DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

HYDRAULIC CONDUCTIVITY OF BENTONITIC MIXTURES TO LANDFILL LEACHATES

by

Merve Ece KOÇ

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İZMİR

HYDRAULIC CONDUCTIVITY OF BENTONITIC MIXTURES TO LANDFILL LEACHATES

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"HYDRAULIC CONDUCTIVITY OF BENTONITIC MIXTURES TO LANDFILL LEACHATES"** completed by **MERVE ECE KOÇ** under supervision of **ASSOC.PROF. DR. A. HAKAN ÖREN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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I dedicate this thesis to my family and my beloved husband for their constant support.

Merve Ece KOÇ

HYDRAULIC CONDUCTIVITY OF BENTONITIC MIXTURES TO LANDFILL LEACHATES

ABSTRACT

The purpose of landfill liner systems is creating an impermeable layer on the ground, thereby to prevent the mixing of hazardous substances into groundwater. Clays are the most commonly used material to ensure impermeability in landfill liners. They prevent waste induced leakage due to their low permeability, besides filter the leakage thanks to their negatively charged surface. However, in various studies it was seen that clay was affected from environmental conditions during time. Thus, researchers put efforts to find out alternative materials by using natural minerals. Zeolite is one of the natural materials. It works as molecular sieve in landfills since its porous structure, negatively charged surface and high specific surface area. Turkey has rich zeolite reserves use of which might be beneficial in terms of territorial economy.

In the scope of this study, bentonite were mixed with proper amount of zeolite to get zeolite-bentonite mixtures (ZBMs). Long term hydraulic conductivities of these mixtures were measured with the leachates that had been taken from landfill liners. Furthermore, bentonite were mixed with proper amount of sand to get sand-bentonite mixtures (SBMs) and after compaction process hydraulic conductivity tests were performed on SBMs. Permeability performances of ZBMs and SBMs were compared by means of permeating liquid and mixing procedure.

Keywords: Permeability, zeolite, hydraulic conductivity, compaction, zeolite-bentonite mixtures, sand-bentonite mixtures.

BENTONİTİK KARIŞIMLARININ SIZINTI SULARI İLE HİDROLİK İLETKENLİKLERİ

ÖZ

Çöp depolama alanlarının amacı zeminde geçirimsiz bir bariyer yaratmak, bu sayede zararlı maddelerin yeraltı sularına karışmasını engellemektir. Killer, depolama alanlarında geçirimsizliği sağlamak için en çok kullanılan malzemedir. Çünkü, killer düşük geçirimliliğe sahip olduklarından sızıntıyı önlerler ayrıca negatif yüzey yükü sayesinde sızıntıyı filtrelerler. Fakat çeşitli araştırmalarda killerin çevre koşullarından zamanla etkilendiği görülmüştür. Bu yüzden bilim adamları killere alternatif olarak yeni malzeme arayışına girmişler ve geosentetik malzemelerin yanında doğal mineralleri kullanarak geçirimliliği ölçmüşlerdir. Zeolit bu doğal minerallerden biridir. Gözenekli yapısı, negatif yüzey yükü ve yüksek katyon değişim kapasitesi dolayısıyla atık depolama alanlarında moleküler elek görevi yapar. Türkiye' de bol bulunması sebebiyle bu kaynağın kullanılması ülke ekonomisine de katkı sağlar.

Bu çalışma kapsamında, zeolit ve bentonit belirli oranlarda karıştırılıp zeolit-bentonit karışımları (ZBM) oluşturulmuş ve bunların uzun dönem hidrolik iletkenlikleri farklı atık depolama alanlarından alınan sızıntı sularıyla ölçülmüştür. Bunun yanında, kum ve bentonit karışımları (SBM) da belli oranlarda karıştırılmış ve kompakte edildikten sonra, sızıntı sularıyla hidrolik iletkenlik deneyine tabi tutulmuştur. Farklı sızıntı suları ve karışım hazırlama yöntemleri dikkate alınarak, hazırlanan ZBM ve SBM karışımlarının geçirgenlik performansları karşılaştırılmıştır.

Anahtar kelimeler: Geçirimlilik, zeolit, hidrolik iletkenlik, kompaksiyon, zeolit-bentonit karışımları, kum-bentonit karışımları.

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CHAPTER ONE
INTRODUCTION

Turkey is at the category of developing countries. However, the waste deposition had been neglected in Turkey until late 1990s. In the period until that time, wastes were stored randomly on clayey soils. In the 2000s, attention was paid on the storage and management of waste.

At the master plan on solid waste management and Ninth Development Plan, it is emphasized that state-funded waste storage applications will continue in the following period. By this way, the most appropriate waste system as per the current conditions of our country needs to be determined.

The suitability of the barrier material in landfill is critical. The selected material must be capable of maintaining low permeability (i.e. $<10^{-7}$ cm/s) for a long time and should be easily supplied.

Clay is the main material that is used to ensure low permeability in landfills. In addition, geomembranes, geosynthetic clay liners or some soil mixtures can be used as barrier material. In Turkey, it is fairly common to use compacted natural clays with geomembranes. However, compacted clay liners may be adversely affected from chemical and environmental conditions during the post construction stage (Foreman & Daniel, 1986; Daniel & Wu, 1993). If this occurs, the hydraulic conductivity of the barrier may increase in the long term. Thus, instead of using compacted clays in landfills, other alternative materials have been still under investigation on worldwide.

Sand-bentonite mixture (SBM) is the one of a good example to alternative materials (O'sadnick et al., 1995; Alston et al., 1997). In comparison to the compacted clay liners, SBMs are affected less from environmental conditions. Because, SBMs have lower hydraulic conductivity and volumetric shrinkage (Kleppe & Olson, 1985). Since zeolite is abundant in Turkey, the use of zeolite bentonite mixture (ZBM) has been suggested during the last two decades instead of SBMs (Kayabalı, 1997; Kayabalı & Mollamahmutoğlu, 1998, Kaya & Durukan, 2004).

At the first glance, due to its porous structure and negative surface charge, zeolite seems to be appropriate. This is because that zeolite may act as a molecular sieve during a possible leak in landfills. Indeed Kayabalı (1997), Tuncan et al. (2003) and Kaya & Durukan (2004) emphasized that hydraulic conductivity of ZBM is as low as the hydraulic conductivity of the SBM. In contrast, Ören et al. (2011) compiled the hydraulic conductivity data of SBMs and ZBMs from literature and evaluated them together with their own data. They found out 20-30 times greater hydraulic conductivities for ZBMs than for SBMs. Ören et al. (2011) attributed this difference to zeolite porous structure which creates a porous network across the specimen.

There are numerous studies in the literature about the factors affecting the hydraulic conductivity of SBMs (Kenney et al., 1992; Haug & Wong, 1992; Kraus et al., 1997; Howell et al., 1997; Gleason et al., 1997; Stern et al., 1998; Tay et al., 2001; Komine, 2004). However, neither of these studies considers ZBMs. Only a small number of studies focus on the hydraulic conductivity of ZBMs and SBMs (Kayabalı & Mollamahmutoğlu, 2000). Therefore, which mixture is more suitable for impermeable barrier is still unclear. One of the main objectives of this thesis is to find the answer of this question.

Within the scope of this thesis, the long-term hydraulic conductivity of ZBMs and SBMs were determined by using flexible wall permeameters.

CHAPTER TWO
BACKGROUND

2.1 Hydraulic Conductivity of Zeolite- Bentonite Mixtures to Water

Zeolite-bentonite mixture (ZBM) is a mixture of materials recommended as an alternative to the sand-bentonite mixture (SBM). Kayabalı (1997) is the first researcher who studied the hydraulic conductivity and shear strength behaviors of ZBMs at different bentonite contents (5% to 40%) and investigated ZBM suitability for landfill liner application. In that study, bentonite content is expressed by B/Z ratio. Kayabalı (1997) conducted these tests with rigid-wall permeameters and used only water as the permeating liquid. For each considered bentonite contents, the hydraulic conductivity tests were conducted on ZBMs, which were compacted at optimum and wet of optimum water contents. Kayabalı (1997) concluded that the hydraulic conductivities of ZBMs did not depend on the bentonite content and were ranged between 5×10^{-9} cm/s and 7.5×10^{-8} cm/s.

Tuncan et al. (2003) studied the influence of curing on some engineering properties of ZBM with 10% bentonite content (B/Z). Flexible wall permeameters were used and after one-day curing period, the hydraulic conductivity was determined about 2.0×10^{-8} cm/s. This value is close to the value reported by Kayabalı (1997) for the same bentonite content.

Kaya and Durukan (2004) performed one-dimensional consolidation experiments with 10% and 20% bentonite contents [B/(B + Z)] and calculated the coefficient of permeability by using the coefficient of consolidation. When applied effective stress on samples were increased, hydraulic conductivity of 10% ZBM decreased from 2.1×10^{-8} cm/s to 3.0×10^{-9} cm/s; whereas that of 20% ZBM decreased from 1.4×10^{-8} cm/s to 4.0×10^{-9} cm/s. Hydraulic conductivities were almost the same as with the previous studies (1.0×10^{-8} cm/s) at low effective stress levels. When high effective stress level is considered, however, hydraulic conductivities were approximately one order of magnitude less than those at lower effective stress level. Kaya and Durukan

(2004) emphasized that there was no significant difference between the hydraulic conductivities of ZBMs with 10% and 20% bentonite contents.

Ören et al. (2011) made numerous experiments with flexible wall permeameters and determined the hydraulic conductivities of ZBMs at different hydraulic gradients. The most important finding of that study is reporting greater hydraulic conductivities for ZBMs. That is, the hydraulic conductivities of ZBMs were one order of magnitude higher than previously reported values in the literature (1.0×10^{-7} cm/s). It was attributed to the backpressure applied in their study and porous structure of zeolite. Ören et al. (2011) reported that hydraulic conductivity of ZBMs reduced when fine zeolite was blended with 20% bentonite content [B/(B + Z)] (5.4×10^{-8} cm/s).

Later on, the hydraulic conductivity tests were conducted on ZBMs and SBMs using flexible wall permeameters and without applying a backpressure in another study. The difference is that the hydraulic conductivities were determined at different compaction water contents (Ören et al., 2014). Accordingly, the mixture containing 10% bentonite and 23% compaction water content (on the dry side of optimum water content) had a hydraulic conductivity of 1.3×10^{-4} cm/s. The hydraulic conductivities at 30%, 40% (optimum), 48% and 55% (on the wet side) water contents were 4.3×10^{-5} cm/s and 2.7×10^{-5} cm/s and 4.6×10^{-6} cm/s and 7.4×10^{-9} cm/s, respectively. For 10% ZBM, the hydraulic conductivity slightly decreased up to a certain water content as the compaction water content increased. However, when ZBM was compacted at water content significantly greater than optimum water content (i.e. 55%), then the hydraulic conductivity was less than 1.0×10^{-8} cm/s. The opposite situation occurred at 20% bentonite content where hydraulic conductivities decreased at the earlier compaction water contents. The hydraulic conductivity was about 9.7×10^{-6} cm/s at the dry side of the optimum water content (20%), whereas hydraulic conductivities were 1.0×10^{-8} cm/s and 2.8×10^{-9} cm/s at optimum (40%) and at wet side of the optimum (57%) water contents, respectively. The hydraulic conductivity of 10% ZBM was greater than 20% ZBM about 13 times at dry side, 4000 times at optimum and 2.6 times at wet side of optimum water contents at most. Earlier studies have been reported in the literature revealed that ZBMs compacted at optimum and 2-5% wet side of optimum water contents were affected limited from bentonite content (Kayabalı, 1997; Kaya & Durukan, 2004; Ören et al., 2011). However Ören et al. (2014) showed that bentonite content has a significant influence on the hydraulic conductivity of ZBMs depending on the compaction water contents.

2.2 Hydraulic Conductivity of Zeolite-Bentonite Mixtures to Different Leachates

The number of studies about the hydraulic conductivity of ZBMs to different leachates is limited when compared to that of ZBMs to water. Only Kayabalı and Mollamahmutoğlu (2000) reported a study regarding to ZBMs. In that study, hydraulic conductivity behavior of 10% ZBM (B/Z) was tested with 5 different liquids. Two of them were very strong acid liquid (pH≈0), one of them was a very strong base (pH = 13) of which were synthetic waters prepared in the laboratory and other two leachates were obtained from the leather industry and landfill. The experiments were repeated three times using rigid wall permeameters and were terminated after 30-40 days. The variations between the hydraulic conductivities of replicates were up to 100 times for the same leachate. Thus, it is not clear which value should be taken as the hydraulic conductivity of ZBM.

Rigid wall permeameter is not recommended for the hydraulic conductivity test when chemical liquid is desired to be used. Clayey soil exhibits shrinkage behavior when in contact with chemical liquids. In the micro scale, adsorbed water layer surrounding the clay particle compresses as a result of chemical composition of the pore fluid (Bohn et al., 1985; Sridharan et al., 1986; Sridharan et al., 1991; Jo et al., 2001). In other words, the absorbed water layer thickness decreases when exposed to chemicals. During this shrinkage, compacted clayey soil detaches from the inner surface of rigid wall permeameter. As a result, gaps occur between the mold and the outer surface of the compacted sample, which causes incorrect determination of hydraulic conductivity. This is called as “side wall leakage” (Daniel, 1994). Thus, flexible-wall permeameters is suggested instead of rigid-wall when synthetic or landfill leachates are used as the permeants.

Another issue is that the hydraulic conductivity tests conducted with chemical liquids should be lasted long enough. When water is used as the permeation liquid, providing the physical stability condition (Q_{out}/Q_{in}=1.0±0.25) is sufficient for the termination of tests. On the other hand, the chemical stability must be observed and provided for the tests conducted with chemical permeating liquids (Shackelford et al., 2000; Jo et al., 2005; Benson et al., 2010). For this reason, liquid samples are taken from both the inflow and the outflow part of the permeameter cell and, pH and electrical conductivities are measured on these samples to check whether chemical equilibrium is established or not (pH_{out}/pH_{in}=1.0±0.1 and Electrical $Conductivity_{out}$/Electrical $Conductivity_{in}$=1.0±0.1). In addition, the cation concentrations in these liquid samples are measured at regular intervals to find out cation exchange between the chemical liquid and soil sample. But it may not be economical on account of expensive equipments needing to determine cation exchange. Therefore, at least pH and electrical conductivity measurements should be conducted periodically for chemical stability control.

Kayabalı and Mollamahmutoğlu (2000) did not consider these two issues in their study. They have repeated the constant head tests for 3 times and obtained up to two orders of magnitude different hydraulic conductivities within each other. Kayabalı and Mollamahmutoğlu (2000) attributed these great differences to the sidewall leakage.

Moreover, when the permeants are taken into consideration, they are accepted as "aggressive" which include very strong acid and base class of synthetic fluids. Considering the hydraulic conductivities with those of similar studies reported in the literature, the hydraulic conductivity tests in Kayabalı and Mollamahmutoğlu (2000) were performed for a period of 15-50 days, which is relatively insufficient. Note that no information was given about the physical and chemical stability of the experiments in their study.

This study was carried out to fill the gaps in the previous studies. The main purpose of the study is to determine "long term" hydraulic conductivity of zeolite-bentonite and sand-bentonite mixtures by using flexible wall permeameters and using different leachates. In this context, "long term" hydraulic conductivity behaviors of the mixtures with different bentonite contents were obtained by permeating real landfill leachates.

2.3 The Studies Comparing The Hydraulic Conductivities of Zeolite-Bentonite and Sand-Bentonite Mixtures

Ören et al. (2011) determined the hydraulic conductivity of the ZBMs to water which were prepared in different bentonite contents. Hydraulic conductivities were determined using flexible wall permeameters. In addition, hydraulic conductivity tests were performed on SBMs which were prepared at the same bentonite contents as with ZBMs. The grain size of sand was similar to that of zeolite. This has been the first study that compares the hydraulic conductivity of ZBMs and SBMs so far. Ören et al. (2011) concluded that the hydraulic conductivity of 10% ZBM was 22 times higher than that of SBM at the same bentonite content (2.4×10^{-7} cm/s versus 9.3×10^{-9} cm/s). This difference increased up to 28 times, when the mixtures have 20% bentonite content (1.5×10^{-7} cm/s versus 3.9×10^{-9} cm/s). As the reason for this difference, Ören et al. (2011) claimed that the zeolite creates a porous network inside the mixture and water can flow more easily in this network. Unlike zeolite, sand material created impermeable network in SBMs, which resulted in lower hydraulic conductivities for SBMs. This conclusion was further supported by additional hydraulic conductivity tests, which were conducted on 10% bentonite that includes 45% sand and 45% zeolite. The hydraulic conductivity of this compacted new mixture was between 10% ZBM and 10% SBM (i.e. 3.3×10^{-8} cm/s).

Ören et al. (2014) re-examined the hydraulic conductivity of zeolite-bentonite and sand-bentonite mixtures by using other bentonite and zeolite materials and at different compaction water contents. In that study, tap water was used as the permeant. In a similar manner with Ören et al. (2011), the hydraulic conductivity of the ZBM was found greater than the hydraulic conductivity of SBM at the same bentonite contents. But the most important finding in this study is the difference between the hydraulic conductivities depending on the compaction water content. The difference in the hydraulic conductivities of ZBMs and SBMs was up to 5 orders of magnitude (100000 times) at the dry side optimum, whereas it was 10-20 times at the wet side of optimum water contents.

The only study, which compares the hydraulic conductivity of the zeolite-bentonite and sand-bentonite mixtures with different leachates, was reported by Kayabalı and Mollamahmutoğlu (2000). In this study, the hydraulic conductivity behaviors of SBMs with 5%, 10%, 15% bentonite contents (B/S) and 10% ZBM (B/Z) were determined. Five different leachates were used in the experiments three of which were prepared in the laboratory as a synthetic leachate and the rest two were supplied from the leather industry and landfill. The synthetic waters were very strong acid (ph≈0), and very strong base (pH = 13). These studies were repeated three times with rigid-wall permeameters and were lasted 15-50 days. Kayabalı and Mollamahmutoğlu (2000) did not make a direct comparison between the hydraulic conductivities of sand-bentonite and zeolite-bentonite mixtures. Instead of this, the hydraulic conductivity behaviors of the mixtures, which were obtained with five leachates, were discussed separately. As a result, it was emphasized that the 15% SBM and 10% ZBM had lower hydraulic conductivities than the other mixtures.

CHAPTER THREE
INSTALLING THE FLEXIBLE WALL PERMEAMETERS IN THE LABORATORY AND PERFORMING HYDRAULIC CONDUCTIVITY TEST

A part of laboratory was used to establish the test unit after manufacturing the permeameter cells. The air pressure and a panel system, which converts compressed air to water pressure (transfer), are needed for the hydraulic conductivity tests. This air pressure was supplied from the air compressor room, which is outside of the laboratory. The air pressure was transported to the pressure panel using polyethylene tubing. Then, the tubing was connected to this panel. In addition, another tubing was used to connect the tap water to pressure panel, which allows filling the pressure panel with water (Figure 3.1a).

