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Effect of Chemicals on Geotechnical Properties of Clay Liners: A Review

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Abstract: This study presents a review of recent research on the geotechnical properties (consistency limits, hydraulic conductivity, shear strength, swelling, and compressibility) of clay liners conducted with organic and inorganic chemicals. Due to its low permeability, a clay liner is the main material used in solid waste disposal landfills. It is exposed there to various chemical, biological and physical events, and the clay liner is affected by the resulting leachate. The geotechnical properties of clay liners are closely related to the chemistry of the leachate. Therefore, when attempting to define the geotechnical characteristics of clay liners, the use of distilled water or tap water is far from being representative of the in-situ conditions.

Key words: Clay liners, geotechnical properties, hydraulic conductivity, leachate

INTRODUCTION

Because population increase leads to an increase in consumption, waste disposal has become one of the most serious of modern environmental problems in developed and developing countries all over the world. One of the preferred methods of dealing with this kind of environmental problem is to dispose of the waste in sanitary landfills (Arasan and Yetimoglu, 2008). Because of its low permeability, a clay liner is the main material used in such landfills. However, compacted clays can have problems with shrinkage and/or desiccation cracking especially those containing an appreciable amount of bentonite. Many studies have shown that compacted clays undergo large changes in physicochemical properties when exposed to shrink-swell and/or freeze-thaw cycling (Othman and Benson, 1993; Benson and Othman, 1993; Othman *et al.*, 1994; Benson *et al.*, 1995; Abdullah *et al.*, 1999; Kaya and Durukan, 2004).
Another alternative material to earthen liners for contaminant confinements is Geosynthetic Clay Liners (GCLs). GCLs are geocomposites consisting of a thin layer of dry bentonite placed between two geotextiles or glued to a geomembrane. Especially, bentonite clays are preferred, because of its fine particle size and consequent micro pores and high surface charges; it possesses low hydraulic conductivity and a high adsorption capacity (Sivapullaiah *et al.*, 2000). When exposed to water, the bentonite in the GCL hydrates and swells to form a thin layer having low hydraulic conductivity (Kraus *et al.*, 1997). There are many studies indicating that GCLs can be successfully employed to reduce leachate migration; however, they are not preferred because of their relatively high cost and uncertainty in their future performance (Ruhl and Daniel, 1997; James *et al.*, 1997; Petrov *et al.*, 1997; Shan and Lai, 2002). The desirable characteristics, such as low hydraulic conductivity, of a barrier may change due to temperature and moisture fluctuations (Kaya and Durukan, 2004).

According to The United States Environmental Protection Agency (USEPA), the compacted soil liner must be at least approximately 60 cm thick and must have a hydraulic conductivity of no more than $1x10^{-7}$ cm/sec (Anonymous, 1993). Additionally, according to The Turkish Solid Waste Disposal Regulation the compacted soil liner must be at least 0,6 m thick and must have a hydraulic conductivity of no more than $1x10^{-6}$ cm/sec (Anonymous, 1991). To meet this requirement, certain characteristics of soil material should be met (Qian *et al.*, 2002). First, the soils should contain at least 15-20% of silt or clay-sized material. Secondly, the Plasticity Index (PI) should be greater than 10%. Soils with very high PI, greater than 30 to 40%, are sticky and are difficult to work with. Also high PI soils form hard clumps when the soils are dry and difficult to break down during compaction. Thirdly, the coarser fragments should be screened to no more than about 10% gravel-size particles (Sivapullaiah and Lakshmikantha, 2004).

On the other hand, clay liners are now commonly used to limit or eliminate the movement of leachate and landfill gases from the landfill site. The liners are exposed there to various chemical, biological and physical events, and they are affected by the resulting leachate. To assess the durability of the liner material, it is important to study the chemical compatibility of the liner material with different pore fluids, or the leachate that the liner may be subject to (Mitchell and Jaber, 1990; Olson and Daniel, 1981; Kaya and Fang, 2000; Mitchell and Madsen, 1987; Sivapullaiah and Lakshmikantha, 2004). In this sense, when attempting to define the geotechnical characteristics of clay liners, the use of distilled water or tap water is far from being representative of the in-situ

