CONTRACTOR REPORT

Bentonite as a Waste Isolation Pilot Plant Shaft Sealing Material

Jaak Daeman, Chongwei Ran
Department of Mining Engineering
University of Nevada-Reno
Reno, Nevada 89557

RECEIVED
JAN 29 1997
OSTI

Approved for public release; distribution is unlimited.

Printed December 1996

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Bentonite as a Waste Isolation Pilot Plant Shaft Sealing Material

Jaak Daemen and Chongwei Ran

Department of Mining Engineering
University of Nevada-Reno
Reno, Nevada 89557

ABSTRACT

Current designs of the shaft sealing system for the Waste Isolation Pilot Plant (WIPP) propose using bentonite as a primary sealing component (DOE/WIPP, 1995). The shaft sealing designs anticipate that compacted bentonite sealing components can perform through the 10,000-year regulatory period and beyond. To evaluate the acceptability of bentonite as a sealing material for the WIPP, this report identifies references that deal with the properties and characteristics of bentonite that may affect its behavior in the WIPP environment.

This report reviews published studies that discuss using bentonite as sealing material for nuclear waste disposal, environmental restoration, toxic and chemical waste disposal, landfill liners, and applications in the petroleum industry. This report identifies the physical and chemical properties, stability and seal construction technologies of bentonite seals in shafts, especially in a saline brine environment. This report focuses on permeability, swelling pressure, strength, stiffness, longevity, and densification properties of bentonites.

Page intentionally left blank.

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

The US Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico as a full-scale, mined geologic repository to demonstrate the safe management, storage, and disposal of transuranic (TRU) radioactive wastes that result from defense programs of the US Government. The WIPP underground facility is located in the brine-bearing, bedded salt of the Salado Formation at about 655 m below the ground surface.

Before disposing of radioactive wastes in the WIPP, the DOE must evaluate the repository based on various regulatory criteria for disposal of the waste components, and the US Environmental Protection Agency (EPA) must certify that compliance has been satisfactorily demonstrated. The regulations in 40 CFR 191.14 (d) (EPA, 1995a) require using both engineered and natural barriers to isolate waste from the accessible environment. The engineered and natural system should (1) limit the flow of fluid (water/brine and gas) through or into the repository over the designed lifetime and (2) limit radionuclide migration to the accessible environment below the acceptable level. Quantitative requirements for potential releases of radioactive and other hazardous materials from the repository system are specified in 40 CFR 191 and 40 CFR 268 (EPA, 1995b). Current designs of the shaft seal system for the WIPP propose to use bentonite as a primary sealing component (DOE/WIPP, 1995). The shaft sealing designs predict that compacted bentonite sealing components can last through the 10,000-year regulatory period and beyond.

Repository sealing requires that the sealing barriers have a low permeability, a long lifetime, a high resistance to erosion, mechanical and chemical stability, and compatibility with host rocks or materials. Bentonite has been used widely as a sealing material for waste containment structures such as landfills (Rowe et al., 1995; Daniel, 1993). Bentonite has excellent sealing performance and has been selected as a principal sealing component for numerous nuclear waste repositories. Bentonite has an extremely low hydraulic conductivity, is self-healing, and has good chemical stability that would provide effective long-term sealing (Gnirk, 1988). Bentonite can penetrate rock fractures either by viscous flow or by expansion (Pusch, 1978). Bentonite suspensions can form barriers at low solids concentrations (Ran and Daemen, 1991, 1992; Ran, 1993).

Bentonite as sealing component in the repository access excavations provides barriers to block fluid flow into or out of the repository. Bentonite can generate swelling pressure when water or brine penetrates the clay. Swelling of the seals increases the internal supporting pressure in the shaft and fractures and should accelerate healing of any disturbed rock zone (DRZ). Swelling of bentonite also can assist in sealing fractures caused by structural damage or by rock block displacement by self penetration into the fractures; it should also help in obtaining tightness between seals and host materials.

Bentonite has been studied as a sealing material in several nuclear waste repository programs. Extensive studies on sealing with bentonite have been conducted for the Swedish, Swiss, Canadian, German, and French programs (IAEA, 1990; Pusch and Bergstrom, 1980; Pusch, 1994; Coulon et al., 1987; Brenner, 1988; Bucher et al., 1986; Dixon et al., 1985).

Extensive studies also have been conducted within the context of the WIPP program, both from a sealing and from a backfill perspective (Butcher, 1994; Pfeifle, 1990).

For the purpose of evaluating the acceptability of bentonite as a sealing material for WIPP we have identified references that deal with the properties and characteristics of bentonite that may affect its behavior in the WIPP environment.

This report reviews published studies of bentonite used as sealing material for nuclear waste disposal, environmental restoration, toxic and chemical waste disposal, liners, and applications in the petroleum industry. This report identifies the physical and chemical properties, stability, and seal construction technologies of bentonites, especially in a brine/ salt environment. This report focuses on permeability, swelling pressure, strength, stiffness, longevity, and the densification properties of bentonites. All information about bentonite on which this report is based is archived in a computerized database system (ClayInfo), and can be obtained from the authors or from the Sandia WIPP Central Files.

2. RELATED REPOSITORY STUDIES

2.1 Waste Isolation Pilot Plant

The WIPP has investigated bentonite as a sealing and as a backfill material. Pfeifle (1990) investigated consolidation, permeability, and strength of crushed-salt/bentonite mixes. Pfeifle and Brodsky (1991) investigated the swelling pressure, water uptake, and permeability of 70%/30% crushed-salt/bentonite mixes.

2.2 Office of Nuclear Waste Isolation

The Office of Nuclear Waste Isolation (ONWI), Battelle Memorial Institute, Columbus, OH, has evaluated the use of clays for sealing nuclear waste repositories. A summary report (Meyer and Howard, 1983) includes these favorable characteristics: low hydraulic conductivity, high sorptivity, high compressibility, and, in some cases, high swelling capacity. Also stressed with respect to the use of clays as sealing materials is the potential of clays and clay minerals to provide long-term sealing, inferred from their geologic persistence, low solubility in repository-like environments, and slow reaction kinetics.

2.3 Swedish Studies

By far the most comprehensive, in-depth, and detailed study of bentonite as a repository sealant has been conducted within the Swedish repository program. The results of this work have been summarized in numerous publications (Pusch, 1978, 1979, 1980, 1994; Pusch et al., 1982, 1985; Pusch and Bergstrom, 1980; Pusch and Carlsson, 1985; Pusch and Güven, 1990; Pusch and Karnland, 1990; Nilsson, 1985). Only the most directly applicable of these reports are referenced here.

2.4 Swiss Studies

The Swiss nuclear waste disposal program has studied bentonite as a sealing material. For geochemical and hydrological reasons (i.e., because of the presence of a rather large concentration of Ca ions in the groundwater at the most likely candidate repository sites) the program has focused primarily on Ca bentonites.

2.5 Canadian Studies

The Canadian nuclear waste disposal program has conducted extensive studies on mixtures of bentonite and sand or crushed rock (granite), primarily for the purpose of evaluating the performance of such mixtures as backfill (Dixon et al., 1985, 1987, 1991, 1992a; Chapuis, 1990; Kjartanson et al., 1992; Yong et al., 1986). Only a few of the large number of publications generated by this work are referenced here.

2.6 Basalt Waste Isolation Project

The Basalt Waste Isolation Project (BWIP) has investigated the use of mixtures of crushed basalt and sodium bentonite as a waste packing material. A summary of BWIP studies is given by Allen and Wood (1988).

3. METHODOLOGY

In this study, two main lines of approach were pursued to identify relevant information:

1. computerized data searches,
2. use of personal documentation files and manual follow-up of references.

The search focused on (1) clay sealing for nuclear waste disposal and nonnuclear waste isolation, and (2) clay applications in petroleum and civil engineering. While researching the use of clay/bentonite for nuclear waste repository sealing, the focus of inquiry was on flow and the chemical and physical properties of bentonite, especially in salt, brine, or saline environments.

Six data bases were searched:

1. COMPENDEX (Electronic Engineering Index), Engineering Information, Inc. (1986 to 1995);
2. NTIS (National Technical Information Service), National Technical Information Service (1975 to 1995);
3. Dissertation Abstracts Ondisc, UMI, University Microfilms International (1861 to 1995);
4. GEOREF (Geological Reference File), American Geological Institute (1785 to 1995);
5. GEOBASE, Elsevier Science, (1980 to 1995)
6. INIS (International Nuclear Information System), International Atomic Energy Agency (1976 to 1995, outside USA only).

The data bases listed above were searched using the following terms as keywords or identifiers (except for the INIS and NTIS from 1975 to 1983, as specified below):

- bentonite,
- montmorillonite,
- smectite,
- clay and waste disposal,
- clay and permeability or hydraulic conductivity,
- clay and brine or salt or saline,
- soil and erosion or piping.

For the INIS data base and NTIS data base from 1975 to 1983, the following search terms were used:

- bentonite,
- montmorillonite,
- clay or bentonite or montmorillonite and salt or brine or saline,
- not in the United States (INIS only).

5

A total of 11,906 references has been located. As is common with computerized literature searches, the results present a mixed picture: A vast number of references were obtained that have marginal, if any, interest to the study at hand. Conversely, a number of important references were identified that otherwise would have been missed. Still, considerable uncertainty remains about the completeness of the searches because some important references we are familiar with did not show up on the searches. Nevertheless, we believe we have completed a fairly comprehensive search of the available literature.

An extensive experimental data base exists for the permeability of sodium bentonites under a variety of conditions. Many other properties of sodium bentonite (such as strength, stiffness, and chemical stability) also have been investigated in detail. The complexity of the material is such, however, that considerable uncertainty remains about its performance (Rowe et al., 1995, pp. 5, 108).

Abstracts of the references that appear relevant have been reviewed by the authors of the present report. Complete copies of the references have been obtained and reviewed to the extent possible within the allowed time frame.

4. BENTONITE COMPOSITION

The composition of a typical commercial sodium bentonite (e.g., Volclay, granular sodium bentonite) contains over 90% montmorillonite and small portions of feldspar, biotite, selenite, etc. A typical sodium bentonite has the chemical composition shown in Table 1.

Table 1. Chemical Composition of Volclay Sodium Bentonite

Elements	Composition (%)
SiO_2	63.02
Al_2O_3	21.05
Fe_2O_3	3.02
FeO	0.35
MgO	2.67
Na_2O	2.57
CaO	0.65
H_2O	5.64
Trace Elements	0.72

Source: Technical Data Sheet, American Colloid Company, 1995.

Sodium bentonite has a three-layer expanding mineral structure of approximately (Al $Fe_{1.67}$ $Mg_{0.33}$) Si_4O_{10} (OH_2) $Na^+Ca^{++}_{0.33}$. Specific gravity of the sodium bentonite is from about 2.5 to 2.8. The dry bulk density of granular bentonite is about 1.04 to 1.24 g/cm^3.

Sodium bentonite has a specific surface area of about 800 m^2/g; when unconfined it can swell to at least 12 mL/g. Densely compacted bentonite (1.75g/cm^3), when confined, can generate a swelling pressure up to 20 MPa when permeated by water (IAEA, 1990, p. 13). The magnitude of the swelling pressure depends on the mineral composition of bentonite and on the chemistry of the permeating water. Bentonite compacted to high bulk densities (>1.7 g/cm^3) has very promising thermal conductivity and thermal stability. Because of the special composition of bentonite, mixtures of bentonite and water can range in rheological characteristics from a virtually Newtonian fluid to a stiff solid, depending on water content. Bentonite can form stiff seals at low moisture content and can penetrate fractures and cracks at higher moisture-content values. Under the latter conditions it can fill spaces in seals and DRZs.

At the WIPP, compacted clay is being considered as a shaft sealing material. Columns of compacted clay will be emplaced in the WIPP shafts during repository closure. A number of optional materials have been investigated for use as the WIPP shaft sealing material. Because the term *clay* includes a large variety of materials, it is possible that some clay materials might satisfy the WIPP sealing requirements. A recurring problem with the use of the term clay is its imprecision and ambiguity, which can cause confusion as to what is intended for sealing purposes.

A standard soil mechanics engineering definition of clays is "fine-grained soil or the fine-grained portion of soil that can be made to exhibit plasticity (putty-like properties) within a range of water contents, and that exhibits considerable strength when air-dry" (ASTM D 653). A long-standing engineering practice has been to define clays as soil particles with a size smaller than a specified size (e.g., 0.002 mm), although ASTM D 653 explicitly recommends against such a definition based on particle size only. The widely (but not exclusively) used Unified Soil Classification System (USCS) (ASTM D 2487, D 2488) defines clay following the above ASTM definition and combining particle size with behavioral aspects.

A second cause of confusion regarding clay terminology is that clay can be defined purely mineralogically (i.e., on the basis of mineral composition) rather than on the basis of size and/or mechanical behavior only. Different investigators propose different definitions:

- "The term clay implies an earthy, fine-grained material which develops plasticity when mixed with a limited amount of water. Chemical analysis of clays shows that they are made up of hydrous aluminosilicates, frequently with appreciable amounts of iron, magnesium, calcium, sodium, and potassium" (Berry and Mason, 1959, pp. 502-503).

- "As a mineral term, it (i.e. clay) refers to specific clay minerals, which are distinguished by (1) small particle size, (2) a net negative electrical charge, (3) plasticity when mixed with water, and (4) high weathering resistance. These minerals are primarily hydrous aluminum silicates, with magnesium or iron occupying all or part of the aluminum positions in some minerals, and with alkalis (e.g., sodium, potassium) or alkaline earths (e.g. calcium) also present in some of them (Grim 1962, 1968)" (Mitchell, 1993, p. 18).

- "As used in this report, 'clay' refers to any fine-grained, earthen, generally plastic material containing a substantial proportion of clay minerals" (Meyer and Howard, 1983, p. 1).

A variety of clays could be considered for nuclear repository sealing purposes. For WIPP, as for most nuclear waste repository projects, bentonite has been and continues to be a prime candidate as a clay type sealing material. "Bentonite clay is chosen here because of its overwhelming positive sealing characteristics" (DOE/WIPP, 1995, p. 43). Bentonite is a highly plastic swelling clay material (e.g., Mitchell, 1993, p. 31), consisting predominantly of smectite minerals (e.g., IAEA, 1990, p. 11). Montmorillonite, the predominant smectite mineral in most bentonites, has the typical platelike structural characteristics of most clay minerals. It has an extremely large surface area, and this in turn directly explains many of the characteristics of bentonite (notably those of importance for sealing performance):

- "Many ... soil properties are attributable to surface phenomena. These properties can be correlated—they are even approximately proportional—to the specific surface area of the solid phase" (Koorevaar et al., 1983, p. 11).

- "The specific surface area of clay minerals, which governs many soil properties, varies from one mineral to another" (Koorevaar et al., 1983, p. 15).

The fundamental structural component of the phyllosilicate minerals, to which clay minerals belong, is the silica (SiO_4) tetrahedron. These tetrahedrons occur in sheets. Octahedral layers of cations (e.g., aluminum) occur parallel to the tetrahedral sheets. In montmorillonite, both surfaces of an octahedral sheet are shared with a tetrahedral sheet, resulting in a three-layer clay mineral. In general, the chemical composition of montmorillonite can be written as $(Na,Ca)_{0.33}(Al,Mg)_2 Si_4O_{10}(OH)_2 \times H_2O$ (Berry et al., 1983, p. 424). The three-layer sheets are loosely bonded with dipolar water molecules and cations. The weakness of the bond between the sheets allows for ready separation and resulting volume changes. The idealized structure as described here is more theoretical than actual, however, as various isomorphous substitutions are common. The weak bonding explains the high cation exchange capacity of montmorillonites.