The desired amount of pressure was easily adjusted with the regulators (pressure regulators) on the panel system. There is an electronic display unit on the panel that shows the adjusted air pressure. This air pressure then was converted to the water pressure. The tubing system was used again to deliver pressurized water to the permeameter cells. The polyethylene tubings were used and they were filled with water for transmitting pressured water. A large number of "T" connections were positioned. Additional valves were added between the cells and the tubings so both the connection point and the second on-off system were created. The valves that were used to provide water pressure to permeameter cells and "T" connections are shown in Figure 3.1b.

During the tests, burettes (scaled glass tubes) were used to read the inflow rate and hence, calculate the hydraulic conductivity. The metal profiles were mounted to the wall and burettes were passed through the drilled holes on it (Figure 3.2a). For connections between the permeameters and burettes, tubings and redactors were used (Fig 3.2b and Figure 3.2c).

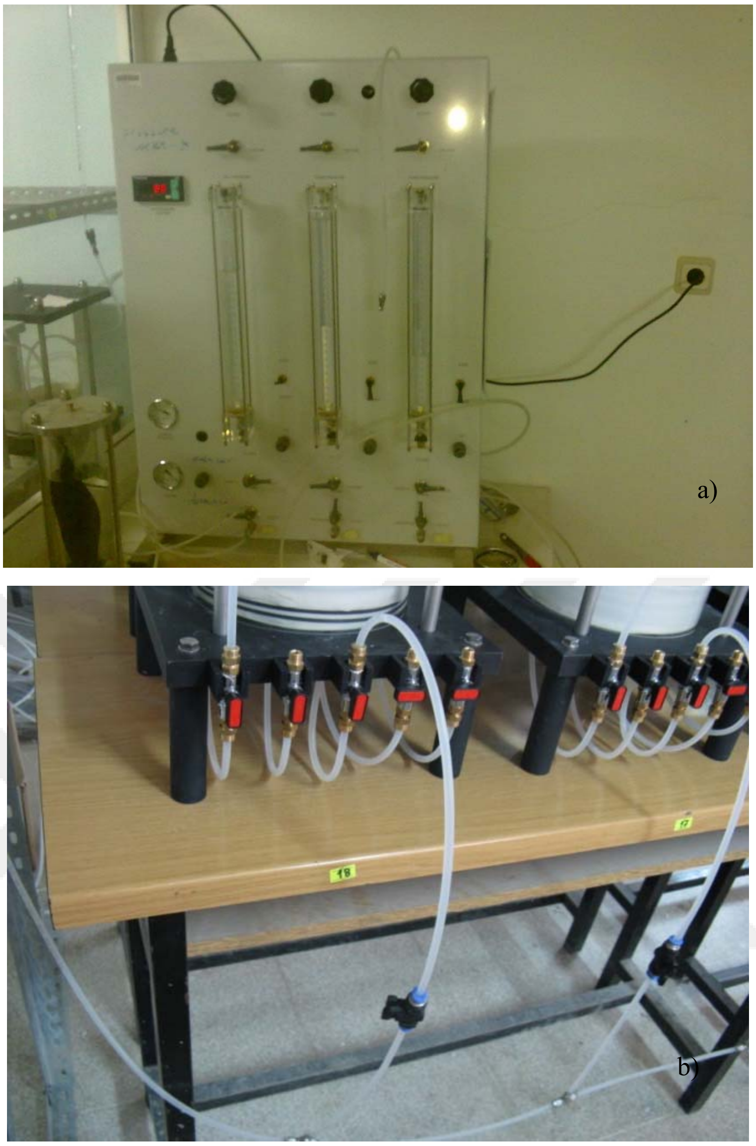


Figure3.1 Experimental setup in the Soils Lab.: a) pressure panel, b) internal connections between the panel and the permeameters.

Six flexible wall permeameter cells were manufactured and used during this study (Figure 3.3). Permeameter cells were designed to test the samples that have 15 cm diameter. The bottom plexiglas headings in 15 cm diameter were attached to the aluminum base plate with the allen wrench. These cells were eligible to fit 10 cm bottom plexiglas headings as well.

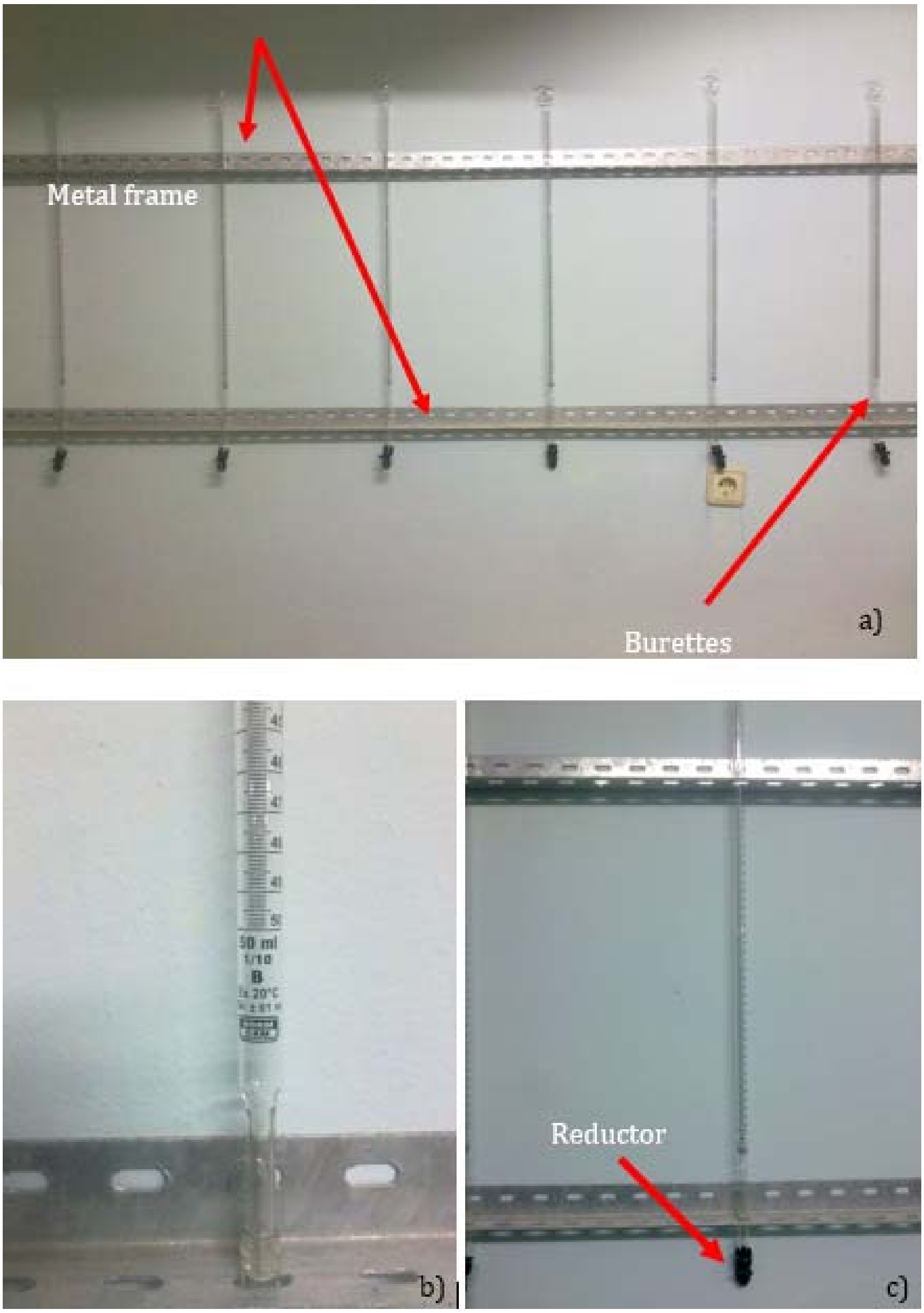


Figure 3.2 Experimental setup in the Soils Lab: a) the metal frame and burettes, b) details of a burette and c) tubing and reductor mounted on the burette.

Figure 3.3 Flexible wall permeameters used in this study.

The sealing control should have been done prior to testing owing to the fact that permeameters will be used under different cell pressures. This control is essential in order to achieve correct test results. When leaking occurs in untested systems, it causes misinterpretation of the experiment results. Therefore the sealing tests were performed before starting the hydraulic conductivity tests. Plexiglass cell was filled with water up to the half and air pressure was given from the top of the cell by closing all valves on the permeameter cell. Air pressure was gradually increased and leakage was controlled at all increment levels by waiting for a certain period (about 5 minutes). Cell pressure was ultimately increased to 300 kPa. When leaks were observed from the fittings, lock seal, special glue, was used to stop leaking. The controlled permeameters were mounted to experimental assembly to use in hydraulic conductivity tests as shown in Figure 3.4.

Figure 3.4 Installed ready-to-use flexible wall permeameters.

CHAPTER FOUR
MATERIALS AND METHODS

4.1 Materials

4.1.1 Index Properties of Zeolite, Sand and Bentonite

Zeolite was supplied from Gördes/Manisa and it has a uniform granulometry. The grain size distribution curve obtained from sieve analysis by wet sieving method indicated that 88% of the zeolite has medium sand, whereas 10% has fine sand particle size (Figure 4.1). On the other hand, the natural bentonite used in the mixture was supplied from Karakaya A.Ş./Ankara. The liquid limit of the bentonite was determined through Casagrande test apparatus and found out as 529%. The plastic limit of the bentonite was 38%. Sieve analysis by wet sieving method showed that the clay fraction of bentonite was 73%. Granulometry diagrams of both zeolite and bentonite materials are given in Figure 4.1 and the index properties are summarized in Table 4.1.

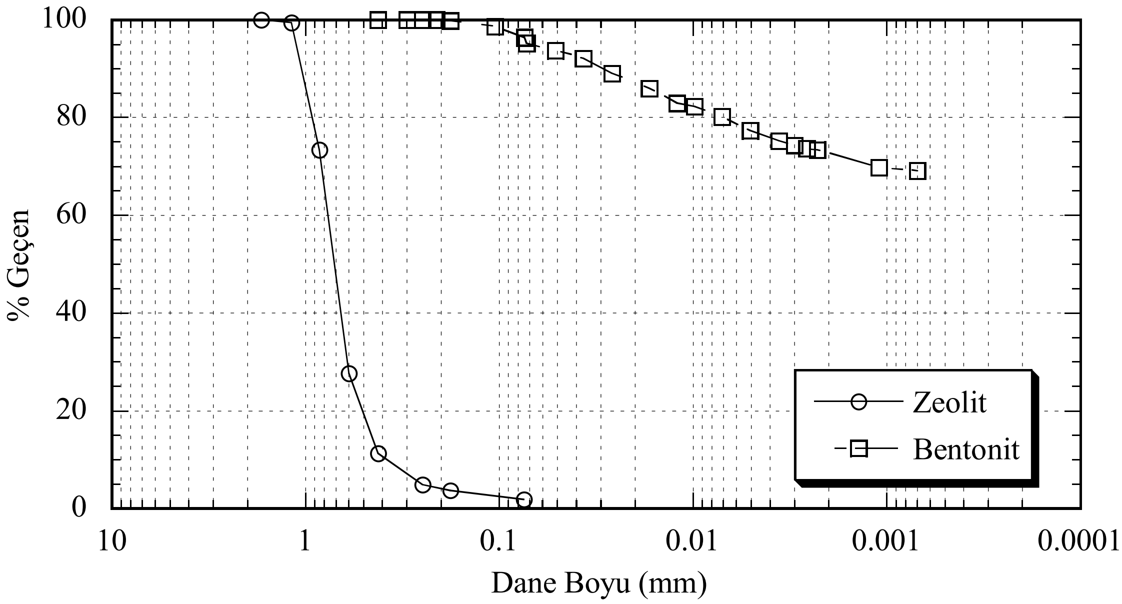


Figure 4.1 The grain size distribution curve of zeolite and bentonite used in experiments.

Table 4.1 Index properties of zeolite and bentonite obtained by following the relevant standards.

	Zeolite	Bentonite	Standards
Sand Particle Size Ratio (%) (2mm - 0.075mm)	98	4	ASTM D 422
Silt Particle Size Ratio (%) (0.075 - 0.002mm)	2	23	ASTM D 422
Clay Particle Size Ratio (%) (<0.002mm)	-	73	ASTM D 423
Uniformity coefficient, C_u	3.0	-	ASTM D2487-11
Coefficient of Curvature, C_c	0.75	-	ASTM D2487-11
Specific weight, G_s	2.35	2.69	ASTM D 854-10
Liquid Limit, w_L (%)	-	529	ASTM D 4318-10
Plastic Limit, w_p (%)	-	38	ASTM D 4318-10
Plasticity Index, I_p (%)	-	350	ASTM D 4318-10

The sand was supplied for another project and already available in Soil Mechanics Laboratory at Dokuz Eylül University. Thus, this sand was used in SBMs. But before using, sand was sieved from relevant sieves to get the same particle size as with zeolite grains.

4.1.2 Supply of Landfill Leachates

The age of landfills were taken into consideration for the provision of leachate. Accordingly, it was preferred to use elderly (LL-A Harmandalı-Izmir) and young landfill (LL-B Aydın) leachates. Before obtaining the leachates from landfills, permissions were taken from the officials. Then, weather conditions were taken into consideration to get the leachates. The leachates (LL-A and LL-B) were taken from Harmandalı (İzmir) (Fig. 4.2a) and Aydın (Fig. 4.2b) landfills on 20.02.2013 and 26.02.2013, respectively. The provision was completed on dry and sunny days. Plastic containers of 20 liters were used to fill the leachates and then, they were transferred to the soil mechanics laboratory of Dokuz Eylül University. The containers were kept in refrigerator throughout the study.

Figure 4.2 The pictures taken during the supply of leachates from landfills: a) Harmandalı-İzmir, b) Aydın.

The cation concentrations of the leachates (i.e. Na^{+}, K^{+}, Mg^{2+}, Ca^{2+}) were determined with ICP-OES (Table 4.2). The pH and electrical conductivity of the leachates were determined with Accumet XL50 and the results are presented in Table 4.2 as well.

Table 4.2 Cation concentrations, pH and electrical conductivity of landfill leachates.

Landfill Leachate	**Na^+ (mg/L)**	**K^+ (mg/L)**	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**pH**	**Electrical Conductivity (mS/cm)**
LL-1	2903	1135	265	101	7.6	20.8
LL-2	1507	1643	173	409	8.3	21.1

4.2 Methods

4.2.1 Sample Preparation

Howell et al. (1997) prepared the samples with two different mixing methods while investigating the compaction behavior of SBM in their study. In the first method, sand was wetted with a suitable amount of water, then dry bentonite was added slowly to the wet sand and the mixture was blended. In the second method, sand and bentonite were mixed in dry state and then an appropriate amount of water was added to the dry mixture. The samples prepared using both methods were compacted after curing at certain times. Howell et al. (1997) concluded that, the compacted samples prepared with dry mixing method (i.e. second method) had higher γ_{dmax} and w_{opt} values than the compacted samples prepared with wet mixing method (i.e. first method). Despite the fact that Howell et al. (1997) mentioned about the impact of sample preparation method on the compaction behavior of SBM, they did not research the potential impact of sample preparation on the hydraulic conductivity behavior. Therefore, in the present study the effect of the sample preparation method on the hydraulic conductivity was investigated as well.

In this study, ZBMs were prepared in two ways. First, both zeolite and bentonite were mixed in the pan at their dry state and then proper amount of water (at target water content) was slowly added by using a spray bottle. Then the wet sample was stirred for half an hour. This mixture will be expressed as "dry mixture" henceforth. In the second way of sample preparation, zeolite was soaked up to the target water content and bentonite was sprinkled slowly on the wet zeolite. After the completion of sprinkling, the mixture was stirred again. This mixture is denoted as "wet mixture" henceforth.

In the literature, generally bentonite quantity in the mixture was expressed as the ratio by dry weight of bentonite to sand (B/S) or bentonite to zeolite (B/Z) (Chapuis, 1990, Kenney et al., 1992; Haug & Wong, 1992; Kayabalı, 1997; Tuncan et al., 2003). On the other side, some researchers used the bentonite ratio in the mixture as the ratio of bentonite quantity to the total amount of the material by dry weight (i.e. B/(B+S) or B/(B+Z)) (Howell et al., 1997; Stern & Shackelford, 1998; Kaya & Durukan, 2004; Ören et al., 2011). In this study, bentonite ratio was expressed as the ratio of the bentonite weight to the mixture weight. The ratio of bentonite in the mixtures was adjusted as 20% and %30 for ZBMs. In this case, %20 ZBM means that 20% of the mixture is bentonite and 80% is zeolite. Similarly, %30 ZBM defines a mixture, consisting of 30% bentonite and 70% zeolite.

SBMs were examined in two different bentonite contents (10% and 20%). Bentonite ratios (contents) were given by weight and were expressed as the ratio of weight of dry bentonite to the total weight of the mixture [B/(B + S)]. The samples containing 20% bentonite were prepared with dry mixing method (i.e. dry mixture), whereas the samples containing 10% bentonite were prepared with the wet mixing method (i.e. wet mixture).

4.2.2 Compaction Tests

The mixtures were compacted with the standard Proctor energy by using an automatic compactor (ASTM D698-07). The molds, which were used in the experiments, are 10 cm in diameter and 11.6 cm in height. The compaction tests were performed on either ZBMs or SBMs. In both cases, the mixtures were not cured. In other words, the mixtures were compacted immediately after the sample preparation was completed.

4.2.3 Hydraulic Conductivity Tests

The hydraulic conductivity tests were performed with the flexible wall permeameters. The water content of the samples used in the experiments was intended to remain in the 3-5% wet side of the optimum water content. Thus, the water contents of the samples were determined by drying in the microwave oven before compaction. In this way, the desired water contents were achieved.

As stated in the previous section, the compaction experiments were conducted in 10 cm diameter mold. However, permeameters that were used in the tests have a diameter of 15 cm. Even though the compaction molds with 15 cm in diameter and 11.6 cm in height are available in the laboratory, a new compaction mold with 15 cm in diameter and 5.8 cm in height was manufactured to shorten the test duration of the hydraulic conductivity tests. To be able to apply the same compaction energy as in the standard Proctor Test, compaction energy for this mold was calibrated. To do this, the mixture was compacted in two layers by applying 36 blows for each layer. This mold was used only to prepare the specimens for hydraulic conductivity tests (Figure 4.3).

Figure 4.3 Compaction mold for hydraulic conductivity tests and compacted zeolite-bentonite mixture (ZBM).

In the experiments, the use of short sample has many benefits: i) the use of excess material is avoided, ii) compaction process is less strenuous, iii) compacted sample is lighter and thus, can be carried by anyone, iv) the hydraulic conductivity tests are terminated more quickly because the flow distance is shortened.

The mixture was prepared by compacting into two layers in the short mold. After compacting the first layer, the surface was scarified using a fine tipped cutter (utility knife or spatula), so that the adhesion was provided between the first layer and the second layer (Figure 4.4). Then, the second layer was laid and compacted.

Figure 4.4 Scratching of the surface after compacting the first layer.