Table 1: Typical compositional properties of leachate in landfills

		Robinson and Maris(1979)	Ehrig (1988)	Hohl (1992)	Tchobanoglous *et al.* (1993) New landfill (less than 2 years)	Tchobanoglous *et al.* (1993) Mature landfill (greater than 10 years)	Kruse (1994)	Timur (1996)	Kjeldsen *et al.* (2002)
pH		6.2-7.6	4.5-9	4.5-9	4.5-7.5	6.6-7.5	6.2-8.3	7.3-7.8	4.5-9
Constituent					Concentration (mg/lt)				
Organic	COD	66-11600	500-60000	500-60000	3000-60000	100-500	460-40000	14900-19980	140-152000
Carbon	BOD_5	2-8000	20-40000	20-40000	2000-30000	100-200	20-27000	6900-11000	20-57000
Constituent	TOC	21-4400	-	100-5000	1500-2000	80-160	150-1200	4550-6000	30-29000
Nitrogen	Org.N	0.9-160	10-4250	-	10-800	80-120	-	-	14-2500
Constituent	NH_3-N	5-730	30-3000	30-3000	10-800	20-40	-	1120-2580	50-2200
	Cl^-	43-2800	100-5000	-	200-3000	100-400	315-12400	5620-6330	150-4500
Anions	PO_4^{2-}	0.02-4.4	-	-	5-100	5-10	-	-	0.1-23
	SO_4^{4-}	55-460	10-1750	10-1750	50-1000	20-50	20-2500	142-352	8-7750
	Na	43-2500	50-4000	-	200-2500	100-200	1-6800	-	70-7700
Metals	Mg	12-480	40-1150	-	50-1500	50-200	25-600	363.8-640	30-15000
	K	20-650	10-2500	-	200-1000	100-200	170-1750	-	50-3700
	Ca	130-1200	10-2500	10-2500	200-3000	100-400	49-2300	97-787.5	10-7200
	Mn	0.19-26	0.03-60	-	-	-	-	0.11-5.3	0.03-1400
	Fe	0.09-380	3-2100	3-2100	50-1200	20-2000	2-500	14.2-44	3-5500
	Cr	0.005-0.14	0.03-1.6	30-1600	-	-	0.002-0.53	0.02-0.78	0.02-1.5
Heavy	Ni	0.02-0.16	0.02-2.05	20-2050	-	-	0.01-1	0.32-0.45	0.015-13
Metals	Cu	0.004-0.15	0.04-1.4	4-1400	-	-	0.005-0.56	0.02-0.13	0.005-10
	Zn	0.02-0.95	0.03-120	0.03-120	-	-	0.05-16	0.38-1.06	0.03-1000
	Cd	0.002-0.13	0.0005-0.14	0.5-140	-	-	0.0007-0.525	0.01	0.0001-0.4
	Pb	0.003-0.22	0.008-1.02	8-1020	-	-	0.008-0.4	0.04	0.001-5

conditions. For this reason, to properly use the compacted clays as impermeable liners, more theoretical and experimental study is needed to investigate the variation of engineering properties with chemicals (Yilmaz *et al.*, 2008a). This study presents a review of recent research on the geotechnical properties (consistency limits, hydraulic conductivity, shear strength, swelling, and compressibility) of clay liners conducted with organic and inorganic chemicals.

LANDFILLS LEACHATE

In most countries, sanitary landfills are nowadays the most common way to eliminate Municipal Solid Wastes (MSW). In spite of many advantages, generation of heavily polluted leachate, presenting significant variations in both volumetric flow and chemical composition, constitutes a major drawback (Renou *et al.*, 2008). Leachate may be defined as liquid that has percolated through solid waste and has extracted, dissolved or suspended materials. In most landfills leachate is composed of the liquid that has entered the landfill from external sources, such as surface drainage, rainfall, groundwater, and water from underground springs and the liquid produced from the decomposition of the wastes, if any. When water percolates through solid wastes that are undergoing decomposition, both biological materials and chemical constituents are leached into solution. The chemical composition of the leachate will vary greatly depending on the age of the landfill and the events before the time of sampling (Tchobanoglous *et al.*, 1993). A large body of work on the chemical composition of landfill leachate can be found in Ehrig (1988), Tchobanoglous *et al.* (1993), Vadillo *et al.* (1999), Kjeldsen *et al.* (2002), Jorstad *et al.* (2004), Aghamohammadi *et al.* (2007), Oshode *et al.* (2008), Renou *et al.* (2008) and Øygard (2009). Typical data on the composition of leachate suggested by different researchers have been summarized in Table 1 (Arasan and Yetimoglu, 2006; Arasan and Yetimoglu, 2008).