Virtually all the physical and mechanical attributes of bentonite will depend on the as-emplaced conditions. Hence such attributes will be a function of the primary design and the specified construction variables, e.g., density (or void ratio) and water content. They possibly are a function of the composition of the water with which the bentonite is prepared.

Page intentionally left blank.

5. BENTONITE PROPERTIES AND CHARACTERISTICS OF PARTICULAR RELEVANCE TO WIPP SEALING

A number of bentonite properties and characteristics are important from a sealing perspective. A primary characteristic is permeability or hydraulic conductivity. Although bentonite is known to have extremely low permeability under many conditions, it also is known to be a rather complex material. Its properties, specifically its permeability, are affected by many factors. A major objective of the data base assembled here is to identify the likely permeability of bentonite under WIPP conditions, or, conversely, to determine bentonite seal design specifications that will meet the minimum WIPP sealing requirements.

5.1. Permeability/Hydraulic Conductivity

A variable of primary interest with respect to repository sealing is the hydraulic conductivity of the seal material. The hydraulic conductivity of bentonite depends on numerous factors, e.g., the emplaced density, the chemical composition of the permeant, the bentonite structure, and the hydraulic gradient.

The permeability of dense bentonite is about 1×10^{-16} to 1×10^{-21} m^2 (1×10^{-9} to 1×10^{-14} m/s). Table 2 and Figures 1 and 2 give reported permeabilities of bentonite and bentonite mixtures. Figure 2 contains all data in Table 2.

5.1.1 Permeability to Water/Brine

Bentonite is widely used as a sealant; as a result, an extensive data base exists with reference to the permeability of bentonite. Bentonite has been researched extensively within the context of the Swedish and Canadian nuclear waste disposal programs, in conjunction with international cooperative programs. Within the context of nuclear waste disposal, the sealing properties of bentonite have been studied in considerable detail, i.e. with attention to the numerous factors that may influence bentonite behavior. Hence results obtained in the nuclear waste disposal context may be more complete and more reliable than results obtained in conventional sealing applications, where investigations may not be as detailed or complete. Figures 1 and 2 show the permeability of typical bentonite and bentonite mixture seals at varied dry density as a function of bentonite content.

Westsik et al. (1982) as quoted by Allen and Wood (1988) measured hydraulic conductivities in the range of 4.6 to 6.7×10^{-20} m^2 for sodium bentonite compacted to a high density (2.1 g/cm^3 dry) with a synthetic basalt groundwater utilizing various hydraulic gradients and heads.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Bentonite/shale	12:88	1.765	2.01×10^{-10}		24	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/shale	12:88	1.765	1.65×10^{-10}		61	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/shale	12:88	1.765	1.58×10^{-10}		121	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/fly ash/sand	12:3:85	1.6	4.0×10^{-10}			triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/sand	15:85	1.865	1.0×10^{-9}		14	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/sand	15:85	1.865	2.0×10^{-9}		28.8	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite/sand	15:85	1.865	6.3×10^{-10}		115	triaxial, lab	4 M NaCl	Haug et al., 1988
Bentonite	100	0.6	$6.1\text{x}10^{-9}$		3000		DDW	Bucher et al., 1986
Bentonite	100	0.6	7.0×10^{-8}		3000		1.2 M Saline	Bucher et al., 1986
Bentonite	100	1.02	2.6×10^{-13}		460		DDW	Dixon et al., 1987
Bentonite	100	1.02	6.3×10^{-13}		1700		DDW	Dixon et al., 1987
Bentonite	100	1.12	4.5×10^{-14}		1550		DDW	Dixon et al., 1987
Bentonite	100	1.12	$1.6\ 10^{-12}$		3100		DDW	Dixon et al., 1987
Bentonite	100	1.12	4.5×10^{-14}		>3100		DDW	Dixon et al., 1987
Bentonite	100	1.22	3.7×10^{-13}		1580		DDW	Dixon et al., 1987
Bentonite	100	1.22	$\sim3.1\times10^{-13}$		>3100		DDW	Dixon et al., 1987
Bentonite	100	1.24	1.0×10^{-13}		1560		Saline	Dixon et al., 1987
Bentonite	100	1.24	5.0×10^{-13}		1560		DDW	Dixon et al., 1987
Bentonite	100	1.24	3.5×10^{-13}		3120		DDW	Dixon et al., 1987
Bentonite	100	1.24	3.2×10^{-13}		>3120		DDW	Dixon et al., 1987
Bentonite	100	1.42	1.9×10^{-13}		2000		DDW	Pusch, 1980
Bentonite	100	1.42	2.1×10^{-13}		5000-10000		DDW	Pusch, 1980
Bentonite	100	1.43	$\sim1.8\times10^{-13}$		1700-3400		DDW	Dixon et al., 1987
Bentonite	100	1.46	1.8×10^{-13}		1600-8000		Saline	Dixon et al., 1987
Bentonite	100	1.5	1.9×10^{-13}		2000		DDW	Dixon et al., 1987
Bentonite	100	1.8	9.0×10^{-14}		2000		DDW	Pusch, 1980
Bentonite	100	1.8	1.1×10^{-13}		500-10000		DDW	Pusch, 1980
Bentonite/sand	50:50	1.21	4.2×10^{-12}	25				Dixon et al., 1987
Bentonite/sand	50:50	1.21	3.7×10^{-12}	50				Dixon et al., 1987
Bentonite/sand	50:50	1.21	8.0×10^{-12}	75				Dixon et al., 1987
Bentonite/sand	50:50	1.32	2.0×10^{-14}	25				Dixon et al., 1987
Bentonite/sand	50:50	1.32	1.6×10^{-13}	50				Dixon et al., 1987
Bentonite/sand	50:50	1.32	3.0×10^{-13}	75				Dixon et al., 1987
Bentonite/fly ash			$1.9\text{-}32\times10^{-11}$					Edil et al., 1987
Bentonite/soil			$2\times10^{-6} - 5.0\times10^{-11}$					Chapuis, 1982
Bentonite/soil			$3\times10^{-6} - 1.0\times10^{-11}$					Lundgren, 1981

[†] T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

12

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)†	Pressure Gradient	Test Type	Permeant	Reference
Bentonite/soil			3.0×10^{-9} - 1.4×10^{-12}					Haile, 1985
Bentonite/soil			1.6×10^{-9} - 1.4×10^{-11}					Gipson, 1985
Bentonite/soil			2.5×10^{-11} - 1.2×10^{-12}					Pusch & Alstermark, 1985
Bentonite/soil			2×10^{-6} - 8.0×10^{-11}					Holopainen, 1985
Bentonite/soil			2×10^{-8} - 7.0×10^{-10}					Jessberger et al., 1985
Bentonite/soil			5×10^{-9} - 8.0×10^{-12}					Haxo et al., 1985
Bentonite/soil			1×10^{-9} - 6.3×10^{-10}					Haug, 1985
Bentonite/soil			2.7×10^{-7} - 1.6×10^{-11}					Garlanger et al., 1987
Bentonite/soil			1×10^{-5} - 1.0×10^{-12}					Kenney et al., 1992
Bentonite/soil			2.7×10^{-8} - 2.9×10^{-9}					Stockmeyer, 1992
Bentonite/sand	4	1.65	8.1×10^{-10}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	4	1.65	2.1×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	4	1.65	5.0×10^{-10}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	4	1.65	1.0×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	4	1.65	6.4×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	4	1.65	1.2×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.51	2.1×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.51	4.8×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.49	2.2×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.49	5.4×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.51	2.1×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.51	5.5×10^{-10}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.56	9.2×10^{-11}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.56	1.5×10^{-10}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	12	1.47	6.1×10^{-11}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	12	1.47	9.1×10^{-11}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	8	1.72	6.4×10^{-9}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	8	1.72	1.2×10^{-9}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite/sand	16	1.71	6.8×10^{-11}			Consolidation cell	DDW	Kenney et al., 1992
Bentonite/sand	16	1.71	3.2×10^{-11}			Consolidation cell	0.7 M NaCl	Kenney et al., 1992
Bentonite	100	0.43	2.1×10^{-11}				DDW	Kenney et al., 1992
Bentonite	100	0.57	5.9×10^{-12}				DDW	Kenney et al., 1992
Bentonite	100	0.74	5.2×10^{-12}				DDW	Kenney et al., 1992
Bentonite	100	0.38	5.7×10^{-11}				DDW	Kenney et al., 1992
Bentonite	100	0.38	1.1×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite	100	0.46	3.1×10^{-11}				DDW	Kenney et al., 1992

† T = temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

13

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)†	Pressure Gradient	Test Type	Permeant	Reference
Bentonite	100	0.46	4.7×10^{-11}				0.7 M NaCl	Kenney et al., 1992
Bentonite	100	0.31	1.6×10^{-10}				DDW	Kenney et al., 1992
Bentonite	100	0.31	3.7×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite	100	0.27	2.9×10^{-10}				DDW	Kenney et al., 1992
Bentonite	100	0.27	4.7×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.66	8.7×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.69	6.4×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.79	2.8×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.91	9.7×10^{-11}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		1.11	2.1×10^{-11}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.58	1.3×10^{-9}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.68	4.4×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.78	2.0×10^{-10}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.78	2.9×10^{-11}				DDW	Kenney et al., 1992
Bentonite*		0.58	1.1×10^{-9}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.58	2.8×10^{-11}				DDW	Kenney et al., 1992
Bentonite*		0.63	3.7×10^{-9}				0.7 M NaCl	Kenney et al., 1992
Bentonite*		0.63	3.8×10^{-11}				DDW	Kenney et al., 1992
Na-bentonite		2.1	2.2×10^{-14}	25		Oedometer		Pusch, 1982
Na-bentonite		1.94	7.8×10^{-14}	25		Oedometer		Pusch, 1982
Na-bentonite		1.94	1.1×10^{-13}	25		Oedometer		Pusch, 1982
Na-bentonite		1.89	1.1×10^{-13}	25		Oedometer		Pusch, 1982
Na-bentonite		1.89	1.2×10^{-13}	25		Oedometer		Pusch, 1982
Na-bentonite		1.92	1.28×10^{-13}	25		Oedometer		Pusch, 1982
Na-bentonite		2.06	1.28×10^{-13}	75		Oedometer		Pusch, 1982
Na-bentonite		1.89	1.4×10^{-13}	75		Oedometer		Pusch, 1982
Na-bentonite		1.94	1.5×10^{-13}	75		Oedometer		Pusch, 1982
Na-bentonite		1.94	1.67×10^{-13}	75		Oedometer		Pusch, 1982
Na-bentonite		1.8-2.1	2.3×10^{-13}				10^{4}	Pusch, 1982
Na-bentonite		1.8-2.1	2.0×10^{-13}				2×10^{3}	Pusch, 1982
Na-bentonite		1.8-2.1	1.9×10^{-13}				10^{3}	Pusch, 1982
Bentonite	100	1.4	1.3×10^{-12}					Mingarro et al., 1991
Bentonite	100	1.6	7.7×10^{-13}					Mingarro et al., 1991
Bentonite	100	1.8	3.3×10^{-13}					Mingarro et al., 1991
Bentonite	100	2.0	8.1×10^{-14}					Mingarro et al., 1991
Bentonite/granite	75:25	1.46	8.3×10^{-12}					Mingarro et al., 1991

† T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

14

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)†	Pressure Gradient	Test Type	Permeant	Reference
Bentonite/granite	75:25	1.63	5.9×10^{-12}					Mingarro et al., 1991
Bentonite/granite	75:25	1.83	9.0×10^{-13}					Mingarro et al., 1991
Bentonite/granite	75:25	2.00	1.3×10^{-13}					Mingarro et al., 1991
Bentonite/granite	50:50	1.40	1.4×10^{-9}					Mingarro et al., 1991
Bentonite/granite	50:50	1.60	5.4×10^{-10}					Mingarro et al., 1991
Bentonite/granite	50:50	1.80	6.3×10^{-11}					Mingarro et al., 1991
Bentonite/granite	50:50	2.00	3.4×10^{-11}					Mingarro et al., 1991
Bentonite/granite	25:75	1.41	3.5×10^{-8}					Mingarro et al., 1991
Bentonite/granite	25:75	1.65	1.4×10^{-8}					Mingarro et al., 1991
Bentonite/granite	25:75	1.80	9.5×10^{-9}					Mingarro et al., 1991
Bentonite/granite	25:75	2.00	4.4×10^{-9}					Mingarro et al., 1991
Bentonite/sands	10	1.46	5.1×10^{-8}					Chapuis, 1990
Bentonite/sands	10	1.71	7.4×10^{-9}					Chapuis, 1990
Bentonite/sands	15	1.52	1.4×10^{-11}					Chapuis, 1990
Bentonite/sands	5	1.15	5.7×10^{-10}					Chapuis, 1990
Bentonite/sands	10	1.28	2.0×10^{-8}					Chapuis, 1990
Bentonite/sands	5	1.34	2.8×10^{-8}					Chapuis, 1990
Bentonite/sands	10	1.19	3.2×10^{-8}					Chapuis, 1990
Bentonite/sands	5	1.22	1.0×10^{-7}					Chapuis, 1990
Bentonite/sands	10	0.92	9.1×10^{-10}					Chapuis, 1990
Bentonite/sands	5	1.47	1.0×10^{-8}					Chapuis, 1990
Bentonite/sands	10	1.36	2.1×10^{-9}					Chapuis, 1990
Bentonite/sands	20	1.32	2.6×10^{-11}					Chapuis, 1990
Bentonite/sands	2	1.31	8.0×10^{-7}					Chapuis, 1990
Bentonite/sands	3	1.52	2.0×10^{-7}					Chapuis, 1990
Bentonite/sands	4	1.36	6.0×10^{-9}					Chapuis, 1990
Bentonite/sands	6	1.78	9.8×10^{-8}					Chapuis, 1990
Bentonite/sands	8	1.77	2.9×10^{-8}					Chapuis, 1990
Bentonite/sands	7	1.85	1.2×10^{-9}					Chapuis, 1990
Bentonite/sands	7	1.85	6.9×10^{-8}					Chapuis, 1990
Bentonite/sands	7	1.83	1.2×10^{-7}					Chapuis, 1990
Bentonite/sands	3	1.79	2.2×10^{-9}					Chapuis, 1990
Bentonite/sands	6	1.75	6.0×10^{-10}					Chapuis, 1990
Bentonite/sands	3	1.75	2.2×10^{-8}					Chapuis, 1990
Bentonite/sands	6	1.74	1.2×10^{-8}					Chapuis, 1990
Bentonite/sands	25	1.43	2.6×10^{-11}					Chapuis, 1990