When the compaction was completed, a cutting edge was used to trim the excess material on the mold. At that time, an artificial and relatively impervious layer may occur on the compacted layer because of bentonite characteristic. This situation is called as "smearing" which may lead to reduce the hydraulic conductivity (Ören and Kaya, 2011). To overcome smearing, the top and the bottom surfaces of the compacted soil were scarified. This was done after compacted specimen was removed from the mold using a hydraulic jack (Figure 4.5a).

Instead of a porous stone, Drefon S-1000 type geotextile – with a thickness of 7.5 mm and having a permeability coefficient of 3.0×10^{0} cm/s under 2 kPa was placed on the plexiglass base plate in the permeameter cell. This geotextile was cut at the same diameter as with plexiglass base plate (15 cm). Then, the sample was mounted on the geotextile (Figure 4.5b). Another geotextile at the same type and same diameter were placed on the sample. After the top cap was placed, the sample was confined in the latex membrane. O-rings were fitted to provide sealing. Then, flow lines were attached to the ports available on the top cap of the permeameter (Figure 4.6).

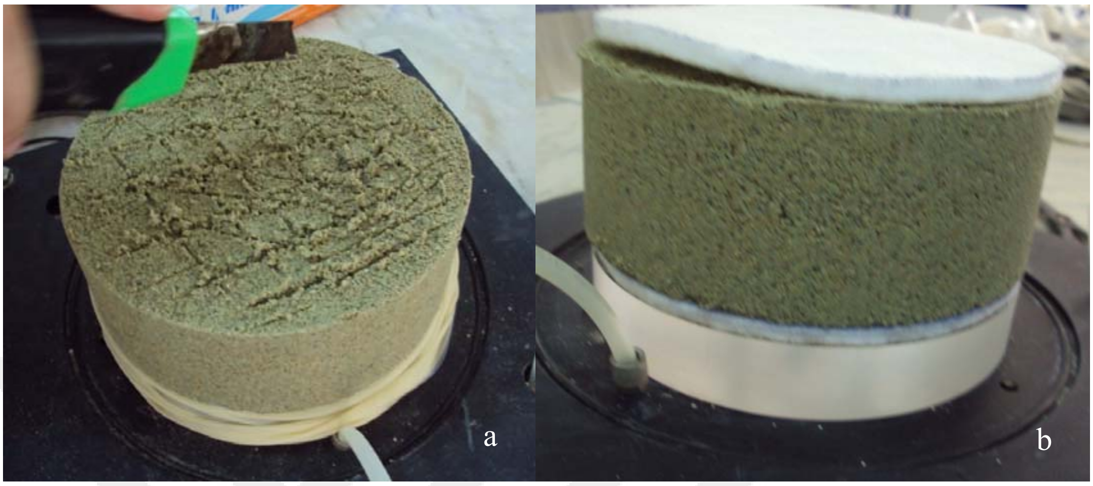


Figure 4.5 a) Scarifying of the surface of the specimen before the hydraulic conductivity test, and b) geotextiles used instead of porous stone which were placed on top and bottom of the compacted samples.

Figure 4.6 Sample ready-to-use in hydraulic conductivity test.

After placing the specimens into the permeameter cells, the hydraulic conductivity tests were initiated. Since the flow was too slow through the sample, falling head method was conducted during the hydraulic conductivity tests. The tests were performed under a constant cell pressure of 50 kPa and a hydraulic gradient of 24. Backpressure was not applied. As a result of given conditions, the average effective stress acting on the specimen was found 42.5 kPa.

In the experiments, different leachates collected from the landfills were used as the permeant. The permeation was from top to the bottom. The tests were initiated after the outflow valve of the permeameter was open to the atmosphere. The effluent fluid was collected in graduated cylinders, so the amount of fluid (i.e. outflow) flowing through the sample was measured. The hydraulic conductivity test system is shown in Figure 4.7.

Figure 4.7 Overview of the hydraulic conductivity system and the test samples.

4.2.4 Electrical Conductivity and pH Measurement

The effluent fluid in a graduated cylinder (sampling was made per 50 ml outflow had been occurred) was poured into plastic tubes and electrical conductivity and pH measurements were made on these samples. Similarly, the samples were taken from influent (from the burette portion) to measure pH and electrical conductivity (EC) as well. The pH and EC values of inflow and outflow were determined throughout the test duration. By observing the ratio of these values, the chemical stability level (pH_{out}/pH_{in} and EC_{out}/EC_{in}) was controlled.

pH and electrical conductivity were determined by Accumet XL 500 pH and EC Meter. Measurements were made with special probes connected to pH and EC Meter. Before starting the pH measurements, pH probe was calibrated via sinking into three standard solutions (pH=4, 7, and 10). Likewise the probe for measuring EC was calibrated with the two standard liquids (0.01 KCl and 0.1 KCl). pH and EC Meter and the probes are shown in Figure 4.8.

Figure 4.8 pH and Electrical Conductivity (EC) Meter and relevant probes that were used to control the chemical stability throughout the hydraulic conductivity tests.

CHAPTER FIVE
RESULTS AND DISCUSSIONS

5.1 Compaction and Hydraulic Conductivity of Zeolite-Bentonite Mixtures to Landfill Leachates

5.1.1 Compaction Test Results

The compaction tests were performed on 20% ZBM (dry and wet mixtures) and 30% ZBM (dry and wet mixtures). The compaction curves for these mixtures are illustrated in Figure 5.1. In Figure 5.1, the maximum dry densities of the compacted ZBMs (γ_{dmax}) are between 10.5 kN/m^3 and 11.0 kN/m^3 and optimum water contents (w_{opt}) are between 38% and 43%.

Depending on the bentonite content, the compaction curves are replotted based on mixing methods. The curves in Figure 5.2a are for dry mixing mixtures, whereas curves in Figure 5.2b are for wet mixtures. When compaction behavior of dry mixtures is examined, it is found that γ_{dmax} slightly increased and w_{opt} decreased as the bentonite content in the mixture was increased (Figure 5.2a).

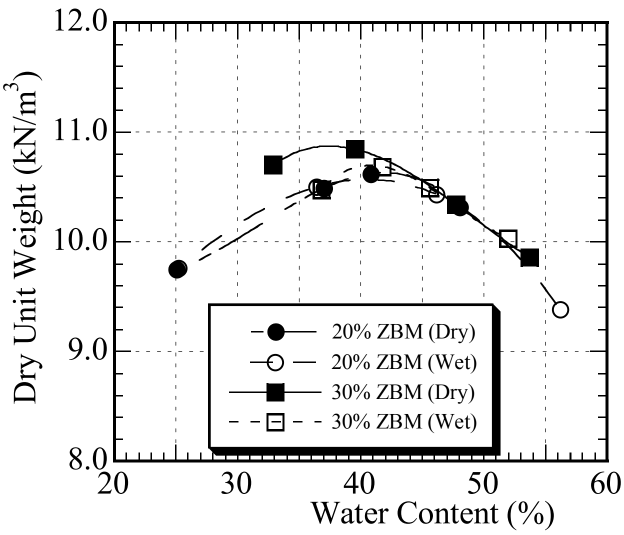


Figure 5.1 Compaction curves of the zeolite-bentonite mixtures (ZBMs).

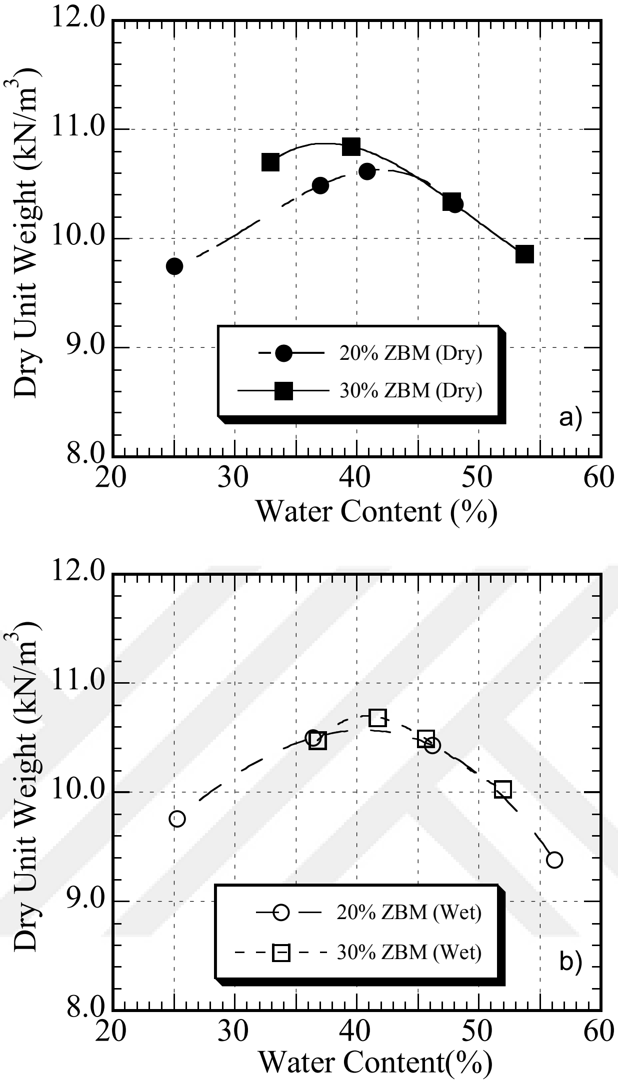


Figure 5.2 Comparison of the compaction curves of zeolite-bentonite mixtures (ZBMs) in terms of bentonite content: a) 20% and b) 30%.

According to Figure 5.2b, for the wet mixtures, although γ_{dmax} of 30% ZBM was greater than γ_{dmax} of 20%, w_{opt} was constant around 41%. Even though this behavior is contrary to the general expectation (increase in the amount of bentonite in the mixture decreases γ_{dmax} and increases w_{opt}), it is compatible with the results reported in the literature (Kayabalı, 1997; Ören & Kaya, 2014).

The comparison of the compaction results in terms of mixing methods is illustrated in Figure 5.3. The mixing procedure had no effect on the state of compaction behavior for 20% ZBM. In other words, during the preparation of the 20% ZBM, initial saturation state of zeolite (dry or wet) does not affect to the compaction behavior. On the other hand, when bentonite content was 30%, γ_{dmax} increased from 10.7 kN/m^3 to 10.9 kN/m^3 and w_{opt} decreased from 42.2% to 38.0% for dry mixtures. The compaction parameters for 30% indicate that better compaction was obtained for dry mixtures.

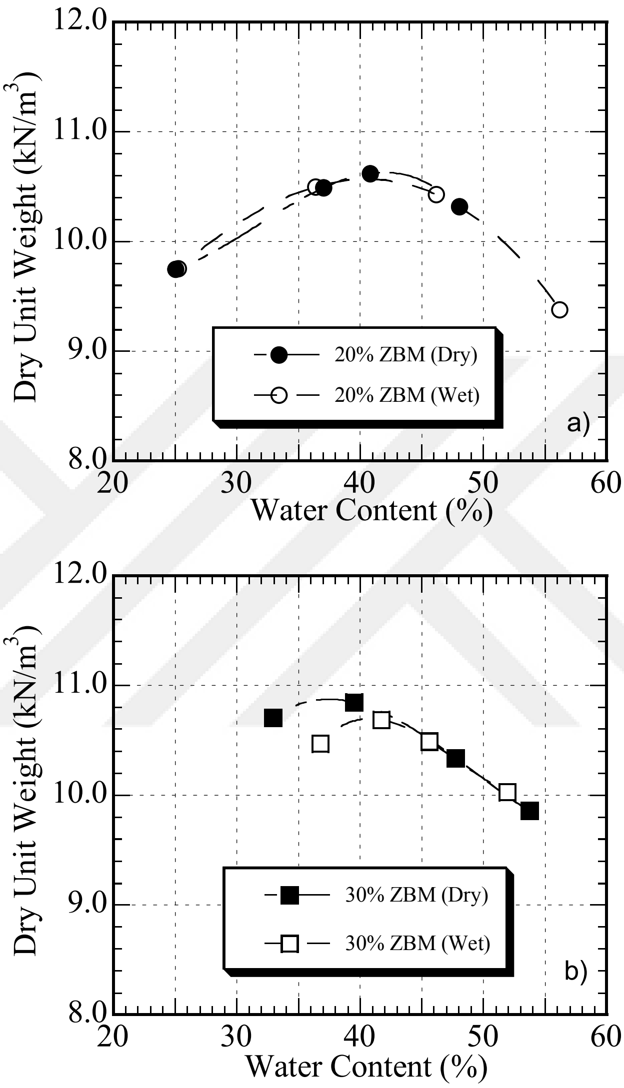


Figure 5.3 Comparison of the compaction curves for zeolite-bentonite mixtures (ZBMs) in terms of mixing method: a) 20% and b) 30%.

5.1.2 Hydraulic Conductivity Test Results

Hydraulic conductivity tests were performed on eight different ZBMs for long-term period (ranging from 4 to 18 months). Hydraulic conductivity behavior was expressed as a function of "pore volumes of flow". The hydraulic conductivity tests for 20% ZBMs were terminated when at least one pore volume of flow passed through specimens (~6 months period). For 30% ZBM, the experiments were terminated between 0.5 PVF and 1.0 PVF.

During the hydraulic conductivity tests, it was controlled if the physical equilibrium was provided. For this purpose, the amount of leachate passed through the compacted sample (inflow) and the leachate accumulated in the graduated cylinder (outflow) were recorded in terms of volume. Then, the volumes were compared with each other (Q_{out}/Q_{in}) and plotted as a function of PVF. The horizontal dashed lines in Figure 5.4 and so forth were defined in ASTM D5084, which represent the lower and upper limit values for the Q_{out}/Q_{in} (1.00±0.25).

5.1.2.1 Hydraulic Conductivity of ZBMs

The hydraulic conductivity tests with leachates were performed on 20% and 30% ZBMs and the hydraulic conductivity results will be initially shown for 20% ZBM. 20% ZBMs, which were prepared by dry mixing method and permeated with LL-A, reached to physical equilibrium at about 0.2 PVF and hydraulic stability at 0.3 PVF (Figure 5.4a). The hydraulic conductivity of the mixture at the beginning of the test was 2.1×10^{-6} cm/s and decreased to approximately 1.2×10^{-8} cm/sec at the end of 0.3 PVF. This reduction in the hydraulic conductivity is about 200 times. From this point until the test was completed (at 1.0 PVF), there was no significant change in the hydraulic conductivity ($\approx9.8\times10^{-9}$ cm / s) (Figure 5.4a).

The ZBM, which was prepared by wet mixing method and permeated with the same leachate (LL-A), reached to physical stability at 0.1 PVF. However this mixture reached to the hydraulic stability at 0.6 PVF (Figure 5.4b). The hydraulic conductivity of this sample was 1.3×10^{-7} cm/s at the initial steps and decreased to 3.1×10^{-9} cm/s at 1.1 PVF (Figure 5.4b). Accordingly, the decrease in the hydraulic conductivity of the wet sample along the test duration was about 40 times.

The hydraulic conductivity behavior of 20% ZBM prepared by dry mixing method and permeated with LL-B is shown in Figure 5.4c. For these specimens both the physical and hydraulic stability were provided at about 0.2 PVF (Figure 5.4c). Although initial hydraulic conductivity of this mixture was 1.6×10^{-7} cm/s, it decreased an order of magnitude and reached 1.0×10^{-8} cm/s at 0.4 PVF. From this point until the test was completed (1 PVF), the hydraulic conductivity was stable (Figure 5.4c). During the test, hydraulic conductivity decreased approximately one order of magnitude (≈10 times).

Hydraulic conductivity values did not change significantly along the test duration for 20% ZBM that was prepared by wet mixing method and permeated with LL-B (Figure 5.4d). Physical equilibrium condition was achieved at 0.4 PVF and final hydraulic conductivity was 2.3×10^{-8} cm / s at 1.1 PVF.

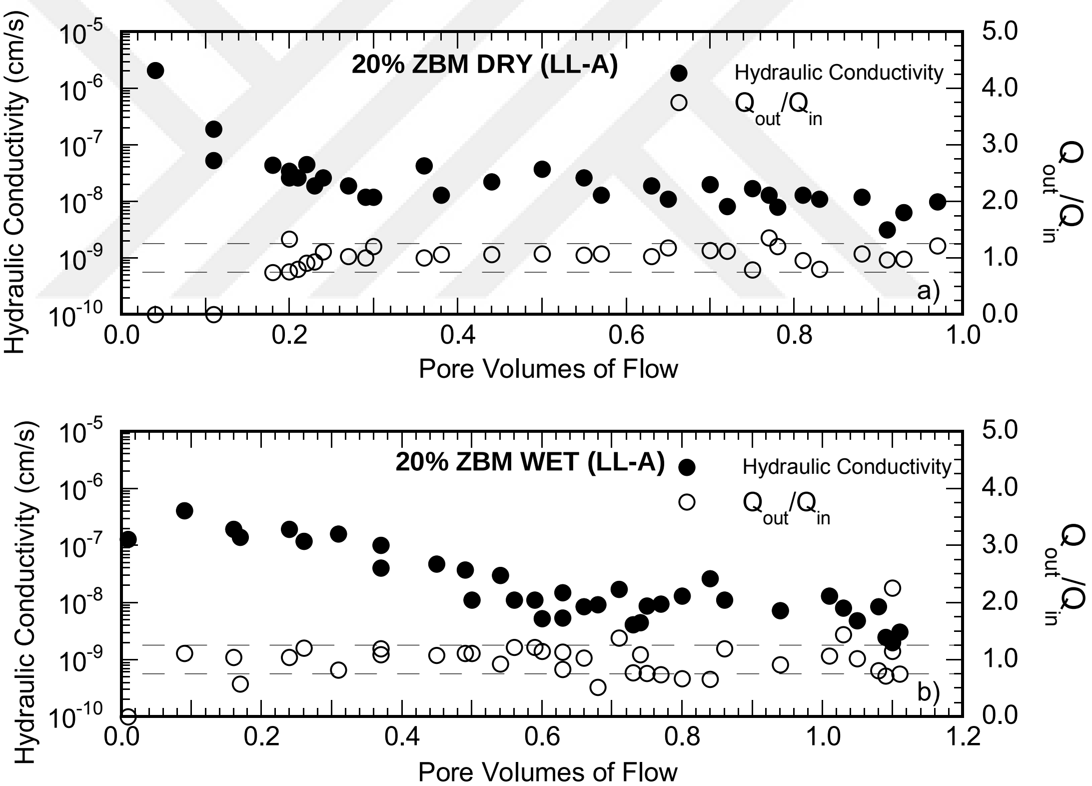


Figure 5.4 Hydraulic conductivity behaviors of ZBMs permeated with: Landfill Leachate-A (LL-A): a) 20% ZBM (dry), b) 20% ZBM (wet) and with Landfill Leachate-B (LL-B): c) 20% ZBM (dry), d) 20% ZBM (wet).