The constituents of leachate can be divided into subgroups of organic carbon compounds, nitrogen compounds, anion, and metal groups. Nitrogen compounds of greatest interest to water quality are those that are biologically available as nutrients to plants or exhibit toxicity to humans or aquatic life. Total ammonia (NH_3 + NH_4^+) in drinking water is more of an esthetic than a health concern. Chlorides are widely distributed in nature, usually in the form of sodium, potassium, and calcium salts (NaCl, KCl and $CaCl_2$) although many minerals contain small amounts of chloride as an impurity. Concentrations in unpolluted surface waters and non-geothermal ground waters are generally low, usually below 10 mg/L. Thus chloride concentrations in the absence of pollution are normally less than those of sulfate or bicarbonate. Sulfate minerals are widely distributed in nature, and the sulfate anion (SO_4^{2-}) is a common constituent of unpolluted water. The USEPA has established a secondary drinking water standard for sulfate of 250 mg/L based on aesthetic effects such as taste and odor. Because water molecules are polar, metal cations always attract a hydration shell of water molecules by electrostatic attraction to the positive charge of the cation. Copper occurs in drinking water primarily due to corrosion of copper pipes and things, which are widely used for interior plumbing of residences and other buildings. Copper is an essential nutrient, but at high doses it has been shown to cause stomach and intestinal distress, liver and kidney damage, and anemia. In the aquatic environment, iron is present in two oxidation states: ferrous (Fe^{2+}) and ferric (Fe^{3+}). The USEPA has no primary drinking water standard for iron. The USEPA secondary drinking water standard (non-enforceable) is 0,3 mg/L as total iron (Weiner, 2000).

Effect of chemicals on geotechnical properties: In the following, the effects of chemicals on the geotechnical properties for clay liners are compared with those from studies in the literature and discussed.

Consistency limits: The consistency limits (Atterberg limits) have been repeatedly shown to be useful indicators of clay behavior (Jefferson and Rogers, 1998). It should be pointed out that there has not been a general consensus regarding the effect of chemicals on the consistency limits of clays. Arasan and Yetimoglu (2006, 2008), based on their experimental study on a CL clay, pointed out that both the liquid limit and the plastic limit somewhat increased when the concentration of salt solutions was increased. Furthermore, Park *et al.* (2006) studied the effects of surfactants (octylphenol polyoxyethylene, biosurfactant, and sodium dodecyl sulfate) and electrolyte solutions ($NaPO_3$ and $CaCl_2$) on some properties of two soil samples (100% kaolinite clay soil, and 30% kaolinite + 70% sand). They found that $CaCl_2$ solution did not affect the liquid limit significantly but decreased the plasticity index of kaolinite soil. Similarly, Sivapullaiah and Manju (2005) investigated the same geotechnical properties of a low plasticity soil (w_L= 38%) using NaOH solution. They reported that the liquid limit of the test soil was increased with increasing NaOH concentration due to forming new swelling compounds. Rao and Mathew (1995), based on their experimental study with marine clay, indicated that the clay particles were dispersed when the clay interacted with chemicals. Due to dispersion and deflocculation of clay, the geotechnical properties (especially, hydraulic conductivity) of clay were significantly changed. Hence, the increase in consistency limits could be attributed to dispersion of the clay particles when CL clay was permeated with salt solutions. Additionally, salt solutions might cause to form new swelling compounds and these new compounds might have increased the liquid limit of CL clay as indicated in Sivapullaiah and Manju (2005).

Contrasts to the findings of CL (low plasticity) clays, some researchers have indicated that the liquid limit decreased with increasing salt concentration for CH clays (Sridharan *et al.*, 1986; Bowders and Daniel, 1987; Daniel *et al.*, 1988; Acar and Olivieri, 1989; Edil *et al.*, 1991; Shackelford, 1994; Gleason *et al.*, 1997; Petrov and Rowe, 1997; Lin and Benson, 2000; Sridharan and Prakash, 2000; Schmitz *et al.*, 2004). Gleason *et al.* (1997) also investigated the consistency limits of Ca and Na-bentonite with different concentration of $CaCl_2$ (varying between 0.01M and 0.735M), NaCl (varying between 0.01M and 0.1M), and methanol (pure methanol and 50% methanol in distilled water), and gasoline. They reported that, when mixed with a strong $CaCl_2$ solution, calcium and sodium bentonite had approximately the same liquid limit and plasticity index.