† T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

15

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Bentonite/sands	33.3	1.29	1.2×10^{-11}					Chapuis, 1990
Bentonite/sands	33.3	1.3	4.9×10^{-11}					Chapuis, 1990
Bentonite/sands	20	1.57	9.7×10^{-11}					Chapuis, 1990
Bentonite/sands	2.5	1.91	2.2×10^{-9}					Chapuis, 1990
Bentonite/sands	3	1.93	8.3×10^{-10}					Chapuis, 1990
Bentonite/sands	4.7	1.75	1.4×10^{-6}					Chapuis, 1990
Bentonite/sands	5.8	1.74	6.4×10^{-7}					Chapuis, 1990
Bentonite/sands	6.4	1.78	2.1×10^{-7}					Chapuis, 1990
Bentonite/sands	7.5	1.81	1.1×10^{-8}					Chapuis, 1990
Bentonite	100	2.1	1.5×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	2.0	2.0×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	1.9	3.0×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	1.8	5.0×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	1.7	8.0×10^{-14}	Room				Pusch & Carlsson, 1985
Bentonite	100	2.1	1.5×10^{-13}	70				Pusch & Carlsson, 1985
Bentonite	100	2.0	2.0×10^{-13}	70				Pusch & Carlsson, 1985
Bentonite	100	1.9	5.0×10^{-13}	70				Pusch & Carlsson, 1985
Bentonite	100	1.8	8.0×10^{-13}	70				Pusch & Carlsson, 1985
Bentonite	100	1.7	1.0×10^{-12}	70				Pusch & Carlsson, 1985
Bentonite	100	1.13	2.6×10^{-12}					Dixon et al, 1992a
Bentonite	100	1.20	9.2×10^{-13}					Dixon et al, 1992a
Bentonite	100	1.31	6.3×10^{-13}					Dixon et al, 1992a
Bentonite	100	1.30	8.2×10^{-13}					Dixon et al, 1992a
Bentonite	100	1.35	3.7×10^{-13}					Dixon et al, 1992a
French clay		1.40	3.0×10^{-13}					Atabek et al., 1990
French clay		1.50	1.0×10^{-13}					Atabek et al., 1990
French clay		1.60	8.0×10^{-14}					Atabek et al., 1990
French clay		1.70	5.0×10^{-14}					Atabek et al., 1990
Bentonite/crushed granite	25:75	1.88	2.1×10^{-11}		30.2			Radhakrishna & Chan, 1982
Bentonite/crushed granite	25:75	1.88	3.7×10^{-11}		277.0			Radhakrishna & Chan, 1982
Bentonite/crushed granite	50:50	1.56	3.7×10^{-12}		90.3			Radhakrishna & Chan, 1982
Bentonite/crushed granite	50:50	1.56	1.8×10^{-12}		967.5			Radhakrishna & Chan, 1982
Bentonite/crushed granite	50:50	1.59	7.8×10^{-12}		70.3			Radhakrishna & Chan, 1982
Bentonite/crushed granite	50:50	1.59	9.2×10^{-11}		70.3			Radhakrishna & Chan, 1982
Na-bentonite		1.09	3.07×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.17	9.92×10^{-13}				DDW	Dixon et al., 1987

[†] T = temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

16

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)†	Pressure Gradient	Test Type	Permeant	Reference
Na-bentonite		1.2	9.67×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.23	6.02×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.25	3.07×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.32	8.54×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.28	6.65×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.3	5.05×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.55	9.43×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.43	9.01×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.57	1.81×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.5	1.34×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.48	9.96×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.47	5.89×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.59	1.78×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.73	1.91×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		2.07	2.11×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.88	9.24×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.69	7.57×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.68	7.76×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.81	4.59×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.86	3.49×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.8	1.91×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.92	7.05×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		2.12	6.54×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		2.2	5.35×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		0.501	1.06×10^{-9}				DDW	Dixon et al., 1987
Na-bentonite		1.25	2.99×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.3	2.84×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.32	2.84×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.34	2.06×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.34	1.68×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.43	3.14×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.41	1.91×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.41	1.38×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.44	1.16×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.52	2.45×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.5	1.77×10^{-13}				DDW	Dixon et al., 1987

† T = temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Na-bentonite		1.5	1.10×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.52	1.38×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.4	2.01×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.71	3.07×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.88	3.56×10^{-13}				DDW	Dixon et al., 1987
Na-bentonite		1.78	9.47×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.68	9.71×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.66	7.20×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.75	5.89×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.78	4.05×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.83	2.79×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		1.9	3.16×10^{-14}				DDW	Dixon et al., 1987
Na-bentonite		2.04	7.79×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		2.17	6.71×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		2.23	6.87×10^{-15}				DDW	Dixon et al., 1987
Na-bentonite		0.67	6.22×10^{-9}				DDW	Dixon et al., 1987
Na-bentonite		1.17	1.24×10^{-12}				DDW	Dixon et al., 1987
Na-bentonite		1.36	6.14×10^{-12}				DDW	Dixon et al., 1987
Na-bentonite		1.31	6.96×10^{-12}				DDW	Dixon et al., 1987
Na-bentonite		1.37	3.71×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.19	1.47×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.1	1.63×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.2	3.20×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.17	3.81×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.14	5.14×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.15	9.12×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.07	5.14×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.04	3.36×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		0.887	2.49×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		1.03	1.47×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		1.08	2.36×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		1.05	2.30×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		1.03	2.48×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		1.02	1.33×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.884	2.55×10^{-11}				DDW	Dixon et al., 1987
Na-bentonite		0.989	4.19×10^{-10}				DDW	Dixon et al., 1987

[†] T= temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.

Table 2. Reported Hydraulic Conductivity of Compacted Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Hydraulic Conductivity (m/s)	T (°C)[†]	Pressure Gradient	Test Type	Permeant	Reference
Na-bentonite		0.904	1.79×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.877	1.93×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.87	4.29×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.836	6.73×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.792	4.29×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		0.609	1.98×10^{-10}				DDW	Dixon et al., 1987
Na-bentonite		2.34	2.28×10^{-14}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		2.1	1.45×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.99	3.08×10^{-14}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		2.08	8.75×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.73	5.47×10^{-14}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.54	1.60×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.39	2.77×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.32	2.16×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.33	4.81×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.34	6.17×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.31	6.49×10^{-13}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.32	1.10×10^{-12}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.28	2.21×10^{-12}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.27	3.64×10^{-12}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.19	1.89×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.12	3.28×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		0.894	1.75×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		0.918	4.00×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		0.935	6.27×10^{-11}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.12	1.17×10^{-10}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.07	1.84×10^{-10}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.07	3.18×10^{-10}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		1.12	9.75×10^{-9}				1.2 M NaCl	Dixon et al., 1987
Na-bentonite		0.681	6.85×10^{-8}				1.2 M NaCl	Dixon et al., 1987

[†] T = temperature (room temperature unless otherwise specified); * = mixed with saltwater; DDW = distilled deionized water. Blank cells indicate that information is not available.
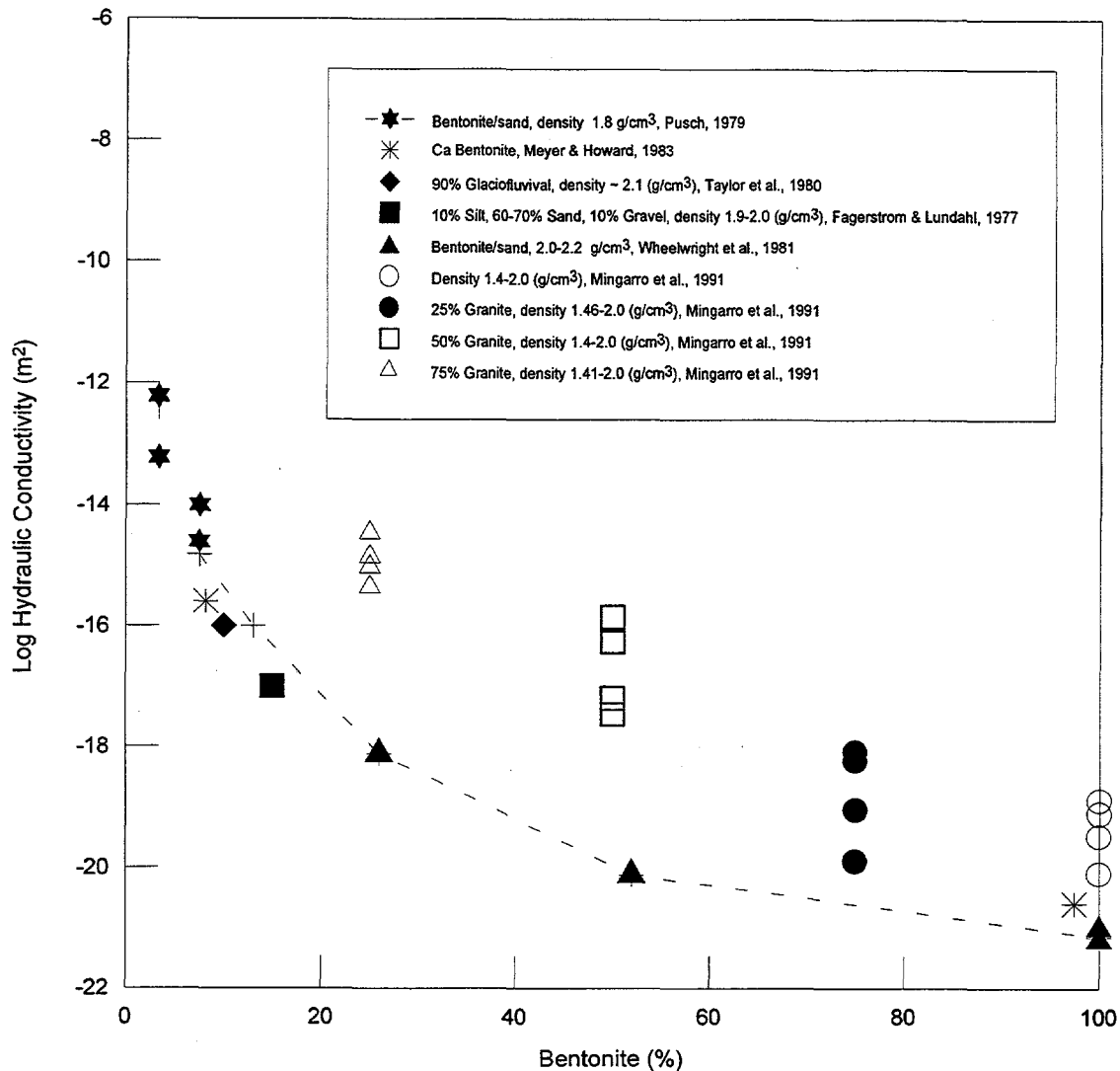
19

Figure 1. Hydraulic conductivity of compacted mixtures of bentonite with sand, crushed granite, or soils as a function of bentonite content (after Meyer and Howard, 1983; Mingarro et al., 1991).

Influence of Compaction/Density

Figure 2 shows the reported permeability of compacted bentonite and of bentonite mixtures with sand, crushed rock, and fly ash. The permeability of a bentonite seal relates to the void space or density. At the same density, pure bentonite has much lower permeability than bentonite mixtures. Compacted bentonite has fewer pore spaces for fluid flow. It is not necessary that materials with the same density have the same void space because the specific gravity of materials varies significantly. The specific gravity of bentonite varies from 2.4 to 2.8, which makes significant difference in terms of the void ratio for seals with the same dry density.
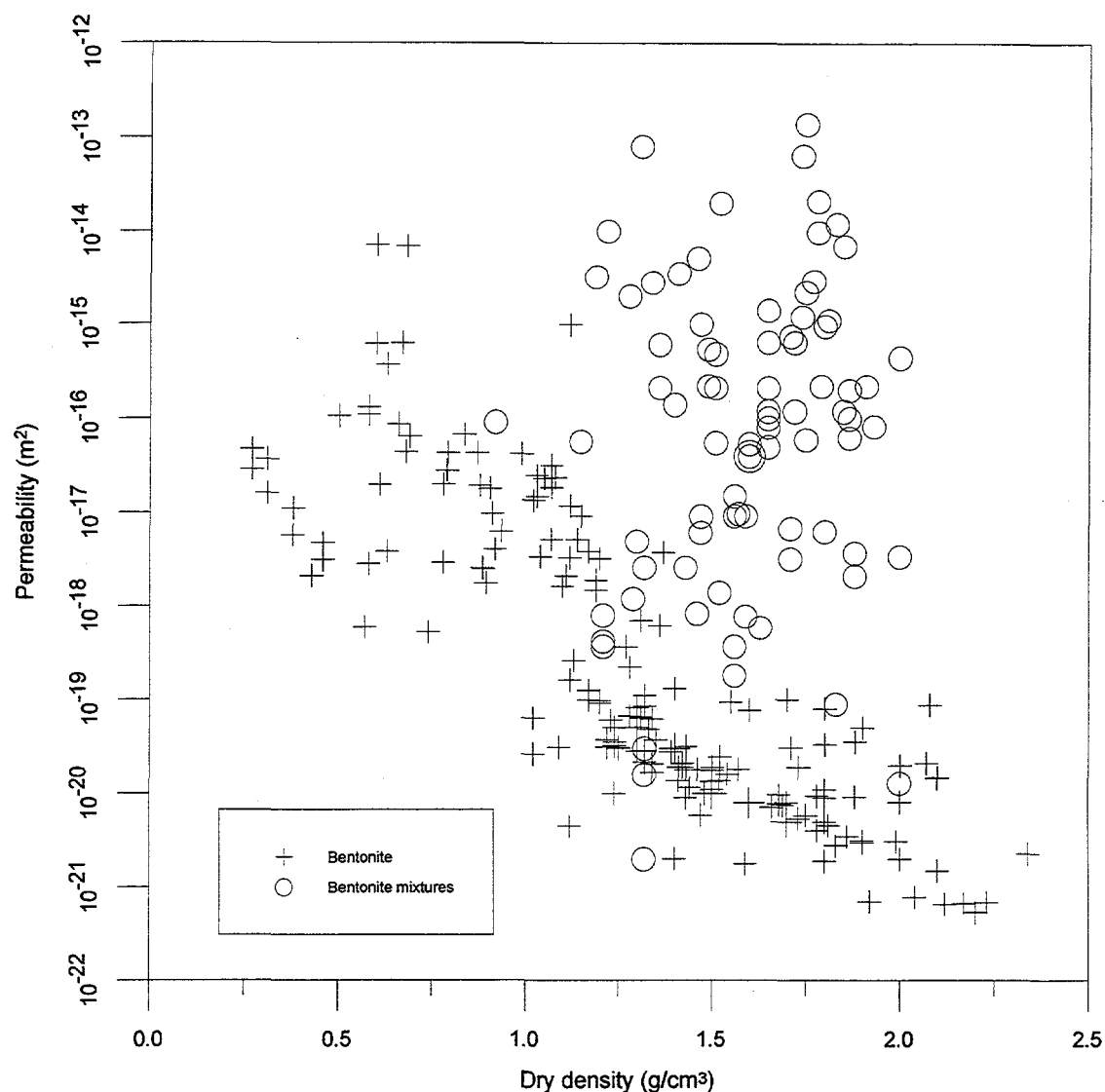
20

Figure 2. Reported hydraulic conductivity of compacted bentonite and bentonite mixtures as a function of dry density.

Influence of Permeant Chemistry/Brine

Alther (1982) summarized the influence of solution chemistry on sodium bentonite permeability (see Table 3). Calcium chloride, calcium sulfate, and calcium phosphates cause an increase in viscosity (i.e., flocculation or gelling) and hence increase permeability drastically. Acids dissolve part of the lattice over longer time periods. In the short term, they also flocculate the clay and cause an increase in permeability. High concentrations of Ca, Mg and total salts also increase permeability. Sodium salts decrease the permeability at certain percentages but increase it at higher percentages because competition for space between the sodium ions takes place, resulting in overcrowding and gelling.

21

Table 3. The Influence of Permeant Chemistry on Bentonite Permeability

Permeant Chemistry	Filter Cake	Soil Bentonite Backfill
Ca^{++} or Mg^{++} @ 1,000 ppm	N	N
Ca^{++} or Mg^{++} @ 10,000 ppm	M	M
NH_4NO_3 @ 10,000 ppm	M	M
HCl (1%)	N	N
H_2SO_4 (1%)	M	N
HCl	M/H*	M/H*
NaOH (1%)	M	M
CaOH (1%)	M	M
NaOH (5%)	M	M/H*
Sea Water	N/M	N/M
Brine (G_s=1.2)	M	M
Acid Mine Drainage $FeSO_4$ (pH=3)	N	N
Lignin (in Ca^{++} solution)	N	N
Alcohol	H(failure)	M/H

Data from D'Appolonia (1980).