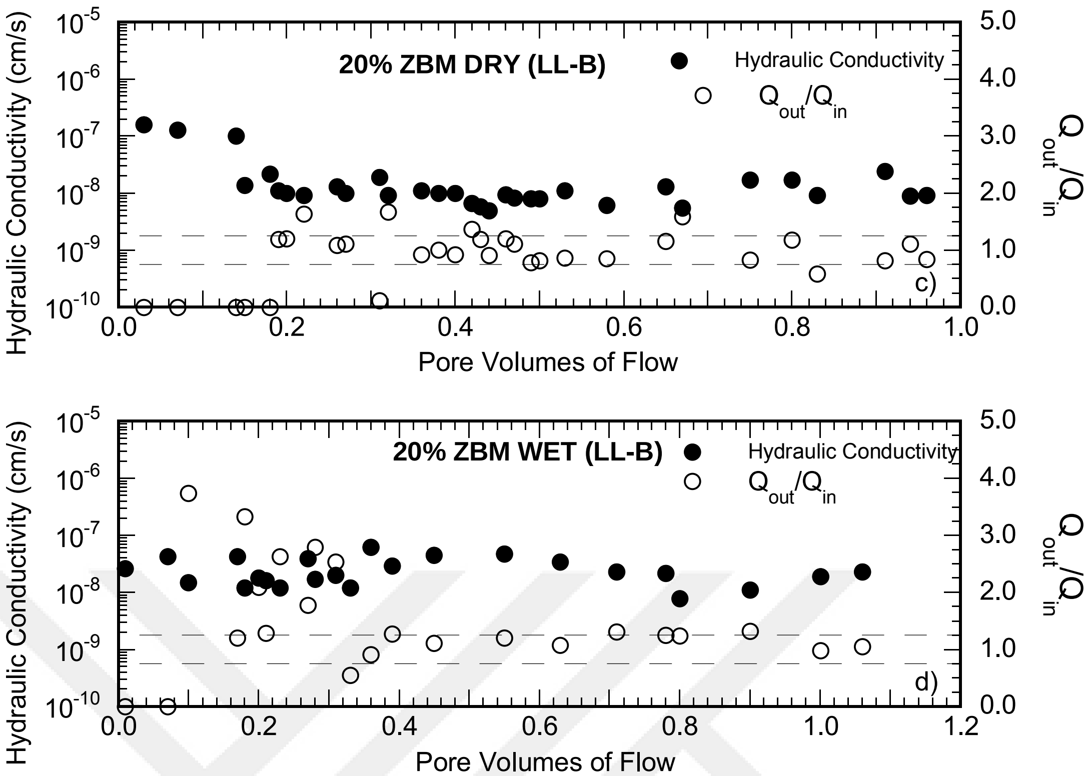


Figure 5.4 Hydraulic conductivity behaviors of ZBMs permeated with: Landfill Leachate-A (LL-A): a) 20% ZBM (dry), b) 20% ZBM (wet) and with Landfill Leachate-B (LL-B): c) 20% ZBM (dry), d) 20% ZBM (wet) (cont.).

The hydraulic conductivity behavior of 30% ZBM is shown in Figure 5.5 in terms of mixing methods. The hydraulic conductivity tests for 30% dry mixture (LL-A), 30% wet mixture (LL-A), 30% dry mixture (LL-B) and 30% wet mixture (LL-B) were completed after 17, 12, 7 and 12 months, respectively (Figure 5.5a-d). The hydraulic conductivity tests for 30% ZBM were terminated between 0.5 and 0.985 PVF. When 30% ZBM is compared with those of 20% ZBM (Figure 5.4a-d), the hydraulic conductivity tests for 30% ZBM were lasted longer than for 20% ZBM. However, the test duration can be accepted as sufficient although 1.0 PVF condition was not achieved.

The hydraulic conductivity of 30% dry mixture to LL-A was in the increasing trend at the beginning (Figure 5.5a). It was initially 1.6×10^{-9} cm/s and increased about one order of magnitude. (i.e. 1.2×10^{-8} cm/s) at the end of 13 months. Then, it decreased and reached the final value of 2.3×10^{-9} cm/s (Figure 5.5a). Initial hydraulic conductivity of 30% wet mixture to LL-A reduced from 1.9×10^{-7} cm/s to 1.3×10^{-9} cm/s. Then, it increased 5 times and reached to 8.2×10^{-9} cm/s at the end of 12 months (Figure 5.5b).

The hydraulic conductivity of 30% dry mixture to LL-B is illustrated in Figure 5.5c. The initial hydraulic conductivity was around 1.2×10^{-8} cm/s and it decreased to 3.1×10^{-9} cm/s after 0.3 PVF. Ultimately, it increased slightly to 6.6×10^{-9} cm/s. The hydraulic conductivity of 30% wet mixture to LL-B is shown in Figure 5.5d. The hydraulic conductivity of this sample had a stable trend up to 0.66 PVF. Then, the tubes were clogged with the colloids inside the leachate and therefore, the flow stopped in the system. After flushing, the test restarted. At this stage, the hydraulic conductivity was suddenly increased to 3.3×10^{-8} cm/s and finally reduced to 8.2×10^{-9} cm/s.

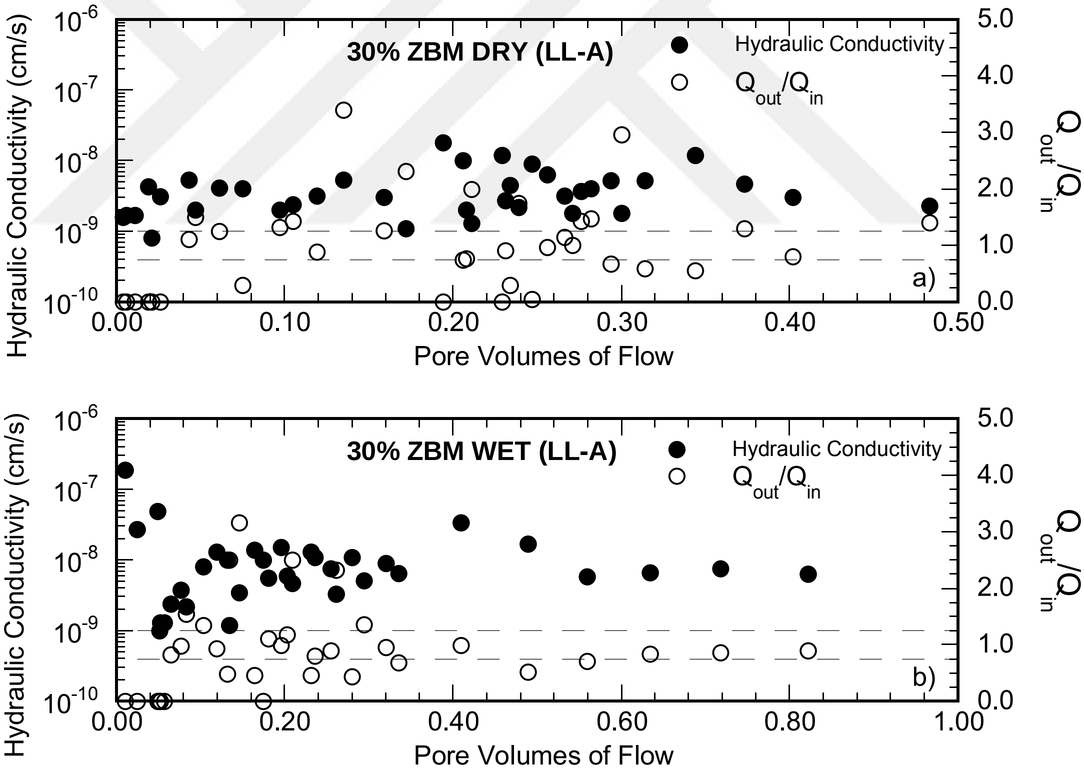


Figure 5.5 Hydraulic conductivity behaviors of ZBMs permeated with: Landfill Leachate-A (LL-A): a) 30% ZBM (dry), b) 30% ZBM (wet) and with Landfill Leachate-B (LL-B): c) 30% ZBM (dry), d) 30% ZBM (wet).

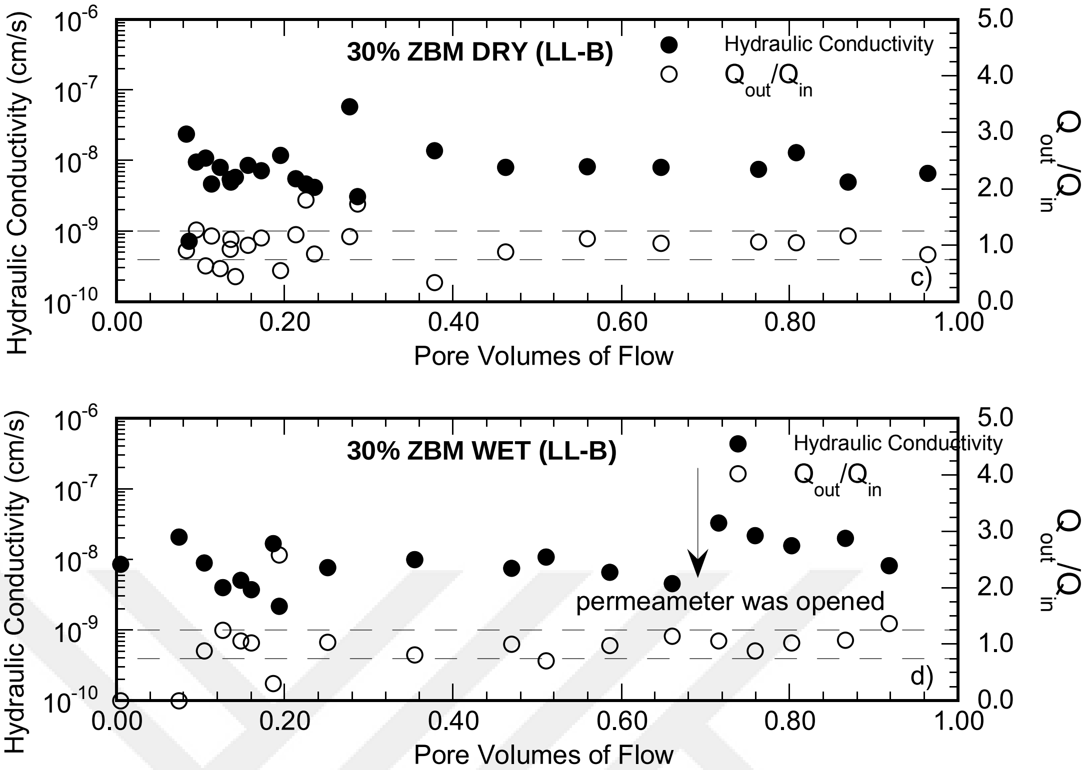


Figure 5.5 Hydraulic conductivity behaviors of ZBMs permeated with: Landfill Leachate-A (LL-A): a) 30% ZBM (dry), b) 30% ZBM (wet) and with Landfill Leachate-B (LL-B): c) 30% ZBM (dry), d) 30% ZBM (wet) (cont.).

When physical stability is examined, it is seen that Q_{out}/Q_{in} exceeded the allowable limits suggested in ASTM D 5084 (Figure 5.5a-d). Such kind of long-term experiments, clogging may occur in geotextile voids or tubing due to the leachate. Indeed, Q_{out}/Q_{in} values were greater than 1.25 or lower than 0.75 in almost all the experiments (Figure 5.5a-d). To avoid this situation, the tubing was flushed with the leachate. In other words, the leachate was passed through the tubing. The leachate used for this purpose was not used again. When the problem persisted, the permeameter was opened and the geotextile was changed (Figure 5.6). After that Q_{out}/Q_{in} values were fell within the allowable limits (Figure 5.5d).

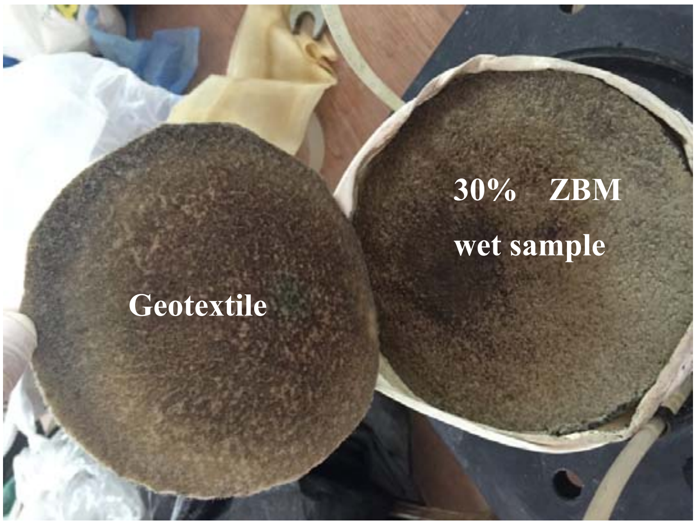


Figure 5.6 The view of the geotextile placed over the sample after clogging of the tubing with LL-B.

As can be seen from Figure 5.4a-d and Figure 5.5a-d, the fluctuations were recorded on the hydraulic conductivities and Q_{out}/Q_{in} values of 20% and 30% ZBM samples during the experiments. The decision about the hydraulic conductivities of ZBMs was made when the experiments were continued for a long time period (approximately one year). Therefore, important information on the need of long-term hydraulic conductivity was provided when landfill leachate was of primary concern.

5.1.2.2 Effect of Mixture Preparation Method on the Hydraulic Conductivity of ZBMs

The effect of the mixture preparation method (dry or wet) on the hydraulic conductivity of ZBMs is shown in Figure 5.7a-b. Accordingly, the hydraulic stability to LL-A was provided earlier for dry mixture than for wet mixture. After reaching the stability, the same hydraulic conductivity behaviors were obtained for both mixing methods (Figure 5.7a). When final hydraulic conductivities are compared, it is obvious that the mixture preparation method had no effect on the hydraulic conductivity. This is in agreement with the compaction behavior of ZBMs. It was found that 20% ZBM prepared with wet and dry mixing methods had the same compaction curves.

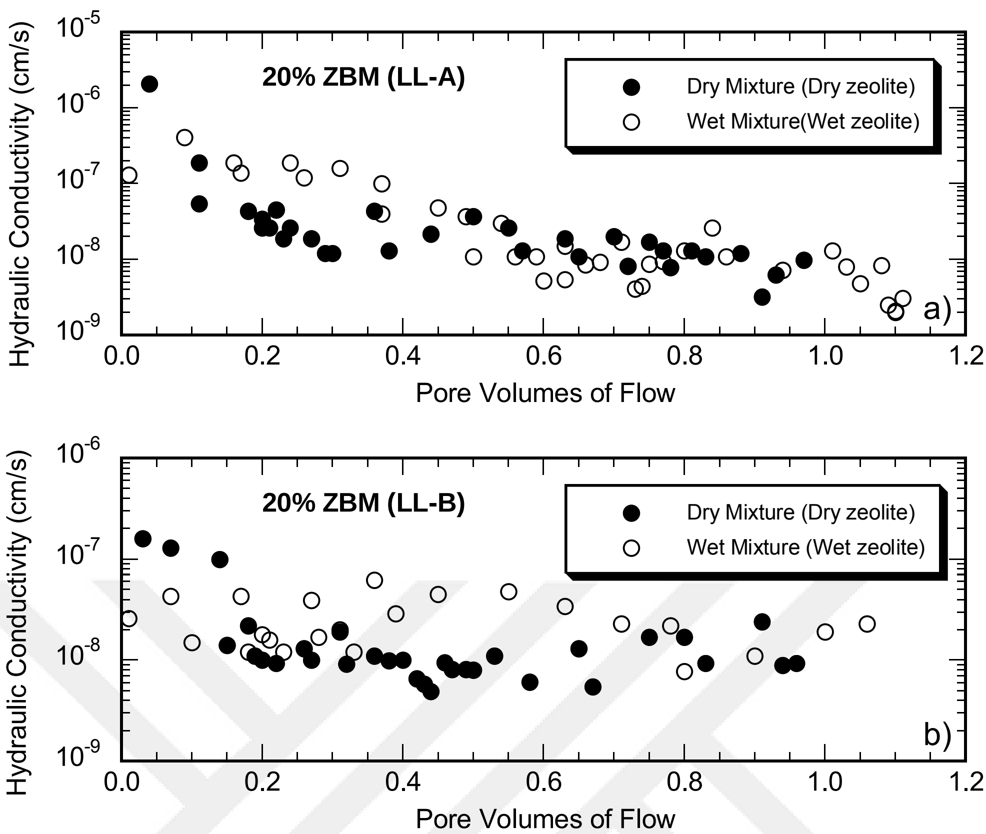


Figure 5.7 The effect of mixing method on the hydraulic conductivity behavior of %20 ZBM: a) Leachate-A (LL-A) and b) Leachate-B (LL-B).

The effect of the mixing method can only be seen on the samples permeated with LL-B. At the beginning, the hydraulic conductivity of dry mixture was one order of magnitude greater than the hydraulic conductivity of the wet mixture. At 0.2 PVF, the hydraulic conductivities were the same (Figure 5.7b). Conversely, between 0.2 and 0.7 PVF, the hydraulic conductivity of the wet mixture was found one order of magnitude greater than that of dry mixture. At the end of the experiment (1 PVF), because of the fact that the permeability of the wet mixture decreased, the hydraulic conductivities of the wet and dry mixtures became similar (Figure 5.7b).

The effect of the mixture preparation method on 30% ZBM is given in Figure 5.8a-b. In the experiments with LL-A, the hydraulic conductivities of the wet and dry mixtures were similar until approximately 0.35 PVF. From this point to the end of the experiment, the hydraulic conductivities varied 2.8 times. When the hydraulic conductivities were compared at 0.5 PVF where the hydraulic conductivity test for dry mixture was terminated, the dry mixture had 7.4 times lower hydraulic conductivity than the wet mixture (2.3×10^{-9} cm/s versus 1.7×10^{-8} cm/s).