Petrov and Rowe (1997) showed that the liquid limit of a bentonite from a GCL decreased from 530 to 96 as the sodium chloride (NaCl) concentration of the testing solution increased from 0 (i.e., water) to 2.0 M. Lee *et al.* (2005) also investigated the effect of $CaCl_2$ solutions with concentration of 5, 10, 20, 50, 100, 500 mM on the liquid limits of GCL's. Similar studies were carried out by van Paassen (2002), di Maio (1996) and Schmitz *et al.* (2004). They determined a reduction in liquid limits of bentonite and colclay (i.e., an industrial smectite clay) when NaCl, KCl and $CaCl_2$ solutions at different concentrations (varying between 0.01 and 4M) were added. Therefore, it could be said that the salt solutions tended to reduce the thickness of the DDL and flocculate the CH clay particles, resulting in a reduction of liquid limit of CH clay. Sridharan *et al.* (2002), studying three marine clays, reported that the liquid limit of Isahaya clay increased with increasing ion concentration; whereas the liquid limit of the other two clays decreased as concentration increased. This behavior has been explained with the flocculation mechanism of kaolinite (nonswelling) clays and Diffuse Double Layer (DDL) theory by the authors. Similarly, Bowders and Daniel (1987) advocated that the many chemicals tended to reduce the thickness of the Diffuse Double Layer (DDL), causing the soil skeleton to shrink and decrease in repulsive forces, thus promoting flocculation of clay particles, and to dehydrate interlayer zones of expandable clays, which subsequently became gritty or granular. Also, Sharma and Lewis (1994) reported that the net electrical forces between clay mineral layers were affected by the concentration and valence of cations. They indicated that increasing cation concentration or cation valence would result in a decrease in net repulsive forces; hence causing clay particles to flocculate.

On the other hand, several researchers have reported that chemical solutions at low concentrations are more effective than at high concentrations for CH clays (Gleason *et al.*, 1997; Alawaji, 1999; Jo *et al.*, 2001). Shackelford *et al.* (2000), Jo *et al.* (2001) and Kolstad *et al.* (2004a) reported that the effects of the divalent and trivalent cations on the clays were different from those of monovalent cations. Shackelford *et al.* (2000) indicated that the thinnest double layer and the smallest swell were obtained with trivalent cations, while monovalent cations had little effect on the thickness of the double layer and the swelling. Similarly, Mishra *et al.* (2005) reported that the divalent cations were more effective than the monovalent cations from the standpoint of permeability and compressibility of mixtures of ballast soil and bentonite permeated with NaCl and $CaCl_2$ solutions.

Clay liners are also affected by temperature of the resulting leachate. The degradation of organic matter within the waste mass is an exothermic process that may result in significant heat generation. Under certain conditions, the heat generated by this process may raise the temperature within the waste mass to 70ºC, with corresponding temperatures in the vicinity of the landfill base in excess of 50ºC (Koerner, 2001; Yoshida and Rowe, 2003). Hence, definition of the geotechnical properties of clays using distilled water and tab water at laboratory temperature is far from mimicking land conditions. The leachate and temperature variations are affected significantly the geotechnical properties of clay liners (Schmitz *et al.*, 2004; Romero *et al.*, 2001). Investigation of the effects of temperature and leachate on the behavior of clay or geosynthentetic clay liners in the landfills is very significant. However, a limited number of studies focused on the effect of temperature on the geotechnical properties of clays (Romero *et al.*, 2001; Villar and Lloret, 2004; Villar *et al.*, 2005). Hamutcu *et al.* (2008) indicated that the variation in liquid limit with increasing concentration and temperature of salt solutions is insignificant for CL clays. However, Kurt *et al.* (2007) indicated that the liquid limit of CH clay decreased with increasing concentration and temperature of NaCl and KCl salt solutions. Additionally, Hamutcu *et al.* (2008) reported that the liquid limit of CH clay with distilled water increased when the temperature was increased. Jefferson and Rogers (1998) also reported that the liquid limit of high plasticity smectite clay increased with increasing of temperature. Therefore, it could be said that the temperature and salt solutions tended to reduce the thickness of the Diffuse Double Layer (DDL) and flocculate the CH clay particles, resulting in a reduction in liquid limit of CH clay and the concentration of salt solutions has a more significant effect than temperature in the solid waste disposal landfills.