N = No significant effect; permeability increase by about a factor of 2 or less at steady state.

M = Moderate effect; permeability increase by about a factor of 2 to 5 at steady state.

H = permeability increase by a factor of 5 to 10.

* = Significant dissolution likely.

Kenney et al. (1991) observed that the "hydraulic conductivity of mixtures containing high-swell bentonite, when permeated with a strong saline solution, increased by only a small amount, indicating that the fabric of bentonite enclosed within the framework was little influenced by this change of system chemistry."

Peterson and Kelkar (1983) observed a slight decrease in the hydraulic conductivity of bentonite samples when flow tested with a brine rich in Na^+ and Mg^{+2} (compared to flow tests with deionized water), from about 2 to 3×10^{-13} m/s to about 1.1 to 2×10^{-13} m/s.

Barbour (1987) presents data that show an increase by a factor of five for the permeability of a sand/Ca-bentonite sample after permeation with a 4.0 M NaCl brine. Barbour argues persuasively, although with limited support from experimental data, that the confining pressure may be a determining factor on whether the permeability will increase or not as a result of brine penetration. This topic may deserve further attention for WIPP shaft sealing, where shaft creep closure is expected to provide an active confining pressure.

Barbour (1987) and Sego et al. (1987) reference work by Ridley (1985) and Ridley et al. (1983) to raise some serious concerns about the validity of a widely used method for measuring permeability, namely rigid wall permeameters for studying the influence of brine on permeability. A rigid wall permeameter may not be appropriate to obtain true permeability measurements because it does not compensate for the shrinkage that may occur in field situations. Fernandez and Quigley (1988) present results that tend to support this concern. Their results of permeability tests on clays using water-soluble organic liquids

show that an even rather modest stress applied to the clay largely eliminates the large permeability increases that are observed in unpressured samples. Fernandez and Quigley note that even a modest stress (about 160 kPa) suffices to prevent permeability increases.

Almanza and Lozano (1990) subjected Ca-montmorillonite to flow tests with fresh water and with NaCl brine of 60% saline saturation at 50°C. The permeability was essentially the same for the two permeants. The authors conclude that a Ca-montmorillonite may be a better sealant against Na brine flow than a Na bentonite, even through it has a much smaller swelling capacity, because the exchange of one Ca^{++} ion by two Na^+ ions results in a permeability decrease.

For sodium bentonite, the permeability increases when saline solutions (0.7 to 1.2 M NaCl) are the permeate (Figure 3). Kenney et al. (1992) conducted hydraulic conductivity tests on compacted bentonite/sand mixtures using distilled water and 0.7 mol/L salt water as the permeants. Samples with dry density of 1.5, 1.65, or 1.85 g/cm^3 and with bentonite to sand ratios of 0.05 to 0.25 were tested. The hydraulic conductivity of bentonite permeated with salt water is about two orders of magnitude higher than that permeated with distilled water. Kenney et al. (1992) also found that bentonite samples mixed with brine and permeated with 0.7 M brine can have a hydraulic conductivity about two orders of magnitude higher than samples mixed with distilled water and permeated with 0.7 M brine.

Yang and Barbour (1992) studied the influence of brine on clay permeability. Fresh water and brine (5.0 M NaCl) were permeated through static-compacted, kneading-compacted, or slurry samples of Regina Clay (45.2 % montmorillonite, calcium based). Yang and Barbour found that brine increases the hydraulic conductivity of the clay 2 to 6 times at confining pressures less than 10 kPa, and about 2 times when the confining pressure is higher than 50 kPa. Haug et al. (1990) obtained test results from which they concluded that a NaCl brine had an insignificant effect on the hydraulic conductivity of illite/bentonite mixes under high confining stresses. Under low confining pressures, hydraulic conductivity increases significantly. Yang and Barbour (1992) concluded that brine permeation through clays does not change the microstructure of the clay significantly; it does, however, increase the size of interaggregate pores.

According to Mitchell (1976, p. 112), NaCl concentration influences the interlayer thickness, which dominates the swelling pressure and hydraulic conductivity of bentonite when it is saturated. For a montmorillonite clay with a specific surface of 800 m^2/g and a cation exchange capacity of 83 meq/100 g, the thickness of the interlayer is 333 Å when saturated with a solution of $0.83{\times}10^{-4}$ M NaCl, and 1.25 Å when saturated with a solution of 6 M NaCl (Figure 4). The decreased thickness of interlayers reduces the swelling capacity of montmorillonite and increases the hydraulic conductivity. It seems that salt/brine has significant influence on the swelling and flow properties of bentonite. However, the bentonite seal should retain its original physical and chemical properties if the emplaced bentonite is never penetrated by brine. For high density bentonite under low injection pressure, the low hydraulic conductivity and higher swelling pressure developed in the bentonite layer adjacent to the permeant source can resist further brine penetration. It is necessary to understand how brine penetrates the bentonite to fully understand the performance of bentonite seals emplaced in salt/brine environment.
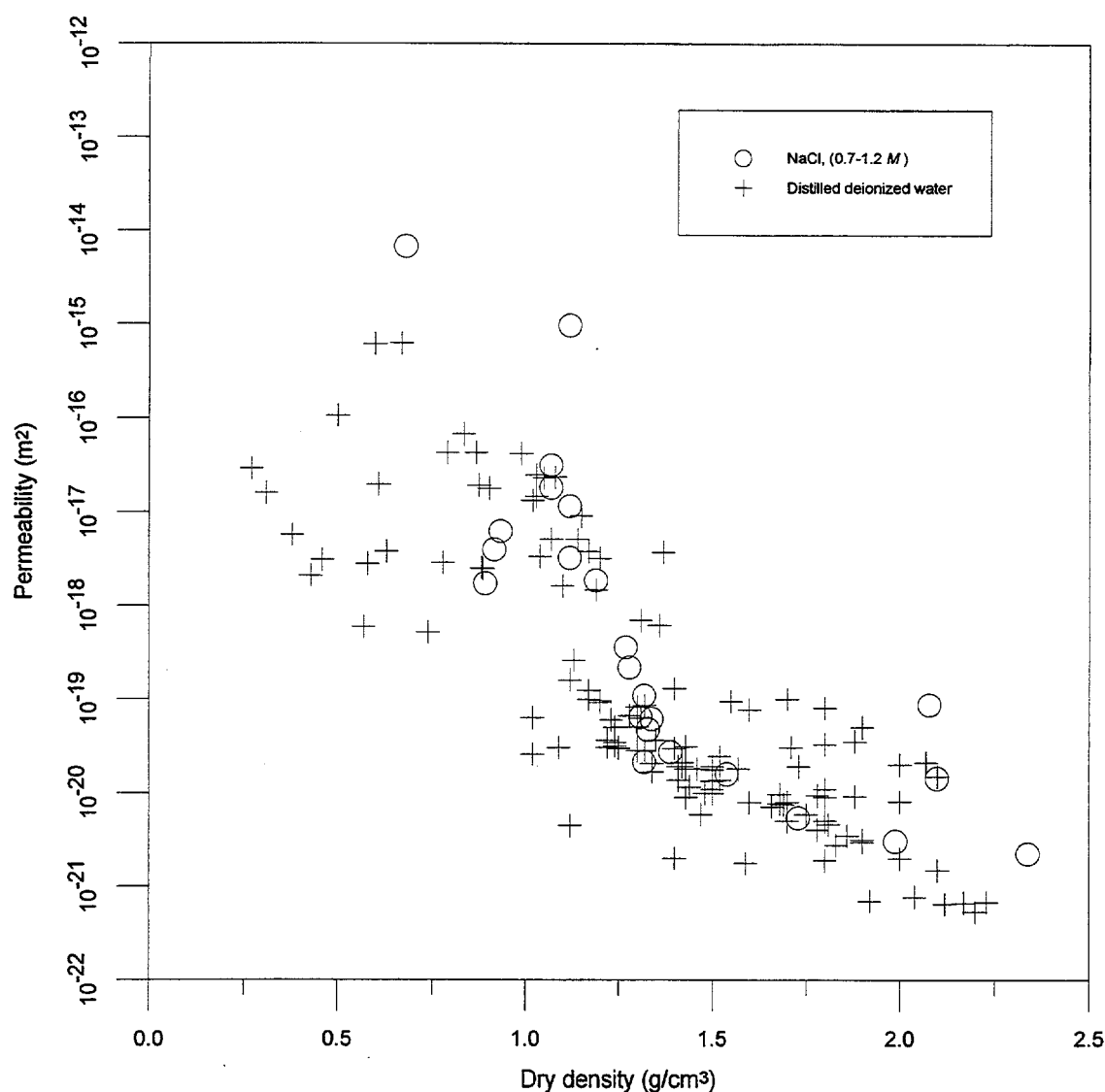
Figure 3. Reported permeability as a function of dry density for permeant with distilled deionized water and brine.

Sodium bentonite that is hydrated and permeated only with relatively fresh water will be effective indefinitely. The interlayer sodium cation can be exchanged with cations that have higher replacing power during hydration and permeation. Cation exchange greatly reduces the amount of water that bentonite can hold in the interlayer, resulting in decreased swell capacity. The loss of swell usually causes increasing porosity and increasing hydraulic conductivity. Mitchell (1976, p. 130) notes that Li^+, K^+, Rb^+, Cs^+, Mg^{2+}, Ca^{2+}, Ba^{2+}, Cu^{2+}, Al^{2+}, Fe^{3+} and Th^{4+} have higher replacing power to replace Na^+ in interlayers of bentonite. Li^+, K^+ and Ca^{2+} in brine tend to replace Na^+ in bentonite during hydration and permeation, hence increasing its hydraulic conductivity.
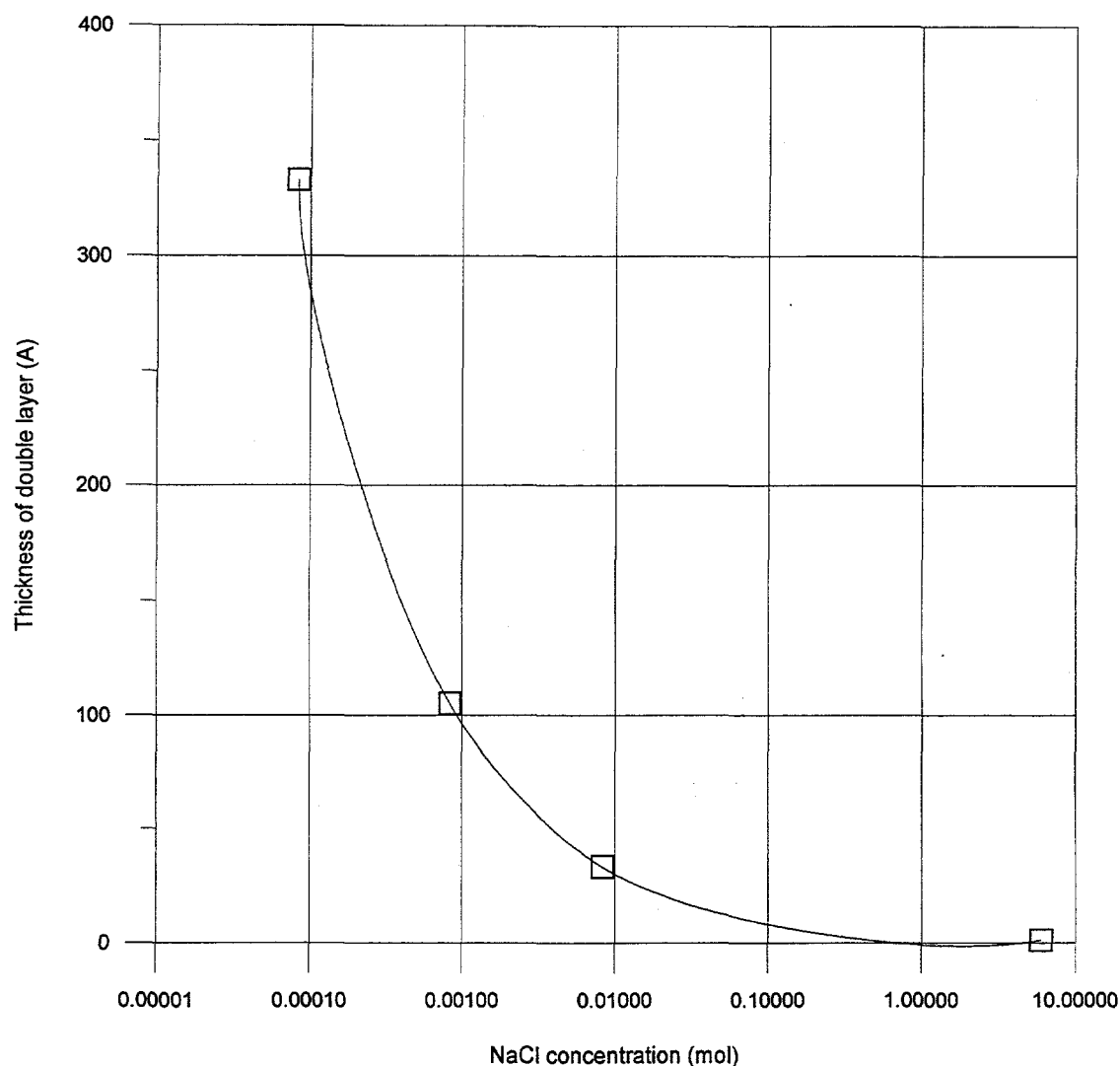
Figure 4. The thickness of interlayer as a function of NaCl concentration in solutions (calculation based on Equation 7.28 in Mitchell, 1976, p. 125).

Size Effects

Permeability may also vary with sample size. The permeability of bentonite measured in the laboratory may differ from that measured in the field. It is generally recognized that permeability increases when samples become larger, because defects or nonuniform density statistically have a better chance of being present in larger samples (Olson and Daniel, 1981). For pure bentonite, such size influence may not be as significant as for other materials, such as soil and mixtures of clay and sand/crushed rock, because of relatively uniform particle size and material components.

Boynton and Daniel (1985) conducted hydraulic conductivity tests for clays with sample-size diameters from 3.8 to 15 cm (1.5 to 6 in.). They concluded that the effect of sample size on permeability depends on water content at time of compaction. For samples compacted slightly dry of optimum, permeability is essentially independent of sample

25

diameter. When samples are compacted drier or wetter than optimum, the permeability increases with increasing sample diameter.

Olson and Daniel (1981) compared the hydraulic conductivity data of clays from 72 sites where field and laboratory hydraulic conductivities have both been measured. The range in the ratio of field permeability to laboratory hydraulic conductivity is from 0.3 to 46,000. However, for nearly 90% of the cases the ratio is from 0.38 to 64.

Daniel (1984) compared hydraulic conductivity results of laboratory and field tests from four projects where soil/bentonite liners were used. The ratio of permeability measured in laboratories to the permeability measured in the field is from 5 to 100,000. Daniel (1984) concluded that the actual hydraulic conductivities of the clay liners were generally 10 to 1,000 times higher than values obtained from laboratory tests. However, many of the factors cited by Daniel (1984) as causes for the discrepancies between laboratory and field testing should not apply for WIPP shaft sealing, or they should be avoidable: Discrepancies seem largest for relatively thin layers (less than 0.6 m [24 in.] thick), desiccation has affected most of the liners where large differences were measured, and construction inspection was not as extensive as it might have been. Benson et al. (1994), in a very careful analysis of size effects including consideration of multiple case studies, essentially conclude that laboratory size permeability tests can be representative of *in situ* compacted clay, on condition that *in situ* compaction is conducted with extreme care.

