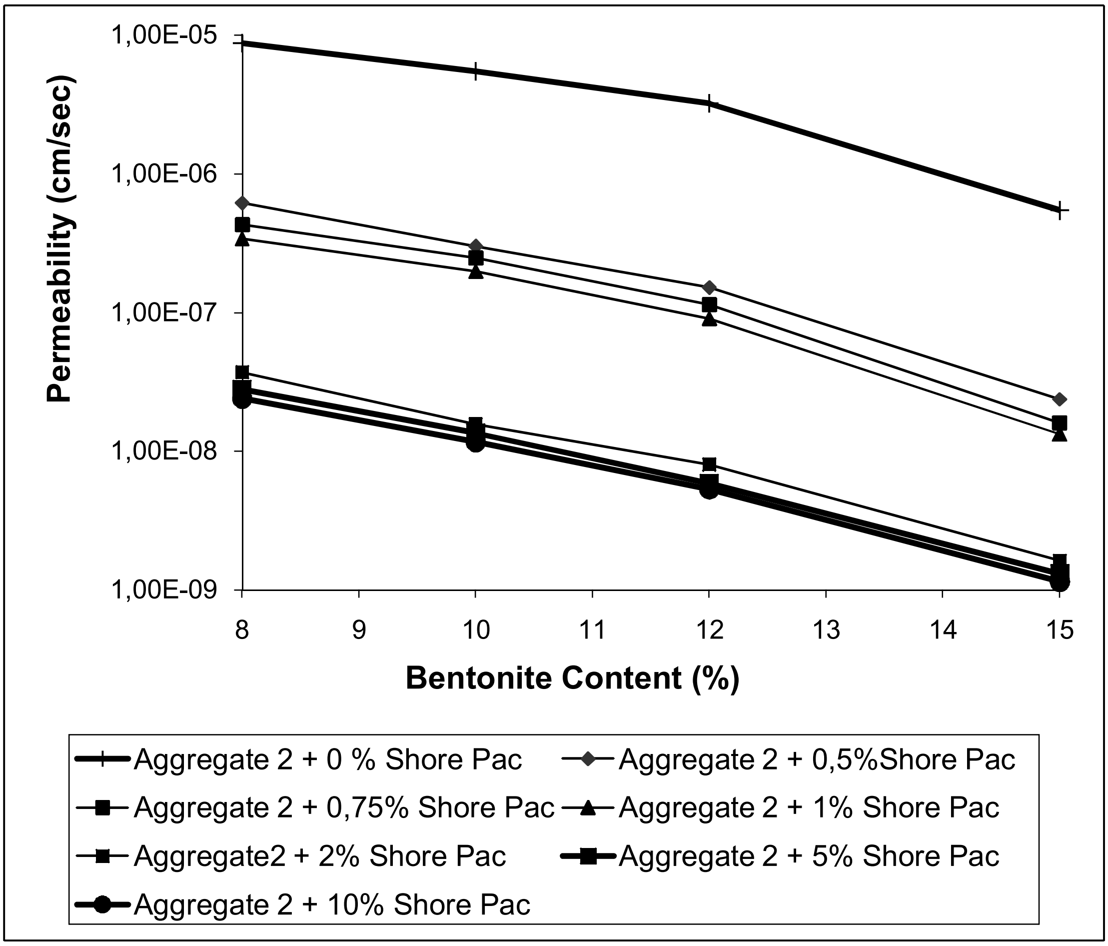


Figure 6.30. Effect of bentonite content on hydraulic conductivity of Aggregate II + several polymer mixtures

6.4. Results of Viscosity Determination Tests

The results of all viscosity determination tests are exhibited in the Figure 6.31. The detailed results of the experiments are provided in Appendix D. The viscosity of pure water was 1 cP. when 0,5 per cent of polymer was added to water the viscosity value was measured as 33 cP. Addition of 0,75 per cent polymer increased the viscosity to 45 cP. 1 per cent polymer addition increased the viscosity of the solution to 98 cP. 2 per cent of polymer was added to water and viscosity value was measured as 760 cP. Addition of 5 per cent polymer led viscosity value to become 2160 cP while viscosity value for 10 per cent polymer was 2950 cP. It was observed that, addition of marginal amount of polymer significantly increased viscosity. The rate of increase in viscosity was not directly proportional with the increase in polymer content. The effect of polymer addition on viscosity gradually decreased for the polymer contents higher than 2 per cent.

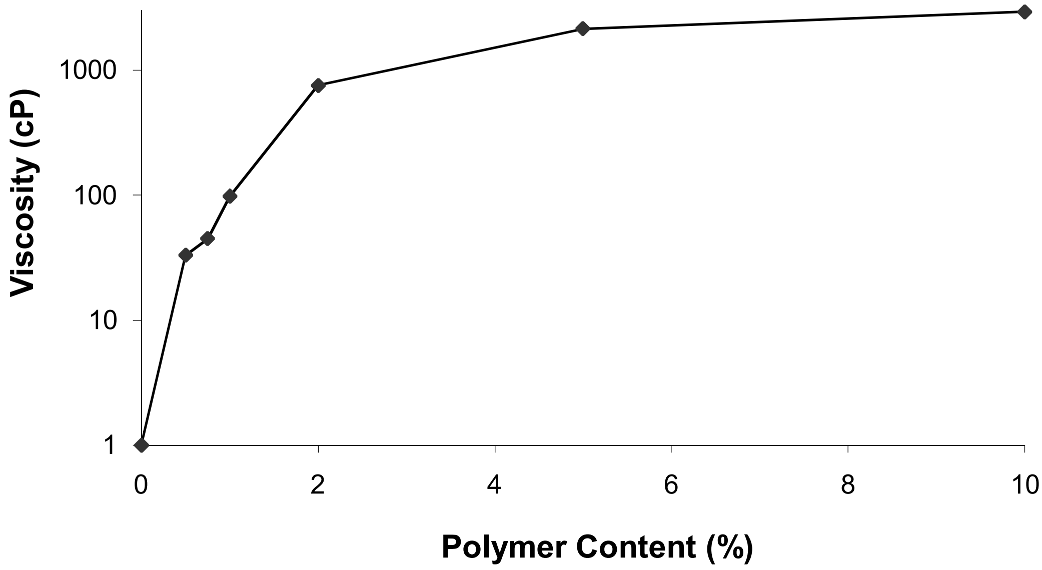


Figure 6.31. Change of viscosity due to polymer addition for polymer solution in water

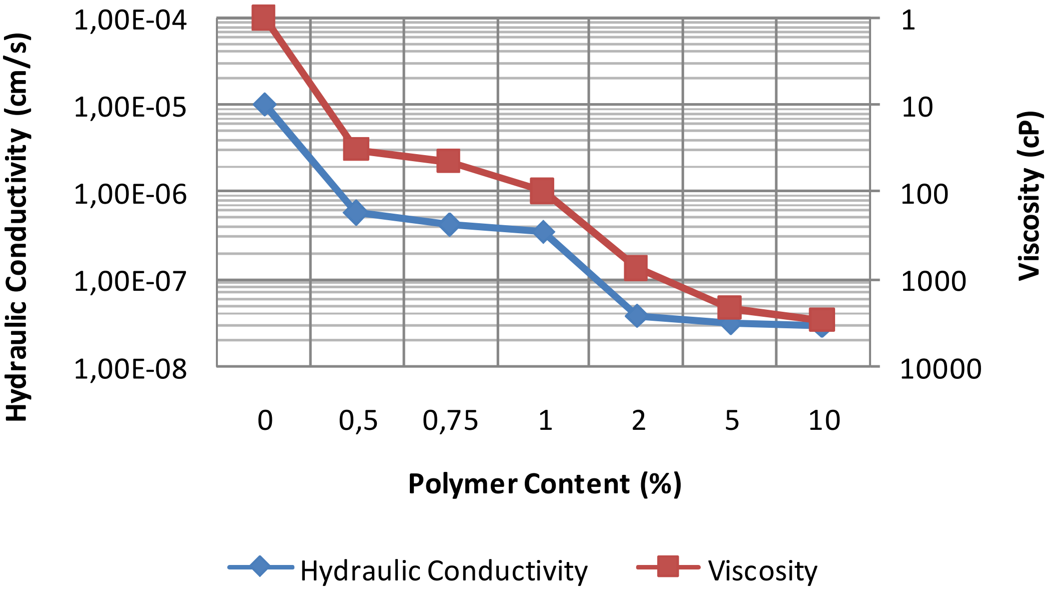


Figure 6.32 Effects of polymer addition on hydraulic conductivity and viscosity for Aggregate I + 8 per cent bentonite mixture

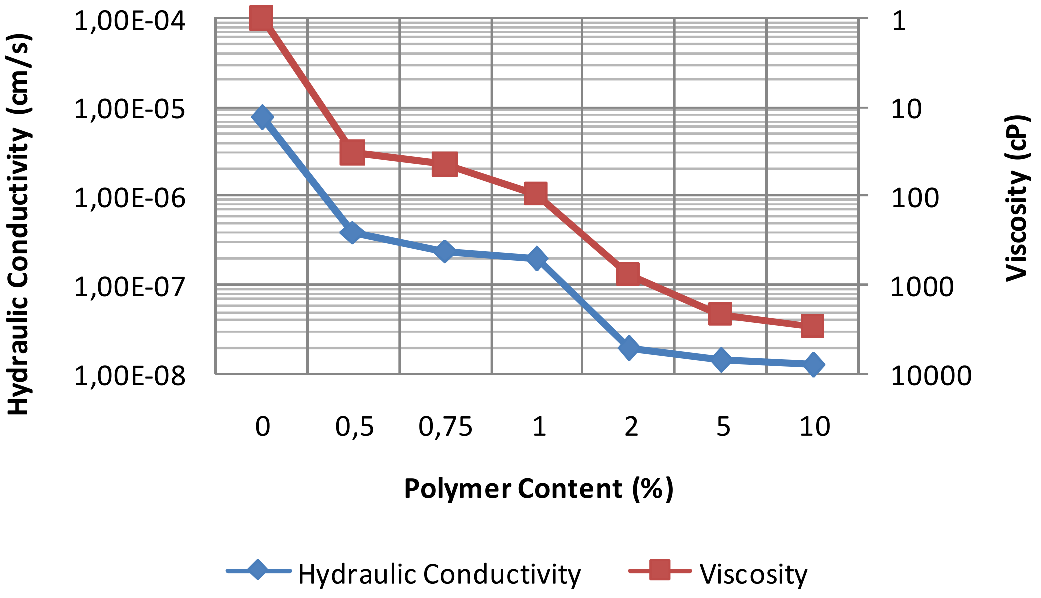


Figure 6.33 Effects of polymer addition on hydraulic conductivity and viscosity for Aggregate I + 10 per cent bentonite mixture

In Figures 6.32-6.41, effects of polymer addition on hydraulic conductivity and viscosity are exhibited on the same graph in order to compare the changes in viscosity and hydraulic conductivity. For all aggregate + bentonite mixtures, changes in viscosity were similar in amount with the changes in hydraulic conductivity when the amount of polymer content in the mixture was lower than 2 per cent. For the polymer contents higher than 2 per cent, viscosity values continued to increase with the increase in polymer amount while hydraulic conductivity values were not affected as much as much viscosity, due to change in polymer content.

In Figure 6.32, the increase of polymer content from 2 per cent to 10 per cent, decreased hydraulic conductivity from 3.82E-08 cm/s to 2.95E-08 cm/s presenting 29 per cent decrease. The increase of polymer content from 2 per cent to 10 per cent, increased viscosity from 760 cP to 2950 cP representing 388 per cent change.

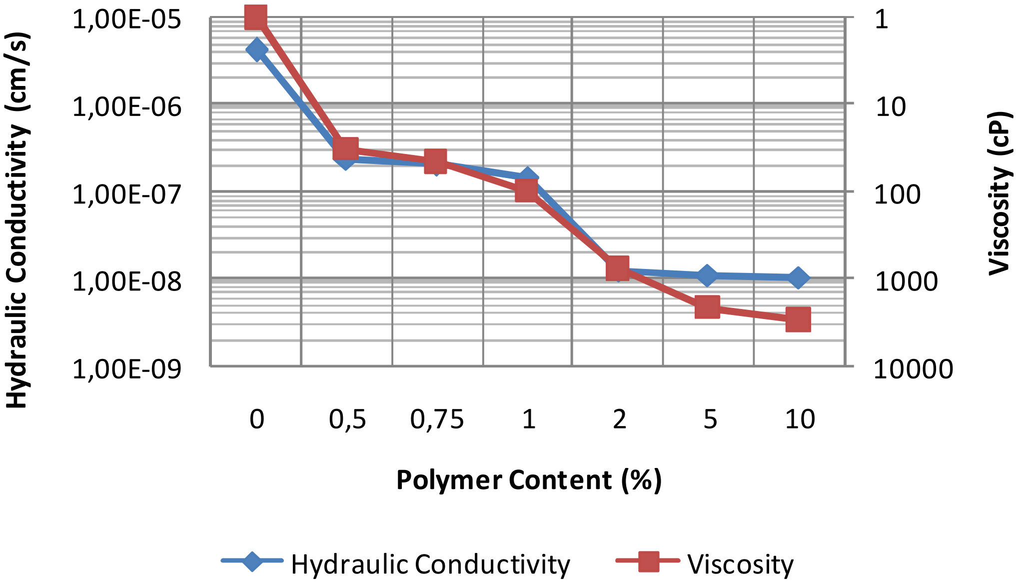


Figure 6.34 Effects of polymer addition on hydraulic conductivity and viscosity for Aggregate I + 12 per cent bentonite mixture

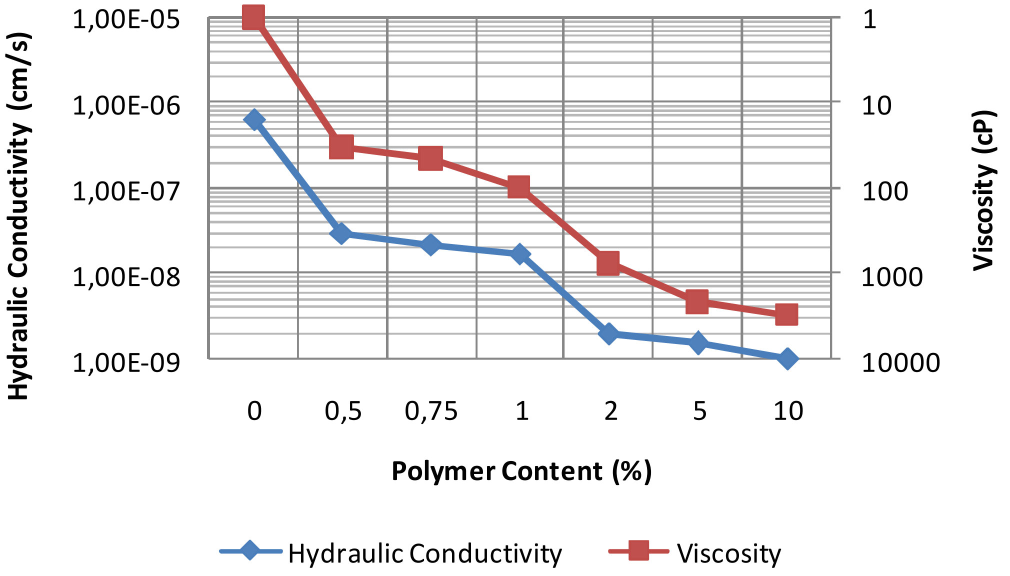


Figure 6.35 Effects of polymer addition on hydraulic conductivity and viscosity for Aggregate I + 15 per cent bentonite mixture

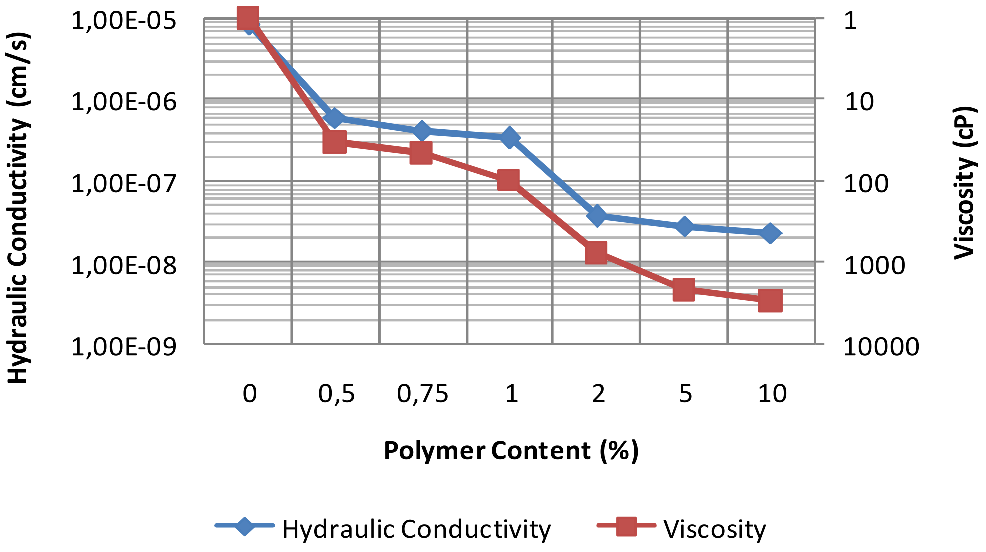


Figure 6.36 Effects of polymer addition on hydraulic conductivity and viscosity for Aggregate II + 8 per cent bentonite mixture

In Figure 6.36, the increase of polymer content from 0,5 per cent to 0,75 per cent, decreased hydraulic conductivity from 6.13E-07 cm/s to 4.28E-07 cm/s presenting 43 per cent decrease. The increase of polymer content from 0,5 per cent to 0,75 per cent, increased viscosity from 33 cP to 45 cP representing 36 per cent change.