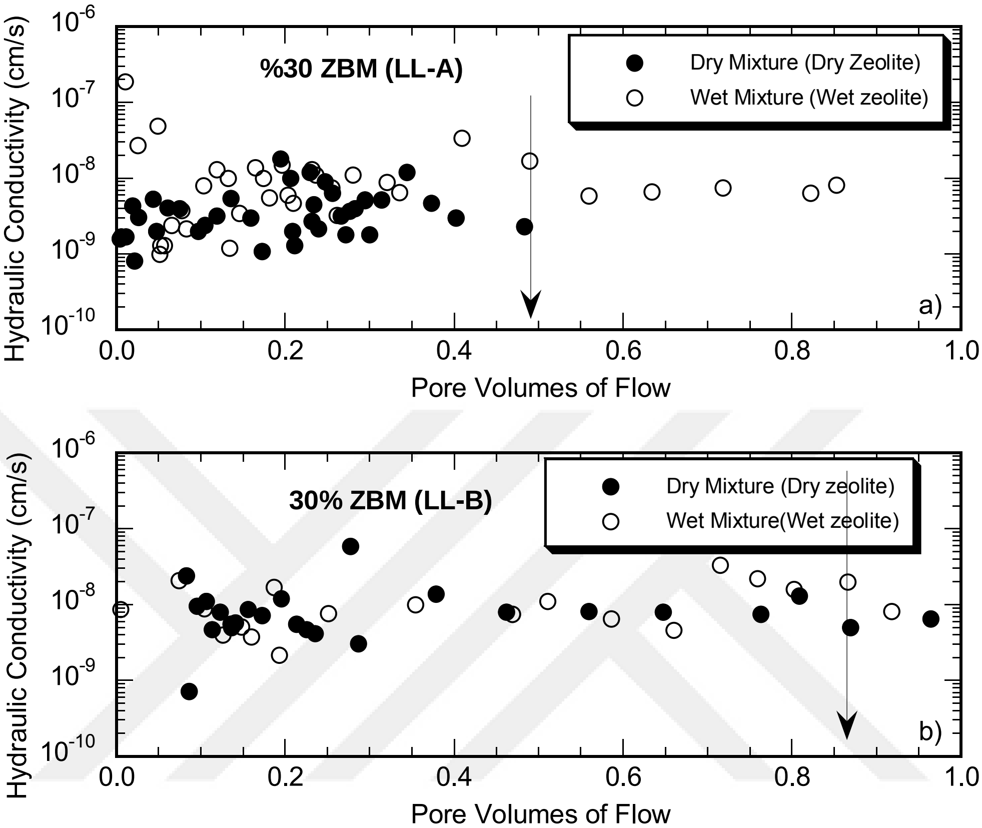


Figure 5.8 The effect of mixing method on the hydraulic conductivity behavior of %30 ZBM: a) Leachate-A (LL-A) and b) Leachate-B (LL-B).

It is also possible to do the same emphasis on 30% ZBM samples when permeated with LL-B. The hydraulic conductivity behaviors remained close for dry and wet mixtures along the test duration. However, dry mixture had 1.2 times lower hydraulic conductivity than the wet mixture at 0.9 PVF. This result is analogous to the results obtained with LL-A.

When the above results are discussed in terms of hydraulic conductivity behavior, it is clear that the permeability of 20% ZBM decreased with PVF whereas it increased for 30% ZBM.

5.1.2.3 Influence of Leachate Type on the Hydraulic Conductivity ZBMs

The effect of leachate type on the hydraulic conductivity behavior of 20% ZBM is shown in Figure 5.9. For dry mixtures, the hydraulic conductivity to LL-A was greater than that to LL-B until 0.6 PVF (Figure 5.9a). At the beginning, the difference between the hydraulic conductivities was 13 times at most. Then, it decreased to 5 times until 0.6 PVF. After 0.6 PVF, the similar hydraulic conductivity behaviors were obtained for both leachates and the final hydraulic conductivities were measured quite close to each other as shown in Figure 5.9a (9.8×10^{-9} cm/s and 9.3×10^{-9} cm/s for LL-A and LL-B, respectively).

In contrast, it is found that the leachate type had an effect on the hydraulic conductivity behaviors of wet mixture (Figure 5.9b). The results showed that the hydraulic conductivity to LL-A decreased with PVF. On the other hand, it was almost stable with LL-B during the tests (Figure 5.9b).

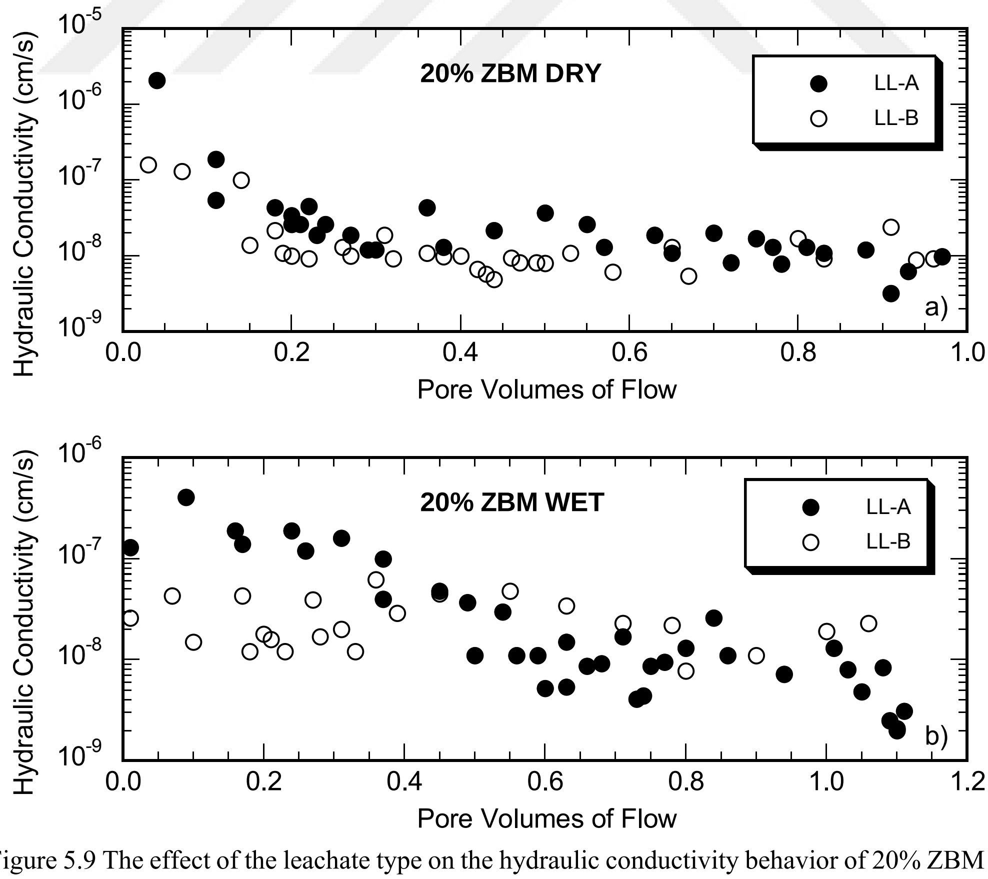


Figure 5.9 The effect of the leachate type on the hydraulic conductivity behavior of 20% ZBM prepared by: a) dry and b) wet mixing methods.

When the final hydraulic conductivities were compared, it is seen that the samples permeated with LL-A had lower hydraulic conductivities than samples permeated with LL-B (Figure 5.9b).

The effect of leachate type on the hydraulic conductivity of 30% dry mixture is shown in Figure 5.10a. As opposed to 20% ZBM, the hydraulic conductivity behavior of 30% dry mixture was similar for both leachates until 0.3 PVF. However, they became different beyond this level. The final hydraulic conductivity to LL-A was 2.9 times lower than the final hydraulic conductivity to LL-B.

The effect of the leachate type on the hydraulic conductivity of 30% wet mixture is shown in Figure 5.10b. Similarto dry mixture, permeabilities were similar until 0.65 PVF and then they began to diverge. It was found that, the samples permeated with LL-A had almost the same permeability as with the samples permeated with LL-B.

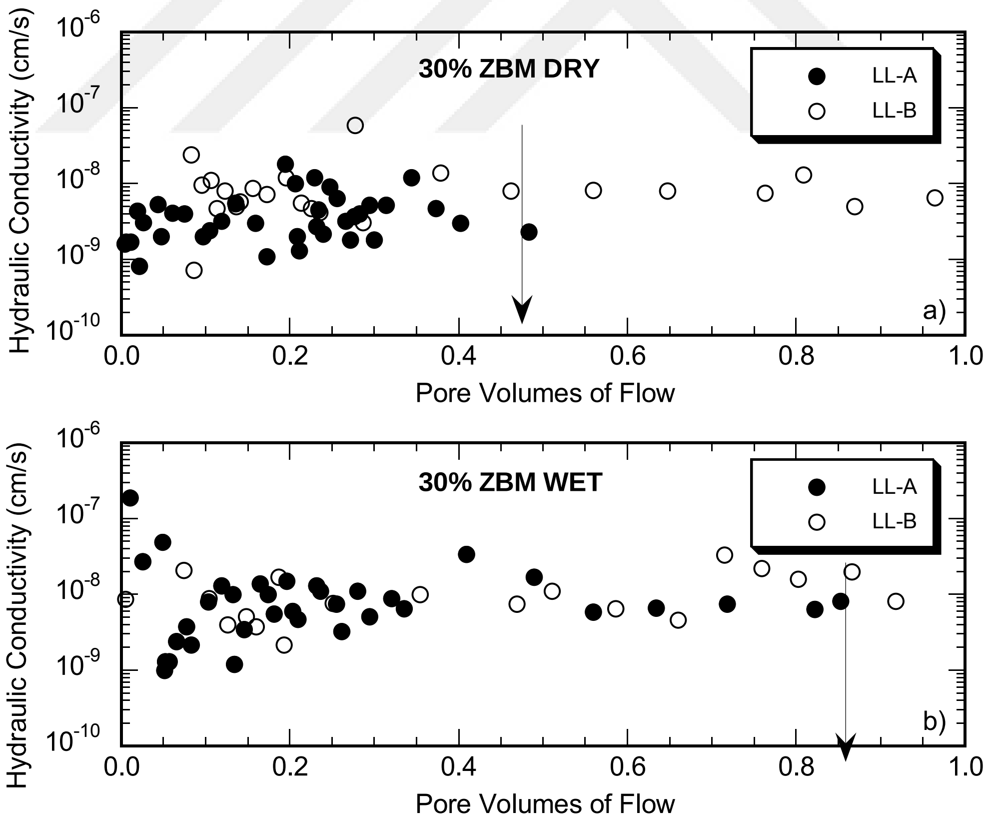


Figure 5.10 The effect of the leachate type on the hydraulic conductivity behavior of 30% ZBM prepared by: a) dry and b) wet mixing methods.

For each landfill leachate, the hydraulic conductivities were measured less than 1.0×10^{-7} cm/s that is a maximum allowable limit for the hydraulic barriers. This result is one of the most important findings of this study.

The results were presented again in Figure 5.11 just in case of final hydraulic conductivities. In addition, when Figure 5.11 was drawn, the average of the last six hydraulic conductivities was taken from Figure 5.4 and Figure 5.5. Because it is thought that these values represent the hydraulic conductivity results better. Therefore, the values in Figure 5.11 are the average of the last six hydraulic conductivity readings.

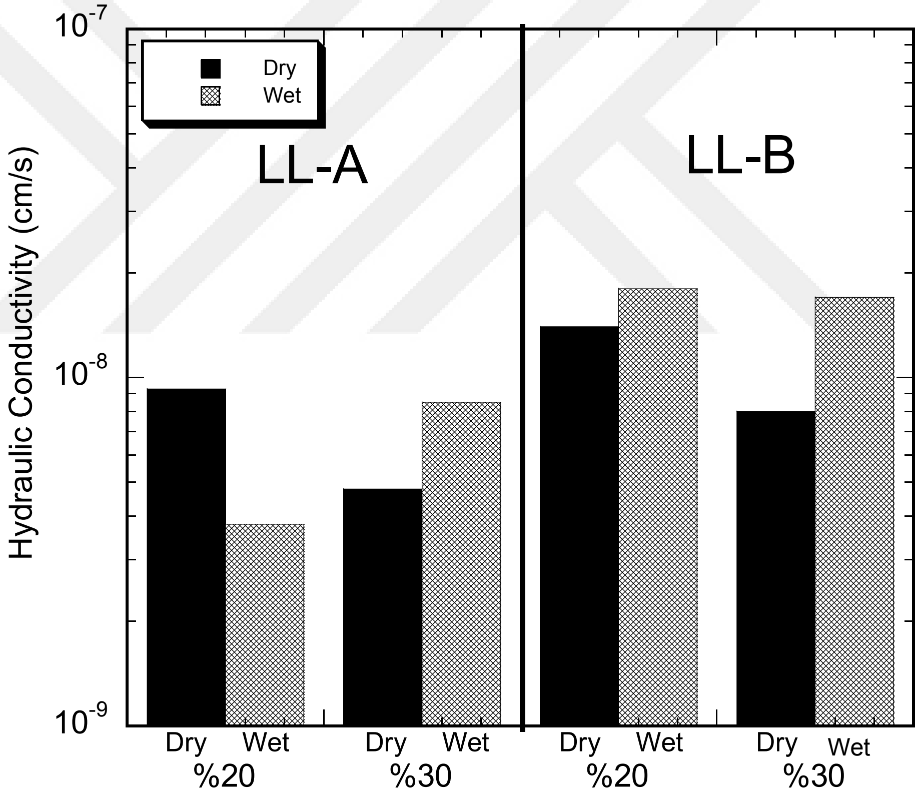


Figure 5.11 Comparison of final hydraulic conductivities of ZBMs in terms of mixing method, bentonite content and leachate type.

Except hydraulic conductivity of 20% ZBM to LL-A, the hydraulic conductivities of wet mixtures were greater than those of dry mixtures regardless of bentonite content and leachate type. It is known that bentonite has high affinity for water and it swells when contacted with water. For dry mixing method, it is expected that bentonite absorbs most of the free water that was added while blending the materials. Because, the suction of bentonite is better than zeolite. Thus, bentonite in dry mixing method tends to swell. Conversely, since zeolite was first moistened with water in wet mixing method, it retains most of the water inside the porous channels. Thus, there is little amount of free water for bentonite to swell when compared to bentonite in dry mixing method (water absorbed from zeolite surface is neglected). Hence, bentonite in wet mixing method has less swelling capacity and relatively less water content. When it comes into contact with the leachate, the swell will be limited as compared to the bentonite in dry mixing method. In other words, the bentonite in dry mixtures is influenced from the negative effects of leachates less than the bentonite in wet mixtures. Thus, it is expected that bentonite in dry mixtures can swell and block the flow paths better than the bentonite in wet mixtures. So that lower hydraulic conductivity values are found for the samples prepared with dry mixing method.

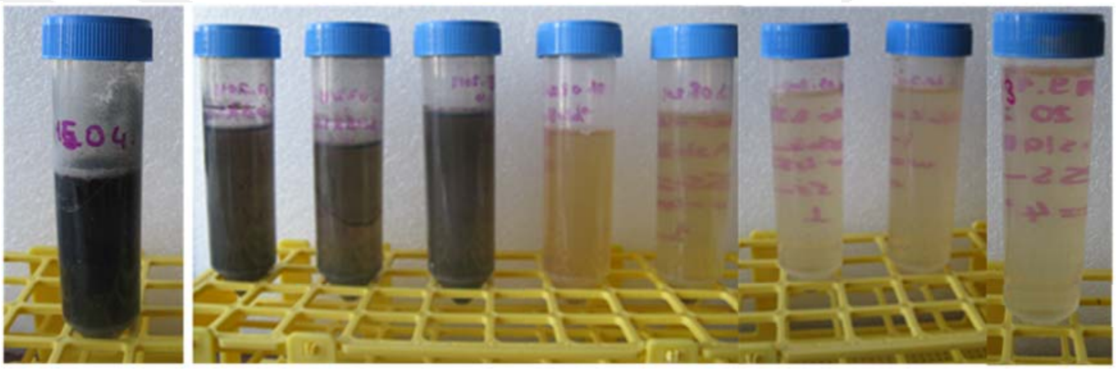
On the other hand, the hydraulic conductivity of 20% ZBM permeated with LL-A was found lower for the wet mixture than for dry mixture. One of the possible reason is that the excessive gas production in the leachate may result in the blocking the flow paths across the tubing. The other reason may be different test durations between wet and dry mixtures. Indeed, at the point where the test for dry mixture was completed (≈ 1.0 PVF), it can be seen that the hydraulic conductivity of dry mixture was lower than the hydraulic conductivity of the wet mixture (9.8×10^{-9} cm/s to 1.3×10^{-8} cm/s). The wet mixture was tested longer; meanwhile the hydraulic conductivity started to decrease and reached the final value of 3.1×10^{-9} cm/s at1.11 PVF (Figure 5.11).

Except the wet mixture permeated with LL-A, the hydraulic conductivities of 30% ZBMs had slightly lower than those of 20% ZBMs. This is an expected behavior. Because when bentonite content increases in the mixture, inter granular voids between zeolite grains will be closed better with the swollen bentonite, resulting in a decrease in the hydraulic conductivity.

On the other hand, the hydraulic conductivity slightly decreased as the bentonite content increased in the mixture. This finding is consistent with the previous results reported in the literature for ZBMs. Kayabalı (1997) and Ören et al. (2011) stated that bentonite content had limited effect on the hydraulic conductivity.

5.1.2.4 pH and Electrical Conductivity Measurement of Percolated Fluids from ZBMs

The accumulated effluent in the graduated cylinder was transferred to plastic tubes and the electrical conductivity (EC) and pH measurements were made on these samples. Similarly, the samples were taken from the influent (from the burette portion) and the EC and pH were measured (Figure 5.12).



Influent Water **Effluent Water Samples**

Figure 5.12 Outflow samples of 20% ZBM wet with LL-A.

First, pH and EC results of 20% wet and dry mixtures were illustrated in Figure 5.13. Except 20% wet mixture permeated with LL-B, pH_{out}/pH_{in} was measured between 0.9 and 1.0 (Figure 5.13a-c). However, this ratio decreased from 0.92 to 0.81 along the test duration for 20% wet mixture when LL-B was the permeant (Figure 5.13d).

EC_{out}/EC_{in} stability of the 20% ZBMs seemed to be partially provided for some samples. The final EC ratios for 20% dry and wet mixtures with LL-A were 0.92 and 0.73, respectively (Figure 5.13a-b). However, EC ratios for 20% dry and wet mixtures with LL-B were 0.25 and 0.47, respectively (Figure 5.13c-d).

Accordingly, when LL-A was used as the permeant, it was seen that 20% dry mixture reached to the physical stability (Figure 5.4a). In addition, pH and EC ratios remained in the limits given in ASTM D6766 (1.0±0.1) (Figure 5.13a). EC ratio of the wet mixture with LL-A was also close to allowable limits as seen in Figure 5.13b (0.73<0.9). Thus it may be claimed that 20% dry and wet mixtures reached to the physical and chemical equilibrium.

In the case of 20% ZBM with LL-B, pH equilibrium was achieved; however, EC equilibrium was not established. From beginning to the end of the experiment, EC ratio slowly increased to 0.25 and 0.47 for dry and wet mixtures, respectively. But these samples had to be terminated before chemical equilibrium was achieved because of time restrictions.

pH and EC ratios of 30% ZBMs are shown in Figure 5.14. In the view of such information, pH ratio remained in the allowable limits given in ASTM D6766 (1.0±0.1). However it was seen that, EC ratios were obtained different according to the leachate type (Figure 5.14). EC ratio of the dry mixture with LL-A was 0.46 and the wet mixture was 1.0 (Figure 5.14a-b). However when LL-B was used, the final EC ratios for the wet and dry mixtures were 0.38 (Figure 5.14c-d). This value is close to the results of 20% ZBM with LL-B (Figure 5.13c-d). Based on these results, the pH and EC equilibrium was obtained more quickly with LL-A than with LL-B. It may be due to the organic and inorganic compounds presented in the leachates.

The EC equilibrium had no effect on the long-term hydraulic conductivity of ZBMs with LL-B. When the hydraulic conductivity results were analyzed, the ZBMs had similar permeability values with both leachates (Figure 5.11).