5.1.2 Gas Permeability

According to Brenner (1988, p. 26) gas flow through saturated compacted bentonite requires displacement of "free" water in the larger pores or, in extremely dense bentonite, a displacement of clay particles. According to Pusch et al. (1985) as quoted by Brenner (1988), a critical gas pressure exists above which a sudden rapid increase in gas flow is observed. This critical gas pressure increases with density and is a material characteristic.

Pusch et al. (1985) conducted experiments in a swelling oedometer on samples of MX-80 bentonite that were 50 mm in diameter and 20 mm thick. The saturated density ranged from 1.70 to 2.14 g/cm^3 (dry density was 1.4 to 1.79 g/cm^3). The samples were saturated with a Nagra water fairly rich in salts. The critical (breakthrough) gas pressure, measured with both nitrogen and hydrogen, ranged from 1.6 to 21 MPa. The ratio of the breakthrough gas pressure to swelling pressure ranged from 0.2 to 0.9, with most typical values in the range of 0.5 to 0.7. The ratio was smaller when the gas pressure increased more rapidly. A mechanistic model explaining the observed gas flow behavior, based on the likely pore structure, is given by Pusch and Hokmark (1990). The macroscopic hydraulic conductivity to gas appears to be of the same order of magnitude as that of water, i.e. about 10^{-13} m/s for dry densities of about 1.7 to 1.8 g/cm^3.

5.2 Porosity

Because the entire pore volume is not available for water flow, the effective porosity (the ratio of the interconnected pore volume to the total volume of the medium) is used to characterize the fluid flow in porous media or clay (Bear, 1972, p. 44; Gillott, 1987, p. 390). The pore properties (size, size distribution, shape, and structures) of clay are affected by

moisture content, pore water chemistry, and confining pressure. A portion of the water adsorbed or retained on solid clay particles is unable to flow freely, and the space occupied by such water is not available for water flow. The amount of water attached on the solid particles depends on the surface area of the solids and the thickness of the diffuse double layer. Chapuis (1990) introduced the term "efficient porosity" to describe the water flow in clay. Efficient porosity is measured by determining the portion of bound water adsorbed on the solid particles and subtracting that portion from the effective porosity. The portion of space (slow-moving water on particles) not available for water flow ranges about 20 to 50% of the total porosity. Chapuis (1990) reports the results of 45 laboratory tests on the porosity of bentonite and of soil bentonite mixtures. The average efficient porosity is 53% of primary porosity. Figure 5 shows the correlation between efficient porosity and total porosity.
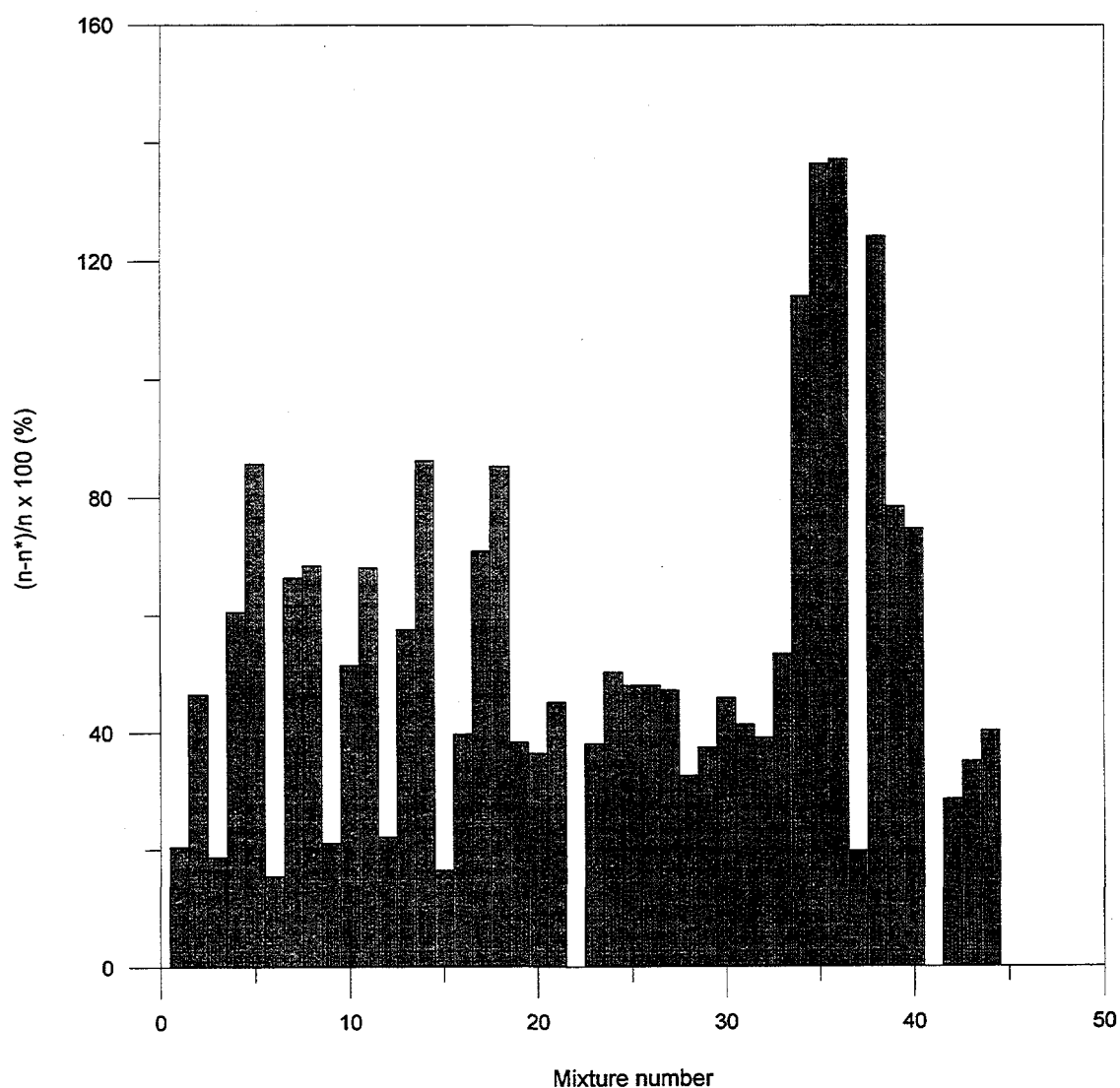

Figure 5. Correlation between total porosity (n) and efficient porosity (n^*) of bentonite/ sand mixtures (data reported by Chapuis, 1990).

27

The primary or total porosity n is given by the expression:

$$n = \frac{e}{1+e} \qquad (1)$$

where e is the void ratio, which can be calculated from the specific gravity (G_s) of bentonite, the dry density (ρ_d) of the bentonite seal, and the density of water (ρ_w), i.e.:

$$e = G_s \frac{\rho_w}{\rho_d} - 1 \qquad (2)$$

The specific gravity of bentonite is about 2.4 to 2.8. For Volclay GPG-30, the specific gravity is 2.5 (American Colloid Company, 1995). The efficient porosity should vary with moisture content and salt concentration. Diamond (1970) measured the effective porosity of montmorillonite as 35% less than the calculated or primary or total porosity. Figure 6 shows dry density plotted as a function of porosity.

The efficient porosity (n^*), defined here as the porosity actually available to water flow, is less than the total porosity because a thin water film adheres to smectite surfaces and is essentially immobile. Chapuis (1990) found no direct correlation between hydraulic conductivity and total or primary porosity, but a correlation exists with efficient porosity.

5.3 Volumetric Behavior: Swelling and Shrinkage

The volumetric behavior of clay sealants may affect waste isolation. Shrinkage could enhance releases, especially of gaseous products. Swelling is likely to tighten the bond between seal and host rock, but swelling must not be so large as to enhance the permeability of the host rock, particularly any unfavorably oriented discontinuities in the host rock.

5.3.1 Swelling

Bentonite is widely considered a desirable repository sealing material because of its swelling capacity. Swelling pressure of bentonite varies significantly, from 50 kPa to more than 58 Mpa (Westsik et al., 1982; Pusch, 1982), depending on the chemical components of the saturation fluid and its material composition. The methods used to measure swelling pressure may also cause variations in measured swelling pressure. An extremely long time is required to saturate the bentonite and to develop swelling pressure. During swelling pressure measurement, if the bentonite is never fully saturated, the measured swelling pressure at that condition may not be representative; it may be much lower than the actual maximum possible.

As shown in Table 4 and Figure 7, the swelling pressure of bentonite saturated with salt water at low density is 3 to 10 times lower than that saturated with fresh water. Pusch (1980) concluded that the swelling pressure of bentonite saturated with brine is identical to that of bentonite saturated with fresh water for densities close to or greater than 2.1 g/cm^3. This may be true when the bentonite has never been saturated. It is clear that this conclusion is applicable for WIPP when the WIPP brine contains up to or more than 5 M NaCl.
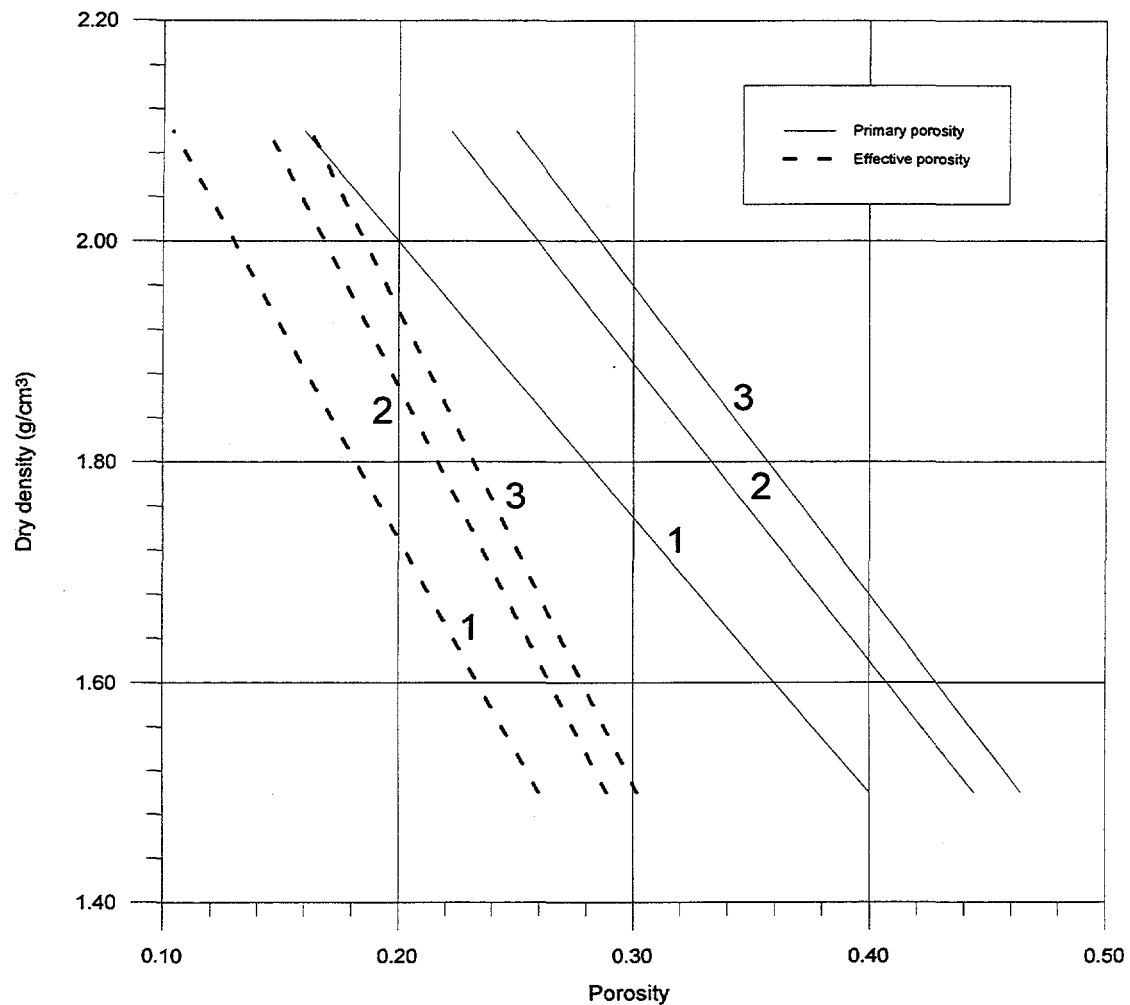
Figure 6. Dry density of bentonite as a function of porosity, where 1: $G_s = 2.5$, 2: $G_s = 2.7$ and 3: $G_s = 2.8$. Effective porosity = 65% of primary porosity (Equations 1 and 2).

Westsik et al. (1982), as recounted by Allen and Wood (1988), measured swelling pressures of 57 to 58 MPa for a pure bentonite at high density, which is in good agreement with pressures reported by Pusch (1979).

According to Brenner (1988, p. 21) the influence of water ions on swelling pressure is negligible: No significant difference was observed in terms of swelling behavior for two bentonites when either demineralized water or water rich in sodium was used.

Table 4. Reported Swelling Pressures of Bentonite and Bentonite Mixtures

Material	Composition (%)	Density	Swelling Pressure (MPa)	Permeant	Reference
Bentonite/sand	10	2.1	0.15		Nilsson, 1985
Bentonite/sand	10	1.9	0.02		Nilsson, 1985
Bentonite/sand	20	2.0	0.13		Nilsson, 1985
Bentonite/sand	20	1.8	0.02		Nilsson, 1985
Na-bentonite		1.4	0.10	Low electrolyte fluid	Pusch, 1994
Na-bentonite		1.8	0.80	Low electrolyte fluid	Pusch, 1994
Na-bentonite		2.1	10.00	Low electrolyte fluid	Pusch, 1994
Ca-bentonite		1.8	0.50	Low electrolyte fluid	Pusch, 1994
Ca-bentonite		2.1	10.00	Low electrolyte fluid	Pusch, 1994
Na-bentonite		1.8	0.30	High electrolyte fluid	Pusch, 1994
Na-bentonite		2.1	10.00	High electrolyte fluid	Pusch, 1994
Ca-bentonite		1.8	0.05	High electrolyte fluid	Pusch, 1994
Ca-bentonite		2.1	10.00	High electrolyte fluid	Pusch, 1994
French clay		1.4	0.9		Atabek et al., 1990
French clay		1.5	2.0		Atabek et al., 1990
French clay		1.6	4.5		Atabek et al., 1990
French clay		1.7	8.0		Atabek et al., 1990
Na-bentonite		0.907	0.092		Oscarson et al., 1990
Na-bentonite		1.02	0.080		Oscarson et al., 1990
Na-bentonite		0.86	0.155		Oscarson et al., 1990
Na-bentonite		0.869	0.259		Oscarson et al., 1990
Na-bentonite		0.955	0.310		Oscarson et al., 1990
Na-bentonite		1.085	0.455		Oscarson et al., 1990
Na-bentonite		1.119	0.451		Oscarson et al., 1990
Na-bentonite		1.164	0.514		Oscarson et al., 1990
Na-bentonite		1.083	0.576		Oscarson et al., 1990
Na-bentonite		1.194	0.591		Oscarson et al., 1990
Na-bentonite		0.975	0.128		Oscarson et al., 1990
Na-bentonite		1.020	0.300		Oscarson et al., 1990
Na-bentonite		0.964	0.679		Oscarson et al., 1990
Na-bentonite		0.993	0.774		Oscarson et al., 1990
Na-bentonite		0.991	0.812		Oscarson et al., 1990
Na-bentonite		1.033	0.860		Oscarson et al., 1990
Na-bentonite		1.022	0.964		Oscarson et al., 1990
Na-bentonite		1.115	0.867		Oscarson et al., 1990
Na-bentonite		1.236	0.941		Oscarson et al., 1990
Na-bentonite		1.164	1.173		Oscarson et al., 1990
Na-bentonite		1.241	1.524		Oscarson et al., 1990
Na-bentonite		1.281	1.884		Oscarson et al., 1990
Na-bentonite		1.273	2.062		Oscarson et al., 1990
Na-bentonite		1.293	2.201		Oscarson et al., 1990
Na-bentonite		1.335	2.591		Oscarson et al., 1990
Na-bentonite		1.146	0.806		Oscarson et al., 1990
Na-bentonite		1.173	1.722		Oscarson et al., 1990
Na-bentonite		1.214	1.794		Oscarson et al., 1990
Na-bentonite		1.234	2.012		Oscarson et al., 1990
Na-bentonite		1.223	2.028		Oscarson et al., 1990