Hydraulic conductivity: It is well known that the hydraulic conductivity of clays can be strongly affected by the clay-fluid system interaction (Mitchell, 1993). A great number of experimental studies dealing with the effects of chemicals on hydraulic conductivity of GCLs and clays are available in the literature. Some of these studies focused on inorganic liquids (Daniel, 1993; Gleason *et al.*, 1997; James *et al.*, 1997; Petrov and Rowe, 1997; Petrov *et al.*, 1997a; Lin and Benson, 2000; Shackelford *et al.*, 2000; Egloffstein, 2001; Jo *et al.*, 2001; Vasko *et al.*, 2001; Jo *et al.*, 2004; Kolstad *et al.*, 2004a; Lee *et al.*, 2005; Lee and Shackelford, 2005; Jo *et al.*, 2005; Mishra *et al.*, 2005; Yılmaz *et al.*, 2008a, b). The other studies focused on organic liquids (Anderson *et al.*, 1985; Foreman and Daniel, 1986; Bowders and Daniel 1987; Fernandez and Quigley, 1989; Kaya and Fang 2000; Anandarajah, 2003; Park *et al.*, 2006; Yong *et al.*, 2007), and leachate components (Ruhl and Daniel, 1997; Kayabalı and Mollamahmutoglu, 2000; Shan and Lai, 2002; Kolstad *et al.*, 2004b). Most of the researchers pointed out that the hydraulic conductivity increased when the concentration of chemical solutions was increased for high plasticity clays. In some cases, interactions between the permeating liquid and the clay can result in significant increases (>10x) in the hydraulic conductivity of the clay relative to that based on water (Mitchell and Madsen, 1987; Shackelford, 1994; Shackelford *et al.*, 2000).

Most of the researchers were focused on the investigation of the hydraulic conductivity of higher activity clays such as bentonite or Geosynthetic Clay Liners (GCL's). Petrov and Rowe (1997) investigated how NaCl solutions of varying concentration affected the hydraulic conductivity of a GCL containing Na-bentonite. Tests were conducted with distilled (DI) water and NaCl solutions having concentrations between 0.1-2.0 M. Hydraulic conductivity of the GCL generally increased as the NaCl concentration increased. At 2.0 M, the hydraulic conductivity was as much as 800 times higher than that with distilled water. Jo *et al.* (2001) investigated hydraulic conductivity and swelling of non-prehydrated GCLs permeated with single-species salt solutions such as LiCl, NaCl, KCl, $CaCl_2$, $MgCl_2$, $ZnCl_2$, $CuCl_2$ and $LaCl_3$. Jo *et al.* (2005) conducted experimental tests to research long-term hydraulic conductivity of a geosynthetic clay liner permeated with some inorganic salt solutions (i.e., NaCl, KCl and $CaCl_2$). Shackelford *et al.* (2000) studied the hydraulic conductivity of GCLs permeated with non-standard liquids such as NaCl, $ZnCl_2$ and $CaCl_2$. Lee *et al.* (2005) used $CaCl_2$ as the testing liquids for the determination of the hydraulic conductivity of geosynthetic clay liners. All of the researchers pointed out that the hydraulic conductivity of bentonite clay or GCL's increased when the concentration of salt solutions was increased.

Some researchers also compared the quality of clays on interaction with chemicals. Gleason *et al.* (1997) investigated some geotechnical properties of Ca and Na-bentonite with different concentrations of $CaCl_2$ (varying between 0.01 and 0.735 M), NaCl (varying between 0.01 and 0.1 M), and methanol (pure methanol and 50% methanol in distilled water), and gasoline. They reported that calcium bentonite would be more resistant than sodium bentonite to chemical constituents in the permeating fluids. Also, it was concluded that permeation with a strong calcium chloride solution would cause large increases in the hydraulic conductivity of sodium bentonite. Similarly, Stern and Shackelford (1998) investigated the substitution of attapulgite clay for bentonite in a sand-bentonite mixture on interaction with $CaCl_2$ solutions. They reported that for mixtures with the same clay soil content, complete substitution of attapulgite clay for bentonite significantly decreased the change in hydraulic conductivity relative to that observed for the sand-bentonite mixtures upon permeation with a 0.5M $CaCl_2$ solution. Another similar study was conducted by Lee and Shackelford (2005). The authors studied the impact of bentonite quality on the hydraulic conductivity of geosynthetic clay liners. They observed that the hydraulic conductivity for high-quality bentonite (k_H) is lower than the hydraulic conductivity for low-quality bentonite (k_L), when specimens are permeated with water. However, k_H is always higher than that for k_L when the specimens are permeated with the $CaCl_2$ solutions. Thus, the GCL with the higher-quality bentonite is more susceptible to chemical attack than the GCL with lower-quality bentonite.