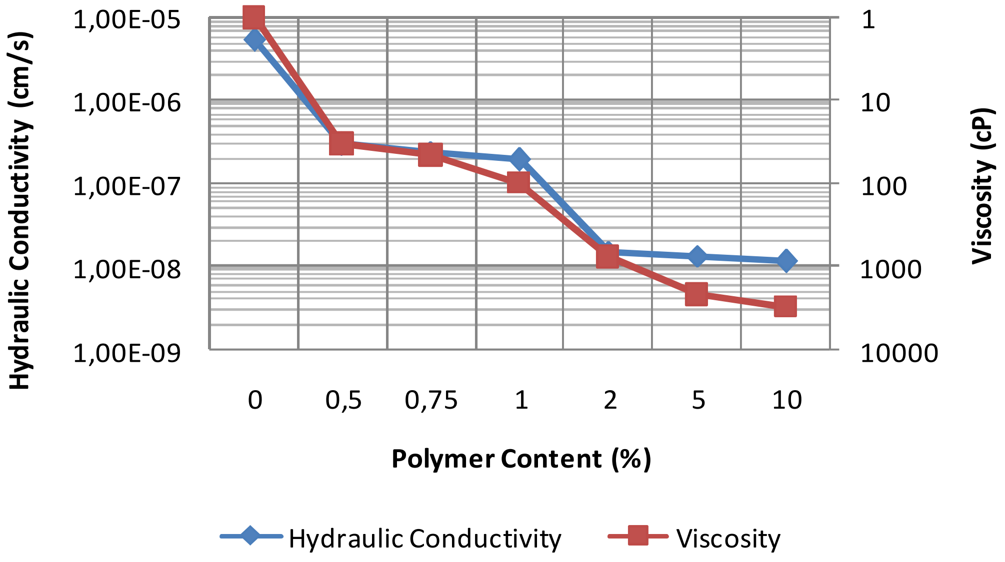


Figure 6.37 Effects of polymer addition on hydraulic conductivity and viscosity for Aggregate II + 10 per cent bentonite mixture

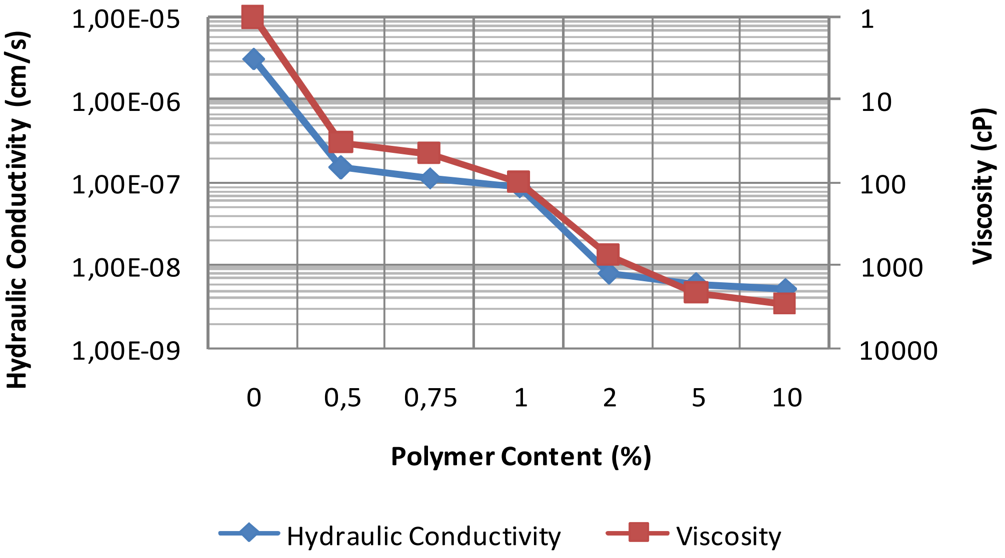


Figure 6.38 Effects of polymer addition on hydraulic conductivity and viscosity for Aggregate II + 12 per cent bentonite mixture

In Figure 6.38, the increase of polymer content from 1 per cent to 5 per cent, decreased hydraulic conductivity from 9.02E-08 cm/s to 5.82E-09 cm/s. The increase of polymer content from 1 per cent to 5 per cent, increased viscosity from 98 cP to 2160 cP.

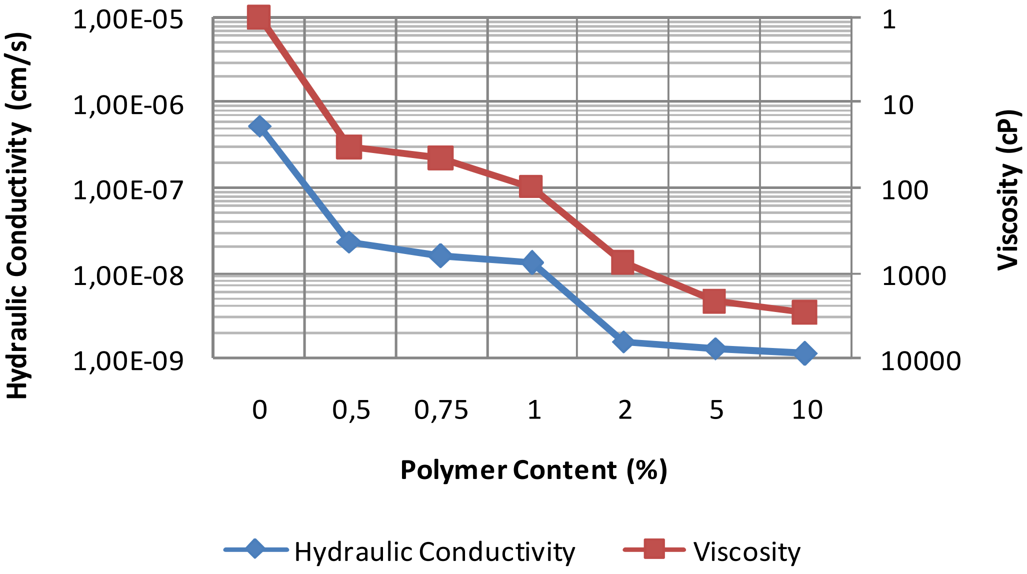


Figure 6.39 Effects of polymer addition on hydraulic conductivity and viscosity for Aggregate II + 15 per cent bentonite mixture

6.5. Evaluation of Test Results

Two different aggregate mixtures were used in the tests. First mixture, “Aggregate I” was composed of 29 per cent number 2 (22-12 mm) crushed stone, 29 per cent number 1 (12-5 mm) crushed stone, 24 per cent number 0 (5mm-0 mm) stone powder and 18 per cent sand by weight. Second mixture “Aggregate II” was composed of 20 per cent number 2 (22-12 mm) crushed stone, 20 per cent number 1 (12-5 mm) crushed stone, 20 per cent number 0 (5mm-0 mm) stone powder and 40 per cent sand by weight. Hydraulic conductivity tests were conducted on these two aggregate mixtures after addition of bentonite and polymer in the mixtures. The void ratio of specimens were mainly controlled by the percentage of fine particles.

Void ratio of Aggregate I mixture was 0,33 while void ratio for Aggregate II was 0,21. Hydraulic conductivity values decreased for both of aggregate mixtures when bentonite was added. Results of hydraulic conductivity tests for different aggregate – bentonite - polymer mixtures are shown in Table 6.2.

In Figure 6.40 effect of bentonite content on hydraulic conductivity of both Aggregate I - bentonite mixtures and Aggregate II - bentonite mixtures are represented. As shown in Figure 6.40, hydraulic conductivity values for Aggregate II which had less void ratio than Aggregate I, were slightly less than Aggregate I. When there was no bentonite in both of aggregate mixtures, hydraulic conductivity of Aggregate I was 10 per cent higher than Aggregate II. Although, the difference between void ratios of two aggregate mixtıres was as high as 0,12, small amount of bentonite addition (0,1 per cent) resulted in similar hydraulic conductivity values for both. The hydraulic conductivity after the addition of 0,1 per cent bentonite was 8.46E-02 for Aggregate I and 7.98E-02 for Aggregate II. The difference between these two hydraulic conductivity values is 6 per cent. When the amount of bentonite added to mixture was 0,2 per cent, hydraulic conductivity was 6.74E-02 for Aggregate I and 5.18E-02 for Aggregate II, representing a difference of 30 per cent. These results shows that, even for very low amounts of bentonite, hydraulic conductivity of the mixture is controlled by bentonite content. Swelling potential of bentonite plays an important role in obtaining low hydraulic conductivities by small amount of bentonite addition.

Table 6.2. Comparison of hydraulic conductivity values for Aggregate I and Aggregate II

Content of aggregate+bentonite+polymer mixture	Aggregate I	Aggregate II
Aggregate + 0 % Bentonite	1,88E-01	1,71E-01
Aggregate + 0,1 % Bentonite	8,46E-02	7,98E-02
Aggregate + 0,2 % Bentonite	6,74E-02	5,18E-02
Aggregate + 1 % Bentonite	2,76E-03	2,40E-03
Aggregate + 2 % Bentonite	3,22E-04	2,39E-04
Aggregate + 5 % Bentonite	7,36E-05	6,08E-05
Aggregate + 8 % Bentonite	1,03E-05	8,73E-06
Aggregate + 8 % Bentonite + %0,5 Shore Pac	5,65E-07	6,13E-07
Aggregate + 8 % Bentonite + %0,75 Shore Pac	4,35E-07	4,28E-07
Aggregate + 8 % Bentonite + % 1 Shore Pac	3,48E-07	3,38E-07
Aggregate + 8 % Bentonite + % 2 Shore Pac	3,82E-08	3,68E-08
Aggregate + 8 % Bentonite + % 5 Shore Pac	3,16E-08	2,77E-08
Aggregate + 8 % Bentonite + % 10 Shore Pac	2,95E-08	2,38E-08
Aggregate + 10 % Bentonite	7,64E-06	5,46E-06
Aggregate + 10 % Bentonite + % 0,5 Shore Pac	3,97E-07	3,00E-07
Aggregate + 10 % Bentonite + % 0,75 Shore Pac	2,43E-07	2,46E-07
Aggregate + 10 % Bentonite + % 1 Shore Pac	1,92E-07	1,98E-07
Aggregate + 10 % Bentonite + % 2 Shore Pac	1,87E-08	1,56E-08
Aggregate + 10 % Bentonite + % 5 Shore Pac	1,38E-08	1,34E-08
Aggregate + 10 % Bentonite + % 10 Shore Pac	1,23E-08	1,16E-08
Aggregate + 12 % Bentonite	4,23E-06	3,20E-06
Aggregate + 12 % Bentonite + % 0,5 Shore Pac	2,42E-07	1,51E-07
Aggregate + 12 % Bentonite + % 0,75 Shore Pac	2,08E-07	1,13E-07
Aggregate + 12 % Bentonite + % 1 Shore Pac	1,48E-07	9,02E-08
Aggregate + 12 % Bentonite + % 2 Shore Pac	1,28E-08	7,96E-09
Aggregate + 12 % Bentonite + % 5 Shore Pac	1,12E-08	5,82E-09
Aggregate + 12 % Bentonite + % 10 Shore Pac	1,04E-08	5,29E-09
Aggregate + 15 % Bentonite	6,51E-07	5,43E-07
Aggregate + 15 % Bentonite + % 0,5 Shore Pac	2,99E-08	2,36E-08
Aggregate + 15 % Bentonite + % 0,75 Shore Pac	2,26E-08	1,59E-08
Aggregate + 15 % Bentonite + % 1 Shore Pac	1,76E-08	1,32E-08
Aggregate + 15 % Bentonite + % 2 Shore Pac	2,01E-09	1,61E-09
Aggregate + 15 % Bentonite + % 5 Shore Pac	1,54E-09	1,30E-09
Aggregate + 15 % Bentonite + % 10 Shore Pac	1,04E-09	1,14E-09

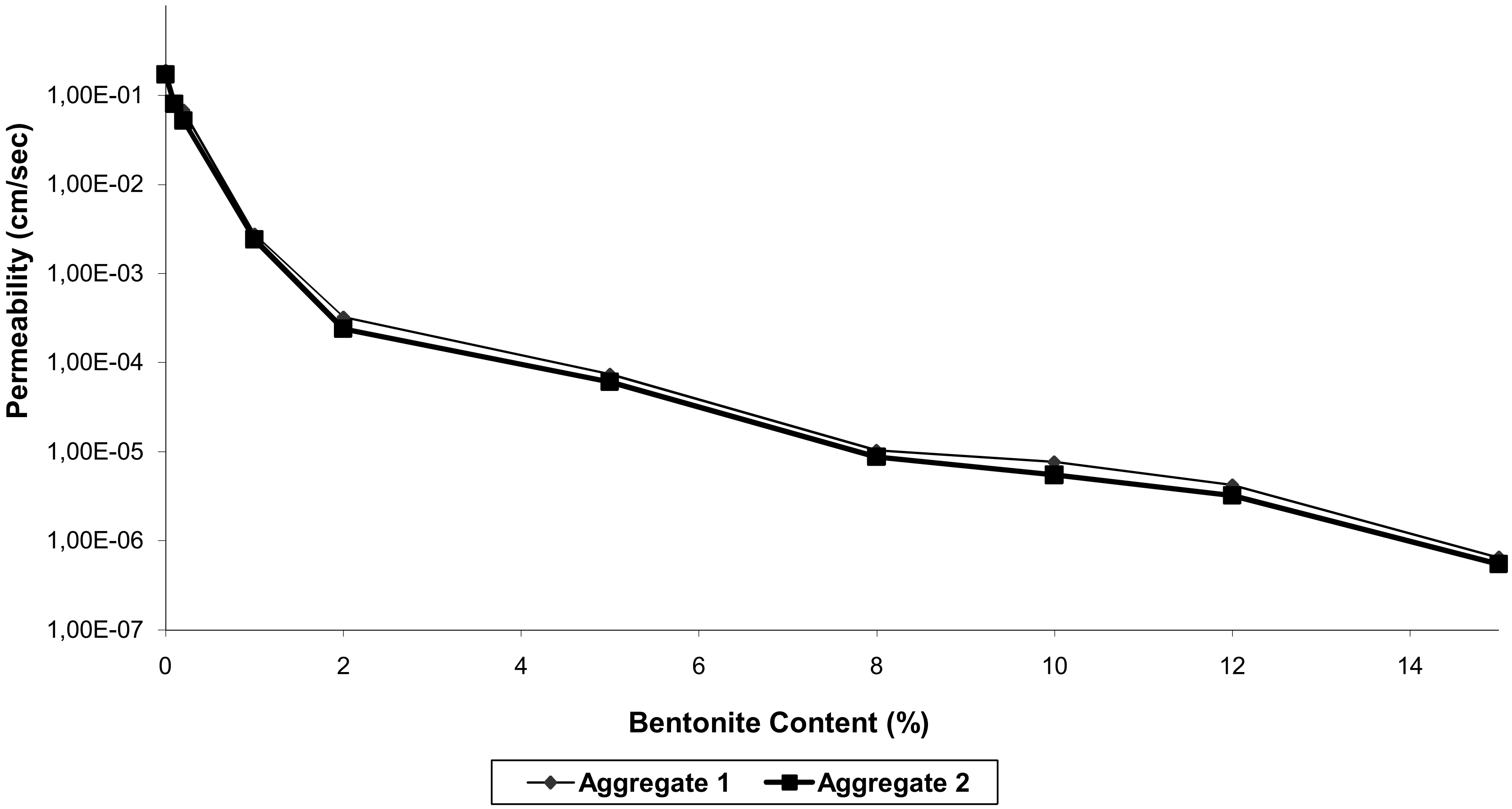


Figure 6.40. Effect of bentonite content on hydraulic conductivity of Aggregate I /Aggregate II - bentonite mixture