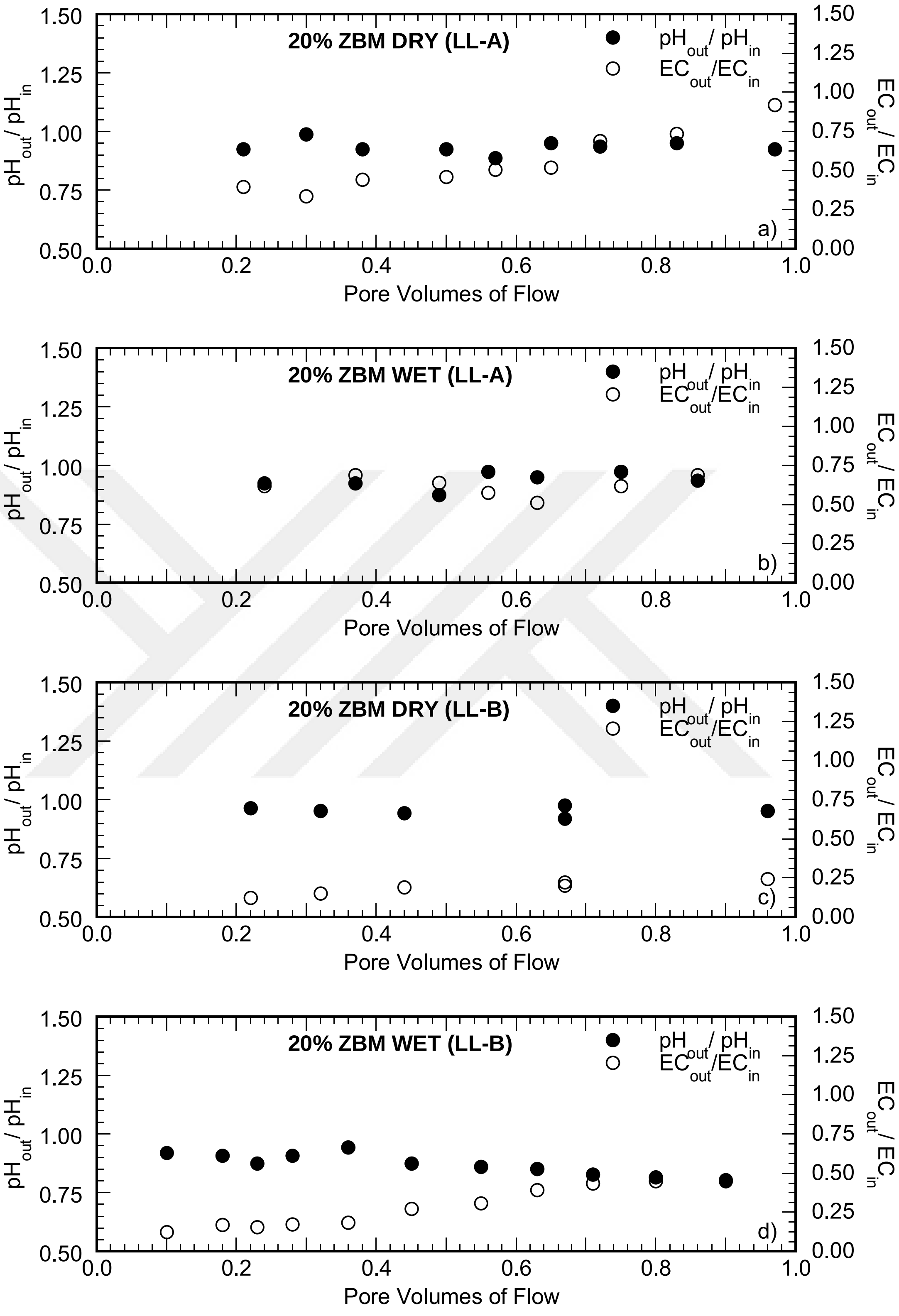


Figure 5.13 pH and EC ratios of ZBMs prepared by dry and wet mixing methods and permeated with LL-A, a) 20% ZBM (dry), b) 20% ZBM (wet) and with LL-B, c) 20% ZBM (dry), d) 20% ZBM (wet).

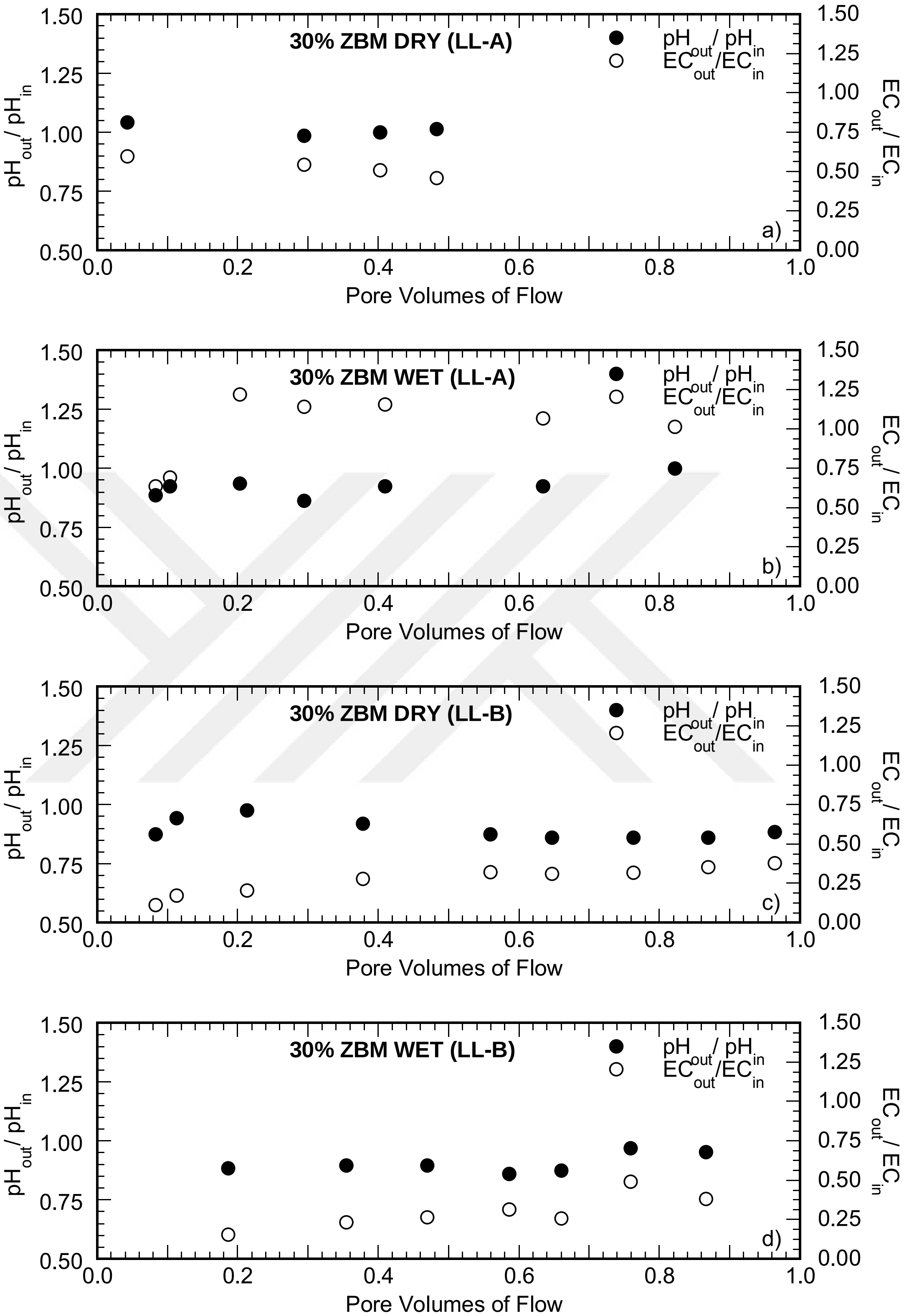


Figure 5.14 pH and EC ratios of ZBMs prepared by dry and wet mixing methods and permeated with LL-A, a) 30% ZBM (dry), b) 30% ZBM (wet) and with LL-B, c) 30% ZBM (dry), d) 30% ZBM (wet).

5.2 Comparison of the Hydraulic Conductivities of Zeolite-Bentonite and Sand-Bentonite Mixtures to Landfill Leachates

5.2.1 Compaction Test Results

Due to different mixing method (dry and wet) and bentonite content (10% and 20%), it is not appropriate to compare the compaction curves of SBMs in the same figure . However it may be useful to give compaction curves for SBMs before evaluating and comparing the compaction behavior of bentonitic mixtures within each other. Therefore, compaction curves of SBMs prepared with wet and dry mixing methods are shown in Figure 5.15.

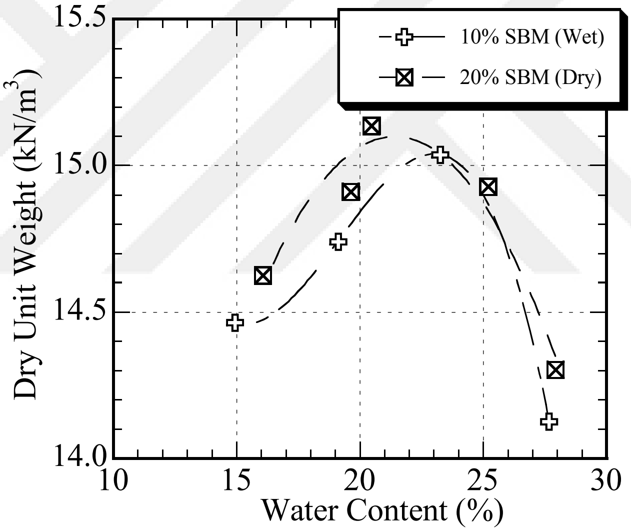


Figure 5.15 Compaction curves for SBMs.

From Figure 5.15, it is indicated that the dry unit weights of the SBMs were between 15.0 kN/m^3 and 15.2 kN/m^3. The compaction water contents were also quite different from the values of the ZBMs (Figure 5.1). To demonstrate this difference, the compaction curves are evaluated together with the ZBMs in Figure 5.16.

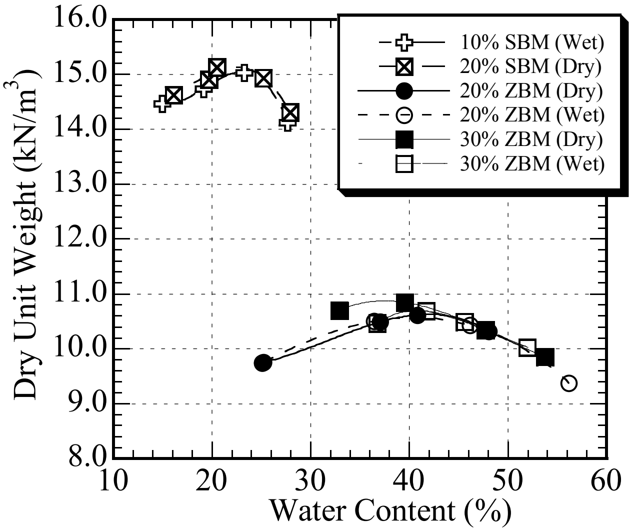


Figure 5.16 Comparison of the compaction curves of ZBMs and SBMs.

When compaction curves in Figure 5.16 are compared, ZBMs had more open and flat compaction curves, whereas SBMs had more bell-like steep curves. The compaction water contents of ZBMs varied within a broader range (from 25% to 55%); however, those of SBMs differed within a rather narrower range (from 14% to 28%).

Ören et al. (2014) collected the compaction parameters for SBMs and ZBMs in the literature and studied the relationships between them. The data gathered from the literature is presented in Table 5.1. Ultimately, a linear relationship was suggested between the compaction parameters (γ_{dmax} and w_{opt}) of SBMs and ZBMs. Compaction parameters were examined through the data in this Table 5.1.

Table 5.1 Compaction parameters for ZBM and SBM that have reported in the literature so far.

Mixture Type	Bentonite Content (B/Total) (%)	w_{opt} (%)	γ_{dmax} (kN/m3)	Reference
ZBM	4.8-28.6	33.0-42.0	11.4-12.4	Kayabalı (1997)
ZBM	9.1	39.0	16.0	Tuncan et al. (2003)
ZBM	3.0-20.0	33.4-35.6	11.8-12.7	Kaya and Durukan (2004)
ZBM	10.0-50.0	37.9-57.3	9.6-11.3	Ören and Kaya (2013)
ZBM	10.0-20.0	39.0-40.0	10.2-10.7	Ören et al. (2014)

Table 5.1 Compaction parameters for ZBM and SBM that have reported in the literature so far (cont.).

ZBM	20.0-30.0	38.0-42.2	10.6-10.9	This study (2015)
SBM	3.8-18.0	12.5-15.0	17.1-18.1	Kenney et al. (1992)
SBM	8.0	14.5	17.8	Haug and Wong (1992)
SBM	10.0-20.0	13.7-17.8	15.9-17.2	Howell et al. (1997)
SBM	5.0-50.0	14.6-19.4	15.8-16.9	Komine (2004)
SBM	15.0-30.0	13.0-16.30	16.9-17.6	Gökalp et al. (2011)
SBM	10.0-50.0	18.6-22.8	14.2-16.1	Ören and Kaya (2013)
SBM	10.0-20.0	16.5-17.5	15.7-16.38	Ören et al. (2014)
SBM	10.0-20.0	22.5-23.3	15.0-15.1	This study (2015)

The compaction parameters of ZBMs and SBMs from this study were combined with the data reported in Ören et al. (2014) and plotted as shown in Figure 5.17. It is seen that there is a linear relationship between the compaction parameters of ZBM and SBM. It is clear that the compaction parameters of SBMs and ZBMs obtained in this study fit well on this curve. Based on this linear trend including the findings of this study, Equation 5.1 can be obtained which is almost the same as Equation 5.2 that was previously reported by Ören et al. (2014):

$$\gamma_{dmax} = -0.23\, w_{opt} + 20.43 \quad (5.1)$$

$$\gamma_{dmax} = -0.23\, w_{opt} + 20.35 \quad (5.2)$$

Equation 5.1 can be used to predict the γ_{dmax} of bentonitic mixtures. Ören et al. (2014) also considered another linear equation for fine-grained soils that was suggested by Gürtuğ and Sridharan (2004) (Figure 5.17). Ören et al. (2014) stated that this equation should be used with caution because it predicts γ_{dmax} for ZBMs accurately, whereas overestimates the γ_{dmax} of SBMs.

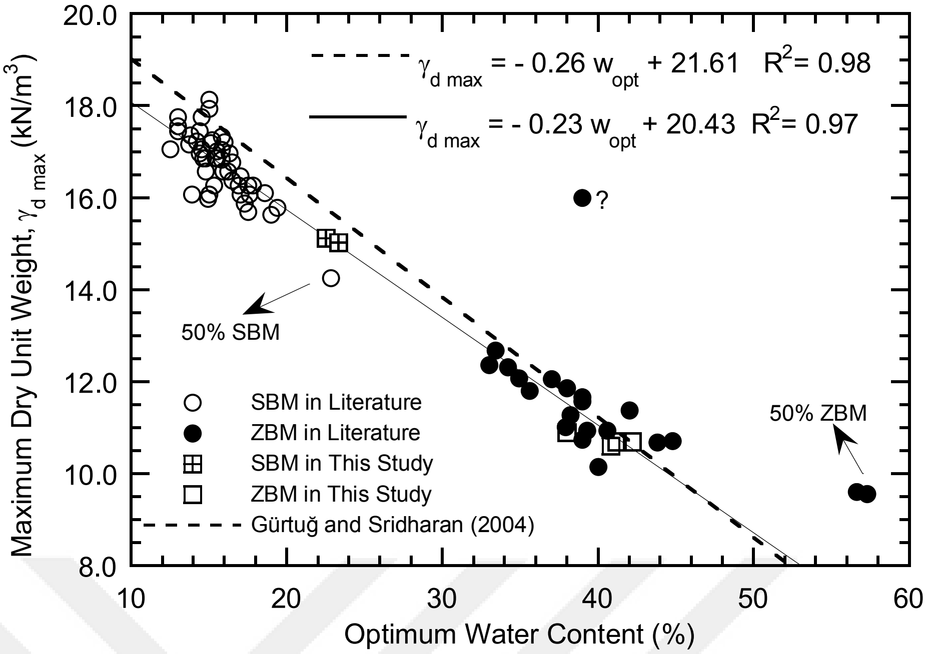


Figure 5.17 Relationship between the compaction parameters of ZBMs and SBMs.

5.2.2 Hydraulic Conductivity Test Results

5.2.2.1 Hydraulic Conductivity of SBMs

Two long-term hydraulic conductivity tests were performed with two different leachates on 10% wet and 20% dry mixtures. Test durations were 9-12 months. When 20% dry SBM was permeated with LL-A, clogging was occurred on the permeameter cell. Therefore, the permeameter cell was open and the experiment had to be restarted.

The test results of SBMs, which were obtained with LL-A and LL-B, are shown in Figure 5.18. Even a high hydraulic conductivity to LL-A was observed for 10% wet mixture at the beginning, it decreased with the increase of PVF (Figure 5.18a). This experiment was continued more than 1 PVF, so it can be said that the hydraulic and physical stability were reached at the end of this period. The final hydraulic conductivity of the 10% wet mixture was measured as 3.6×10^{-9} cm/s.

The hydraulic conductivity of 10% SBM wet mixture with LL-B is shown in Figure 5.18b. The sample reached to 0.51 PVF after about 1.5 year permeation period. As can be seen from Figure 5.18b, the hydraulic and physical stability were provided when test were terminated. The final hydraulic conductivity of the sample was measured as 5.1×10^{-9} cm/s.