Consequently, it could be said that, the increase in hydraulic conductivity when the concentration of the salt solutions was increased is attributed to the decrease in the thickness of DDL, resulting in flocculation of the clay particles. Quigley (1993) indicated that clay minerals might undergo large interlayer shrinkage in contact with certain chemicals. This is accompanied by enormous loss in Diffuse Double Layer (DDL) thickness, potential cracking, and increase in hydraulic conductivity values. The thickness of the DDLs is an important controlling factor for the structural development, hydraulic conductivity, and other physico-chemical and mechanical properties of soils (Mitchell, 1993; Fukue *et al.*, 1999). Additionally, the thickness of DDLs around clay particles is governed by the concentration of salt and type of cation(s) in the soil water (van Olphen, 1963). As indicated by Gouy-Chapman theory, the thickness of the DDL decreases as the ion concentration increases, resulting in flocculation of the clay particles and larger pore channels through which flow can occur (Mitchell, 1993; Gleason *et al.*, 1997; Kaya and Durukan, 2004). Furthermore, Bowders and Daniel (1987) advocated that the many chemicals tended to reduce the thickness of the DDL, causing the soil skeleton to shrink and causing a decrease in repulsive forces, thus promoting flocculation of clay particles, and to dehydrate interlayer zones of expandable clays, which subsequently became gritty or granular. Kaya and Fang (2000) also indicated that as repulsive forces decreased, the soil particles tended to flocculate and form aggregates due to attractive forces among particles, leading to a net increase in the effective flow area, resulting in increased hydraulic conductivity of the soil-pore fluid.

Flocculated and dispersed structures have different hydraulic conductivities. The thickness of the diffused double layer can influence the soil structure, resulting in permeability changes. The thickness of this diffused double layer can be affected by parameters such as the dielectric constant of the medium, cation valence, electrolyte concentration, and so on. When fluids containing various chemicals or leachate permeate underlying clay liners, they may change various factors that can influence the thickness of the diffused double layer and hence the permeability of the permeated clays (Sharma and Levis, 1994). According to the double layer theories (Mitchell, 1993), a decrease in the fluid's dielectric constant decreases the double-layer thickness, allowing clay particles to approach closer to each other. This leads to shrinkage of soil clusters. Similarly, many investigators indicated that liquids with low dielectric constant may cause the clays to shrink. Shrinkage can lead to cracking and large increases in hydraulic conductivity (Gleason *et al.*, 1997; Ruhl and Daniel, 1997; Kaya and Fang, 2000).

It should be also pointed out that the hydraulic conductivity of clays permeated with chemical solutions depends on many other several possible parameters. Some studies have shown that permeation with either strong ($\geq$50 mM) solutions or solutions containing a large fraction of polyvalent cations can cause the hydraulic conductivity of GCLs to increase one order of magnitude or more. These studies also have shown that the hydraulic conductivity of GCLs permeated with weak ($\leq$20 mM) solutions tends to be comparable to the hydraulic conductivity obtained with deionized (DI) or tap water. However, the durations of most tests employing weak solutions typically have been too short (<0.5 year and 10 pore volumes of flow) to establish chemical equilibrium (Shackelford *et al.*, 2000). Cation valence is also parameter which affects the hydraulic conductivity of GCL and very high plasticity clays such as bentonite. In this sense, Shackelford *et al.* (2000), Jo *et al.* (2001) and Kolstad *et al.* (2004b) reported that the effects of the divalent and trivalent cations on the bentonite were different from those of monovalent cations. As a result, comparison of hydraulic conductivity (k) for different salt solutions showed that the divalent cations had more effect than monovalent cation (Mishra *et al.*, 2005). However, the results of Yilmaz *et al.* (2008b) indicated that the hydraulic conductivity of CH clay is not significantly affected by the cation valence of salt solutions. The difference between the findings of Yilmaz *et al.* (2008b) and the findings in the literature could be attributed to the differences in the type of the permeameter and the plasticity of clays. Shackelford *et al.* (2000), Jo *et al.* (2001) and Kolstad *et al.* (2004b) used flexible-wall permeameters in their experimental study, following the procedures described in ASTM D5084. But Yilmaz *et al.* (2008b) was conducted with rigid-wall permeameters, following the procedures described in ASTM D5856. Foreman and Daniel (1986) indicated that the type of the permeameter had little effect when the soils were permeated with water. They also indicated that the type of the permeameter affected the hydraulic conductivity values when the soils were permeated with organic compounds. Furthermore, Shackelford *et al.* (2000) and Kolstad *et al.* (2004b) used GCLs while Jo *et al.* (2001) used bentonite which had a liquid limit of 746%. However, the CL and CH clays used in Yilmaz *et al.* (2008b) had liquid limit of 40 and 113%, respectively. The clay mineralogy and liquid limit are seen among the most influencing parameters (Arasan and Yetimoglu, 2006).