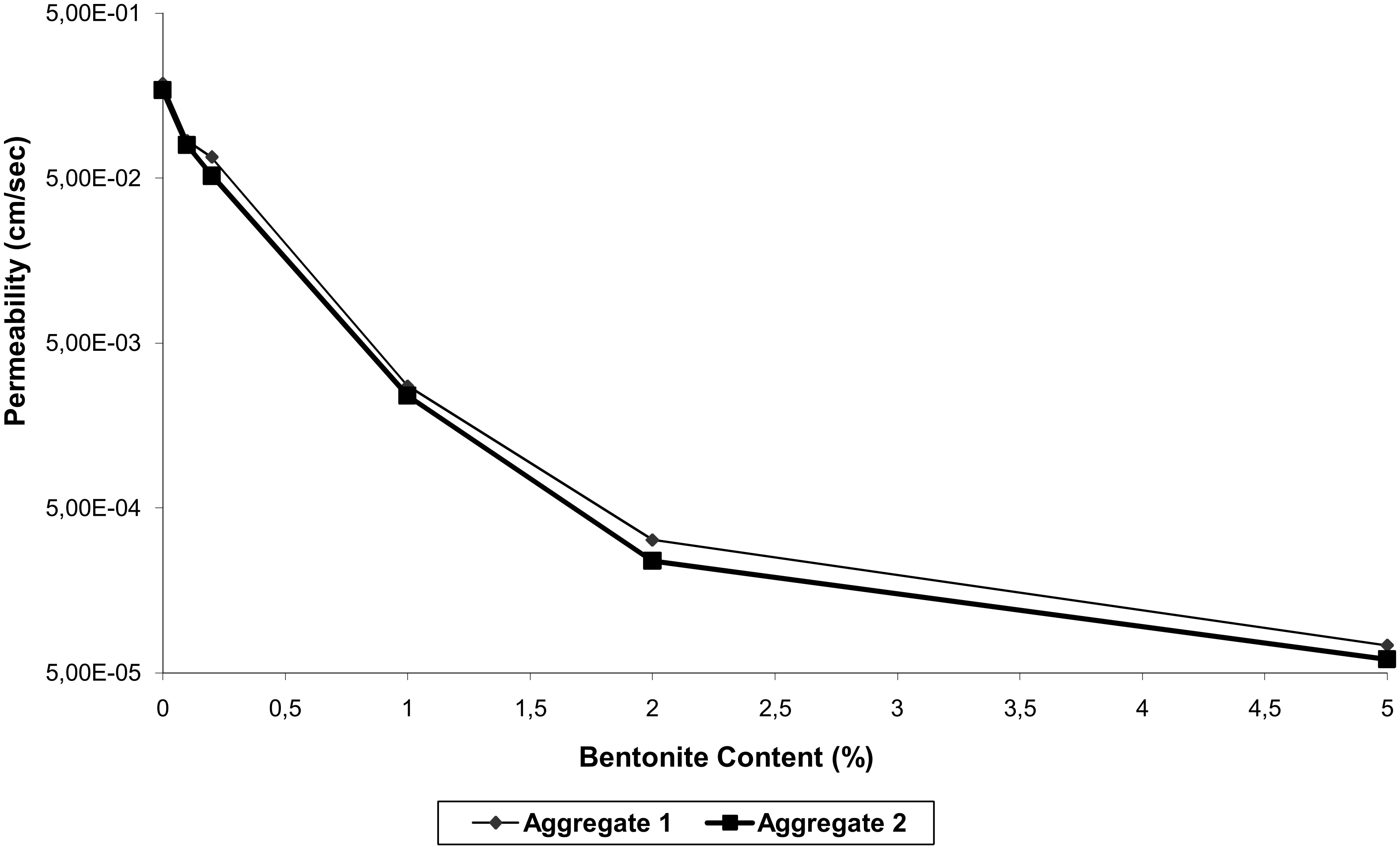


Figure 6.41. Effect of bentonite content on hydraulic conductivity of Aggregate I /Aggregate II - bentonite mixture

In Figure 6.41 Effect of bentonite content on hydraulic conductivity of Aggregate I /Aggregate II - bentonite mixtures when the bentonite content was lower than 5 per cent are exhibited. When 0,1 per cent bentonite was added to aggregate mixture, a slight difference in hydraulic conductivity trends occured for Aggregate I and Aggregate II. For higher bentonite contents hydraulic conductivity trends were similar.

Addition of one per cent bentonite decreased hydraulic conductivity 68 times for Aggregate I and 71 times for Aggregate II. The difference between the hydraulic conductivity values for Aggregate I and Aggregate II including 1 per cent bentonite was 15 per cent. Two per cent bentonite addition decreased hydraulic conductivity 583 times for Aggregate I and 715 times for Aggregate II when compared with aggregate samples without bentonite. The difference between the hydraulic conductivity values for Aggregate I and Aggregate II including 2 per cent bentonite was 35 per cent. The hydraulic conductivity after the addition of 5 per cent bentonite was 7.36E-05 for Aggregate I and 6.08E-05 for Aggregate II. The difference between these two hydraulic conductivity values is 21 per cent. When the amount of bentonite added to mixture was 8 per cent, hydraulic conductivity was 1.034E-05 for Aggregate I and 8.73E-06 for Aggregate II, representing a difference of 18 per cent. Ten per cent bentonite addition decreased hydraulic conductivity value to 7.64E-06 for Aggregate I and 5.46E-06 for Aggregate II representing a 40 per cent difference. The hydraulic conductivity after the addition of 12 per cent bentonite was 4.23E-06 for Aggregate I and 3.20E-06 for Aggregate II. The difference between these two hydraulic conductivity values is 32 per cent. When the amount of bentonite added to mixture was 15 per cent, hydraulic conductivity was 6.51E-07 for Aggregate I and 5.43E-07 for Aggregate II, representing a difference of 20 per cent.

Free swelling index of bentonite used in this study was 6. The porosity of Aggregate I was 0,25 while it was 0,17 for Aggregate II. The percentage of bentonite needed to fully fill the voids in Aggregate I is calculated as follows:

Volume of sample = 944 cm^3
The volume of voids to be filled by bentonite: 944X0,25=236 cm^3
The free swelling index of bentonite = 6
The weight of bentonite needed to fully fill the voids = 236 cm^{3}x1,70 gr/cm^3/3,6=66,87 gr.

Percentage of bentonite needed to fully fill the voids in aggregate

% of bentonite = 66,87 gr/(2,1gr/cm^{3}x944cm^3)= 3,37 per cent

The percentage of bentonite needed to fully fill the voids in Aggregate II is calculated as follows:

Volume of sample = 944 cm^3

The volume of voids to be filled by bentonite: 944X0,17=160,48 cm^3

The free swelling index of bentonite = 6

The weight of bentonite needed to fill the voids = 160,48 cm^{3}x1,70 gr/cm^3/3,6=45,47 gr

Percentage of bentonite needed to fully fill the voids in aggregate

% of bentonite = 45,47 gr/(2,22gr/cm^{3}x944cm^3)= 2,17 per cent

For Aggregate I and Aggregate II, theoretically 8 per cent bentonite content would fully fill all the voids in the sample. Test results showed that, for bentonite contents higher than 8 per cent, hydraulic conductivity values continued to decrease.

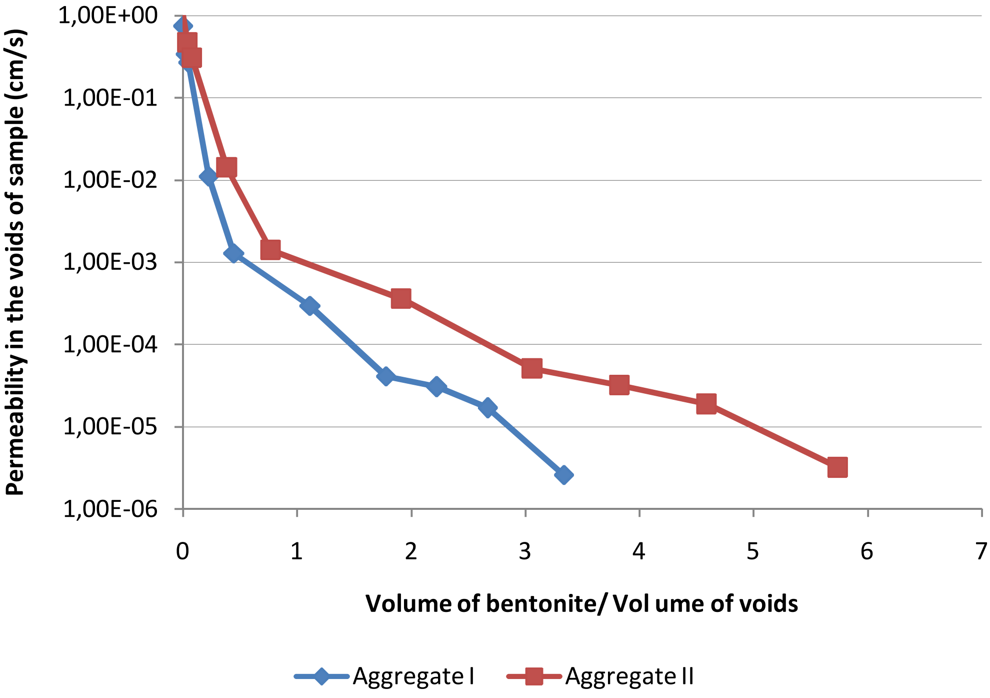


Figure 6.42. Relationship between permeability in the voids of sample and volume of bentonite / volume of voids.

In Figure 6.42, it can be seen that when the volume of bentonite / volume of voids ratio is one, the decrease in permeability values for both Aggregate I and Aggregate II samples reduces. Beyond this point, permeability values continue to decrease with a flattened slope.

According to test results, addition of polymer in aggregate-bentonite mixture extremely reduced hydraulic conductivity. Addition of 0,5 per cent polymer in Aggregate I + 8 per cent bentonite mixture decreased hydraulic conductivity 14 times. When the amount of polymer increased to 2 per cent the decrease in hydraulic conductivity was 237 times with respect to sample without polymer. Tests results are similar for Aggregate II - bentonite mixtures.

When the results of hydraulic conductivity tests obtained in this study are compared with former studies on bentonite-sand mixtures, for the same amount of bentonite in the mixture, bentonite-aggregate and bentonite-sand mixtures seems to have similar hydraulic conductivity values. Tests conducted by Haug and Boldt-Leppin (1992) revealed that for 8 per cent bentonite-Ottawa sand mixture hydraulic conductivity value was around 2E-05 cm/s, while in this study for 8 per cent bentonite-Aggregate I/Aggregate II had hydraulic conductivity value around 1E-05 cm/s. In the study of Sivapullaiah et al., (2000), for 15 per cent bentonite content in bentonite-sand mixture, hydraulic conductivity value was around 1E-07 cm/s. For 15 per cent benonite-Aggregate I/Aggregate II mixture, hydraulic conductivity was 6E-07 in this study which is in the same order with the results of Sivapullaiah et al., (2000).

The change in viscosity of water due to polymer addition was determined by viscosity determination tests. Viscosity increased as the amount of polymer increased in all tests. As hydraulic conductivity is inversely proportional with viscosity of permeant, polymer addition expected to decrease hydraulic conductivity by increasing viscosity. The viscosity of pure water was 1 cP. When 0,5 per cent of polymer was added to water the viscosity value was measured as 33 cP which means there would be 33 times increase in hydraulic conductivity. According to hydraulic conductivity tests for 15 per cent bentonite + Aggregate II mixture, the change in k due to 0,5 per cent polymer addition is 23 times. Addition of 0,75 per cent polymer increased the viscosity of water to 45 cP while the change in k due to 0,75 per cent polymer addition in 15 per cent bentonite + Aggregate II mixture is 34 times. One per cent polymer addition increased the viscosity of the solution by 98 times to 98 cP. 1 per cent increase in polymer content for 15 per cent bentonite + Aggregate II mixture lead 41 times decrease in k. Two per cent of polymer was added to water and viscosity value was measured as 760 cP. while the change in k due to 2 per cent polymer addition in 15 per cent bentonite + Aggregate II mixture is 337 times. Addition of 5 per cent polymer led viscosity value to become 2160 cP while viscosity value for 10 per cent polymer addition was 2950 cP. Hydraulic conductivity values of 15 percent bentonite + Aggregate II mixture decreased 417 and 476 times due to 5 and 10 percent polymer addition. These results show that the changes in hydraulic conductivity due to polymer addition are mainly caused by the effect of polymer on solution viscosity. The changes in hydraulic conductivity values due to viscosity are low than expected. According to Eq. 4.2, the magnitude of change in viscosity have to be same with the change in hydraulic conductivity. However, impossibility of homogeneously mixing of polymer with water, dilution of polymer-water solution due to pure water flow through sample are among the factors that cause inconsistency of viscosity and hydraulic conductivity values.

7. CONCLUSIONS

This study consists of an experimental programme to obtain an optimum aggregate-bentonite mixture to be used as liner for waste disposal facilities. In the study, hydraulic conductivity, viscosity and void ratio determination tests have been conducted to assess hydraulic conductivity performance of different aggregate-bentonite-polymer mixtures.

Laboratory hydraulic conductivity tests were conducted on two granular soil mixtures with different void ratios and various bentonite contents. These tests revealed that, addition of bentonite decreased hydraulic conductivity of granular soils used in this study. Addition of eight per cent bentonite in aggregate resulted in a decrease in hydraulic conductivity of approximately four orders of magnitude. (10^{-1} cm/s to 10^{-5} cm/s).

The addition of bentonite significantly decreased hydraulic conductivity till the bentonite content reached two per cent. Additional increases in bentonite content had less effect on hydraulic conductivity. Two percent bentonite addition in plain sample resulted in three orders of magnitude decrease in hydraulic conductivity while 15 per cent bentonite content led to additional three orders of magnitude change.

Laboratory tests showed that similar trends of hydraulic conductivity occurred for both granular soil mixtures, while the amount of bentonite in the mixture increased. For all specimens with equal amount of bentonite content, aggregate with higher void ratio had higher hydraulic conductivity. Even for very low bentonite contents such as 0,1 per cent, hydraulic conductivity for two aggregate mixtures were close to each other. Considering that flow through the mixture is through the bentonite phase occupying the pores of the coarse soil matrix, the bentonite content highly controls the flow of liquid. The fact that sodium bentonite swells many times its mass is the key factor in obtaining low hydraulic conductivities by small amount of bentonite addition. The hydraulic conductivity values obtained for aggregate-bentonite mixtures were similar with the results of former studies conducted on bentonite-sand mixtures, when the amount of bentonite in the mixtures were same.

It is considered that the decrease of permeability until all the voids of the aggregate matrix is completely filled is understandable, however when the amount of bentonite in the bentonite-aggregate mixture increased beyond the level at which all voids were filled with bentonite, hydraulic conductivity values continued to decrease. This could be caused by shortening of the real flow path, because the swelling bentonite may increase the distance between granular aggregates.

Despite having less void ratio, aggregate composition including higher stone powder amount did not have a better performance in terms of hydraulic conductivity when compared with the aggregate that has initially higher void ratio. This can be due to the addition of the stone powder to further decrease the void ratio in the aggregate.

For enhancing hydraulic conductivity performance of bentonite-aggregate mixtures, a water soluble polymer was added. Hydraulic conductivity tests revealed that a small concentration of polymer had a significant impact on the hydraulic conductivity of bentonite-granular soil mixture. Addition of two per cent polymer resulted in a decrease in hydraulic conductivity of approximately two orders of magnitude. (10^{-6} cm/s to 10^{-8} cm/s). Initial impact of a small quantity of polymer was very high, however, further increases in polymer content had a decreasing impact on lowering hydraulic conductivity. For all aggregate specimens including different amounts of bentonite, the highest decrease in hydraulic conductivity occurred when the percentage of polymer increased from one per cent to two per cent by air dry weight of bentonite in the mixture. No significant change in hydraulic conductivity was observed for polymer contents higher than two per cent with respect to polymer contents lower than two per cent.

It was observed that, addition of polymer increased viscosity of water. Viscosity determination tests revealed that, the change in viscosity due to polymer addition was up to three orders of magnitude for 10 per cent polymer addition. The increase in viscosity due to polymer addition was not directly proportional with the polymer content in the solution. There had been a considerable increase in viscosity with addition of 0,5 per cent polymer in water, while further increases in polymer content affected viscosity much more. Beyond two per cent polymer content, effect of polymer concentration on viscosity gradually decreased.

It is noted in the literature that there is an inverse relationship between viscosity of permeant and hydraulic conductivity. In the light of relationship between viscosity and hydraulic conductivity, it was concluded that the changes in hydraulic conductivity due to polymer addition are mainly caused by the effect of polymer on solution viscosity. The changes in hydraulic conductivity values due to viscosity, which are lower than expected, thought to be occurred because of impossibility of homogeneously mixing of polymer with water and dilution of polymer-water solution due to pure water flow through sample.

These conclusions suggest that polymer enhanced bentonite-granular soil mixtures can effectively be used as a barrier layer in containment facilities. Marginal amount of polymer (two per cent) addition in bentonite-granular soil mixtures provided hydraulic conductivity values in order of 10^{-9} cm/s. The use of polymer enhanced bentonite-granular soil mixtures as solid waste liners is not recommended due to temperature dependence of polymer solution viscosity. High temperatures at solid waste disposal areas may decrease viscosity, resulting in an increase in hydraulic conductivity.

APPENDIX A: RESULTS OF SPECIFIC GRAVITY & VOID RATIO DETERMINATION TESTS

The results of the specific gravity & void ratio determination tests are given in the Tables A.1. to A.18.