30

Table 4. Reported Swelling Pressures of Bentonite and Bentonite Mixtures

| Material	Composition (%)	Density	Swelling Pressure (MPa)	Permeant	Reference
Na-bentonite		1.281	2.488		Oscarson et al., 1990
Na-bentonite		1.333	3.338		Oscarson et al., 1990
Na-bentonite		1.403	3.393		Oscarson et al., 1990
Na-bentonite		1.309	3.899		Oscarson et al., 1990
Na-bentonite		1.335	4.028		Oscarson et al., 1990
Na-bentonite		1.353	3.963		Oscarson et al., 1990
Na-bentonite		1.40	0.677		Mingarro et al., 1991
Na-bentonite		1.57	2.354		Mingarro et al., 1991
Na-bentonite		1.80	3.543		Mingarro et al., 1991
Na-bentonite		2.13	31.883		Mingarro et al., 1991
Bentonite/sand	75:25	1.42	0.128		Mingarro et al., 1991
Bentonite/sand	75:25	1.60	0.795		Mingarro et al., 1991
Bentonite/sand	75:25	1.81	3.541		Mingarro et al., 1991
Bentonite/sand	75:25	2.04	24.525		Mingarro et al., 1991
Bentonite/sand	50:50	1.38	0.284		Mingarro et al., 1991
Bentonite/sand	50:50	1.60	0.471		Mingarro et al., 1991
Bentonite/sand	50:50	1.80	2.747		Mingarro et al., 1991
Bentonite/sand	50:50	2.00	15.267		Mingarro et al., 1991
Bentonite/sand	25:75	1.41	0.049		Mingarro et al., 1991
Bentonite/sand	25:75	1.58	0.334		Mingarro et al., 1991
Bentonite/sand	25:75	1.81	0.589		Mingarro et al., 1991
Bentonite/sand	25:75	2.03	5.886		Mingarro et al., 1991
Na-bentonite		1.917	1.399	0.3 M CaCl$_2$	Pusch, 1980
Na-bentonite		2.000	1.854	0.3 M CaCl$_2$	Pusch, 1980
Na-bentonite		1.989	3.259	0.3 M CaCl$_2$	Pusch, 1980
Na-bentonite		2.081	19.178	0.3 M CaCl$_2$	Pusch, 1980
Na-bentonite		2.151	46.833	0.3 M CaCl$_2$	Pusch, 1980
Na-bentonite		1.751	0.705	Distilled water	Pusch, 1980
Na-bentonite		1.801	1.034	Distilled water	Pusch, 1980
Na-bentonite		1.832	1.746	Distilled water	Pusch, 1980
Na-bentonite		1.888	3.007	Distilled water	Pusch, 1980
Na-bentonite		1.998	6.464	Distilled water	Pusch, 1980
Na-bentonite		2.009	16.995	Distilled water	Pusch, 1980
Na-bentonite		2.079	24.421	Distilled water	Pusch, 1980
Na-bentonite		2.189	73.927	Distilled water	Pusch, 1980
Na-bentonite		1.818	0.863	Ground water	Pusch, 1980
Na-bentonite		1.846	0.993	Ground water	Pusch, 1980
Na-bentonite		1.819	1.055	Ground water	Pusch, 1980
Na-bentonite		2.003	5.502	Ground water	Pusch, 1980
Na-bentonite		2.036	15.999	Ground water	Pusch, 1980
Na-bentonite		2.112	38.034	Ground water	Pusch, 1980
Na-bentonite		2.189	65.513	Ground water	Pusch, 1980
Na-bentonite		1.859	0.780	0.6 M NaCl	Pusch, 1980
Na-bentonite		1.913	1.055	0.6 M NaCl	Pusch, 1980
Na-bentonite		2.003	3.194	0.6 M NaCl	Pusch, 1980
Na-bentonite		2.059	24.917	0.6 M NaCl	Pusch, 1980
Na-bentonite		2.151	55.764	0.6 M NaCl	Pusch, 1980
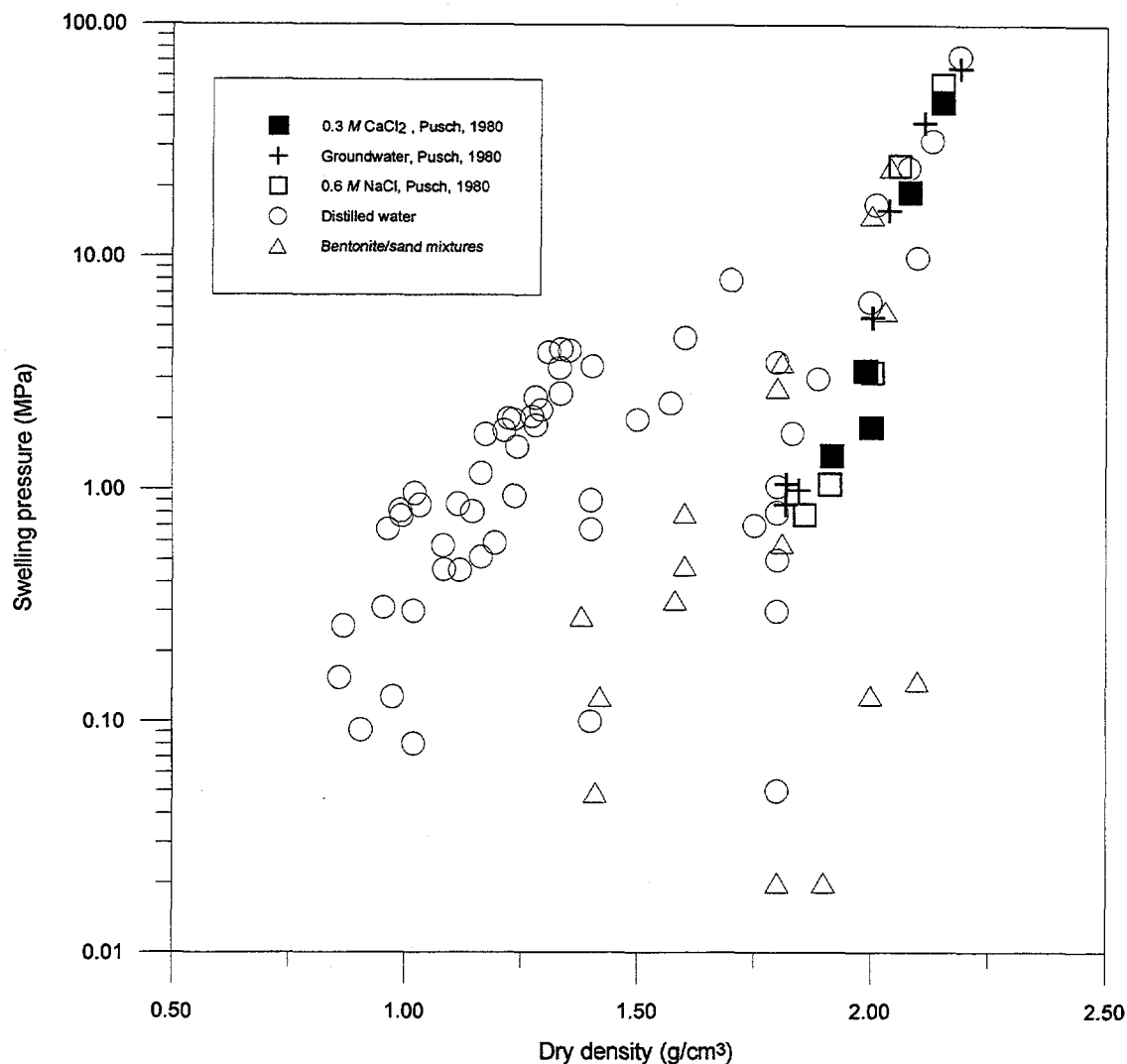
Figure 7. Reported swelling pressure as a function of dry density of bentonite and bentonite mixtures.

Allison et al. (1990) conducted swelling pressure measurements on bentonites and measured swelling pressures significantly lower than those reported by Pusch (1980), as shown in Figure 8. Allison et al. (1990) attribute the differences to inconsistency in measurement methods, and they describe the measurement methods used by Pusch (1980) as unrealistic or as not representative of actual conditions. The merits of the argument are not necessarily obvious. It is clear, however, that (1) swelling pressures may vary significantly depending on the details of the method used to measure the swelling pressure and (2) the most representative or realistic method (i.e., the method that most appropriately simulates field conditions) is far from obvious.
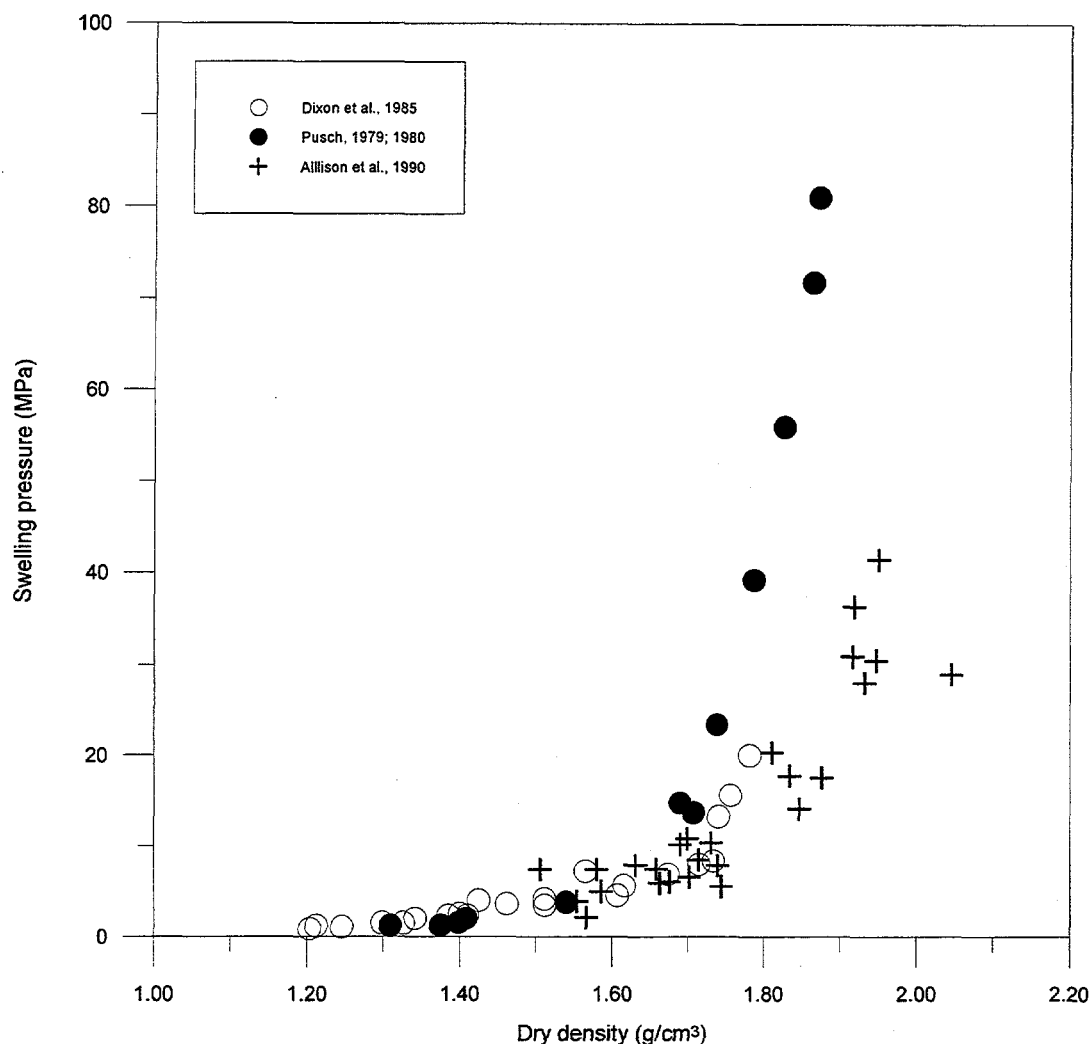
Figure 8. Comparison of swelling pressure for Na-bentonite from various researchers (after Allison et al., 1990).

Dixon et al. (1991) investigated three different methods for measuring the swelling pressure of highly compacted mixtures of sand and bentonite: triaxial consolidation, 1-D oedometer consolidation, and tests in a rigid constant-volume cell. They concluded that for tests on highly precompacted mixtures the results were largely independent of the test method used. Note that the materials tested generated relatively low swelling pressures, in the 1 to 3 MPa range.

5.3.2 Shrinkage

Compacted bentonite shrinks when it is dried to low water content. An increase in confining pressure reduces the volume of the compacted bentonite, especially when permeated by permeants containing numerous types of cations and electrolytes such as Na^+. Other factors (such as type of bentonite, temperature, fabric, and density) also change the

volume of the compacted bentonite. The shrinkage of compacted bentonite caused by loss of moisture content is directly related to clay mineral composition. The thickness of the diffuse double layer varies with changes of the pore fluid chemistry. Haug et al. (1988) reported a 7% volume decrease for 20:80 sodium bentonite/sand mixtures when NaCl concentration increased from 0 to 4 mol/L and when a 200 kPa surcharge was applied. Barbour and Yang (1993) observed that, for clay initially remolded with distilled water, the clay always shrinks when the pore fluid is replaced by brine.

5.4 Mechanical Properties

Compacted clay seals in shafts also act as structural components to support the shaft walls, which prevents collapse and allows healing of the DRZ. To provide the necessary resistance, the bentonite seals should have enough mechanical stiffness and strength to resist shaft closure and prevent separation from the upper sealing columns, which may result from over shrinkage and subsidence. Although the mechanical properties of bentonite are as important to sealing as its fluid-conduction properties, few studies have focused on the mechanical properties of compacted bentonite.

5.4.1 Strength

Radhakrishna and Chan (1982) studied the strength and deformation characteristics of compacted Black Hills bentonite, Avonlea bentonite, and Pembina bentonite, as well as the attributes of bentonite mixtures with crushed granite or sand. The results of their investigations are given in Table 5.