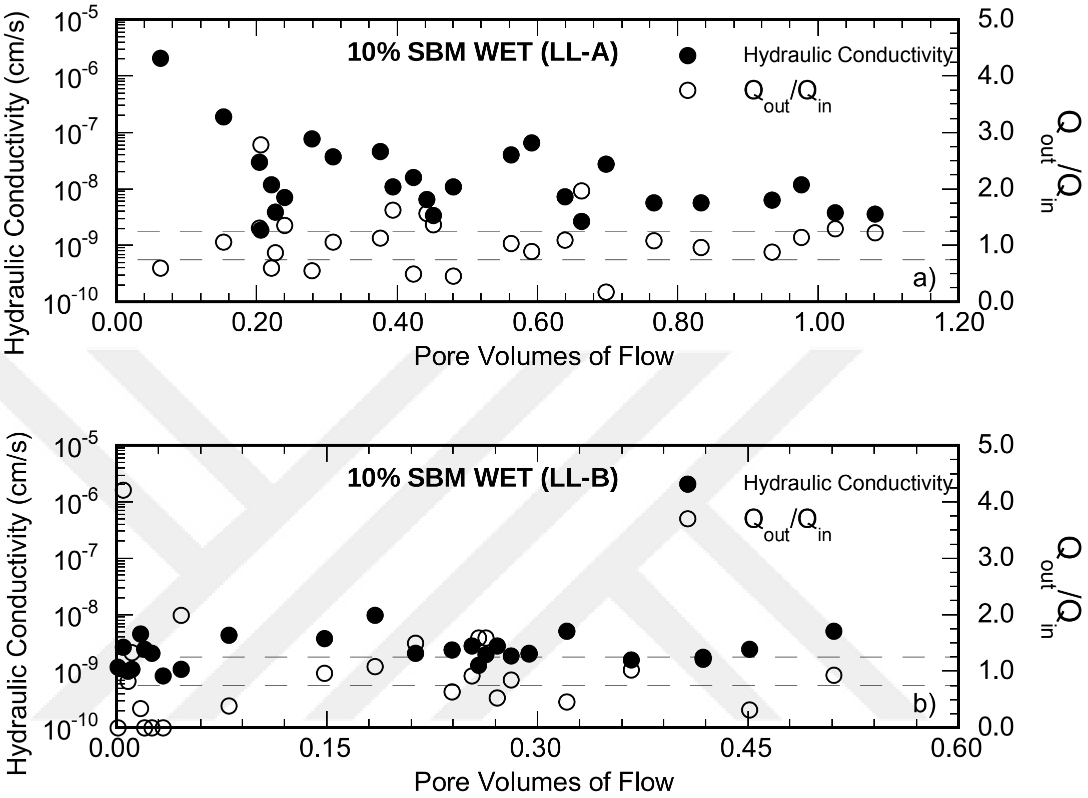


Figure 5.18 Hydraulic conductivity behaviors of 10% SBM prepared by wet mixing method and permeated with: a) LL-A and b) LL-B.

Hydraulic conductivity test results of 20% SBM, which were prepared with dry mixing method, are depicted in Figure 5.19. These experiments were continued with LL-A and LL-B until the hydraulic and physical stability were reached at 0.32 PVF and 0.29 PVF,and the final hydraulic conductivities of the samples were measured as 1.4×10^{-9} cm/s and 1.5×10^{-9} cm/s, respectively.

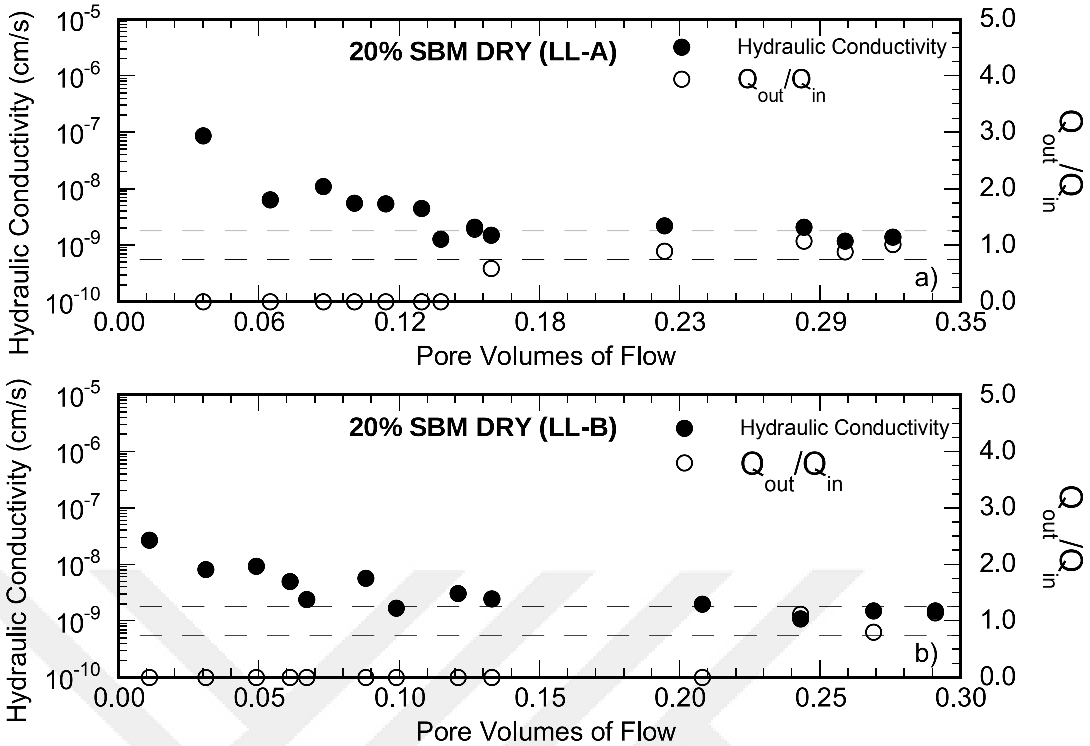


Figure 5.19 Hydraulic conductivity behaviors of 20% SBM prepared by dry mixing method and permeated with: a) LL-A and b) LL-B.

5.2.2.2 Comparison of the Hydraulic Conductivities of ZBMs and SBMs

The hydraulic conductivity was compared between 10% SBM, 20% ZBM and 30% ZBM which were prepared with wet mixing method (Figure 5.20). Similar hydraulic conductivities were obtained between 10% SBM, 20% ZBM and 30% ZBM when the permeant was LL-A. On the other hand, the hydraulic conductivity of 10% SBM to LL-B was measured lower than the hydraulic conductivities of 20% ZBM and 30% ZBM with the same leachate.

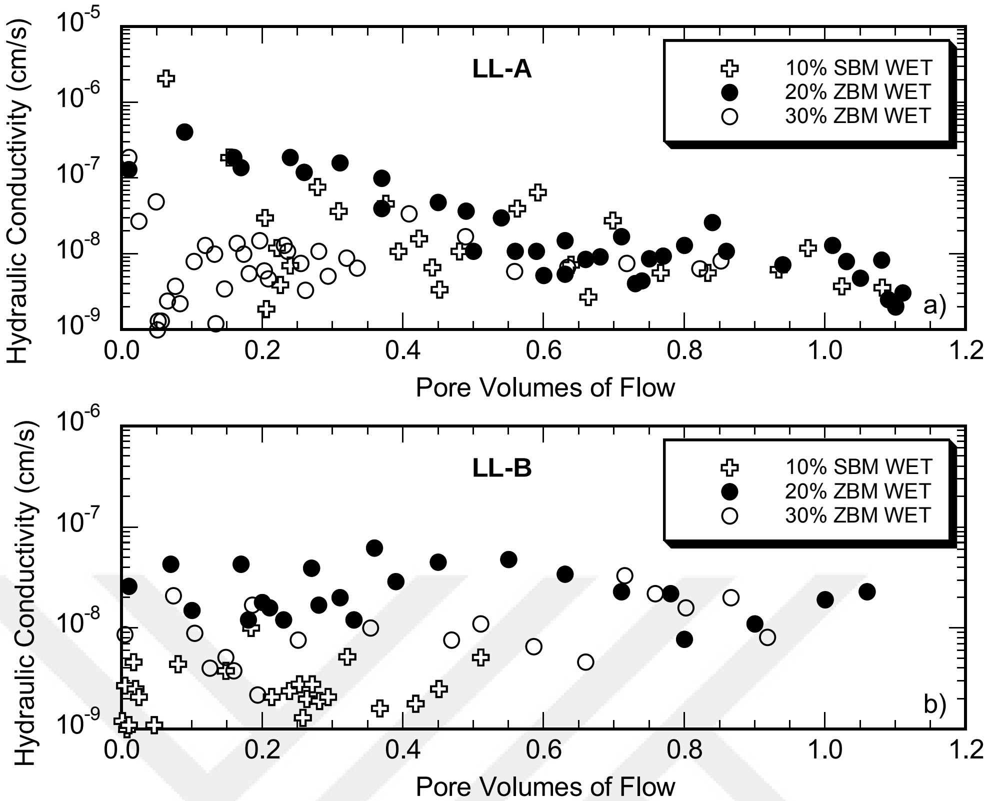


Figure 5.20 Comparison of the hydraulic conductivity of 10% SBM, 20% ZBM, and 30% ZBM that were prepared with wet mixing method: a) LL-A and b) LL-B.

In the previous studies, it was revealed that hydraulic conductivity of 10% ZBM was around 1.0×10^{-7} cm/s (Ören et al., 2011; Ören et al., 2014). Therefore, the hydraulic conductivity of 10% ZBM was not investigated in the scope of this study. The hydraulic conductivity of 10% SBM is lower than 10% ZBM and this could be explained as follows: In SBMs, which is prepared with wet mixing method, the water cannot penetrate into the sand particles. Thus, free water is kept in the voids between sand particles by capillary forces. When bentonite is added to sand, bentonite absorbs the water in the voids and it swells with a considerably amount. The swollen bentonite fills the voids between sand particles and it is not affected from negative effects of the leachates in the short-term period of testing. In contrast since zeolite has a porous body and water can penetrate into the intra-granular pores by capillary forces, there is less free water in the inter-granular pores of zeolite for bentonite. Thus, bentonite absorbs relatively lower water and it swells less in ZBMs than in SBMs. Thus, the higher amount of bentonite is needed to fill the voids between zeolite grains and to reduce the hydraulic conductivity. Therefore, compared to SBMs, it is needed to increase the proportion of bentonite in ZBMs. The results obtained in this study are consistent with the definition above.

The hydraulic conductivity tests for 20% dry mixture with LL-A and LL-B were terminated after 10 months. The hydraulic conductivity was compared between 20% SBM, 20% ZBM and 30% ZBM which were prepared with dry mixing method (Figure 5.21). The hydraulic conductivity of 20% SBM was measured lower than the hydraulic conductivities of 20% ZBM and 30% ZBM with these leachates. This result is very similar to 10% SBM prepared with wet mixing method (Figure 5.20a-b).

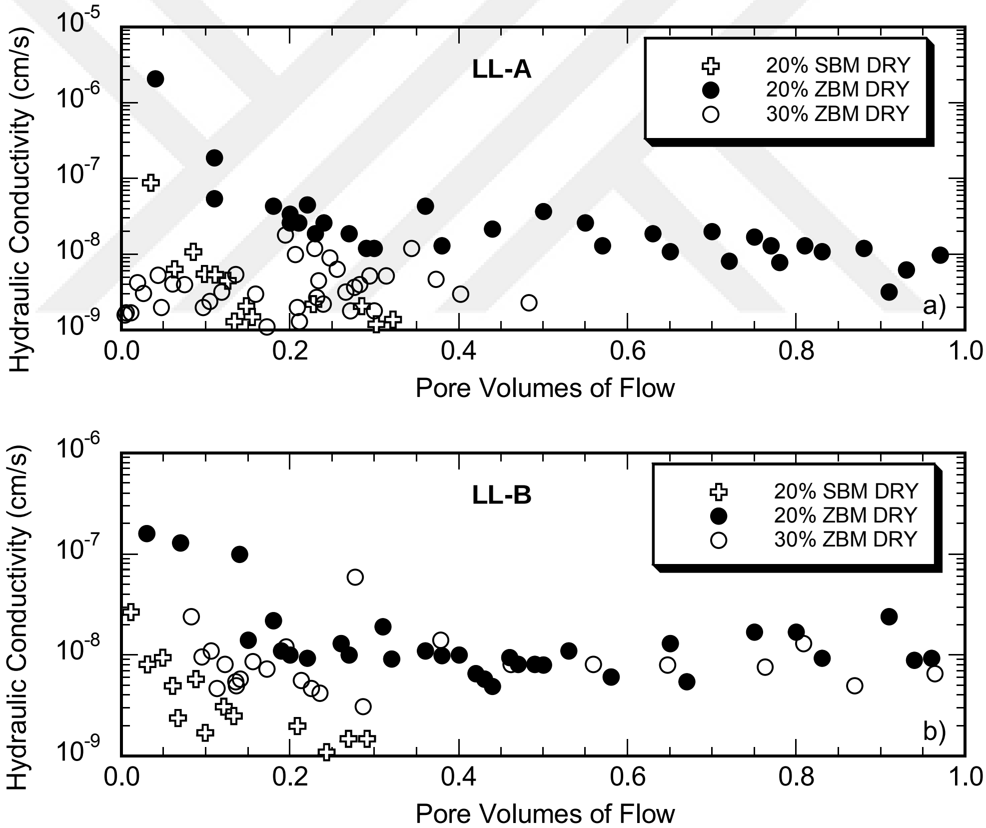


Figure 5.21 Comparison of the hydraulic conductivity of 20% SBM, 20% ZBM and 30% ZBM that were prepared with dry mixing method: a) LL-A and b) LL-B.

The final hydraulic conductivities of ZBMs and SBMs were compared regarding to the average of the last six readings and shown in Figure 5.22. Dark columns indicate hydraulic conductivities of ZBMs (for the mixture in dry and wet state) and open and striped bars indicate hydraulic conductivities of SBMs. Hydraulic conductivity of 10% SBM is almost identical to the 20% and 30% ZBM when LL-A was the permeant. However, hydraulic conductivity of 10% SBM was lower than that of 20% and 30% ZBM when LL-B was used as the permeant. Note that 20% SBM had the lowest hydraulic conductivities among others (i.e. 20% and 30% ZBM and 10% SBM).

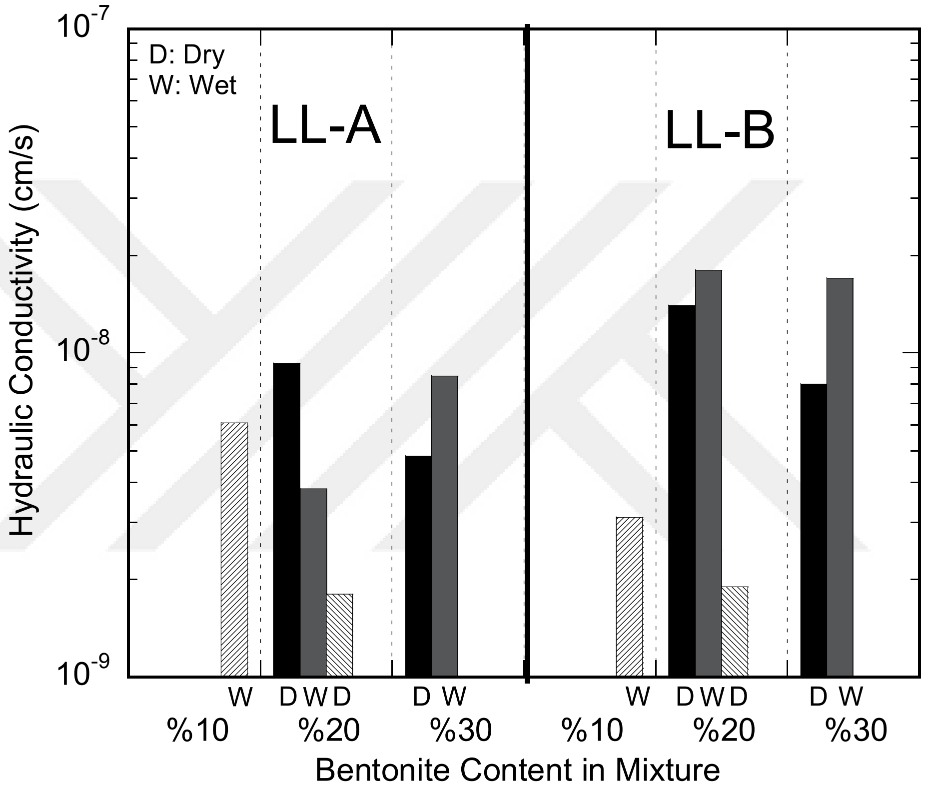


Figure 5.22 Comparison of final hydraulic conductivities of ZBM and SBM in terms of mixing method, bentonite content and leachate type.

5.2.2.3 Visual Evaluations on Outflow Liquids

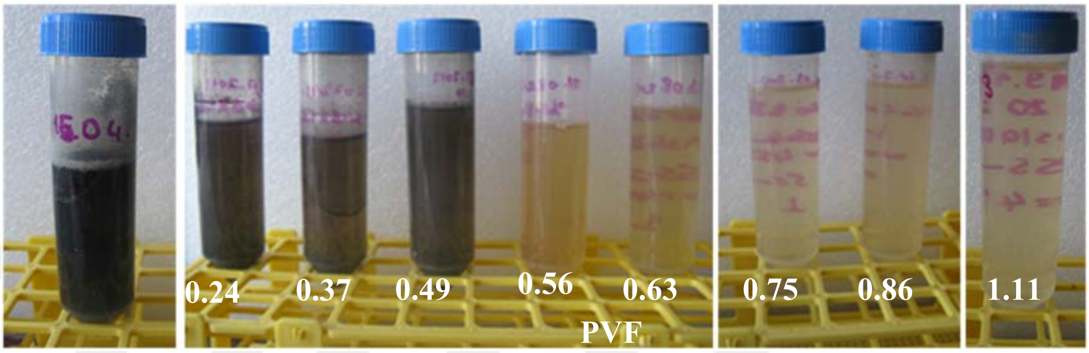
The inflow and outflow pictures of wet mixtures permeated with LL-A are given in Figure 5.23 as a function of PVF. The outflow pictures of 20% ZBM are shown in Figure 5.23a. This experiment was completed and 8 outflow liquids were obtained during the test. The first outflow sample was obtained at 0.24 PVF and the last one was obtained when the test was completed at 1.11 PVF. As can be seen from Figure

5.23a, colors of the first three outflow liquids are similar to inflow liquid. This is an expected situation. Because the flow was rapid until 0.49 PVF and the hydraulic conductivity was obtained about 1.0×10^{-7} cm/s. Then, the color of outflow became lighter with the reduction in the hydraulic conductivity. The lightest outflow was taken at the end of the experiment. The zeolite, used in the mixture, caused this color change. Zeolites are commonly used as both chemical and physical filtration material in many activities. In this mixture, zeolite could not have time to filtrate leachate on account of the rapid flow at the initial stage. However, zeolite began to filter leachate when the hydraulic conductivity started to decrease.

This observation was also supported by other hydraulic conductivity test conducted on 30% ZBM and with LL-A (Figure 5.23b). Hydraulic conductivity was initially 2.2×10^{-7} cm/s (Figure 5.23b). Then, hydraulic conductivity reduced and zeolites had time to filter the leachate. As a consequence, the color of the effluents began to lighten at 0.13 PVF and became quite clear when compared to influent. The light color maintained until the test was completed (0.82 PVF).