Table A.1. Results of specific gravity & void ratio determination tests for aggregate composed of 29 per cent no:2 crushed stone, 29 per cent no:1 crushed stone, 18 per cent no:0 stone powder and 24 per cent sand

Specific Gravity and void ratio determination Experiment 1

Sample :

Aggregate composed of: 29 % no 2 crushed stone,
29 % no 1 crushed stone,
18 % no 0 stone powder
24 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	159,27	256,83
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	257,39	356,39
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	98,12	99,56
Weight of pycnometer filled with water, gr	W_A =	662,96	639,01
Weight of pycnometer filled with water and soil, gr	W_B =	724,52	701,38
$G_s = \alpha W_0/(W_0+W_A-W_B)$	G_s =	2,68	2,68

Average Gs= 2,68

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d = W_s/V$	γ_d =	2,01
Void Ratio, e= $G_s \cdot \gamma_w/\gamma_d - 1$	e =	0,33
Porosity, n= e/(1+e)	n =	0,25

Table A.2. Results of specific gravity & void ratio determination tests for aggregate composed of 100 per cent no:2 crushed stone

Specific Gravity and void ratio determination Experiment 2

Sample : Aggregate composed of: 100 % no 2 crushed stone,

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	159,28	164,43
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	258,79	264,22
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,51	99,79
Weight of pycnometer filled with water, gr	W_A =	663,21	667,37
Weight of pycnometer filled with water and soil, gr	W_B =	726,42	730,57
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,74	2,73

Average Gs=	2,73

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d=W_s/V$ (gr/cm^3)	γ_d =	1,51
Void Ratio, e= $G_s.\gamma_w/\gamma_d-1$	e =	0,81
Porosity, n= e/(1+e)	n =	0,45

Table A.3. Results of specific gravity & void ratio determination tests for aggregate composed of 100 per cent no:1 crushed stone

Specific Gravity and void ratio determination Experiment 3

Sample : Aggregate composed of: 100 % no 1 crushed stone

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,43	159,27
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	264,56	258,93
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	100,13	99,66
Weight of pycnometer filled with water, gr	W_A =	667,11	662,86
Weight of pycnometer filled with water and soil, gr	W_B =	730,55	726,03
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,73	2,73

Average Gs= 2,73

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d=W_s/V$ (gr/cm^3)	γ_d =	1,62
Void Ratio, e= $G_s.\gamma_w/\gamma_d-1$	e =	0,68
Porosity, n= e/(1+e)	n =	0,41

Table A.4. Results of specific gravity & void ratio determination tests for aggregate composed of 100 per cent sand

Specific Gravity and void ratio determination Experiment 4

Sample : Aggregate composed of: 100 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,43	159,28
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	264,21	258,73
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,78	99,45
Weight of pycnometer filled with water, gr	W_A =	666,53	662,47
Weight of pycnometer filled with water and soil, gr	W_B =	728,13	723,75
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,61	2,60

Average Gs=	2,61

The temperature correction coefficient α is 0,9998 for 21 °C.

Description	:	Sample is compacted under w:0 % (Standard Compaction)	
Hammer	:	2,5	kg
Mold Dimensions			
Area of the sample	:	8170	mm^2
Length of the sample	:	118	mm

$\gamma_d=W_s/V$ (gr/cm³)	γ_d =	1,92
Void Ratio, e= $G_s.\gamma_w/\gamma_d-1$	e =	0,36
Porosity, n= e/(1+e)	n =	0,26

Table A.5. Results of specific gravity & void ratio determination tests for aggregate composed of 100 per cent stone powder

Specific Gravity and void ratio determination Experiment 5

Sample : Aggregate composed of: 100 % no 0 stone powder

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	159,28	164,43
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	259,21	264,29
Weight of sample of oven-dry soil, gr	$W_o= W_{PS} - W_P$ =	99,93	99,86
Weight of pycnometer filled with water, gr	W_A =	663,45	667,18
Weight of pycnometer filled with water and soil, gr	W_B =	726,56	730,38
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,71	2,72

Average Gs=	2,72

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)

Hammer : 2,5 kg

Mold Dimensions

Area of the sample : 8170 mm^2

Length of the sample : 118 mm

$\gamma_d=W_s/V$ (gr/cm^3)	γ_d =	2,25
Void Ratio, e= $G_s.\gamma_w/\gamma_d-1$	e =	0,21
Porosity, n= e/(1+e)	n =	0,17

Table A.6. Results of specific gravity & void ratio determination tests for aggregate composed of 25 per cent no:2 crushed stone, 25 per cent no:1 crushed stone, 25 per cent no:0 stone powder and 25 per cent sand

Specific Gravity and void ratio determination Experiment 6

Sample : Aggregate composed of: 25 % no 2 crushed stone,
25 % no 1 crushed stone,
25 % no 0 stone powder
25 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	159,27	164,44
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	259,83	263,87
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	100,56	99,43
Weight of pycnometer filled with water, gr	W_A =	662,26	667,12
Weight of pycnometer filled with water and soil, gr	W_B =	725,48	729,68
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,69	2,70

Average Gs=	2,69

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d=W_s/V$	γ_d =	2,08
Void Ratio, e= $G_s.\gamma_w/\gamma_d-1$	e =	0,30
Porosity, n= e/(1+e)	n =	0,23

Table A.7. Results of specific gravity & void ratio determination tests for aggregate composed of 20 per cent no:2 crushed stone, 20 per cent no:1 crushed stone, 40 per cent no:0 stone powder and 20 per cent sand

Specific Gravity and void ratio determination Experiment 7

Sample : Aggregate composed of: 20 % no 2 crushed stone,
20 % no 1 crushed stone,
40 % no 0 stone powder
20 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	159,28	164,43
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	258,92	265,17
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,64	100,74
Weight of pycnometer filled with water, gr	W_A =	663,16	666,29
Weight of pycnometer filled with water and soil, gr	W_B =	725,78	729,43
$G_s = \alpha W_0/(W_0+W_A-W_B)$	G_s =	2,69	2,68

Average Gs= 2,68

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d = W_s/V$	γ_d =	2,22
Void Ratio, e= $G_s.\gamma_w/\gamma_d - 1$	e =	0,21
Porosity, n= e/(1+e)	n =	0,17

Table A.8. Results of specific gravity & void ratio determination tests for aggregate composed of 40 per cent no:2 crushed stone, 30 per cent no:1 crushed stone, 10 per cent no:0 stone powder and 20 per cent sand

Specific Gravity and void ratio determination Experiment 8

Sample : Aggregate composed of: 40 % no 2 crushed stone,
30 % no 1 crushed stone,
10 % no 0 stone powder
20 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,43	159,28
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	262,84	258,66
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	98,41	99,38
Weight of pycnometer filled with water, gr	W_A =	668,42	663,19
Weight of pycnometer filled with water and soil, gr	W_B =	730,38	725,68
$G_s = \alpha W_0/(W_0+W_A-W_B)$	G_s =	2,70	2,69

Average Gs=	2,70

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d = W_s/V$	γ_d =	1,85
Void Ratio, e= $G_s.\gamma_w/\gamma_d - 1$	e =	0,46
Porosity, n= e/(1+e)	n =	0,31

Table A.9. Results of specific gravity & void ratio determination tests for aggregate composed of 30 per cent no:2 crushed stone, 30 per cent no:1 crushed stone, 20 per cent no:0 stone powder and 20 per cent sand

Specific Gravity and void ratio determination Experiment 9

Sample : Aggregate composed of: 30 % no 2 crushed stone,
30 % no 1 crushed stone,
20 % no 0 stone powder
20 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,43	159,28
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	263,15	258,92
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	98,72	99,64
Weight of pycnometer filled with water, gr	W_A =	667,82	662,49
Weight of pycnometer filled with water and soil, gr	W_B =	729,88	725,2
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,69	2,70

Average Gs= 2,69

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d=W_s/V$	γ_d =	2,03
Void Ratio, e= $G_s.\gamma_w/\gamma_d-1$	e =	0,33
Porosity, n= e/(1+e)	n =	0,25

Table A.10. Results of specific gravity & void ratio determination tests for aggregate composed of 36 per cent no:2 crushed stone, 28 per cent no:1 crushed stone, 18 per cent no:0 stone powder and 18 per cent sand

Specific Gravity and void ratio determination Experiment 10

Sample : Aggregate composed of: 36 % no 2 crushed stone,
28 % no 1 crushed stone,
18 % no 0 stone powder
18 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,43	159,29
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	265,12	260,54
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	100,69	101,25
Weight of pycnometer filled with water, gr	W_A =	668,12	663,65
Weight of pycnometer filled with water and soil, gr	W_B =	731,59	727,28
$G_s = \alpha W_0/(W_0+W_A-W_B)$	G_s =	2,70	2,69

Average Gs= 2,70

The temperature correction coefficient α is 0,9998 for 21 °C.

Description	:	Sample is compacted under w:0 % (Standard Compaction)	
Hammer	:	2,5	kg
Mold Dimensions			
Area of the sample	:	8170	mm^2
Length of the sample	:	118	mm

	$\gamma_d = W_s/V$	γ_d =	2
Void Ratio, e=	$G_s \cdot \gamma_w/\gamma_d - 1$	e =	0,35
Porosity, n=	e/(1+e)	n =	0,26

Table A.11. Results of specific gravity & void ratio determination tests for aggregate composed of 35 per cent no:2 crushed stone, 35 per cent no:1 crushed stone, 10 per cent no:0 stone powder and 20 per cent sand

Specific Gravity and void ratio determination Experiment 11

Sample : Aggregate composed of: 35 % no 2 crushed stone,
35 % no 1 crushed stone,
10 % no 0 stone powder
20 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,44	159,28
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	263,72	261,23
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,28	101,95
Weight of pycnometer filled with water, gr	W_A =	667,92	662,86
Weight of pycnometer filled with water and soil, gr	W_B =	730,35	726,98
$G_s = \alpha W_0/(W_0+W_A-W_B)$	G_s =	2,69	2,69

Average Gs= 2,69

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d = W_s/V$	γ_d =	1,93
Void Ratio, e= $G_s.\gamma_w/\gamma_d - 1$	e =	0,40
Porosity, n= e/(1+e)	n =	0,28

Table A.12. Results of specific gravity & void ratio determination tests for aggregate composed of 30 per cent no:2 crushed stone, 30 per cent no:1 crushed stone, 10 per cent no:0 stone powder and 30 per cent sand

Specific Gravity and void ratio determination — Experiment 12

Sample : Aggregate composed of: 30 % no 2 crushed stone,
30 % no 1 crushed stone,
10 % no 0 stone powder
30 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	159,28	164,44
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	260,13	263,32
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	100,85	98,88
Weight of pycnometer filled with water, gr	W_A =	662,33	668,75
Weight of pycnometer filled with water and soil, gr	W_B =	725,49	730,86
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,68	2,69

Average Gs=	2,68

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d=W_s/V$	γ_d =	1,97
Void Ratio, e= $G_s.\gamma_w/\gamma_d-1$	e =	0,36
Porosity, n= e/(1+e)	n =	0,27

Table A.13. Results of specific gravity & void ratio determination tests for aggregate composed of 20 per cent no:2 crushed stone, 25 per cent no:1 crushed stone, 35 per cent no:0 stone powder and 20 per cent sand

Specific Gravity and void ratio determination Experiment 13

Sample : Aggregate composed of: 20 % no 2 crushed stone,
25 % no 1 crushed stone,
35 % no 0 stone powder
20 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	159,28	164,44
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	258,73	264,11
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,45	99,67
Weight of pycnometer filled with water, gr	W_A =	663,85	667,19
Weight of pycnometer filled with water and soil, gr	W_B =	726,19	729,86
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,68	2,69

Average Gs=	2,69

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

	$\gamma_d=W_s/V$	γ_d =	2,18
Void Ratio, e=	$G_s.\gamma_w/\gamma_d-1$	e =	0,23
Porosity, n=	e/(1+e)	n =	0,19

Table A.14. Results of specific gravity & void ratio determination tests for aggregate composed of 15 per cent no:2 crushed stone, 15 per cent no:1 crushed stone, 60 per cent no:0 stone powder and 10 per cent sand

Specific Gravity and void ratio determination   Experiment 14

Sample : Aggregate composed of: 15 % no 2 crushed stone,
15 % no 1 crushed stone,
60 % no 0 stone powder
10 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	159,28	164,44
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	259,24	264,03
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,96	99,59
Weight of pycnometer filled with water, gr	W_A =	663,3	666,95
Weight of pycnometer filled with water and soil, gr	W_B =	725,99	729,46
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,68	2,69

Average Gs=	2,68

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

	$\gamma_d=W_s/V$	γ_d =	2,22
Void Ratio, e=	$G_s.\gamma_w/\gamma_d-1$	e =	0,21
Porosity, n=	e/(1+e)	n =	0,17

Table A.15. Results of specific gravity & void ratio determination tests for aggregate composed of 30 per cent no:2 crushed stone, 30 per cent no:1 crushed stone, 15 per cent no:0 stone powder and 25 per cent sand

Specific Gravity and void ratio determination Experiment 15

Sample :

Aggregate composed of: 30 % no 2 crushed stone,
30 % no 1 crushed stone,
15 % no 0 stone powder
25 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,44	159,28
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	264,17	258,77
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,73	99,49
Weight of pycnometer filled with water, gr	W_A =	667,25	664,12
Weight of pycnometer filled with water and soil, gr	W_B =	730,05	726,76
$G_s=\alpha W_0/(W_0+W_A-W_B)$	G_s =	2,70	2,70

Average Gs=	2,70

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d=W_s/V$	γ_d =	2
Void Ratio, e= $G_s.\gamma_w/\gamma_d-1$	e =	0,35
Porosity, n= e/(1+e)	n =	0,26

Table A.16. Results of specific gravity & void ratio determination tests for aggregate composed of 25 per cent no:2 crushed stone, 25 per cent no:1 crushed stone, 40 per cent no:0 stone powder and 10 per cent sand

Specific Gravity and void ratio determination Experiment 16

Sample : Aggregate composed of: 25 % no 2 crushed stone,
25 % no 1 crushed stone,
40 % no 0 stone powder
10 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,43	159,28
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	263,87	260,12
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,44	100,84
Weight of pycnometer filled with water, gr	W_A =	666,65	662,35
Weight of pycnometer filled with water and soil, gr	W_B =	729,52	725,96
$G_s = \alpha W_0/(W_0+W_A-W_B)$	G_s =	2,72	2,71

Average Gs= 2,71

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d = W_s/V$	γ_d =	2,17
Void Ratio, e= $G_s.\gamma_w/\gamma_d - 1$	e =	0,25
Porosity, n= e/(1+e)	n =	0,20

Table A.17. Results of specific gravity & void ratio determination tests for aggregate composed of 23 per cent no:2 crushed stone, 23 per cent no:1 crushed stone, 40 per cent no:0 stone powder and 14 per cent sand

Specific Gravity and void ratio determination Experiment 17

Sample :

Aggregate composed of: 23 % no 2 crushed stone,
23 % no 1 crushed stone,
40 % no 0 stone powder
14 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,43	159,28
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	264,4	259,15
Weight of sample of oven-dry soil, gr	$W_o = W_{PS} - W_P$ =	99,97	99,87
Weight of pycnometer filled with water, gr	W_A =	667,2	662,93
Weight of pycnometer filled with water and soil, gr	W_B =	730,15	725,93
$G_s = \alpha W_0/(W_0+W_A-W_B)$	G_s =	2,70	2,71

Average Gs=	2,70

The temperature correction coefficient α is 0,9998 for 21 °C.

Description : Sample is compacted under w:0 % (Standard Compaction)
Hammer : 2,5 kg
Mold Dimensions
Area of the sample : 8170 mm^2
Length of the sample : 118 mm

$\gamma_d = W_s/V$	γ_d =	2,18
Void Ratio, e= $G_s.\gamma_w/\gamma_d - 1$	e =	0,24
Porosity, n= e/(1+e)	n =	0,19

Table A.18. Results of specific gravity & void ratio determination tests for aggregate composed of 25 per cent no:2 crushed stone, 25 per cent no:1 crushed stone, 35 per cent no:0 stone powder and 15 per cent sand

Specific Gravity and void ratio determination Experiment 18

Sample : Aggregate composed of: 25 % no 2 crushed stone,
25 % no 1 crushed stone,
35 % no 0 stone powder
15 % sand

		Test 1	Test2
Weight of the empty and dry pycnometer, gr	W_p =	164,43	159,29
The weight of the pycnometer containing the dry soil, gr	W_{ps} =	264,86	260,69
Weight of sample of oven-dry soil, gr $W_o = W_{PS} - W_P$ =		100,43	101,40
Weight of pycnometer filled with water, gr	W_A =	668,35	663,27
Weight of pycnometer filled with water and soil, gr	W_B =	731,63	726,93
$G_s = \alpha W_0/(W_0+W_A-W_B)$	G_s =	2,70	2,69

Average Gs=	2,69

The temperature correction coefficient α is 0,9998 for 21 °C.

Description	:	Sample is compacted under w:0 % (Standard Compaction)	
Hammer	:	2,5	kg
Mold Dimensions			
Area of the sample	:	8170	mm^2
Length of the sample	:	118	mm

$\gamma_d = W_s/V$	γ_d =	2,14
Void Ratio, e= $G_s . \gamma_w / \gamma_d - 1$	e =	0,26
Porosity, n= e/(1+e)	n =	0,21

APPENDIX B: RESULTS OF PROCTOR COMPACTION TESTS

The results of the Proctor compaction tests are given in the Tables B.1. to B.4.

