TECHNICAL MEMO: POTENTIAL FAILURE MECHANISMS OF CLAY LINERS

It has been shown that much of the groundwater degradation of today originated from waste handling facilities of the past. This definite connection has given rise to a critical reevaluation of the materials and practices typically employed in the construction of such facilities.

In general, facilities such as landfills and surface impoundments have been designed and constructed to prevent the migration of fluid outside the facility. Clay has been used extensively as a barrier to fluid migration. Clay's usefulness for this purpose is derived from its inherent structure. This structure is a function of the particle arrangement and resultant pore spaces/interlayer spacing as established by the fine fraction of the soil. Soils are typically classified as clays if the fine fraction (particles less than 2 microns in size) is greater than 20 percent by weight. In general, clay soils with the greatest fine fraction can provide the lowest permeabilities. Based on its mineral makeup, both in composition and in structure, a clay can be characterized as either a Kaolinite, an Illite or a Smectite.

Kaolinites are made up of relatively large (as compared to other clays), and pure mineral particles with no internal cleavage. This lack of internal surfaces along with its natural purity, make kaolinitic clays quite invulnerable to changes in moisture content (i.e. lack shrink/swell tendencies). These same characteristics, coupled with a minimal cation exchange capacity, make kaolinite quite resistant to chemical activity as well.

Illites are also relatively inactive, with a cation exchange capacity approximately three times that of kaolinites, but only one fourth that of smectites (montmorillonites). Also, the crystalline structure of illite promotes rigidity and impedes water penetration, thereby limiting the swelling potential. Smectite has the smallest particle size of the three basic clay minerals. Its structure, involving areas of minimal cohesion between successive layers, allows for a high rate of chemical activity. Smectite exhibits the greatest surface area, cation exchange capacity and shrink-swell potential of the three types of clay. In water, it can absorb on its interlayer surfaces 300% of its solid phase weight. If this water is displaced by other liquids that yield a lower interlayer spacing, the potential for shrinkage can be of definite concern. Some of the essential properties of the three clays are tabulated in Table 1.

In many cases, smectite clays such as Na-montmorillonite, have been favored for use as liners due to their relative impermeability in the dispersed, hydrated state. However, the impermeability provided by such clays is readily lost when the easily exchangeable sodium ion is replaced by some other cation, such as calcium. This causes the original dispersed structure to flocculate and become more permeable, although less reactive. Applying this principle to the other clay types, one can readily see that kaolinite and illite, being less reactive, could provide a more stable liner than smectite. However, some of the same reasons for their stability, such as larger particle size and more rigid structure, denies them the impermeability obtainable with smectites.

Field experience and research activities have identified several failure mechanisms in clay liners. One such mechanism, alluded to above, involves the increase in permeability throughout the liner due to volume changes. These volume changes may occur in response to various conditions that have the potential to alter a clay's interlayer spacing. It has been shown that interlayer spacing is a characteristic of a particular soil/liquid system depending on the clay mineralogy, the nature of the dominant adsorbed cation, and the properties of the saturating liquid. Modifications to these dependant bases can, and will, alter the spacing.

For example, increasing the salt content of the saturating fluid from zero to 5.0 N NaCl was shown to reduce the original infinite spacing to less than 1.57 nanometers (Table 2) - At spacings below 1.5 nm, the clay tends to flocculate. This same effect can be correlated to the dielectric constant of the saturating liquid (see Table 3).

Another mechanism for failure of a clay liner involves the dissolution of portions of the clay itself. Clay minerals typically contain both silica and aluminum in large quantities. It has been shown that these components can be solubilized in even dilute basic and acidic solutions. A dramatic example of acid solubilization was presented by Pask et. al. (1945) when 3%, 11% and greater than 33% of the original alumina content was solubilized from kaolinite, ilite, and montmorillonite, respectively, when harshly exposed to an acid. Alkaline solutions have been shown to have a similar, but less dramatic, effect on silica.

Another concern regarding the effectiveness of clay liners was highlighted by Brown, Anderson, et. al. (1982), while studying the effects of organic liquids on compacted clay soils. They found that in nearly every case, the effectiv permeability of the soil increased significantly when the standard permeant (0.01N calcium sulfate) was replaced by organic fluids (see Figures 1-3). Although this research looked only at the effects of concentrated organics (some recent studies involving dilute solutions have shown minimal effects), the data obtained and chemical explanations of the same offered, clearly demonstrate an area for concern.

The intent of this memo is not to bring an end to the usage of clay as a liner material, for it does indeed have some desireable qualities, including its adsorptive capacity for various metals. However, to rely on clay liners for their "impermeable" characteristics must be done with caution and with the knowledge that permeability is usually expressed in terms of water flow through a water saturated soil. This typically is not the conditions to which clay liners are subjected in an industrial environment.

Additional information relative to soil-based liners, as well as many other types, can be found in U.S. EPA's Technical Resource Document "Lining of Waste Impoundment and Disposal Facilities" (SW-870), Revised Edition (March, 1983).