In comparison with high plasticity clays, there are a limited number of studies in the literature on the effects of chemical solutions on the hydraulic conductivity of low plasticity clays. Park *et al.* (2006) studied the effects of surfactants (octylphenol polyoxyethylene, biosurfactant, and sodium dodecyl sulfate) and electrolyte solutions ($NaPO_3$ and $CaCl_2$) on some properties of two soil samples (100% kaolinite clay soil, and 30% kaolinite + 70% sand). They found that chemical solutions did not significantly affect the hydraulic conductivity. Yilmaz *et al.* (2008a, b) studied the effect of inorganic salt solutions (NaCl, NH_4Cl, KCl, $CaCl_2$ and $FeCl_3$) on the hydraulic conductivity of CL and CH class clays. It was indicated that the hydraulic conductivity decreased when the concentration of the salt solution was increased for CL clays. Similarly, some experimental tests on kaolinite clay showed that hydraulic conductivity decreased when clay samples were permeated with chemical solutions such as acetone, benzene, diethylene glycol, nitrobenzene, phenol (Dragun, 1988). Rao and Mathew (1995), based on their experimental study with marine clay, indicated that the reduction in hydraulic conductivity was related to the dispersion and deflocculation of clay. Also, Park *et al.* (2006), after conducting an experimental study on low plasticity kaolinite clay, reported that the hydraulic conductivity was not significantly affected, but slightly decreased due to pore clogging and the high viscosity of the solutions. Similarly, Petrov *et al.* (1997) determined that for ethanol concentrations less than 50%, the hydraulic conductivity of the GCL decreased due to the increase in viscosity. Hence, the decrease in hydraulic conductivity could be attributed to dispersion of the clay particles when CL clay was permeated with inorganic salts. It could be also said that the decrease in hydraulic conductivity is due to formation of new swelling type of compounds as well (Sivapullaiah and Manju, 2005).

Shear strength: The shear strength of the landfill is an important parameter. The liner material should be strong enough to sustain the static load exerted by the overlying body of waste (Kenney *et al.*, 1992; Tuncan *et al.*, 1998). Limited information is currently available on the shear strength of clay liners interacted with chemicals. However, some of the researchers were focused on the investigation of the shear strength of lower activity clays such as kaolinite, sub soil or red earth. Ayininuola *et al.* (2009) investigated the shear strength of subsoil saturated with $CaSO_4$ at different concentrations. The laboratory results of this study showed that there were initial increments in soil angle of friction and cohesion due to presence of $CaSO_4$ salt. Similarly, Sivapullaiah and Lakshmikantha (2005) researched the utilization of Indian red earth (kaolinitic soil) as a liner material with bentonite and lime addition. It was found that the peak stress of the liner in NaOH and water are higher than those of HCl and NaCl. They indicated that the lower strength of the soil with NaCl solutions was due to reduction in soil cohesion by reduced water adsorption capacity consequent on reduced thickness of the diffused double layer. Park *et al.* (2006) also indicated the addition of the electrolyte solutions (Triton X-100 and biosurfactant) caused an increase in electrolyte concentration, which decreased the double layer thickness. The large increase in interparticle attraction made possible by the reduction of the diffuse double layer was responsible for the flocculation of the clay mixture on mechanical remolding. This effect resulted in increased strength of kaolinite mixtures. Similar to the low plasticity clay, Sharma and Levis (1994) reported that the internal friction angle of GCL was partially increased with mild leachate, harsh leachate and diesel fuel. Consequently, it could be said that, the increase in shear strength when the concentration of the solutions was increased is attributed to the changing in the thickness of DDL for clays.

Swelling and compressibility: In comparison to hydraulic conductivity studies, there are a limited number of studies in the literature on the effects of solutions on the swelling and compressibility of compacted clay liners. Also, it should be pointed out that there has not been a general consensus regarding the effect of chemicals on the swelling and compressibility of clay liners. Some researchers indicated that the increase in the chemical concentration shrinks the Diffuse Double Layer (DDL), resulting in a flocculation of the clay particles and reduces the swelling of the clays (Alawaji, 1999; Kolstad *et al.*, 2004a; Lee *et al.*, 2005). Di Maio (1996) investigated volume changes bentonite exposed to NaCl, KCl or CaCl solutions and reexposed to water. Exposure of specimens to saturated solutions produced large volume decreases. Bowders and Daniel (1987) advocated that the many chemicals tended to reduce the thickness of the DDL, causing the soil skeleton to shrink and causing a decrease in repulsive forces, thus promoting flocculation of clay particles, which subsequently became gritty or granular. Alawaji (1999) investigated the role of liquid chemistry on the swell and compressibility characteristics. Swell and compressibility were evaluated by oedometer test using various concentrations (0, 0.1, 0.5, 1, 4 N) of