Table B.1. Results of Proctor compaction test for Aggregate I + 8 per cent bentonite

SAMPLE	Aggregate I + 8% Bentonite Initial Water Content: 6% % increase: 3%					
NO. OF LAYERS	3		VOLUME OF THE MOLD	944	cm^3
BLOW / LAYER	25		WEIGHT OF THE MOLD	1693	g
RAMMER WEIGHT	24,5	N	COMPACTIVE EFFORT	593,7	kJ/m^3
RAMMER FALL	0,305	m			

Determination of water contents

Sample no	1		2		3		4		5	
Can no	1	2	3	4	5	6	7	8	9	10
wt of can, g	49,35	50,76	50,14	51,32	50,17	51,52	48,56	50,71	52,34	50,54
wt of sample+can, g	94,12	98,12	119,22	103,75	111,13	126,43	119,39	118,14	127,46	122,32
wt of dry sample+can, g	91,62	95,33	113,48	99,25	104,54	118,12	110,23	109,74	115,29	111,27
Water content, %	5,91	6,26	9,06	9,39	12,12	12,48	14,85	14,23	19,33	18,20
Ave. water content, %	6,09		9,23		12,30		14,54		18,76	

Determination of dry unit weights

wt of mold+sample, g	3358	3471	3522	3503	3481
wt of wet sample, g	1659	1786	1835	1824	1792
Wet unit weight, g/cm3	1,757	1,892	1,944	1,932	1,898
Dry unit weight, g/cm3	1,657	1,732	1,731	1,687	1,598

Table B.2. Results of proctor compaction test for Aggregate I + 10 per cent bentonite

SAMPLE Aggregate I + 10 % Bentonite
Initial Water Content: 5%
% increase: 3%

NO. OF LAYERS	3		VOLUME OF THE MOLD	944	cm^3
BLOW / LAYER	25		WEIGHT OF THE MOLD	1693	g
RAMMER WEIGHT	24,5	N	COMPACTIVE EFFORT	593,7	kJ/m^3
RAMMER FALL	0,305	m			

Determination of water contents

Sample no	1		2		3		4		5		6	
Can no	1	2	3	4	5	6	7	8	9	10	11	12
wt of can, g	51,56	50,36	53,14	53,61	51,20	51,23	50,23	49,43	50,35	53,04	49,88	51,54
wt of sample+can, g	93,62	99,93	123,58	124,78	118,65	117,65	131,24	126,52	136,92	139,45	174,35	133,21
wt of dry sample+can, g	91,45	97,31	118,12	118,80	111,72	110,82	120,88	116,79	124,02	126,87	152,78	119,23
Water content, %	5,44	5,58	8,40	9,17	11,45	11,46	14,66	14,44	17,51	17,04	20,96	20,65
Ave. water content, %	5,51		8,79		11,46		14,55		17,27		20,81	

Determination of dry unit weights

wt of mold+sample, gf	3328	3412	3490	3542	3526	3492
wt of wet sample, gf	1635	1719	1797	1849	1833	1799
Wet unit weight, gf/cm^3	1,732	1,821	1,904	1,959	1,942	1,906
Dry unit weight, gf/cm^3	1,642	1,674	1,708	1,710	1,656	1,577

Table B.3. Results of proctor compaction test for Aggregate I + 12 per cent bentonite

SAMPLE Aggregate I + 12 % Bentonite
Initial Water Content: 8%
% increase: 3%

NO. OF LAYERS	3		VOLUME OF THE MOLD	944	cm^3
BLOW / LAYER	25		WEIGHT OF THE MOLD	1693	g
RAMMER WEIGHT	24,5	N	COMPACTIVE EFFORT	593,7	kJ/m^3
RAMMER FALL	0,305	m			

Determination of water contents

Sample no	1		2		3		4		5		6	
Can no	1	2	3	4	5	6	7	8	9	10	11	12
wt of can, g	52,48	49,97	52,35	49,82	52,91	51,52	48,66	51,44	53,01	50,85	53,10	51,62
wt of sample+can, g	123,75	111,78	115,62	125,41	126,45	137,16	130,43	135,43	125,22	129,22	130,24	127,77
wt of dry sample+can, g	118,27	106,74	109,23	117,42	117,59	126,70	119,21	123,44	113,52	116,63	116,02	114,01
Water content, %	8,33	8,88	11,23	11,82	13,70	13,91	15,90	16,65	19,34	19,14	22,60	22,05
Ave. water content, %	8,60		11,53		13,81		16,28		19,24		22,33	

Determination of dry unit weights

wt of mold+sample, g	3421	3511	3568	3582	3552	3497
wt of wet sample, g	1728	1818	1875	1889	1859	1804
Wet unit weight, g/cm3	1,831	1,926	1,986	2,001	1,969	1,911
Dry unit weight, g/cm3	1,685	1,727	1,745	1,721	1,652	1,562

Table B.4. Results of proctor compaction test for Aggregate I + 15 per cent bentonite

SAMPLE	Aggregate I + 15 % Bentonite Initial Water Content: 8% % increase: 3%

NO. OF LAYERS	3		VOLUME OF THE MOLD	944	cm^3
BLOW / LAYER	25		WEIGHT OF THE MOLD	1693	g
RAMMER WEIGHT	24,5	N	COMPACTIVE EFFORT	593,7	kJ/m^3
RAMMER FALL	0,305	m			

Determination of water contents

Sample no	1		2		3		4		5	
Can no	1	2	3	4	5	6	7	8	9	10
wt of can, g	50,12	49,32	49,68	48,58	50,43	50,42	50,73	52,53	52,03	50,91
wt of sample+can, g	113,22	129,12	118,15	123,75	131,18	135,12	129,76	166,37	175,16	152,27
wt of dry sample+can, g	108,11	122,50	110,52	115,73	120,25	124,11	117,43	148,13	153,08	133,97
Water content, %	8,81	9,05	12,54	11,94	15,65	14,94	18,49	19,08	21,85	22,03
Ave. water content, %	8,93		12,24		15,30		18,78		21,94	

Determination of dry unit weights

wt of mold+sample, g	3441	3538	3601	3572	3524
wt of wet sample, g	1748	1845	1908	1879	1831
Wet unit weight, g/cm3	1,852	1,954	2,021	1,990	1,940
Dry unit weight, g/cm3	1,700	1,741	1,753	1,676	1,591

APPENDIX C: RESULTS OF HYDRAULIC CONDUCTIVITY TESTS

The results of the hydraulic conductivity tests are given in the Tables C.1. to C.68.

Table C.1. Results of hydraulic conductivity test for Aggregate I + 0,1 per cent bentonite mixture

Experiment no:1
Sample : Aggregate I + 0,1% Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, sec	HYDRAULIC CONDUCTIVITY, cm/s
1	10.12	13:10:00	0		
2	10.12	13:10:02	60	2	8,47E-02
3	10.12	13:16:00	0		
4	10.12	13:16:02	64	2	9,68E-02
5	11.12	10:40:00	0		
6	11.12	10:40:03	72	3	8,67E-02
7	11.12	10:50:00	0		
8	11.12	10:50:02	59	2	8,20E-02
9	12.12	11:05:00			
10	12.12	11:05:02	58	2	7,94E-02
11	12.12	11:07:00	0		
12	12.12	11:07:03	71	3	8,33E-02
13	12.12	11:09:00	0		
14	12.12	11:09:02	58	2	7,94E-02
Hydraulic conductivity value cm/s					8,46E-02

Table C.2. Results of hydraulic conductivity test for Aggregate I + 0 per cent bentonite

Experiment no:2

Sample	:	Aggregate I + 0 Bentonite	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height ($h_{1)}$	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, sec	HYDRAULIC CONDUCTIVITY, cm/s
1	08.12	10:05:00	0		
2	08.12	10:05:02	81	2	2,12E-01
3	08.12	10:08:00	0		
4	08.12	10:08:02	77	2	1,64E-01
5	09.12	13:35:00	0		
6	09.12	13:35:02	81	2	2,12E-01
7	09.12	13:37:00	0		
8	09.12	13:37:02	80	2	1,96E-01
9	09.12	14:12:00	0		
10	11.12	14:12:02	78	2	1,73E-01
11	11.12	14:16:00	0		
12	11.12	14:16:02	75	2	1,48E-01
13	11.12	14:20:00	0		
14	11.12	14:20:02	81	2	2,12E-01
Hydraulic conductivity value cm/s					1,88E-01

Table C.3. Results of hydraulic conductivity test for Aggregate I + 5 per cent bentonite mixture

Experiment no:3
Sample : Aggregate I + 5 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	12:12	10:35	0		
2	12:12	10:52	35	17	7,20E-05
3	12:12	11:05	54	30	7,76E-05
4	13:12	09:40	0		
5	13:12	09:51	25	11	7,31E-05
6	13:12	10:12	54	32	7,28E-05
7	13:12	10:50	75	70	7,06E-05
8	14:12	13:10	0		
9	14:12	13:27	38	17	8,05E-05
10	14:12	14:03	68	53	7,01E-05
11	14:12	14:35	79	85	7,20E-05
Hydraulic conductivity value cm/s					7,36E-05

Table C.4. Results of hydraulic conductivity test for Aggregate I + 0,2 per cent bentonite mixture

Experiment no:4
Sample : Aggregate I + 0,2 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, sec	HYDRAULIC CONDUCTIVITY, cm/s
1	14.12	10:12:00	0		
2	14.12	10:12:02	52	2	6,55E-02
3	14.12	10:15:00	0		
4	14.12	10:15:03	68	3	7,43E-02
5	14.12	10:18:00	0		
6	14.12	10:18:02	51	2	6,35E-02
7	15.12	13:13:00	0		
8	15.12	13:13:03	64	3	6,45E-02
9	15.12	13:17:00	0		
10	15.12	13:17:02	54	2	6,98E-02
11	16.12	13:42:00	0		
12	16.12	13:42:03	65	3	6,68E-02
13	16.12	13:48:00	0		
14	16.12	13:48:02	53	2	6,77E-02
Hydraulic conductivity value cm/s					6,74E-02

Table C.5. Results of hydraulic conductivity test for Aggregate I + 1 per cent bentonite mixture

Experiment no:5
Sample : Aggregate I + 1 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height ($h_{1)}$: 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	05:12	10:10	0		
2	05:12	10:11	57	1	2,56E-03
4	06:12	09:40	0		
5	06:12	09:41	62	1	3,02E-03
6	06:12	09:42	79	2	3,06E-03
7	08:12	10:23	0		
8	08:12	10:24	55	1	2,40E-03
7	08:12	10:28	0		
8	08:12	10:29	59	1	2,73E-03
Hydraulic conductivity value cm/s					2,76E-03

Table C.6. Results of hydraulic conductivity test for Aggregate I + 2 per cent bentonite mixture

Experiment no:6
Sample : Aggregate I + 2 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	18.12	09:30	0		
2	18.12	09:31	12	1	3,51E-04
3	18.12	09:36	48	6	3,20E-04
4	19.12	13:20	0		
5	19.12	13:23	28	3	3,07E-04
6	19.12	13.24	37	4	3,30E-04
7	19.12	13.25	41	5	3,04E-04
8	20.12	11:23	0		
9	20.12	11:24	11	1	3,20E-04
10	20.12	11:25	21	2	3,28E-04
11	20.12	11:27	36	4	3,18E-04
Hydraulic conductivity value cm/s					3,22E-04

Table C.7. Results of hydraulic conductivity test for Aggregate I + 8 per cent bentonite mixture

Experiment no:7
Sample : Aggregate I + 8 % Bentonite
Description : Sample is compacted under w:15% (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	21.12	10:00	0		
2	21.12	10:15	6	15	1,13E-05
3	21.12	10:20	7	20	9,92E-06
4	23.12	13:40	0		
5	23.12	13:52	4	12	9,27E-06
6	23.12	14:10	0		
7	23.12	14:21	4	11	1,01E-05
8	24.12	11:10	0		
9	24.12	11:23	5	13	1,08E-05
10	24.12	11:34	9	24	1,08E-05
Hydraulic conductivity value cm/s					1,03E-05

Table C.8. Results of hydraulic conductivity test for Aggregate I + 10 per cent bentonite mixture

Experiment no:8
Sample : Aggregate I + 10 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	05.01	09:35	0		
2	05.01	10:05	8	30	7,61E-06
3	05.01	10:44	16	69	6,98E-06
4	05.01	11:05	0		
5	05.01	11:56	13	51	7,51E-06
6	05.01	12:35	22	90	7,68E-06
7	05.01	13:20	31	135	7,76E-06
8	06.01	10:10	0		
9	06.01	11:20	18	70	7,85E-06
10	06.01	11:54	26	104	8,10E-06
11	06.01	13:15	39	185	7,66E-06
Hydraulic conductivity value cm/s					7,64E-06

Table C.9. Results of hydraulic conductivity test for Aggregate I + 12 per cent bentonite mixture

Experiment no:9
Sample : Aggregate I + 12 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	14.01	09.10	0		
2	14.01	10:05	8	55	4,15E-06
3	14.01	10:50	15	100	4,48E-06
4	16.01	12:20	0		
5	16.01	13:45	12	85	4,13E-06
6	16.01	14:35	19	135	4,33E-06
7	16.01	16:40	32	260	4,19E-06
8	17.01	11:15	0		
9	17.01	13:40	19	145	4,03E-06
10	17.01	14:40	26	205	4,11E-06
11	17.01	15:25	31	250	4,19E-06
12	18.01	09:20	0		
13	18.01	10:25	10	65	4,44E-06
14	18.01	11:05	15	105	4,27E-06
Hydraulic conductivity value cm/s					4,23E-06

Table C.10. Results of hydraulic conductivity test for Aggregate I + 15 per cent bentonite mixture

Experiment no:10
Sample : Aggregate 1 + 15 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	02.02	09:40	0,0		
2	02.02	11:05	2,1	85	6,79E-07
3	02.02	11:55	3,2	135	6,45E-07
4	03.02	10:15	0,0		
5	03.02	12:26	3,2	131	6,65E-07
6	03.02	14:32	5,9	257	6,26E-07
7	03.02	16:12	7,9	357	6,04E-07
8	05.02	09:50	0,0		
9	05.02	12:15	3,5	145	6,57E-07
10	05.02	16:20	9,1	390	6,37E-07
11	06.02	10:20	37,1	1470	7,01E-07
12	06.02	15:46	41,8	1796	6,48E-07
Hydraulic conductivity value cm/s					6,51E-07

Table C.11. Results of hydraulic conductivity test for Aggregate II + 0,1 per cent bentonite mixture

Experiment no:11
Sample : Aggregate II + 0,1 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height ($h_{1)}$: 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, sec	HYDRAULIC CONDUCTIVITY, cm/s
1	02.02	09:20:00	0		
2	02.02	09:20:01	40	1	8,81E-02
3	02.02	09:23:00	0		
4	02.02	09:23:02	61	2	8,76E-02
5	02.02	10:40:00	0		
6	02.02	10:40:02	56	2	7,45E-02
7	03.02	10:43:00	0		
8	03.02	10:43:02	55	2	7,21E-02
9	03.02	11:35:00			
10	03.02	11:35:02	60	2	8,47E-02
11	04.02	13:35:00	0		
12	04.02	13:35:02	56	2	7,45E-02
13	04.02	13:39:00	0		
14	04.02	13:39:02	57	2	7,69E-02
Hydraulic conductivity value cm/s					7,98E-02

Table C.12. Results of hydraulic conductivity test for Aggregate II + 0,2 per cent bentonite mixture

Experiment no:12
Sample : Aggregate 2 + 0,2 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, sec	HYDRAULIC CONDUCTIVITY, cm/s
1	06.02	09:15:00	0		
2	06.02	09.15.03	54	3	4,66E-02
3	06.02	09:17:00	0		
4	06.02	09:17:02	45	2	5,22E-02
5	06.02	09:19:00	0		
6	06.02	09:19:02	45	2	5,22E-02
7	07.02	10:12:00	0		
8	07.02	10:12:03	58	3	5,29E-02
9	07.02	10:15:00	0		
10	07.02	10:15:02	43	2	4,88E-02
11	08.02	13:47:00	0		
12	08.02	13:47:02	46	2	5,40E-02
13	08.02	13:51:00	0		
14	08.02	13:51:02	47	2	5,57E-02
Hydraulic conductivity value cm/s					5,18E-02

Table C.13. Results of hydraulic conductivity test for Aggregate II + 0 per cent bentonite mixture

Experiment no:13
Sample : Aggregate II + 0 Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, sec	HYDRAULIC CONDUCTIVITY, cm/s
1	10.02	09:05:00	0		
2	10.02	09:05:01	60	1	1,69E-01
3	10.02	09:12:00	0		
4	10.02	09:12:02	78	2	1,73E-01
5	10.02	09:15:00	0		
6	10.02	09:15:01	58	1	1,59E-01
7	10.02	09:22:00	0		
8	10.02	09:22:01	59	1	1,64E-01
9	11.02	14:26:00	0		
10	11.02	14:26:02	80	2	1,96E-01
11	11.02	14:32:00	0		
12	11.02	14:32:02	77	2	1,64E-01
Hydraulic conductivity value cm/s					1,71E-01

Table C.14. Results of hydraulic conductivity test for Aggregate II + 1 per cent bentonite mixture