Table 5. Mechanical Properties of Bentonite and Bentonite/Crushed Granite Mixtures

Sample	Bentonite Content (%)	As Compacted				After Saturation			
		Dry Density (g/cm^3)	Moisture Content (%)	Compressive Strength (MPa)	Young's Modulus (MPa)	Dry Density (kg/m^3)	Moisture Content (%)	Compressive Strength (MPa)	Young's Modulus (MPa)
CGBB	50	1.765	15.3	0.822	50.0	1.685	19.7	0.374	7.1
CGBB	50	1.655	22.5	0.358	19.6	1.585	24.7	0.136	6.2
CGBB	50	2.138	9.7	1.339	58.3	2.076	11.5	0.560	12.0
CGBB	50	2.015	12.0	0.872	21.6	1.976	12.5	0.360	2.0
BB	100	1.670	22.3	2.524	68.0	1.338	37.3	1.200	25.9
AVB	100	1.557	19.6	4.578	313.0	1.554	25.1	1.780	43.6
PB	100	1.443	25.5	2.948	352.0	1.435	34.1	2.104	108.6
CGAVB	50	1.784	18.2	1.956	98.0	1.797	18.9	1.768	87.1
CGBB	50	1.795	16.8	3.384	154.0	1.770	21.2	1.360	68.7
CGBB	50	1.883	13.1	1.230	31.9	1.897	16.5	0.876	25.8
CGBB	25	1.935	14.0	0.522	63.6	1.885	15.1	0.580	53.6

After Radhakrishna and Chan (1982).
CGBB = Mixture of Black Hills bentonite and crushed granite; BB = Black Hills bentonite;
AVB = Avonlea bentonite; PB = Pembina bentonite;
CGAVB = Mixture of Avonlea bentonite and crushed granite.

Di Maio and Fenelli (1994) investigated the residual strength of bentonite as a function of pore fluid chemistry. The residual friction angle of bentonite increases significantly when distilled water is replaced with a 1 M NaCl solution, and even more when a saturated sodium chloride solution is used (from 6° to 9° to 18°). Barbour (1987) quotes data from triaxial tests reported by Ho (1985) and Ho and Pufahl (1987) on Regina clay (a clay containing 45% montmorillonite, 28% illite, 18% kaolinite and 9% trichloride). After exposing the samples to a 4.0 M solution of NaCl brine, the friction angle increases from 33° to 37°. Mitchell (1993, p. 364) cites friction values from Kenney (1967), which show a significant increase for Na-montmorillonite when prepared with a NaCl brine as compared to fresh water: the residual friction angle increased from 6° to about 17°. Borgesson et al. (1995) conducted triaxial tests on MX-80 bentonite samples with wet density of 2.0 g/cm^3 and found that the friction angle is 12.9° and cohesion is 106 kPa when pore water with 3.5% NaCl is used. When blocks with a dry density of 1.8 g/cm^3 are used, the finished seal in shafts should have a dry density slightly less than 1.8 g/cm^3.

5.4.2 Stiffness

Bentonite and bentonite-based seals are likely to be characterized by highly complex, strongly nonlinear mechanical behavior. Yin et al. (1990) used a three-modulus hypoelastic constitutive model for compacted sand-bentonite mixtures.

Young's Modulus

Figure 9 shows the relationship between Young's modulus and minor principal stress, σ_3. The Young's modulus (E) of clay is given by Janbu (1963) in the formula:

$$E = Kp_a \left(\frac{\sigma_3}{p_a} \right)^n \tag{3}$$

where K is a dimensionless modulus number that varies from about 300 to 2000 (Mitchell, 1993, p. 339); for saturated bentonite, the range probably is much narrower, about 100 to 300 or less. The variable n is an exponent usually in the range of 0.3 to 0.6 (Mitchell, 1993, p. 339). Pa is a unit constant equal to atmospheric pressure, and σ_3 is minor principal stress.

Yin et al. (1990) concluded that the Young's modulus of a 50:50 bentonite sand mixture can be calculated as:

$$E = kp' \tag{4}$$

where k is a constant: $k = 80$ for 50:50 bentonite sand mixture; p' is the effective mean stress: $p' = 1/3 \ (\sigma_1' + 2\sigma_3')$.

The Young's modulus of bentonite should be lower than that of a bentonite/sand mixture. Highly compacted and relatively dry bentonite (2.0 g/cm^3 with 10% water content) has a Young's modulus up to 300 MPa, which decreases with the uptake of water (Meyer and Howard, 1983).
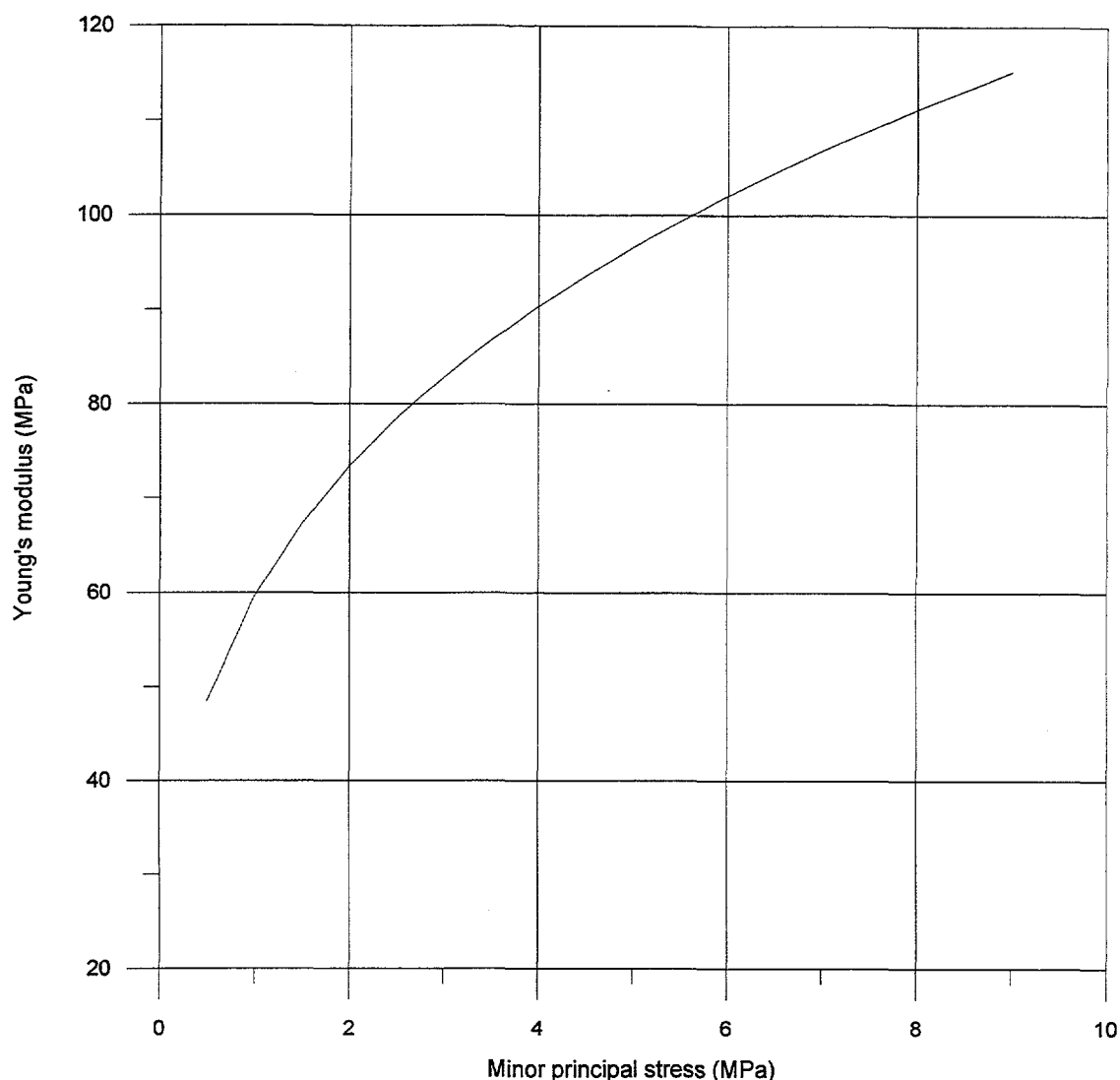
Figure 9. Young's modulus of clay as a function of minor principal stress with $K = 300$, $P_a = 14.4$ psi, and $n = 0.3$ in Equation 3 (after Janbu, 1963).

Bulk Modulus

Yin at al. (1990) concluded that the bulk modulus of a 50:50 bentonite/sand mixture is 13.7 p'. Again, for pure bentonite, the bulk modulus is almost certainly lower.

Poisson's Ratio

Meyer and Howard (1983) reported that for highly compacted and relatively dry bentonite (2.0 g/cm^3 with 10% water content), the Poisson's ratio is about 0.15. For soft clay, the Poisson's ratio should be about 0.375, according to Dunn et al. (1980, p. 113). Saturated bentonite is known to be extremely plastic; therefore Poisson's ratio is expected to be larger, i.e., at least 0.4 and probably 0.45 or larger.

Mechanical Behavior

The preceding extremely brief description of bentonite stiffness in terms of single isotropic elastic constants is at best extremely simplistic and at worst rather misleading. More complete and complex mechanical behavior models have been developed for clays. Barbour (1987) summarizes numerous references in a model that explicitly includes a solid phase, a pore fluid phase, and a diffuse double layer phase. A constitutive model including these phases clearly is far more realistic for describing relations between stress and strain, including for example the effects of salt migration. It is unclear whether or not sufficient information is available yet to implement such a model.

5.5 Sorption

Ion exchange, or sorptive retardation of radionuclides, is one of the main reasons that clays, specifically bentonites, have been selected as backfill and sealing materials for many repositories. An extensive literature exists on sorptive and retardation studies of radionuclides in clays. Although many references for this topic are included in the computerized data bases accompanying this document, no effort was made to review and summarize those references. One example may suffice to show that sorption studies on clay, specifically bentonite, have been conducted within the context of most repository programs.

Brodda and Merz (1983) describe experimental investigations of the sorption of strontium and cesium on six clay types, including two bentonites. The authors observe that sorption efficiency is greatly reduced when saline brines flow through the clays.

5.6 Index Properties

The liquid and plastic limits of bentonite depend greatly on the type of the adsorbed cations (Mitchell, 1976). The range of reported index properties of bentonite are given in Table 6. The plastic limit of bentonite is 50 to 100 (Mitchell, 1976, p. 173) or 83 to 250 (Grim and Güven, 1978, p. 218). The liquid limit of bentonite ranges from 100 to 900 (Mitchell, 1976, p. 173) and from 160 to 500 (Grim and Güven, 1978, p. 218).

Table 6. Reported Index Properties of Bentonite

Material	Liquid Limit	Plastic Limit	Free Swell*	Fluid	References
Bentonite	500	40	25	DDW	Kenney et al., 1992
Bentonite	105	35	5.4	0.7 M NaCl	Kenney et al., 1992
Ca-bentonite	75.5	24.3			Yang and Barbour, 1992
Na-bentonite	250				Dixon et al., 1992a
Bentonite	355	55			Yong and Cabral, 1992
Bentonite	100-900	50-100			Mitchell, 1976, p. 173
Bentonite	160-500	83-250			Grim and Güven, 1978, pp. 218-220

* = Void ratio; DDW = Distilled deionized water

The liquid limit increases with increasing amounts of exchangeable sodium cations; the liquid limit does not relate to size fraction of bentonite (Sridharan et al., 1986). For sodium bentonite, the liquid limit is 250 and the plastic limit is 49 (Dixon et al., 1991).

Kenney et al. (1992) report that the liquid limit of bentonite reduces from 500 to 105 when a 0.7 mol/L solution of NaCl is used for saturation instead of distilled water. The plastic limit of bentonite reduces also, from 40 to 35, when a 0.7 mol/L solution of NaCl is introduced.

For clay liners affected by landfill leachate, Bowders et al. (1985) recommend that the index properties of clay be determined for clay mixed with fresh water and for clay mixed with leachate. If no significant differences in the index properties are measured, it is then likely that the permeability will not be affected significantly. Bagchi (1994, p. 142) indicates that this relation between index properties and permeability was recognized by Terzaghi (1936).

5.7 Longevity

The argument that clays, particularly bentonites, have persisted in nature over long geologic times has frequently been invoked as a primary criterion for their selection as sealing materials. Detailed studies have been conducted within the framework of many repository programs to evaluate the likely longevity of clays, specifically bentonites, particularly for backfill studies. When used as a backfill component in a high-level waste repository, clay will likely be exposed to much higher temperatures than when used as a seal component; it may also be exposed to high radiation levels. WIPP is not a heated repository. Nevertheless, data about alteration at elevated temperature may be relevant or applicable, to the extent that such results can be considered representative as accelerated tests.

The longevity of bentonite seals is directly related to the stability of smectites under installed and site conditions (Güven, 1990). The conversion of montmorillonite to hydrous mica is one of the changes that can influence the stability of bentonite seals. In a brine environment, excess sodium may decrease the swelling ability and increase the permeability of the bentonite seal. Several methodologies have been adopted to study the longevity of bentonite seals, including montmorillonite conversion, microstructure changes, observation of long-term permeability, and comparison of the swelling pressure and permeability of processed and unprocessed bentonites.

The primary longevity requirement is stability: the performance of compacted clay seals should not deteriorate excessively over time. Krumhansl (1986) conducted an extensive scoping investigation of the long-term stability of bentonite in a saline environment. Because the investigation was designed to improve understanding of the long-term stability of bentonite when used as a backfill for high-level waste (HLW) packages, he subjected bentonite to environments far more severe than those likely to be encountered by WIPP shaft seals. Krumhansl (1986, p. 3) reported that

> "...most experiments were done at the most extreme conditions likely to occur in a commercial HLW repository. These experiments can also be considered as accelerated tests (or "overtests") for repositories isolating cooler forms of waste, such as the defense

wastes.... These results make a strong case that bentonite is sufficiently stable to warrant the additional research required to fully demonstrate bentonite backfill feasibility.

In a technical report on underground repository sealing, the International Atomic Energy Agency (IAEA) summarized the results from a number of studies on the longevity of clay seals. The IAEA (1990, p. 58) concluded that

...for highly compacted clays, within the range of values expected in a repository, even in the near field, temperature and ionic concentration in the groundwater should not significantly affect swelling potential or hydraulic conductivity.

Pusch and Karnland (1990) studied the conversion of montmorillonite to illite when potassium is available. The conversion of smectite to illite takes place in the environment either at high effective pressure and at temperature exceeding about 60°C or drying (Pusch, 1994, p. 352). Pusch and Güven (1990) studied the microstructure of Na-bentonite with a bulk density of 2.0 g/cm^3 under temperatures from 150 to 200°C for six months. The microstructure of the bentonite changed, with an enlargement of the pores. No mineralogical and chemical changes were observed. Howard and Roy (1985) conducted laboratory studies of sodium-saturated bentonite to investigate smectite alteration at 150 to 250°C for 30 to 180 days. They found that potassium transfers smectite into illite. The rate of transformation depends on temperature, potassium content, and fluid composition. Although WIPP salt only contains 0.151 to 0.232% potassium (Brodsky, 1994), the smectite to illite transformation may occur.

Oscarson et al. (1990) compared the swelling pressures and hydraulic conductivity of processed and unprocessed bentonites to identify the longevity of the bentonite seal. They found that processed bentonite has higher swelling capacity and lower permeability for bentonites with dry densities from 0.9 to 1.4 g/cm^3. Unprocessed bentonite maintains a significantly high swelling capacity and low permeability after millions of years of water erosion, thermal alteration, loading, and unloading.

Ran (1993) studied the flow properties of pure bentonite grout before and after healing from washing out some particles and channeling for over 200 days. After being washed out twice and subjected to varied pressure gradients for over 200 days, the bentonite can maintain low hydraulic conductivity.

Page intentionally left blank.

6. EMPLACEMENT/CONSTRUCTION

The major sealing characteristics of bentonites and clays (i.e., hydraulic conductivity and swelling behavior), as well as most other properties, are a strong function of emplacement density. Various emplacement options have been considered; among them are *in situ* compaction of powdered bentonite, emplacement in the form of precompacted blocks, and hydraulic or pneumatic emplacement.