$Ca(NO_3)_2$ and $NaNO_3$. The results indicated that swell potential (SP), swell time, swell pressure, and volume compressibility decreased with increasing of chemical concentrations for the two types of mixtures. The results of swell index tests on sodium bentonite from a GCL reported by Shackelford *et al.* (2000) and Jo *et al.* (2001) also showed that swell index of the bentonite was sensitive to the cation valence and/or electrolyte concentration in a manner that was consistent with changes in the thickness of the adsorbed layer of cations. Similarly, Arasan *et al.* (2007) reported that the swelling pressure decreased when the concentration of salt solutions increased for high plasticity clays. Mathew and Rao (1997) indicated that by increasing the valence of exchangeable cations in the homoionized clay the overall compression in the system is reduced and the preconsolidation pressure (p_p) is increased. It is further noticed in this study that an increase in liquid concentration reduces the coefficient of compressibility of the sand-bentonite mixture. Another remarkable research was conducted on Lateritic and Shedi soils (high plasticity soils) with NaCl solution by Nayak *et al.* (2010). The experimental results indicated that, maximum dry density of both the soils tested increases with NaCl added. The authors reported that this could be due to the reduction of double layer water surrounding the clay particles. The reduction of the double layer thickness brings the particles closer and hence the maximum dry density increases. Consequent on particles becoming closer and decreased water holding capacity the optimum water content decreases.

Contrasts to the findings of high plasticity clays, some researchers have indicated that the swelling potential of low plasticity clays increased with increasing the chemical concentrations (Arasan *et al.*, 2007). Some other experimental tests on kaolinite clay also showed that swelling index and swelling pressure increased with increasing the concentration of chemical solutions such as $Pb(NO_3)_2$, $Zn(NO_3)_2$ and NaOH (Sivapullaiah and Manju, 2005; Turer, 2007). Rao and Mathew (1995), based on their experimental study with marine clay, indicated that the clay particles were dispersed when the clay interacted with chemicals. Due to dispersion and deflocculation of clay, the geotechnical properties of clay were significantly changed. Hence, the increase in swelling pressures could be attributed to dispersion of the clay particles when CL clay was contaminated with salt solutions. Sivapullaiah and Manju (2005) also indicated that NaOH solution caused to formation of new swelling type of compounds (i.e., sodium aluminum silicate hydroxide hydrate-NASH) and these new compounds increased the swelling of clay. On the other hand, due to their low permeability, high plasticity clays (CH) are generally preferred in compacted clay liners. However, CH clays pose problems when they interact with chemicals in landfill leachate, leading to a reduction in their swelling capacity and increase in hydraulic conductivity. Thus their ability to perform a containment role diminishes with time (Daniel, 1993). In this sense, the increase in volume of expansive soils may be considered as a desirable behavior in many hydraulic containment applications such as soil barriers in landfill liner and backfilled vertical cutoff walls (Alawaji, 1999).

CONCLUSION AND RECOMMENDATION

The geotechnical properties of clay liners are closely related to the chemistry of the leachate. Therefore, this study presents a review of recent research on the geotechnical properties (consistency limits, hydraulic conductivity, shear strength, swelling, and compressibility) of clay liners conducted with chemicals. The following conclusions are made, based on the studies in the literature and on the discussion presented in this study:

- The chemicals significantly affect the geotechnical properties of clay and clay liners.
- There has not been a general consensus regarding the effect of chemicals on the geotechnical properties of clay and clay liners.
- The behavior of the low plasticity clays (CL and kaolinite clay) is different from the high plasticity clay (CH and bentonite clay).
- The liquid limit and swelling decreases with increasing chemical concentration for high plasticity clay. However, the liquid limit and swelling increases with increasing chemical concentration for low plasticity clay.
- The hydraulic conductivity increases with increasing chemical concentration for high plasticity clay. However, the hydraulic conductivity decreases with increasing chemical concentration for low plasticity clay.
- Limited information is currently available on the shear strength of clay and clay liners interacted with chemicals. However, it could be said that the shear strength of clays increases with chemicals.
- The effect of chemicals on the geotechnical properties may be explained by Diffuse Double Layer (DDL) and Gouy-Chapman theories. The chemical solutions tended to reduce the thickness of the DDL and flocculate the clay particles, resulting in reduction of liquid limit, reduction of swelling and increasing of hydraulic conductivity of high plasticity clays. However, the chemical solutions tended to increase the thickness of the DDL and disperse the clay particles, resulting in increasing of liquid limit, increasing of swelling and reduction of hydraulic conductivity of low plasticity clays.

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