Experiment no:14
Sample : Aggregate II + 1 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, sec	HYDRAULIC CONDUCTIVITY, cm/s
1	10.02	09:32:00	0		
2	10.02	09:32:10	15	10	2,69E-03
3	10.02	09:32:20	26	20	2,53E-03
4	10.02	09:45:00	0		
5	10.02	09:45:15	20	15	2,48E-03
6	10.02	09:45:30	34	30	2,36E-03
7	10.02	09:45:50	51	50	2,54E-03
8	12.02	10:22:00	0		
9	12.02	10:22:10	14	10	2,49E-03
10	12.02	10:22:30	36	30	2,54E-03
11	12.02	10:23:00	57	60	2,56E-03
12	12.02	10:41:00	0		
13	12.02	10:41:20	17	20	1,55E-03
14	12.02	10:41:50	48	50	2,30E-03
Hydraulic conductivity value cm/s					2,40E-03

Table C.15. Results of hydraulic conductivity test for Aggregate II + 2 per cent bentonite mixture

Experiment no:15
Sample : Aggregate II + 2 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	10.02	10:12	0		
2	10.02	10:13	9	1	2,58E-04
3	10.02	10:16	39	6	2,36E-04
4	10.02	10:20	0		
5	10.02	10:23	22	3	2,30E-04
6	10.02	10:26	38	6	2,28E-04
7	10.02	10:28	48	8	2,40E-04
8	12.02	11:10	0		
9	12.02	11:13	22	3	2,30E-04
10	12.02	11:18	45	8	2,17E-04
11	12.02	11:19	50	9	2,28E-04
12	12.02	11:28		0	
13	12.02	11:30	17	2	2,58E-04
14	12.02	11:36	51	8	2,64E-04
Hydraulic conductivity value cm/s					2,39E-04

Table C.16. Results of hydraulic conductivity test for Aggregate II + 5 per cent bentonite mixture

Experiment no:16			
Sample	:	Aggregate II + 5 % Bentonite	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height (h_{1})	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	15:02	09:32	0,0		
2	15:02	09:52	33,5	20	5,78E-05
3	16:02	09:45	0,0		
4	16:02	09:58	25,6	13	6,36E-05
5	17:02	10:05	0,0		
6	17:02	10:18	25,4	13	6,30E-05
7	17:02	10:36	47,3	31	6,05E-05
8	17:02	12:05	0,0		
9	17:02	12:35	46,4	30	6,07E-05
10	17:02	12:54	60,6	49	5,88E-05
Hydraulic conductivity value cm/s					6,08E-05

Table C.17. Results of hydraulic conductivity test for Aggregate II + 10 per cent bentonite mixture

Experiment no:17
Sample : Aggregate II + 10 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	15.02	10:38	0,0		
2	15.02	10:58	3,9	20	5,42E-06
3	15.02	11:21	8,8	43	5,87E-06
4	15.02	11:24	0,0		
5	15.02	11:52	5,4	28	5,41E-06
6	16.02	12:26	12,2	62	5,77E-06
7	16.02	12:48	14,5	84	5,14E-06
8	16.02	13:01	0,0		
9	16.02	13:46	8,1	45	5,14E-06
10	16.02	14:25	15,6	84	5,57E-06
11	17.02	13:10	0,0		
12	17.02	13:39	5,7	29	5,53E-06
13	17.02	14:12	11,3	62	5,31E-06
Hydraulic conductivity value cm/s					5,46E-06

Table C.18. Results of hydraulic conductivity test for Aggregate II + 8 per cent bentonite mixture

Experiment no:18
Sample : Aggregate II + 8 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h$_1$) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	21.02	11:05	0,0		
2	21.02	11:21	4,9	16	8,57E-06
3	21.02	11:44	10,7	39	7,96E-06
4	21.02	11:58	16,3	53	9,27E-06
5	21.02	12:10	18,5	65	8,72E-06
6	22.02	09:45	0,0		
7	22.02	09:58	4,2	13	9,00E-06
8	22.02	10:15	8,3	30	7,91E-06
9	22.02	10:32	14,3	47	9,05E-06
10	22.02	10:58	18,2	73	7,62E-06
11	23.02	10:10	0,0		
12	23.02	10:23	4,4	12	1,02E-05
13	23.02	10:38	8,7	28	8,90E-06
14	23.02	10:51	12,3	41	8,80E-06
Hydraulic conductivity value cm/s					8,73E-06

Table C.19. Results of hydraulic conductivity test for Aggregate II + 12 per cent bentonite mixture

Experiment no:19
Sample : Aggregate II + 12 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	23.02	10:15	0,0		
2	23.02	11:20	7,7	65	3,37E-06
3	23.02	12:25	14,8	130	3,40E-06
4	23.02	13:20	0,0		
5	23.02	13:45	3,1	25	3,43E-06
6	23.02	14:40	7,8	80	2,78E-06
7	24:02	09:50	0,0		
8	24.02	10:27	3,9	37	2,93E-06
9	24.02	11:15	8,5	85	2,86E-06
10	24.02	11:20	0,0		
11	24.02	12:26	8,2	66	3,55E-06
12	24.02	14:35	20,4	195	3,25E-06
Hydraulic conductivity value cm/s					3,20E-06

Table C.20. Results of hydraulic conductivity test for Aggregate II + 15 per cent bentonite mixture

Experiment no:20
Sample : Aggregate II + 15 % Bentonite
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	23.02	10:20	0,0		
2	23.02	13:25	3,8	185	5,71E-07
3	23.02	16:27	7,1	367	5,49E-07
4	24:02	09:10	0,0		
5	24.02	12:46	3,8	216	4,89E-07
6	24.02	14:55	6,4	345	5,24E-07
7	24.02	16:00	7,8	410	5,42E-07
8	25.02	09:40	0,0		
9	25.02	13:22	4,2	212	5,52E-07
10	26.02	09:20	0,0		
11	26.02	12:27	4,0	197	5,65E-07
12	26.02	16:05	8,1	415	5,57E-07
Hydraulic conductivity value cm/s					5,43E-07

Table C.21. Results of hydraulic conductivity test for Aggregate I + 8 per cent bentonite + 0,5 per cent polymer mixture

Experiment no:21
Sample : Aggregate I + 8 % Bentonite + 0,5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	25.02	10:00	0,0		
2	25.02	12:25	2,8	145	5,33E-07
3	25.02	14:37	6,2	277	6,31E-07
4	25.02	14:40	0,0		
5	25.02	16:23	2,2	103	5,88E-07
6	26.02	09:45	0,0		
7	26.02	12:18	3,1	153	5,61E-07
8	27.02	10:15	0,0		
9	27.02	12:34	3,1	139	6,17E-07
10	27.02	13:25	3,9	190	5,71E-07
11	28.02	11:20	0,0		
12	28.02	13:53	2,8	153	5,05E-07
13	28.02	14:46	3,8	206	5,12E-07
Hydraulic conductivity value cm/s					5,65E-07

Table C.22. Results of hydraulic conductivity test for Aggregate I + 8 per cent bentonite + 0,75 per cent polymer mixture

Experiment no:22
Sample : Aggregate I + 8 % Bentonite + 0,75 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	25.02	10:05	0,0		
2	25.02	15:12	4,5	307	4,09E-07
3	26.02	09:10	0,0		
4	26.02	14:20	4,8	310	4,22E-07
5	26.02	16:28	6,8	438	4,23E-07
6	27.02	09:45	0,0		
7	27.02	16:02	5,9	377	4,26E-07
8	28.02	10:15	0,0		
9	28.02	12:19	2,1	124	4,60E-07
10	28.02	14:43	4,6	268	4,67E-07
Hydraulic conductivity value cm/s					4,35E-07

Table C.23. Results of hydraulic conductivity test for Aggregate I + 8 per cent bentonite + 1 per cent polymer mixture

Experiment no:23
Sample : Aggregate I + 8 % Bentonite + 1 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	25.02	10:07	0,0		
2	25.02	15:10	3,9	303	3,58E-07
3	26.02	09:15	0,0		
4	26.02	14:35	4,2	320	3,66E-07
5	26.02	16:28	5,5	438	3,53E-07
6	27.02	09:45	0,0		
7	27.02	16:55	4,6	430	2,99E-07
8	28.02	10:15	0,0		
9	28.02	11:40	1,1	85	3,54E-07
10	28.02	15:40	4,2	325	3,60E-07
Hydraulic conductivity value cm/s					3,48E-07

Table C.24. Results of hydraulic conductivity test for Aggregate I + 8 per cent bentonite + 2 per cent polymer mixture

Experiment no:24			
Sample	:	Aggregate I + 8 % Bentonite + 2 % Shore Pac	
Description	:	Sample is compacted under w:15% (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height ($h_{1)}$	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	27.02	09:50	0,0		
2	28.02	09:58	2,1	1448	3,99E-08
3	01.03	10:55	0,0		
4	02.03	10:20	2,0	1405	3,91E-08
5	02.03	15:55	0,0		
6	04.03	14:25	3,8	2790	3,78E-08
7	04.03	14:30	0,0		
8	05.03	16:02	2,0	1532	3,59E-08
Hydraulic conductivity value cm/s					3,82E-08

Table C.25. Results of hydraulic conductivity test for Aggregate I + 8 per cent bentonite + 5 per cent polymer mixture

Experiment no:25
Sample : Aggregate I + 8 % Bentonite + 5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	01.03	15:25	0,0		
2	03.03	09:25	3,1	2520	3,40E-08
3	03.03	11:45	0,0		
4	06.03	13:45	5,1	4440	3,22E-08
5	06.03	13:50	0,0		
6	07.03	17:35	2,0	1665	3,30E-08
7	08.03	14:30	0,0		
8	10.03	10:10	3,0	2620	3,17E-08
9	10.03	10:20	0,0		
10	14.03	11:00	5,6	5800	2,71E-08
Hydraulic conductivity value cm/s					3,16E-08

Table C.26. Results of hydraulic conductivity test for Aggregate I + 8 per cent bentonite + 10 per cent polymer mixture

Experiment no:26
Sample : Aggregate I + 8 % Bentonite + 10 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	02.03	09:10	0,0		
2	03.03	15:25	1,9	1815	2,88E-08
3	03.03	15:25	0,0		
4	05.03	13:50	2,7	2785	2,68E-08
5	05.03	14:00	0,0		
6	09.03	13:20	5,8	5720	2,85E-08
7	09:03	13:30	0,0		
8	11.03	09:50	3,1	2660	3,22E-08
9	11.03	10:25	0,0		
10	16.03	14:25	8,1	7440	3,11E-08
Hydraulic conductivity value cm/s					2,95E-08

Table C.27. Results of hydraulic conductivity test for Aggregate I + 10 per cent bentonite + 0,5 per cent polymer mixture

Experiment no:27
Sample : Aggregate I + 10 % Bentonite + 0,5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	03.03	09:25	0,0		
2	03.03	16:14	6,3	409	4,35E-07
3	04.03	10:15	19,2	1480	3,99E-07
4	04.03	10:20	0,0		
5	04.03	16:05	5,3	405	3,67E-07
6	05.03	13:00	22,1	1690	4,11E-07
7	09:03	13:30	0,0		
8	11.03	09:45	28,9	2655	3,61E-07
9	11.03	10:35	0,0		
10	16.03	15:00	62,5	7465	4,11E-07
Hydraulic conductivity value cm/s					3,97E-07

Table C.28. Results of hydraulic conductivity test for Aggregate I + 10 per cent bentonite + 0,75 per cent polymer mixture

Experiment no:28
Sample : Aggregate I + 10 % Bentonite + 0,75 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	03.03	09:30	0,0		
2	03.03	15:05	3,0	335	2,48E-07
3	04.03	10:20	11,6	1490	2,27E-07
4	04.03	10:25	0,0		
5	04.03	15:35	3,1	310	2,77E-07
6	05.03	13:20	11,9	1615	2,16E-07
7	09:03	13:35	0,0		
8	11.03	09:40	20,7	2645	2,44E-07
9	11.03	10:40	0,0		
10	16.03	16:20	47,3	7540	2,49E-07
Hydraulic conductivity value cm/s					2,43E-07

Table C.29. Results of hydraulic conductivity test for Aggregate I + 10 per cent bentonite + 1 per cent polymer mixture

Experiment no:29
Sample : Aggregate I + 10 % Bentonite + 1 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	03.03	09:40	0,0		
2	03.03	14:05	1,9	265	1,97E-07
3	04.03	10:25	9,6	1485	1,86E-07
4	04.03	10:30	0,0		
5	05.03	13:20	10,4	1610	1,87E-07
6	09:03	13:40	0,0		
7	11.03	09:50	17,6	2650	2,02E-07
8	11.03	10:40	0,0		
9	16.03	16:20	39,2	7540	1,89E-07
10	16.03	16:30	0,0		
11	18.03	15:45	17,5	2835	1,88E-07
Hydraulic conductivity value cm/s					1,92E-07

Table C.30. Results of hydraulic conductivity test for Aggregate I + 10 per cent bentonite + 2 per cent polymer mixture

Experiment no:30
Sample : Aggregate I + 10 % Bentonite + 2 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	05.03	09:33	0,0		
2	06.03	13:12	1,2	1659	1,98E-08
3	06.03	13:15	0,0		
4	08.03	11:20	1,9	2765	1,89E-08
5	08.03	11:25	0,0		
6	11.03	13:47	2,7	4462	1,67E-08
7	11.03	13:50	0,0		
8	16.03	10:45	4,8	7015	1,91E-08
9	16.03	12:48	0,0		
10	21.03	07:58	4,7	6910	1,90E-08
Hydraulic conductivity value cm/s					1,87E-08

Table C.31. Results of hydraulic conductivity test for Aggregate I + 10 per cent bentonite + 5 per cent polymer mixture

Experiment no:31			
Sample	:	Aggregate I + 10 % Bentonite + 5 % Shore Pac	
Description	:	Sample is compacted under w:15% (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height ($h_{1)}$	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	05.03	14:10	0,0		
2	08.03	09:20	1,9	4010	1,30E-08
3	08:03	09:25	0,0		
4	16.03	11:20	5,7	11635	1,38E-08
5	16.03	11:25	0,0		
6	21.03	16:47	3,8	7522	1,40E-08
7	21.03	16:50	0,0		
8	27.03	10:15	4,3	8245	1,45E-08
Hydraulic conductivity value cm/s					1,38E-08

Table C.32. Results of hydraulic conductivity test for Aggregate I + 10 per cent bentonite + 10 per cent polymer mixture

Experiment no:32
Sample : Aggregate I + 10 % Bentonite + 10 % Shore Pac
Description : Sample is compacted under w:15% (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_{1}) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	05.03	14:15	0,0		
2	08.03	14:25	1,8	4310	1,15E-08
3	08:03	14:30	0,0		
4	16.03	10:20	5,2	11270	1,29E-08
5	16.03	10:25	0,0		
6	19:03	11:47	2,0	4402	1,25E-08
7	19:03	11:50	0,0		
8	27.03	09:05	5,0	11355	1,23E-08
Hydraulic conductivity value cm/s					1,23E-08

Table C.33. Results of hydraulic conductivity test for Aggregate I + 12 per cent bentonite + 0,5 per cent polymer mixture

Experiment no:33
Sample : Aggregate I + 12 % Bentonite + 0,5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	07:03	09:35	0,0		
2	08.03	15:42	13,5	1807	2,21E-07
3	08.03	15:50	0,0		
4	09.03	10:20	9,5	1110	2,46E-07
5	09.03	10:25	0,0		
6	10.03	11:50	12,7	1525	2,45E-07
7	10.03	11:55	0,0		
8	12.03	09:45	22,4	2750	2,57E-07
9	12.03	09:50	0,0		
10	14.03	12:20	23,1	3030	2,42E-07
Hydraulic conductivity value cm/s					2,42E-07

Table C.34. Results of hydraulic conductivity test for Aggregate I + 12 per cent bentonite + 0,75 per cent polymer mixture

Experiment no:34
Sample : Aggregate I + 12 % Bentonite + 0,75 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	07:03	09:37	0,0		
2	08.03	15:43	12,8	1806	2,09E-07
3	08.03	15:45	0,0		
4	09.03	10:15	8,1	1110	2,08E-07
5	09.03	10:20	0,0		
6	10.03	11:47	10,3	1527	1,95E-07
7	10.03	11:50	0,0		
8	12.03	09:42	18,7	2752	2,08E-07
9	12.03	09:45	0,0		
10	14.03	10:25	20,8	2920	2,22E-07
Hydraulic conductivity value cm/s					2,08E-07

Table C.35. Results of hydraulic conductivity test for Aggregate I + 12 per cent bentonite + 1 per cent polymer mixture

Experiment no:35
Sample : Aggregate I + 12 % Bentonite + 1 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	07:03	09:50	0,0		
2	08.03	15:23	9,2	1773	1,49E-07
3	08.03	15:25	0,0		
4	09.03	10:30	6,3	1145	1,55E-07
5	09.03	10:33	0,0		
6	10.03	11:40	8,0	1507	1,51E-07
7	10.03	11:42	0,0		
8	12.03	09:30	13,6	2748	1,46E-07
9	12.03	09:50	0,0		
10	14.03	11:03	14,2	2953	1,43E-07
11	14:03	11:05	0,0		
12	16:03	12:40	14,2	2975	1,42E-07
Hydraulic conductivity value cm/s					1,48E-07