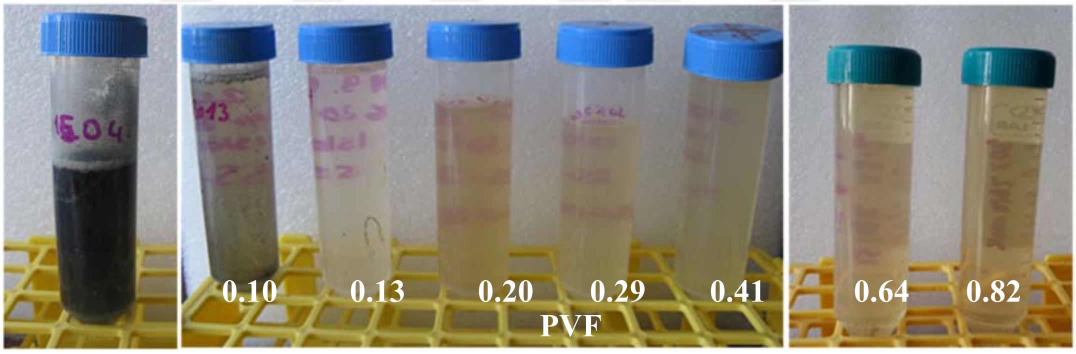
The outflow of 10% SBM are shown in Figure 5.23c. Accordingly, initial observations showed that light colored samples were provided at 0.15 PVF sampling stage. However, darker outflow samples were then provided until 0.48 PVF which had closer color with inflow leachates. From this point of view, it can be said that filtering capacity of 10% SBM came to an end in a short time. On the other hand, when the long-term hydraulic conductivities of 10% SBM is considered, Figure 5.23c shows that the outflow colors became lighter from 0.59 PVF to 1.08 PVF. If Figure 5.18 is reexamined, a fluctuation in the hydraulic conductivities until 0.7 PVF can be seen. This fluctuation caused to obtain different colors of outflow samples before 0.59 PVF. Following this, the color of outflow became lighter due to reduction in the hydraulic conductivity that was continued until the end of the test.

When the final outflow samples were compared, the color of 10% SBM at 1.08 PVF was darker than the color of 20% ZBM at 1.11 PVF and the color of 30% ZBM at 0.82 PVF (Figure 5.23). Due to negative surface charge of zeolite, all particles in ZBMs participate to the filtration process. In contrast, since sands have the neutral surface charge, SBMs have limited ability to filter the leachate. Sand play a minor role in chemical filtration with respect to zeolite in ZBMs and thus, filtration is governed only by the bentonite portion of SBMs. As a result, bentonite quickly reaches saturation, resulting rapid reduction in the filtration process.



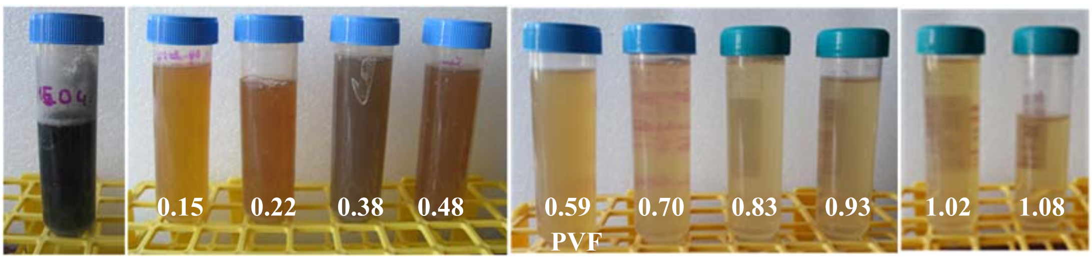
Inflow sample **Outflow samples**

(a)



Inflow sample **Outflow samples**

(b)



Inflow sample **Outflow samples**

(c)

Figure 5.23 Outflow samples of ZBM and SBM during hydraulic conductivity experiments permeated with LL-A: (a) 20% ZBM (wet), (b) 30% ZBM (wet), (c) %10 SBM (wet).

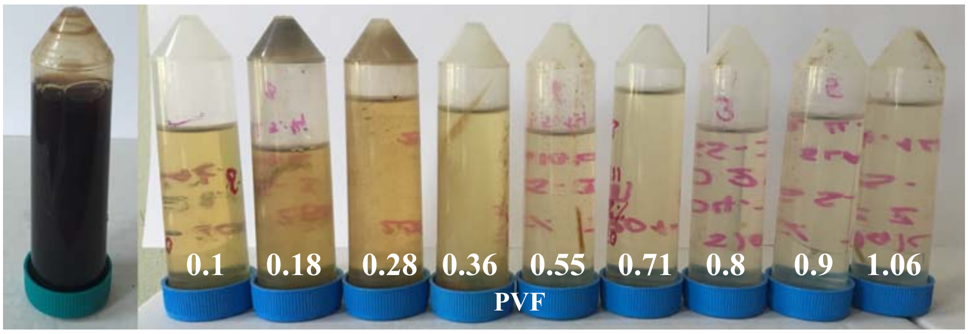
The inflow and outflow of wet mixtures with LL-B are given in Figure 5.24. The hydraulic conductivity experiment of 20% ZBM was completed and 9 outflow liquids were obtained during the test (Figure 5.24a). The first sample was obtained at 0.1 PVF and the last one was obtained when the test was completed at 1.06 PVF. As can be seen from Figure 5.24a, the lightest outflow liquid was taken at the end of the experiment. This is an expected situation. Because the flow slowed down from 0.8 PVF and the hydraulic conductivity was about 7.8×10^{-9} cm/s.

The outflows for 30% ZBM are shown in Figure 5.24b. Accordingly, initial observations showed that light colored samples were provided at 0.186 PVF. However, outflow color turned to dark until 0.9 PVF, which resemble the color of inflow leachates. This observation is consistent with the hydraulic conductivity results. The flow was slow until 0.66 PVF (1.0×10^{-9} cm/s) and the color of outflows were lighter. The color turned to dark when the hydraulic conductivity started to increase around one order of magnitude. For the hydraulic conductivity test performed with 10% SBM, three different sampling of outflows were provided at different stages of the test (Figure 5.24c). The observed outflow colors were light from the initial sampling to the end due to the low hydraulic conductivity of test specimen.

When the final outflows of dry mixtures 20%-30% ZBM and 20% SBM were compared, it was observed that the color of 20% SBM at 0.322 PVF was lighter than the color of 20% ZBM at 0.97 PVF and 30% ZBM at 0.483 PVF (Figure 5.25). Hence, the lowest HC value was obtained for 20% SBM (1.4×10^{-9} cm/s). Similar conclusions can be drawn for dry mixtures of bentonitic mixtures as shown in Figure 5.26.

When 10% and 20% SBM are taken into consideration, it is seen that outflow of 20% SBM had lighter colors. The greater the bentonite content the lower is the hydraulic conductivity. Increase in the bentonite content in SBMs led to decrease the hydraulic conductivity and hence, increase the reaction time to filter the landfill leachates.

There are some observations made about the smell of the outflow liquids. Outflows of SBM have tangy and nauseous smell. On the other hand, unpleasant smells of leachate liquids were eliminated better with ZBM filtrations.



Inflow sample **Outflow samples**

(a)

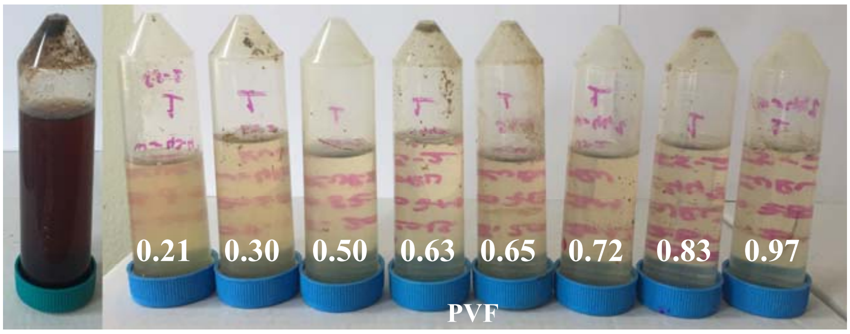
Inflow sample **Outflow samples**

(b)

Inflow sample **Outflow samples**

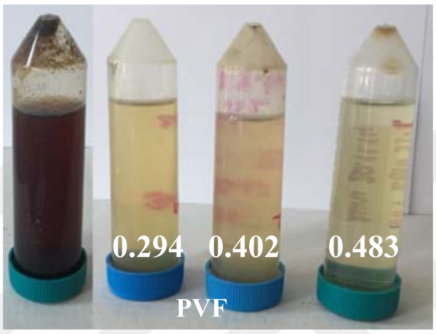
(c)

Figure 5.24 Outflow samples of ZBM and SBM during hydraulic conductivity experiments permeated with LL-B: a) 20% ZBM (wet), b) 30% ZBM (wet), c) %10 SBM (wet).



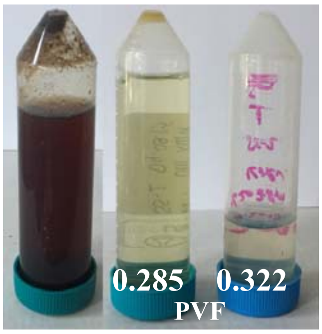
Inflow sample **Outflow samples**

(a)



Inflow sample **Outflow samples**

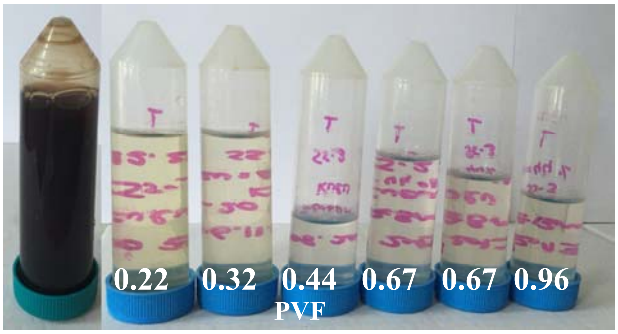
(b)



Inflow sample **Outflow samples**

(c)

Figure 5.25 Outflow samples of ZBM and SBM during hydraulic conductivity experiments permeated with LL-A: a) 20% ZBM (dry), b) 30% ZBM (dry), c) %20 SBM (dry).



Inflow sample **Outflow samples**

(a)

Inflow sample **Outflow samples**

(b)

Inflow sample **Outflow samples**

(c)

Figure 5.26 Outflow samples of ZBM and SBM during hydraulic conductivity experiments permeated with LL-B: a) 20% ZBM (dry), b) 30% ZBM (dry), c) %20 SBM (dry).

5.2.2.4 pH and Electrical Conductivity Measurement of Percolated Fluids from SBM

pH and EC ratios of 10% SBM and 20% SBM are shown in Figure 5.27 and Figure 5.28, respectively. According to the test results obtained from 10% and 20% SBM with LL-A permeation, pH values were determined between the allowable limits (Figure 5.27a and Figure 5.28a). However, EC ratios were 0.5 for 10% SBM and 0.7 for 20% SBM at the final stage (Figure 5.27a and Figure 5.28a). These values are considerably less than the allowable limits.

On the other hand, only two samples of LL-B outflow could be obtained while SBM was tested (Figure 5.27b and Figure 5.28b). It was determined that the pH values were within the allowable ranges, however the EC ratios were less 1.0±0.1. The obtained results are in agreement with the ZBM tests carried out with LL-B (Figure 5.13 and Figure 5.14).

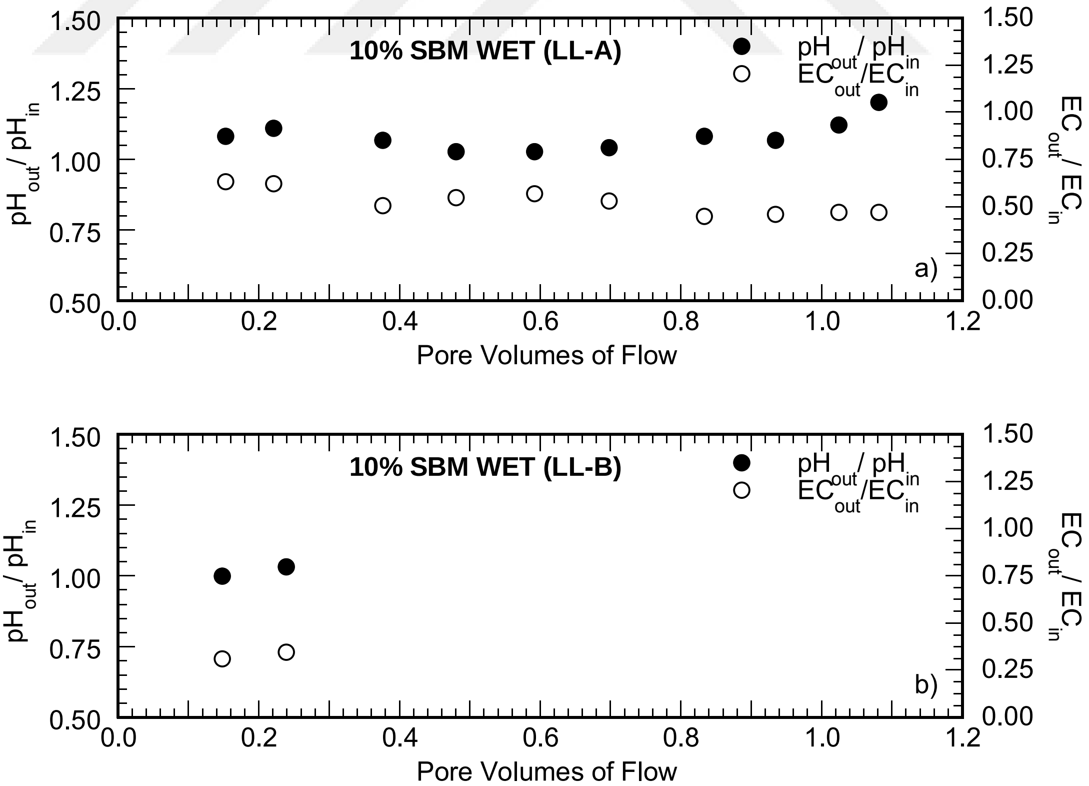


Figure 5.27 pH and EC ratios of 10% SBM prepared by wet mixing method and permeated with: a) LL-A and b) LL-B.

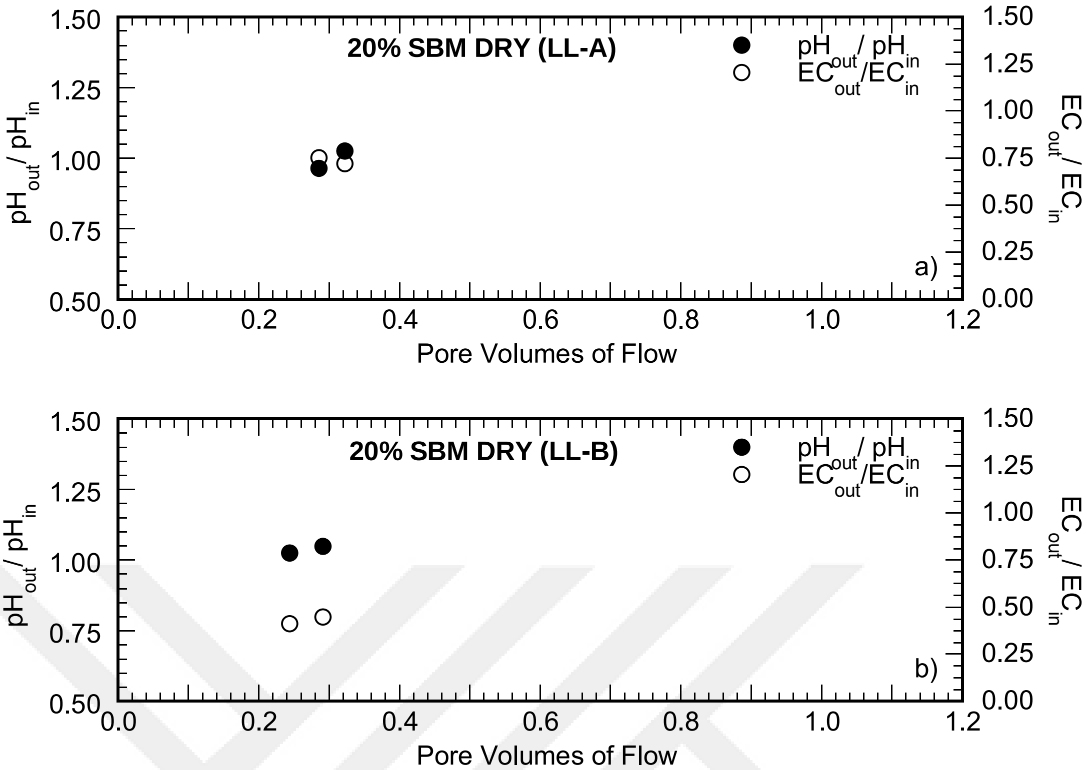


Figure 5.28 pH and EC ratios of 20% SBM prepared by dry mixing method and permeated with: a) LL-A and b) LL-B.

CHAPTER SIX
CONCLUSIONS

This study investigates and discusses the hydraulic conductivities of ZBMs and SBMs in terms of bentonite content, leachate type and mixing methods. The findings are summarized below:

- In the case of dry mixing method, 30% ZBM had higher γ_{dmax} and lower w_{opt} than 20% ZBM. This difference between the compaction parameters can be considered as insignificant. In the case of wet mixing method, it is seen that the compaction curves of 30% ZBM and 20% ZBM overlapped.

- ZBMs had lower γ_{dmax} and higher w_{opt} when compared to the compaction parameters of any natural soil. Compaction behavior of ZBMs were considerably different from SBMs as well. ZBMs had lower dry unit weights (9.5-11.0 kN/m^3) and greater optimum water contents (%25-%55).

- The compaction parameters (γ_{dmax} and w_{opt}) of ZBMs and SBMs obtained throughout this study were in agreement with those of data reported in literature.

- The hydraulic conductivity tests, which were carried out on ZBMs, reached stable values after a certain period. The differences between the initial and final hydraulic conductivities were within the range of 10-200. This shows the necessity of long-term tests when landfill leachates are of interest as the permeant.

- The differences between the hydraulic conductivities of 20% ZBM and 30% ZBM were very low. This indicates that the bentonite content has limited effect on the hydraulic conductivity of ZBM.

- The effect of mixing method (dry and wet) on the hydraulic conductivity of ZBM is limited. This result is in line with the compaction test results.

- Considering the same PVFs, ZBMs permeated with LL-B had almost 3.0 times greater hydraulic conductivities than ZBMs permeated with LL-A.

- Hydraulic conductivities of ZBMs are less than 1.0×10^{-7} cm/s which is allowable maximum limit for landfill liners suggested by many environmental regulatory agencies. Thus, it can be argued that landfill leachates used in this study had no important effect on the hydraulic conductivity of ZBMs.

- The hydraulic conductivity of 10% SBM was almost the same as with the hydraulic conductivities of 20% and 30% ZBMs when permeated with LL-A. However, the hydraulic conductivity of 10% SBM to LL-B was lower than the hydraulic conductivities of 20% and 30% ZBMs to LL-B.

- Among others, 20% SBM prepared by dry mixing method had the lowest hydraulic conductivity to LL-A and LL-B. This is due to the rather greater bentonite content used in SBM.

- It was observed that ZBMs had an excellent leachate filtering performance than SBMs. Colors of outflow liquids were lighter and brighter for ZBMs. Additionally unpleasant smells of leachates were eliminated better with ZBMs.

- pH_{out}/pH_{in} and EC_{out}/EC_{in} ratios were determined on ZBM and SBM inflow and outflow liquids. The results showed that chemical equilibrium was provided for pH values, whereas it was not provided for EC. The equilibrium level varies with leachate type for EC. Equilibrium was partially provided for LL-A but the results are unstable for LL-B.

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