TABLE 1

TYPICAL VALUES FOR PROPERTIES OF KAOLINITE, ILLITE, AND MONTMORILLONITE[a]

Clay Mineral	Particle dimensions, m: Largest Surface Dimension	Thickness	Largest Dimension Thickness	Lattice Thickness nm	Charge Deficiency[b] Per Unit Cell	Surface area, m^2/g: Theoretical	Water Vapor	Exchange Capacity m equiv/100 g: Cation pH = 7	Anion
Kaolinite (non-expansive 1:1 lattice)	0.3-4.0	0.05-2.0	...	0.74[c]	0	...	12[d]	3-15	5-20[e,f]
Illite (non-expansive 2:1 lattice)	0.1-0.3	>0.003	...	1.00	1.3-1.5[g]	...	52-82[d]	10-40	...
Ca-montmorillonite (limited expansion 2:1 lattice)	Not easily determinable, but smaller than the figures for illite		10-100	0.96-1.80[h]	0.65	ca 750[i]	164-206[d]	80-150	10-30[e,f]
Na-montmorillonite (very expansive 2:1 lattice)	Not easily determinable, but smaller than the figures for illite		10-100	>0.96[j]	0.65	ca 750[i]	203-250[d]	80-150	10-30[e]

[a] Values from Grim, 1968, unless otherwise stated.
[b] Units are multiples of electrostatic units (esu). One charge = 4.8029×10^{-7} esu.
[c] Newnham, 1956; Brindey and Robinson, 1946.
[d] Johansen and Dunning, 1959.
[e] Hoffman et. al., 1956.
[f] pH dependent.
[g] Grim et. al., 1937.
[h] Frequently, two molecular layers of water with 1.45-1.55 nm.
[i] Van Olphen, 1963.
[j] Frequently, one molecular layer of water with 1.25 nm.

TABLE 2

EFFECT OF SALT CONCENTRATION
ON INTERLAYER SPACING OF SODIUM SMECTITE

Immersion Liquid	Interlayer Spacing (nm)
Distilled Water	Infinite
0.01 N NaCl	Infinite
1.0 N NaCl	1.92
3.0 N NaCl	1.60
5.0 N NaCl	< 1.57

TABLE 3

INTERLAYER SPACING OF CALCIUM SMECTITES
IN RELATION TO DIELECTRIC CONSTANTS OF VARIOUS ORGANICS

Sorbed Fluid	Dielectric Constant	Interlayer Spacing (nm)
Water	78.5	1.92
Methanol	32.4	1.71
Butanol	17.7	1.45
Benzene	2.3	0.99

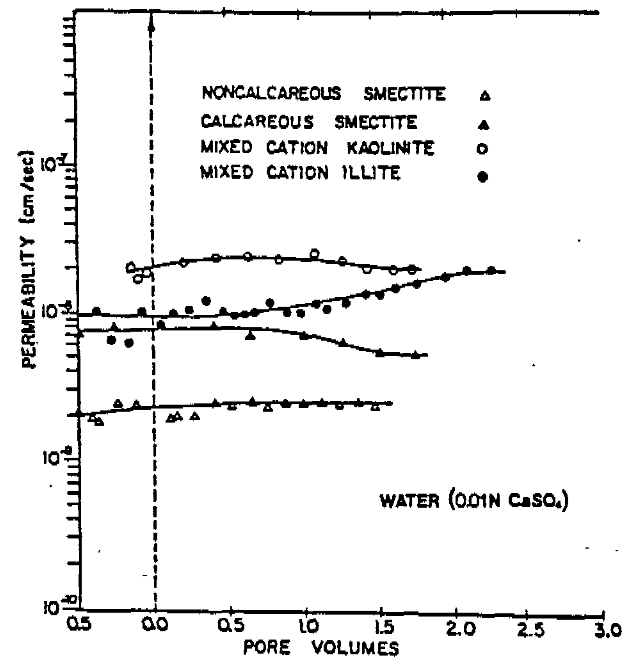

FIGURE 1: Permeability of the four clay soils to standard aqueous permeant (0.01N $CaSO_4$).

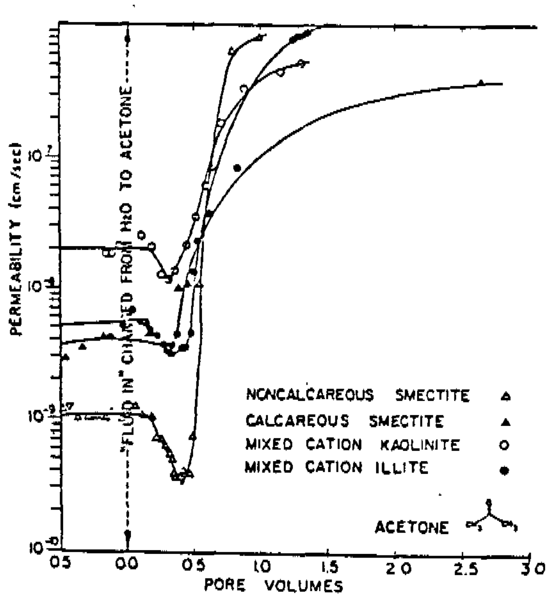

FIGURE 2: Permeability of the four clay soils to acetone.