Table C.36. Results of hydraulic conductivity test for Aggregate I + 12 per cent bentonite + 2 per cent polymer mixture

Experiment no:36
Sample : Aggregate I + 12 % Bentonite + 2 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_{1}) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	10.03	09:40	0,0		
2	14.03	16:05	2,8	6145	1,26E-08
3	14.03	16:38	0,0		
4	16.03	09:05	1,2	2427	1,35E-08
5	16.03	09:10	0,0		
6	20.03	13:10	2,6	6000	1,20E-08
7	20.03	13:12	0,0		
8	26.03	09:35	4,0	8423	1,32E-08
Hydraulic conductivity value cm/s					1,28E-08

Table C.37. Results of hydraulic conductivity test for Aggregate I + 12 per cent bentonite + 5 per cent polymer mixture

Experiment no:37
Sample : Aggregate I + 12 % Bentonite + 5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	14.03	16:40	0,0		
2	16:03	09:07	0,9	2427	1,01E-08
3	16.03	09:17	0,0		
4	23.03	09:08	4,2	10071	1,16E-08
5	23.03	09:10	0,0		
6	31.03	15:40	4,7	11910	1,10E-08
7	31.03	15:43	0,0		
8	11.04	17:12	6,5	15929	1,15E-08
9	11.04	10:16	0,0		
10	18.04	15:45	4,4	10409	1,18E-08
Hydraulic conductivity value cm/s					1,12E-08

Table C.38. Results of hydraulic conductivity test for Aggregate I + 12 per cent bentonite + 10 per cent polymer mixture

Experiment no:38
Sample : Aggregate I + 12 % Bentonite + 10 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	14.03	16:40	0,0		
2	16:03	09:10	0,9	2430	1,01E-08
3	16.03	09:15	0,0		
4	23.03	09:09	4,1	10074	1,13E-08
5	23.03	09:12	0,0		
6	31.03	15:41	4,4	11909	1,03E-08
7	31.03	15:45	0,0		
8	11.04	17:11	5,9	15926	1,04E-08
9	11.04	10:18	0,0		
10	18.04	15:50	3,7	10412	9,87E-09
Hydraulic conductivity value cm/s					1,04E-08

Table C.39. Results of hydraulic conductivity test for Aggregate I + 15 per cent bentonite + 0,5 per cent polymer mixture

Experiment no:39
Sample : Aggregate I + 15 % Bentonite + 0,5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	16.03	09:32	0,0		
2	17.03	15:47	2,1	1815	3,18E-08
3	17.03	15:50	0,0		
4	18.03	09:20	1,1	1050	2,86E-08
5	18.09	09:25	0,0		
6	19.03	14:50	1,8	1765	2,80E-08
7	19.03	14:55	0,0		
8	21.03	09:45	2,8	2570	3,01E-08
9	21.03	09:50	0,0		
10	25.03	16:20	6,7	6150	3,08E-08
Hydraulic conductivity value cm/s					2,99E-08

Table C.40. Results of hydraulic conductivity test for Aggregate I + 15 per cent bentonite + 0,75 per cent polymer mixture

Experiment no:40
Sample : Aggregate I + 15 % Bentonite + 0,75 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	16.03	10:35	0,0		
2	20.03	14:20	4,8	5995	2,24E-08
3	20.03	14:25	0,0		
4	26.03	15:53	6,9	8728	2,24E-08
5	26.03	15:58	0,0		
6	31.03	14:50	5,5	7132	2,17E-08
7	31.03	14:55	0,0		
8	08.04	09:45	9,0	11210	2,30E-08
9	08.04	09:47	0,0		
10	15.04	16:22	8,6	10475	2,35E-08
Hydraulic conductivity value cm/s					2,26E-08

Table C.41. Results of hydraulic conductivity test for Aggregate I + 8 per cent bentonite + 1 per cent polymer mixture

Experiment no:41

Sample	:	Aggregate I + 15 % Bentonite + 1 % Shore Pac	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height (h_1)	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	16.03	10:30	0,0		
2	20.03	14:15	3,8	5995	1,76E-08
3	20.03	14.18	0,0		
4	26.03	15:43	5,2	8725	1,67E-08
5	26.03	15:46	0,0		
6	31.03	15:06	4,9	7160	1,91E-08
7	31.03	15:08	0,0		
8	08.04	10:10	6,7	11232	1,69E-08
9	08.04	10:15	0,0		
10	15.04	16:30	6,5	10455	1,76E-08
Hydraulic conductivity value cm/s					1,76E-08

Table C.42. Results of hydraulic conductivity test for Aggregate I + 15 per cent bentonite + 2 per cent polymer mixture

Experiment no:42
Sample : Aggregate I + 15 % Bentonite + 2 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	20.03	10:30	0,0		
2	31.03	14:15	1,2	16065	2,04E-09
3	31.03	14.18	0,0		
4	15.04	15:45	1,5	21687	1,90E-09
5	15.04	15:52	0,0		
6	28.04	11:10	1,4	18438	2,08E-09
7	28.04	11:15	0,0		
8	30.05	14:25	3,4	46270	2,04E-09
Hydraulic conductivity value cm/s					2,01E-09

Table C.43. Results of hydraulic conductivity test for Aggregate I + 15 per cent bentonite + 5 per cent polymer mixture

Experiment no:43

Sample : Aggregate I + 15 % Bentonite + 5 % Shore Pac

Description : Sample is compacted under w:15 % (Standard Compaction)

Hammer : 2,5 kg

Burette Dimensions

Area (a) : 0,96 cm^2

Height ($h_{1)}$: 85 cm

Mold Dimensions

Area of the sample : 81,70 cm^2

Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	20.03	09:25	0,0		
2	31.03	14:20	0,9	16135	1,52E-09
3	31.03	14:15	0,0		
4	15.04	15:50	1,2	21685	1,51E-09
5	15.04	15:55	0,0		
6	28.04	11:05	1,1	18430	1,63E-09
7	28.04	11:10	0,0		
8	30.05	14:35	2,5	46285	1,49E-09
Hydraulic conductivity value cm/s					1,54E-09

Table C.44. Results of hydraulic conductivity test for Aggregate I + 15 per cent bentonite + 10 per cent polymer mixture

Experiment no:44
Sample : Aggregate I + 15 % Bentonite + 10 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	18.03	09:25	0,0		
2	04.04	11:10	0,9	24575	1,00E-09
3	04.04	11:12	0,0		
4	24.04	14:15	1,1	28983	1,04E-09
5	24.04	14:20	0,0		
6	11.05	09:35	1,0	25635	1,07E-09
7	11.05	09:38	0,0		
8	16.06	16:23	2,0	52245	1,05E-09
Hydraulic conductivity value cm/s					1,04E-09

Table C.45. Results of hydraulic conductivity test for Aggregate II + 8 per cent bentonite + 0,5 per cent polymer mixture

Experiment no:45

Sample : Aggregate II + 8 % Bentonite + 0,5 % Shore Pac

Description : Sample is compacted under w:15 % (Standard Compaction)

Hammer : 2,5 kg

Burette Dimensions

Area (a) : 0,96 cm^2

Height (h_1) : 85 cm

Mold Dimensions

Area of the sample : 81,70 cm^2

Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	20.03	09:25	0,0		
2	20.03	11:38	2,8	133	5,81E-07
3	20.03	14:02	6,2	278	6,29E-07
4	20.03	14:05	0,0		
5	20.03	15:35	2,1	90	6,42E-07
6	21.03	15.37	0,0		
7	21.03	17.01	1,9	84	6,21E-07
8	22.03	09:20	0,0		
9	22.03	14:25	6,5	305	6,02E-07
10	22.03	16:40	9,6	440	6,29E-07
11	24.03	09:08	0,0		
12	24.03	12:03	3,9	175	6,20E-07
13	24.03	14:25	6,7	317	5,98E-07
14	24.03	16:02	8,6	414	5,95E-07
Hydraulic conductivity value cm/s					6,13E-07

Table C.46. Results of hydraulic conductivity test for Aggregate II + 8 per cent bentonite + 0,75 per cent polymer mixture

Experiment no:46			
Sample	:	Aggregate II + 8 % Bentonite + 0,75 % Shore Pac	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height (h_1)	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	20.03	09:30	0,0		
2	20.03	11:40	1,9	130	4,01E-07
3	20.03	13:58	4,2	268	4,36E-07
4	20.03	14:00	0,0		
5	20.03	16:05	1,9	125	4,17E-07
6	21.03	15.32	0,0		
7	21.03	16:34	1,0	62	4,41E-07
8	22.03	09:15	0,0		
9	22.03	14:25	4,8	310	4,33E-07
10	22.03	16:40	6,9	445	4,39E-07
Hydraulic conductivity value cm/s					4,28E-07

Table C.47. Results of hydraulic conductivity test for Aggregate II + 8 per cent bentonite + 1 per cent polymer mixture

Experiment no:47
Sample : Aggregate II + 8 % Bentonite + 1 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED , min	HYDRAULIC CONDUCTIVITY, cm/s
1	20.03	09:30	0,0		
2	20.03	11:40	0,9	80	3,07E-07
3	20.03	13:58	3,3	268	3,41E-07
4	20.03	14:00	0,0		
5	20.03	16:43	2,1	163	3,54E-07
6	21.03	09:48	0,0		
7	21.03	16:34	4,8	406	3,30E-07
8	22.03	09:20	0,0		
9	22.03	14:25	3,9	305	3,55E-07
10	22.03	16:55	5,5	455	3,39E-07
Hydraulic conductivity value cm/s					3,38E-07

Table C.48. Results of hydraulic conductivity test for Aggregate II + 8 per cent bentonite + 2 per cent polymer mixture

Experiment no:48
Sample : Aggregate II + 8 % Bentonite + 2 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	05.04	09:17	0,0		
2	11.04	10:35	11,5	8718	3,85E-08
3	11.04	10:38	0,0		
4	24.04	15:20	22,2	19002	3,68E-08
5	24.04	15:24	0,0		
6	13.05	09:37	29,6	27013	3,66E-08
7	13.05	09:41	0,0		
8	31.05	13:40	29,1	26159	3,70E-08
9	31.05	13:45	0,0		
10	10.06	11:15	16,7	14250	3,54E-08
11	10.06	11:20	0,0		
12	13.07	12:42	45,1	47602	3,67E-08
Hydraulic conductivity value cm/s					3,68E-08

Table C.49. Results of hydraulic conductivity test for Aggregate II + 8 per cent bentonite + 5 per cent polymer mixture

Experiment no:49
Sample : Aggregate II + 8 % Bentonite + 5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	05.04	09:19	0,0		
2	11.04	10:30	8,4	8711	2,76E-08
3	11.04	10:35	0,0		
4	24.04	15:22	16,8	19007	2,67E-08
5	24.04	15:25	0,0		
6	13.05	09:35	23,1	27010	2,71E-08
7	13.05	09:40	0,0		
8	31.05	13:42	24,2	26162	2,96E-08
9	31.05	13:50	0,0		
10	10.06	11:17	13,1	14247	2,71E-08
11	10.06	11:22	0,0		
12	13.07	12:40	37,2	47598	2,79E-08
Hydraulic conductivity value cm/s					2,77E-08

Table C.50. Results of hydraulic conductivity test for Aggregate II + 8 per cent bentonite + 10 per cent polymer mixture

Experiment no:50
Sample : Aggregate II + 8 % Bentonite + 10 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	05.04	09:10	0,0		
2	11.04	10:21	7,4	8711	2,41E-08
3	11.04	10:23	0,0		
4	24.04	15:18	14,1	19015	2,20E-08
5	24.04	15:20	0,0		
6	13.05	09:25	21,3	27005	2,47E-08
7	13.05	09:28	0,0		
8	31.05	13:38	20,3	26170	2,41E-08
9	31.05	13:41	0,0		
10	10.06	11:18	10,7	14257	2,18E-08
11	10.06	11:23	0,0		
12	13.07	12:35	35,2	47592	2,59E-08
Hydraulic conductivity value cm/s					2,38E-08

Table C.51. Results of hydraulic conductivity test for Aggregate II + 10 per cent bentonite + 0,5 per cent polymer mixture

Experiment no:51
Sample : Aggregate II + 10 % Bentonite + 0,5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	15.06	09:20	0,0		
2	17.06	11:15	27,9	2995	3,07E-07
3	17.06	11:18	0,0		
4	19.06	13:45	28,3	3027	3,09E-07
5	19.06	13:50	0,0		
6	22.06	09:22	34,1	4052	2,92E-07
7	22.06	09:24	0,0		
8	25.06	11:16	38,4	4432	3,13E-07
9	25.06	11:20	0,0		
10	30.06	16:28	52,3	7508	2,94E-07
11	30.06	16:32	0,0		
12	04.07	12:25	42,1	5513	2,86E-07
Hydraulic conductivity value cm/s					3,00E-07

Table C.52. Results of hydraulic conductivity test for Aggregate II + 10 per cent bentonite + 0,75 per cent polymer mixture

Experiment no:52			
Sample	:	Aggregate II + 10 % Bentonite + 0,75 % Shore Pac	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height ($h_{1)}$	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	15.06	09:18	0,0		
2	17.06	11:13	24,1	2995	2,57E-07
3	17.06	11:15	0,0		
4	19.06	13:40	24,8	3025	2,63E-07
5	19.06	13:42	0,0		
6	22.06	09:18	29,6	4056	2,44E-07
7	22.06	09:21	0,0		
8	25.06	11:17	31,7	4436	2,43E-07
9	25.06	11:23	0,0		
10	30.06	16:26	46,8	7503	2,46E-07
11	30.06	16:40	0,0		
12	04.07	12:32	35,2	5512	2,24E-07
Hydraulic conductivity value cm/s					2,46E-07

Table C.53. Results of hydraulic conductivity test for Aggregate II + 10 per cent bentonite + 1 per cent polymer mixture

Experiment no:53
Sample : Aggregate II + 10 % Bentonite + 1 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	15.06	09:19	0,0		
2	17.06	11:14	19,3	2995	1,99E-07
3	17.06	11:17	0,0		
4	19.06	13:37	19,8	3020	2,03E-07
5	19.06	13:44	0,0		
6	22.06	09:17	24,6	4053	1,95E-07
7	22.06	09:19	0,0		
8	25.06	11:19	27,9	4440	2,07E-07
9	25.06	11:22	0,0		
10	30.06	16:27	38,1	7505	1,83E-07
11	30.06	16:43	0,0		
12	04.07	12:33	32,5	5510	2,02E-07
Hydraulic conductivity value cm/s					1,98E-07

Table C.54. Results of hydraulic conductivity test for Aggregate II + 10 per cent bentonite + 2 per cent polymer mixture

Experiment no:54
Sample : Aggregate II + 10 % Bentonite + 2 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	16.07	10:24	0,0		
2	20.07	09:32	3,2	5708	1,55E-08
3	20.07	09:35	0,0		
4	26.07	15:20	4,7	8295	1,58E-08
5	26.07	15:22	0,0		
6	31.07	14:05	4,1	7123	1,60E-08
7	31.07	14:08	0,0		
8	11.08	10:36	8,6	15628	1,58E-08
9	11.08	10:40	0,0		
10	19.08	13:26	6,2	11686	1,50E-08
Hydraulic conductivity value cm/s					1,56E-08

Table C.55. Results of hydraulic conductivity test for Aggregate II + 10 per cent bentonite + 5 per cent polymer mixture

Experiment no:55
Sample : Aggregate II + 10 % Bentonite + 5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	16.07	10:22	0,0		
2	20.07	09:32	2,9	5710	1,40E-08
3	20.07	09:36	0,0		
4	26.07	15:21	4,2	8295	1,41E-08
5	26.07	15:21	0,0		
6	31.07	14:01	3,3	7123	1,28E-08
7	31.07	14:03	0,0		
8	11.08	10:37	7,2	15624	1,31E-08
9	11.08	10:41	0,0		
10	19.08	13:28	5,3	11687	1,27E-08
Hydraulic conductivity value cm/s					1,34E-08

Table C.56. Results of hydraulic conductivity test for Aggregate II + 10 per cent bentonite + 10 per cent polymer mixture

Experiment no:56			
Sample	:	Aggregate II + 10 % Bentonite + 10 % Shore Pac	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height ($h_{1)}$	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	16.07	10:25	0,0		
2	20.07	09:33	2,1	5708	1,01E-08
3	20.07	09:39	0,0		
4	26.07	15:24	3,8	8295	1,27E-08
5	26.07	15:26	0,0		
6	31.07	14:02	2,8	7119	1,09E-08
7	31.07	14:03	0,0		
8	11.08	10:39	6,7	15626	1,21E-08
9	11.08	10:46	0,0		
10	19.08	13:26	5,0	11680	1,20E-08
Hydraulic conductivity value cm/s					1,16E-08

Table C.57. Results of hydraulic conductivity test for Aggregate II + 12 per cent bentonite + 0,5 per cent polymer mixture

Experiment no:57
Sample : Aggregate II + 12 % Bentonite + 0,5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h$_1$) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	04.07	11:22	0,0		
2	10.07	13:45	37,3	8783	1,52E-07
3	10.07	13:47	0,0		
4	15.07	09:04	31,5	6917	1,54E-07
5	15.07	09:11	0,0		
6	19.07	15:47	26,8	5796	1,51E-07
7	19.07	15:50	0,0		
8	25.07	10:15	36,9	8305	1,58E-07
9	25.07	10:20	0,0		
10	31.07	14:36	37,4	8896	1,50E-07
11	31.07	14:40	0,0		
12	06.08	09:55	34,1	8355	1,42E-07
Hydraulic conductivity value cm/s					1,51E-07

Table C.58. Results of hydraulic conductivity test for Aggregate II + 12 per cent bentonite + 0,75 per cent polymer mixture

Experiment no:58
Sample : Aggregate II + 12 % Bentonite + 0,75 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	04.07	11:21	0,0		
2	10.07	13:44	29,8	8783	1,13E-07
3	10.07	13:46	0,0		
4	15.07	09:05	26,1	6919	1,22E-07
5	15.07	09:08	0,0		
6	19.07	15:48	22,2	5800	1,20E-07
7	19.07	15:51	0,0		
8	25.07	10:16	27,8	8305	1,10E-07
9	25.07	10:19	0,0		
10	31.07	14:35	28,9	8896	1,08E-07
11	31.07	14:41	0,0		
12	06.08	09:53	27,1	8352	1,06E-07
Hydraulic conductivity value cm/s					1,13E-07

Table C.59. Results of hydraulic conductivity test for Aggregate II + 12 per cent bentonite + 1 per cent polymer mixture

Experiment no:59			
Sample	:	Aggregate II + 12 % Bentonite + 1 % Shore Pac	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height (h_1)	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	04.07	11:16	0,0		
2	10.07	13:42	25,3	8786	9,28E-08
3	10.07	13:47	0,0		
4	15.07	09:06	19,7	6919	8,80E-08
5	15.07	09:09	0,0		
6	19.07	15:47	16,5	5798	8,59E-08
7	19.07	15:53	0,0		
8	25.07	10:18	22,8	8305	8,68E-08
9	25.07	10:18	0,0		
10	31.07	14:36	27,2	8898	1,00E-07
11	31.07	14:39	0,0		
12	06.08	09:55	23,1	8356	8,76E-08
Hydraulic conductivity value cm/s					9,02E-08

Table C.60. Results of hydraulic conductivity test for Aggregate II + 12 per cent bentonite + 2 per cent polymer mixture

Experiment no:60
Sample : Aggregate II + 12 % Bentonite + 2 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	10.07	11:42	0,0		
2	18.07	15:52	3,3	11690	7,82E-09
3	18.07	15:55	0,0		
4	28.07	16:20	4,2	14425	8,11E-09
5	28.07	16:23	0,0		
6	06.08	10:10	3,6	12587	7,94E-09
7	06.08	10:15	0,0		
8	21.08	15:28	6,1	21913	7,84E-09
9	21.08	15:30	0,0		
10	05.09	11:42	6,1	21452	8,01E-09
11	05.09	11:45	0,0		
12	28.09	13:35	9,3	33230	8,05E-09
Hydraulic conductivity value cm/s					7,96E-09

Table C.61. Results of hydraulic conductivity test for Aggregate II + 12 per cent bentonite + 5 per cent polymer mixture

Experiment no:61
Sample : Aggregate II + 12 % Bentonite + 5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	10.07	11:40	0,0		
2	18.07	15:54	2,5	11694	5,89E-09
3	18.07	15:51	0,0		
4	28.07	16:21	3,1	14425	5,95E-09
5	28.07	16:24	0,0		
6	06.08	10:08	2,7	12584	5,92E-09
7	06.08	10:12	0,0		
8	21.08	15:27	4,4	21915	5,60E-09
9	21.08	15:31	0,0		
10	05.09	11:44	4,3	21453	5,59E-09
11	05.09	11:47	0,0		
12	28.09	13:36	7,0	33229	5,97E-09
Hydraulic conductivity value cm/s					5,82E-09

Table C.62. Results of hydraulic conductivity test for Aggregate II + 12 per cent bentonite + 10 per cent polymer mixture

Experiment no:62
Sample : Aggregate II + 12 % Bentonite + 10 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED , min	HYDRAULIC CONDUCTIVITY, cm/s
1	10.07	11:37	0,0		
2	18.07	15:53	2,4	11696	5,65E-09
3	18.07	15:55	0,0		
4	28.07	16:22	2,8	14422	5,36E-09
5	28.07	16:25	0,0		
6	06.08	10:07	2,3	12582	5,03E-09
7	06.08	10:11	0,0		
8	21.08	15:28	4,1	21917	5,21E-09
9	21.08	15:34	0,0		
10	05.09	11:42	4,1	21448	5,32E-09
11	05.09	11:49	0,0		
12	28.09	13:39	6,1	33230	5,17E-09
Hydraulic conductivity value cm/s					5,29E-09

Table C.63. Results of hydraulic conductivity test for Aggregate II + 15 per cent bentonite + 0,5 per cent polymer mixture

Experiment no:63
Sample : Aggregate II + 15 % Bentonite + 0,5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h$_1$) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	07.08	14:25	0,0		
2	13.08	10:32	7,1	8407	2,39E-08
3	13.08	10:35	0,0		
4	22.08	16:04	11,3	13289	2,48E-08
5	22.08	16:10	0,0		
6	31.08	11:13	10,1	12663	2,31E-08
7	31.08	11:15	0,0		
8	08.09	15:14	9,8	11759	2,40E-08
9	08.09	15:18	0,0		
10	12.09	12:02	4,6	5564	2,31E-08
11	12.09	12:05	0,0		
12	17.09	16:44	6,1	7479	2,30E-08
Hydraulic conductivity value cm/s					2,36E-08

Table C.64. Results of hydraulic conductivity test for Aggregate II + 15 per cent bentonite + 0,75 per cent polymer mixture

Experiment no:64
Sample : Aggregate II + 15 % Bentonite + 0,75 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	07.08	14:23	0,0		
2	13.08	10:30	4,8	8407	1,60E-08
3	13.08	10:34	0,0		
4	22.08	16:05	7,3	13291	1,56E-08
5	22.08	16:08	0,0		
6	31.08	11:14	7,1	12666	1,59E-08
7	31.08	11:16	0,0		
8	08.09	15:15	6,4	11759	1,54E-08
9	08.09	15:19	0,0		
10	12.09	12:03	3,3	5564	1,64E-08
11	12.09	12:04	0,0		
12	17.09	16:46	4,3	7482	1,60E-08
Hydraulic conductivity value cm/s					1,59E-08

Table C.65. Results of hydraulic conductivity test for Aggregate II + 15 per cent bentonite + 1 per cent polymer mixture

Experiment no:65

Sample	:	Aggregate II + 15 % Bentonite + 1 % Shore Pac	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height (h_1)	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	07.08	14:20	0,0		
2	13.08	10:35	3,9	8415	1,29E-08
3	13.08	10:36	0,0		
4	22.08	16:04	6,2	13288	1,32E-08
5	22.08	16:07	0,0		
6	31.08	11:13	5,8	12666	1,29E-08
7	31.08	11:17	0,0		
8	08.09	15:16	5,3	11759	1,26E-08
9	08.09	15:23	0,0		
10	12.09	12:05	2,7	5562	1,34E-08
11	12.09	12:08	0,0		
12	17.09	16:50	3,8	7482	1,41E-08
Hydraulic conductivity value cm/s					1,32E-08

Table C.66. Results of hydraulic conductivity test for Aggregate II + 15 per cent bentonite + 2 per cent polymer mixture

Experiment no:66			
Sample	:	Aggregate II + 15 % Bentonite + 2 % Shore Pac	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height (h_1)	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	15.07	09:25	0,0		
2	04.08	13:40	1,8	29055	1,70E-09
3	04.08	13:43	0,0		
4	29.08	11:20	2,2	35857	1,69E-09
5	29.08	11:25	0,0		
6	27.09	15:35	2,3	42010	1,51E-09
7	27.09	15:40	0,0		
8	20.10	10:54	2,0	34274	1,60E-09
9	20.10	11:00	0,0		
10	21.11	13:20	2,6	46220	1,55E-09
Hydraulic conductivity value cm/s					1,61E-09

Table C.67. Results of hydraulic conductivity test for Aggregate II + 15 per cent bentonite + 5 per cent polymer mixture

Experiment no:67
Sample : Aggregate II + 12 % Bentonite + 5 % Shore Pac
Description : Sample is compacted under w:15 % (Standard Compaction)
Hammer : 2,5 kg

Burette Dimensions
Area (a) : 0,96 cm^2
Height (h_1) : 85 cm

Mold Dimensions
Area of the sample : 81,70 cm^2
Length of the sample : 11,8 cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	15.07	09:25	0,0		
2	04.08	13:40	1,4	29055	1,32E-09
3	04.08	13:43	0,0		
4	29.08	11:20	1,8	35857	1,38E-09
5	29.08	11:25	0,0		
6	27.09	15:35	1,8	42010	1,18E-09
7	27.09	15:40	0,0		
8	20.10	10:54	1,4	34274	1,12E-09
9	20.10	11:00	0,0		
10	21.11	13:20	2,5	46220	1,49E-09
Hydraulic conductivity value cm/s					1,30E-09

Table C.68. Results of hydraulic conductivity test for Aggregate I + 15 per cent bentonite + 10 per cent polymer mixture

Experiment no:68			
Sample	:	Aggregate II + 12 % Bentonite + 10 % Shore Pac	
Description	:	Sample is compacted under w:15 % (Standard Compaction)	
Hammer	:	2,5	kg
Burette Dimensions			
Area (a)	:	0,96	cm^2
Height ($h_{1)}$	:	85	cm
Mold Dimensions			
Area of the sample	:	81,70	cm^2
Length of the sample	:	11,8	cm

NUMBER OF READING	DATE	TIME	READING cm	TIME ELAPSED, min	HYDRAULIC CONDUCTIVITY, cm/s
1	15.07	09:25	0,0		
2	04.08	13:40	1,1	29055	1,03E-09
3	04.08	13:43	0,0		
4	29.08	11:20	1,6	35857	1,22E-09
5	29.08	11:25	0,0		
6	27.09	15:35	1,8	42010	1,18E-09
7	27.09	15:40	0,0		
8	20.10	10:54	1,3	34274	1,04E-09
9	20.10	11:00	0,0		
10	21.11	13:20	2,0	46220	1,19E-09
Hydraulic conductivity value cm/s					1,13E-09

APPENDIX D: RESULTS OF VISCOSITY DETERMINATION TESTS

The results of the viscosity determination tests are given in the Tables D.1. to D.6.

Table D.1. Results of viscosity determination test for water + 0,5 per cent polymer solution

Viscosity determination				Experiment 1		
Sample : Water + 0,5 % polymer						
Viscosity μ = 2 g r2 (d'-d) / 9v						
		Test 1	Test 2	Test 3	Test 4	Test 5
Radius of the sphere, m	r =	0,002	0,002	0,002	0,002	0,002
Fall height, m	x =	0,4	0,4	0,4	0,4	0,4
Fall time, s	t =	1	1,1	1,1	1	1,1
Equivalent fall velocity of the sphere, m/s	v =	0,4	0,36364	0,36364	0,4	0,36364
Gravitational constant, m/s^2	g =	9,81	9,81	9,81	9,81	9,81
Density of the sphere, kg/m^3	d^1 =	1410	1410	1410	1410	1410
Density of the viscous fluid, kg/m^3	d =	0,9983	0,998	0,9987	0,9981	0,9984
Viscosity μ = 2 g r2 (d'-d) / 9v, kg m^{-1} s^{-1}	μ =	0,03072	0,03379	0,03379	0,03072	0,03379
			Average μ=		0,033	kg m^{-1} s^{-1}

Table D.2. Results of viscosity determination test for water + 0,75 per cent polymer solution

Viscosity determination				Experiment 2		
Sample : Water + 0,75 % polymer						
Viscosity μ = 2 g r2 (d'-d) / 9v						
		Test 1	Test 2	Test 3	Test 4	Test 5
Radius of the sphere, m	r =	0,002	0,002	0,002	0,002	0,002
Fall height, m	x =	0,4	0,4	0,4	0,4	0,4
Fall time, s	t =	1,4	1,5	1,6	1,4	1,4
Equivalent fall velocity of the sphere, m/s	v =	0,28571	0,26667	0,25	0,28571	0,28571
Gravitational constant, m/s^2	g =	9,81	9,81	9,81	9,81	9,81
Density of the sphere, kg/m^3	d^1 =	1410	1410	1410	1410	1410
Density of the viscous fluid, kg/m^3	d =	0,9983	0,998	0,9987	0,9981	0,9984
Viscosity μ = 2 g r2 (d'-d) / 9v, kg m^{-1} s^{-1}	μ =	0,043	0,04607	0,04915	0,043	0,043
			Average μ=		0,045	kg m^{-1} s^{-1}

Table D.3. Results of viscosity determination test for water + 1 per cent polymer solution

Viscosity determination Experiment 3

Sample : Water + 1 % polymer

Viscosity μ = 2 g r2 (d’-d) / 9v

		Test 1	Test 2	Test 3	Test 4	Test 5
Radius of the sphere, m	r =	0,002	0,002	0,002	0,002	0,002
Fall height, m	x =	0,4	0,4	0,4	0,4	0,4
Fall time, s	t =	3,2	3,1	3,2	3,2	3,3
Equivalent fall velocity of the sphere, m/s	v =	0,125	0,12903	0,125	0,125	0,12121
Gravitational constant, m/s^2	g =	9,81	9,81	9,81	9,81	9,81
Density of the sphere, kg/m^3	d^1 =	1410	1410	1410	1410	1410
Density of the viscous fluid, kg/m^3	d =	0,9983	0,998	0,9987	0,9981	0,9984
Viscosity μ = 2 g r2 (d’-d) / 9v, kg m^{-1} s^{-1}	μ =	0,09829	0,09522	0,09829	0,09829	0,10136
			Average μ=		0,098	kg m^{-1} s^{-1}

Table D.4. Results of viscosity determination test for water + 2 per cent polymer solution

Viscosity determination Experiment 4

Sample : Water + 2 % polymer

Viscosity μ = 2 g r2 (d’-d) / 9v

		Test 1	Test 2	Test 3	Test 4	Test 5
Radius of the sphere, m	r =	0,005	0,005	0,005	0,005	0,005
Fall height, m	x =	0,4	0,4	0,4	0,4	0,4
Fall time, s	t =	2,1	2,2	2	2,2	2,1
Equivalent fall velocity of the sphere, m/s	v =	0,19048	0,18182	0,2	0,18182	0,19048
Gravitational constant, m/s^2	g =	9,81	9,81	9,81	9,81	9,81
Density of the sphere, kg/m^3	d^1 =	2620	2620	2620	2620	2620
Density of the viscous fluid, kg/m^3	d =	0,9983	0,998	0,9987	0,9981	0,9984
Viscosity μ = 2 g r2 (d’-d) / 9v, kg m^{-1} s^{-1}	μ =	0,74936	0,78505	0,71368	0,78505	0,74936
			Average μ=		0,76	kg m^{-1} s^{-1}

Table D.5. Results of viscosity determination test for water + 5 per cent polymer solution

Viscosity determination Experiment 5

Sample : Water + 5 % polymer

Viscosity μ = 2 g r2 (d'-d) / 9v

		Test 1	Test 2	Test 3	Test 4	Test 5
Radius of the sphere, m	r =	0,005	0,005	0,005	0,005	0,005
Fall height, m	x =	0,4	0,4	0,4	0,4	0,4
Fall time, s	t =	6,1	5,8	5,7	6,2	6,4
Equivalent fall velocity of the sphere, m/s	v =	0,06557	0,06897	0,07018	0,06452	0,0625
Gravitational constant, m/s^2	g =	9,81	9,81	9,81	9,81	9,81
Density of the sphere, kg/m^3	d^1 =	2620	2620	2620	2620	2620
Density of the viscous fluid, kg/m^3	d =	0,9983	0,998	0,9987	0,9981	0,9984
Viscosity μ = 2 g r2 (d'-d) / 9v, kg m^{-1} s^{-1}	μ =	2,17672	2,06967	2,03398	2,2124	2,28377
			Average μ=		2,16	kg m^{-1} s^{-1}

Table D.6. Results of viscosity determination test for water + 10 per cent polymer solution

Viscosity determination Experiment 6

Sample : Water + 10 % polymer

Viscosity μ = 2 g r2 (d'-d) / 9v

		Test 1	Test 2	Test 3	Test 4	Test 5
Radius of the sphere, m	r =	0,005	0,005	0,005	0,005	0,005
Fall height, m	x =	0,4	0,4	0,4	0,4	0,4
Fall time, s	t =	2,7	2,7	2,8	2,8	2,9
Equivalent fall velocity of the sphere, m/s	v =	0,14815	0,14815	0,14286	0,14286	0,13793
Gravitational constant, m/s^2	g =	9,81	9,81	9,81	9,81	9,81
Density of the sphere, kg/m^3	d^1 =	7800	7800	7800	7800	7800
Density of the viscous fluid, kg/m^3	d =	0,9983	0,998	0,9987	0,9981	0,9984
Viscosity μ = 2 g r2 (d'-d) / 9v, kg m^{-1} s^{-1}	μ =	2,86906	2,86906	2,97532	2,97532	3,08158
			Average μ=		2,95	kg m^{-1} s^{-1}

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