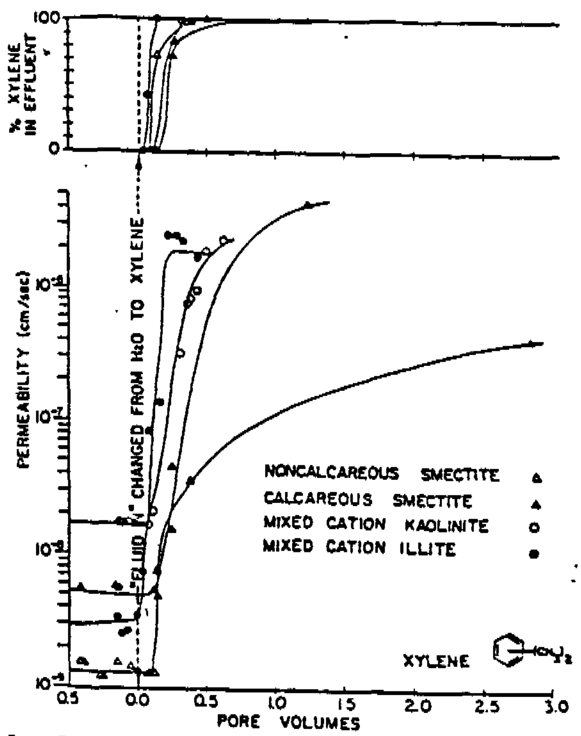

FIGURE 3: Permeability and breakthrough curves of the four clay soils treated with xylene.

DO 074503
CONFIDENTIAL

Distribution List
SWTC-TM-85-5

Global Focal Points

Jakob Schmerling, Franco da Rocha
Dan MacDougall, Sarnia (Corp.)
Steve Bolt, Sarnia Div.
Bob Lutz, Fort Saskatchewan
Dan Bosatra, Horgen
Eberhard Dreher, Stade
Harry Spaas, Terneuzen
Rick Young, Coral Gables
Clifton Sim, Hong Kong

U.S. Area Environmental Managers

W. E. Anderson, Western Div.
J. B. Martin, Louisiana Div Plaquemine
J. L. Mason, Consumer Products, Ind.
K. W. Shewbart, Texas Operations
G. R. Veurink, Michigan Div.
T. M. Vinciguerra, Merrell-Dow, Cincinnati
W. G. Wanamaker, Eastern Div.- Strongsville

Other

C. A. Royalty, 2030
B. A. Weaver, 2020
R. O. Kagel, 2030
J. Castledine, Altona
P. Canete, Coral Gables
G. Bellinzona, Milan
S. L. Daniels, 1702
R. E. Bailey, 1701
J. D. Wilson, 628
P. J. Sienknecht, 628
J. G. Hughes, Horgen
F. A. Blanchard, 1702
J. VanAtten, EE&CS, Rotterdam
J. J. Leddy, Freeport, OCD
R. R. Oubre, Freeport, OCD
R. A. DeGesero, Freeport, B-2616
R. R. Swanke, P.O. Box 77, Clute, TX 77531
D. E. Waite, Midland, 433
R. L. Casteel, Midland, 834

Groundwater Resource Team

Doug Gray, Eastern Division, Strongsville
Fred Teeters, Eastern Division, Strongsville
Melissa Guise, Louisiana Div., Plaquemine, 3502-E
Mel Heidner, Louisiana Div. Plaquemine, 3502-E
Ben Baker, Michigan Division, 628
Millard Etling, Michigan Division, 1564-T
Charlie Reed, Texas Operations, Freeport, B-1226
Marshal Turner, Texas Operations, Freeport, B-2621
Andree Youngson, Western Division, Pittsburg
Ken Tsang, Canada, Ft. Saskatchewan, 151-A
Dave Shortt, Canada Sarnia
Eberhard Dreher, Europe, Stade
Harry Spaas, Europe, Terneuzen

Groundwater Engineering Contacts

John Tushek, Texas Operations, B-2401
Ralph Hendricks, Texas Operations, B-2401
Don Jones, Louisiana Division, 3301
Gene Wejrowski, Michigan Division, 433
Dick Davis, Michigan Division, 572
Bob Thiele, E&CS, Houston, Bin 2C7
Ray Frankson, E&CS, Houston, Bin 2A7
Randy Carson, Eastern Division, Strongsville, OH
G. S. (Singh) Vij, Western Division, Pittsburg, CA
Jorgen Liber, Canada, Sarnia
Darryl Baron, Canada, Fort Saskatchewan
Paul Cooper, Europe, EE&CS, Rotterdam
Chuck Oliver, E&CS, Houston