In situ compaction with conventional compaction equipment is unlikely to produce acceptable densities if extremely low hydraulic conductivities are deemed necessary or desirable. Although one can conceptually visualize *in situ* static compaction equipment that could provide the pressures necessary to compact to high densities, such equipment would require design and construction.

A few emplacement investigations have been conducted for pure bentonite seals and for shaft sealing. Most investigations for seal emplacement technologies have focused on using sand or quartz bentonite mixtures to seal nuclear waste emplacement rooms. However, shaft sealing design can benefit from those investigations. Two emplacement methods have been investigated. One is the use of bentonite blocks, and another is *in situ* compaction.

The Canadian nuclear waste program has conducted extensive testing, both *in situ* and in large scale laboratory simulators, of the compaction of clay-based barrier materials with dynamic hydraulically powered impact hammers (e.g., Kjartanson et al., 1992). The Swedish program similarly has investigated field compaction of bentonite-based tunnel backfill by means of plate vibrators (e.g., Nilsson, 1985). Both studies demonstrated the feasibility of *in situ* compaction of bentonite-based materials to a high density. However, such manual backfill compaction might be excessively slow for the compaction of several hundred ft of shaft seals. Therefore the alternative of using sheepsfoot compactors is recommended, although it will require some modification of the driving systems for the compaction equipment. Heavy sheepsfoot rollers should allow the use of higher lifts than are possible with manual or semi-manual compaction, providing the kneading compaction that will minimize the permeability (Mitchell et al., 1965). They should also allow application of a large compaction energy in a reasonable amount of time.

Sheepsfoot roller compaction is widely used for construction of impervious liners for earth dams (Hilf, 1975) and for the construction of clay liners for waste disposal facilities (Daniel, 1993). Geotechnical textbooks and most experts interviewed recommend the use of sheepsfoot or tamping foot rollers for compacting cohesive (clay) soils to achieve low permeability (Goldman et al., 1990). The fundamental explanation for the effectiveness of sheepsfoot compaction in reducing permeability appears to be that kneading compaction and the associated large shear strains induce a dispersed structure that greatly reduces permeability (Mitchell et al., 1965). More detailed investigations of the soil structure resulting from sheepsfoot compaction are referenced by Seed and Chan (1959), according to Mitchell et al. (1965). Sufficient compaction passes will have to be made to assure that the required compaction energy is applied.

In Sweden, Nilsson (1985) conducted compaction tests of bentonite/sand mixtures in the field. The tests were conducted in a tunnel with six nuclear waste emplacement rooms. A dynamic roller (vibrator) was used to compact 10/90% or 20/80% bentonite/sand mixtures. The compaction after 25 runs resulted in dry densities of 1.59 to 1.71 g/cm^3 for the 10/90% bentonite/sand mixture, and 1.5 to 1.6 g/cm^3 for the 20/80% bentonite/sand mixture. The moisture content of the bentonite/sand mixture at compaction ranged from 8% to 16%.

In Germany, Bucher and Jedelhauser (1985) conducted laboratory compactions of quartz-sand/bentonite mixtures. The mixtures have Na-bentonite (MX-80) content from 17% to 33% or Ca-bentonite (Montigel) from 26% to 31% by weight. The mixtures were statically compacted in a compaction mold with 80 to 320 MPa compactive pressure. Their final density was 1.5 g/cm^3.

In Canada, Dixon et al. (1985) conducted laboratory compactions of bentonite and bentonite/sand mixtures. Standard Proctor molds and modified molds were used for compaction. The sand/bentonite mixtures had 25, 32.5, 40 and 75% bentonite contents. When the modified compactive energy was applied, the achieved dry density varied with bentonite content and moisture content. The compaction of the bentonite under the modified compactive effort was about 1.3 g/cm^3.

For bentonite/sand mixtures with more than 50% bentonite content, the modified compactive energy is insufficient to overcome the high shearing resistance of the water attached to the bentonite particles (Dixon et al., 1985). If the mixture has less than 50% bentonite content, greater compaction can be achieved (Nilsson, 1985; Dixon et al., 1985). However, Bucher and Jedelhauser (1985) note that the static pressure required to reach a given dry density of the bentonite filling the pores between sand grains is 10 to 20 times greater than that required to fill spaces between bentonite particles in a specimen of bentonite alone.

Highly compacted bentonite blocks were placed at the WIPP site. Bentonite blocks were produced in a block machine with 26.2 MPa (3800 psi) static pressure, and 1.8 g/cm^3 density was achieved (Howard, 1989). Pusch (1994) and Pusch et al. (1982) propose to use precompacted bentonite blocks to seal shafts. Bentonite blocks can be manufactured by uniaxial or three-dimensional compression. A dry density of 1.8 g/cm^3 with water content of 6% to 7% can be achieved by applying pressure up to 150 MPa (Pusch, 1994).

In situ compaction of clays is a widely used practice for many sealing applications, particularly, hazardous waste sites, heap leach pads, and similar engineered waste-containment structures. Emplacement, compaction, and verification methods are well established and readily available. Modifications of standard procedures may be required for emplacement in shafts, primarily because the equipment most likely to be recommended for clay compaction (i.e., sheepsfoot rollers) may not be readily available in sizes and weights desirable in shafts. Also, it seems quite likely that the required performance in WIPP shafts may be more stringent than the requirements for most other applications.

A potentially serious problem for *in situ* compaction may arise from the selected performance requirements. If the bentonite seals are designed for minimal hydraulic

conductivity at emplacement, it is likely that the recommended moisture content will be wetter than optimum (e.g., Mitchell et al., 1965). A highly plastic clay such as bentonite is likely to be very sticky, as well as very soft, at such high moisture contents, which may result in operational difficulties (Daniel, 1993).

The performance of bentonitic seals depends on many variables. Main factors to be taken into account during design and construction include compaction procedures to be used, moisture content, density, and type of fluid (i.e., water composition) mixed with bentonite.

Three important considerations with regard to compaction are (1) the type of equipment to be used, (2) the amount of energy to be applied, and (3) procedures to be used to assure that no preferential flowpaths develop between lifts. It is highly desirable to achieve the lowest practically possible permeability; therefore a kneading type compaction will be prescribed, most probably in the form of sheepsfoot roller type compaction, assuming the equipment can be operated in a shaft.

It is probable that a large energy application will be prescribed, i.e., the application of multiple compaction passes. Special indentation/kneading type preparation of interfaces between lifts will be prescribed to assure the development of a tight interface between lifts.

The development of desiccation cracks in emplaced lifts must be prevented. Most likely, large quantities of dry air will be blown into the bottom of the shafts during seal emplacement. Thus consideration must be given to either assure that the airflow does not cause excessive drying of emplaced bentonite (e.g., by artificially increasing the moisture content of the air) or to provide surface protection on top of emplaced seal material.

In addition to technical concerns, it is necessary to implement close supervision and inspection procedures. Several clay liner failures have been attributed to lack of inspection (e.g., Daniel, 1984; 1993), presumably reflecting inadequate construction. Daniel (1990) summarizes construction quality control procedures for compacted soil liners, many of which would be applicable and appropriate for shaft seals.

Page intentionally left blank.

7. RESERVES, SUPPLIES, AND LONG-TERM AVAILABILITY

Because repository backfilling and sealing may not take place for several decades, concern exists about the long term availability of bentonite. According to Miles (1995) "High swelling sodium bentonite is rare... Lower grade sodium bentonite deposits stretch north from Wyoming, through Montana and into the Canadian Provinces. In contrast, high quality calcium bentonite occurs throughout the USA and the world."

The availability question has been investigated within the context of the Canadian nuclear waste disposal program. According to Dixon et al. (1992b) the proven reserves of North American sodium bentonite exceed 1.9×10^9 Mg, and vast supplies are known to exist, though they have not yet been proven. The Canadian reference repository would require, for backfill and sealing, some 2.5×10^6 Mg of bentonite. The Canadian conceptual disposal vault would require 6×10^4 Mg of sodium bentonite each year for forty years. The North American bentonite industry has an installed annual bentonite production capacity of 2×10^7 Mg. The Canadian repository therefore would require approximately 2% of industry capacity. The Canadian program has screened a number of commercial products for potential suitability as backfill material and has identified ten currently marketed bentonite products that meet the initial quality standards for the buffer/backfill material, as well as two noncommercial bentonites.

According to Rath (1986) a conservative estimate of the remaining Wyoming bentonite reserves is about 90 to 100 million tons. Hosterman and Patterson (1992) concluded that the bentonite reserves in the United States are 800 million tons. There is considerable uncertainty about these estimates, however, because most companies do not willingly reveal reserve figures. Moreover, the figures change significantly with economic conditions. "Geologically, there is considerably more bentonite available than is presently commercially mineable." (Rath, 1986). In recent years (i.e., 1989 through 1993) production of Wyoming sodium bentonite has been on the order of 2.5 to 3 million short tons per year (Arrington-Webb, 1994; Virta, 1994).

A conservative approximation of the bentonite required for WIPP shaft sealing can be made assuming that the total cross-sectional areas of the compacted clay seals for four shafts will be 100 m^2 (DOE/WIPP, 1995, p. D-5), the maximum total length of the seals will be 400 m, and the seals will be compacted to a maximum dry density of 2 g/cm^3. It is assumed that the bentonite from the manufacturer contains 10% water. Under these assumptions, for four shafts about 88,000 metric tons (96,976 short tons) of bentonite would be needed for the shaft seals. This quantity represents about 3% of the current annual US sodium bentonite production.

Page intentionally left blank.

8. CONCLUSIONS

Bentonite has been widely studied as a primary sealing material for nuclear waste repositories (IAEA, 1990; Pusch and Bergstrom, 1980; Pusch, 1994; Coulon et al., 1987; Brenner, 1988; Bucher et al., 1986; Dixon et al., 1985; Butcher, 1994; Pfeifle, 1990). The swelling, longevity, and flow properties of bentonites and bentonite mixtures with sand or crushed rock have been extensively characterized with distilled deionzied water as the permeate. A few studies (Pusch, 1980; Dixon et al., 1987; Kenney et al., 1992) have been conducted using brines with low NaCl concentration (from 0.7 to 1.2 M) as pore fluid.

The permeability of compacted sodium bentonite (from 0.5 to 2.2 g/cm^3) ranges from 1×10^{-16} to 1×10^{-21} m^2. The permeability of bentonite mixtures varies significantly with density depending on the bentonite content. The permeability of compacted sodium bentonite increases two to three orders of magnitude when saline solutions (0.7 to 1.2 M NaCl) are the permeate. NaCl concentration in permeation fluid has a slight influence on the permeability of Ca-bentonite. If the confining pressure is high enough to compress the increased pores, such influence may be reduced. The permeability of bentonite mixtures with sand or crushed rock does not closely relate to the density of the seal (see Figure 2), but more to the bentonite content (see Figure 1).

The gas permeability of compacted bentonite depends on the moisture content of the bentonite and its density. Gas penetration through bentonite requires displacing free water in pores; hence a breakthrough pressure is needed. The breakthrough pressure increases with increasing moisture content and density. For saturated compacted bentonite, the breakthrough pressure ranges from 1.6 to 21 MPa for dry densities from 1.4 to 1.79 g/cm^3 (Pusch and Hokmark, 1990). For WIPP shaft sealing, bentonite seals should maintain enough density and moisture content to limit gas migration to an acceptable level.

For compacted sodium bentonite, the swelling pressure ranges from 0.1 to 74 MPa for dry densities from 0.86 to 2.19 g/cm^3 (Pusch, 1980, 1994; Oscarson et al., 1990; and Mingarro et al., 1991). The swelling pressure for compacted bentonite with a dry density less than 1.0 g/cm^3 is less than 1.0 MPa. Certain cations (i.e., NaCl, CaCl$_2$, etc.) in the permeate fluid can significantly reduce the swelling capacity of bentonite (Mitchell, 1976). A bentonite seal in a NaCl-bearing environment may generate much less swelling pressure.

Bentonite has persisted in nature over geologic time scales. Geologic evidence, laboratory data, and theoretical analysis show that highly compacted bentonite can maintain physical, thermal, and chemical stability in environments other than Na$^+$ and Ca$^+$-rich ones. In the WIPP environment, two factors may potentially influence the stability of compacted bentonite. The first is cation exchanges, which lead to conversion of the sodium bentonite into other types of bentonites that have higher permeability. Illite may be an inevitable product of reaction of smectite with K$^+$-rich pore fluid. Calcium bentonite may be formed when the pore fluid is rich enough in Ca^{2+}. A second factor is that bentonite may decrease its volume when brine penetrates because NaCl in brine can reduce the thickness of the double layer.

The mechanical properties of compacted bentonite are not well characterized when the pore fluid contains a high NaCl concentration (i.e., similar to WIPP conditions of >5 M).

The shear strength of compacted bentonite increases significantly when distilled water is replaced by 1 M NaCl solution as pore fluid (Di Maio and Fenelli, 1994). The reported compressive strength ranges from 2.5 to 4.6 MPa for compacted dry bentonite, and reduces to 1.2 to 2.1 MPa after saturation (Radhakrishna and Chan, 1982). The Young's modulus of compacted bentonite decreases with water uptake, from 68 – 352 MPa to 26 – 109 MPa (Radhakrishna and Chan, 1982; Meyer and Howard, 1983).

In situ compaction with conventional equipment is unlikely to produce the desirable density for bentonite seal construction. Two technologies (dynamic compaction and precompacted blocks) have been studied for bentonite seal construction for Swedish, Canadian, German, and US nuclear waste programs. Dynamic compaction technology has been evaluated both in the laboratory and in the field for mixtures of bentonite with sand or crushed rock. *In situ* compaction using a dynamic impact hammer (Kjartanson et al., 1992) or a plate vibrator (Nilsson, 1985) can densify mixtures of bentonite and sand or crushed rock to a dry density of 1.75 to 2.0 g/cm^3. Dixon et al. (1985) and Yong et al. (1986) reported that a dry density of 1.3% can only be achieved by dynamic compaction for bentonite when the modified Proctor effort is applied. Howard (1989), Pusch (1994), and Pusch et al. (1982) report that bentonite blocks with a dry density higher than 1.8 g/cm^3 can be produced in a block machine under 26 to 150 MPa static compression pressure.

A conservative estimate of the remaining Wyoming bentonite reserves is about 90 to 100 million tons (Rath, 1986). The proven high quality sodium bentonite reserves are about 1900 million tons in North America (Dixon et al., 1992b). The North American bentonite industry has an annual production capacity of 20 million tons (Dixon et al., 1992b). The WIPP shaft sealing system requires only about 88,000 metric tons of bentonite, which is about 3% of the current annual US production.

9. REFERENCES

Allen, C.C., and M.I. Wood. 1988. "Bentonite in Nuclear Waste Disposal: A Review of Research in Support of the Basalt Waste Isolation Project," *Applied Clay Science*. Vol. 3, no. 1, 11-30.

Allison, J.A., J. Wilson, J.M. Mawditt, and J.C. Hurt. 1990. *Research on Swelling Clays and Bitumen as Sealing Materials for Radioactive Waste Repositories*. DoE/HMIP-RR-91.0009. London: Her Majesty's Inspectorate of Pollution, Department of the Environment. (Available from the National Technical Information Service (NTIS), Springfield, VA as DE91646142/XAB.) (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM as WPO#41503.)

Almanza, R., and M.C. Lozano. 1990. "Tests of Ca-Montmorillonite Clay to be Used as a Liner in Solar Ponds," *Clean and Safe Energy Forever, Proceedings of the 1989 Congress of the International Solar Energy Society, Kobe City, Japan, September 4-8, 1989*. Eds. T. Horigome, K. Kimura, T. Takakura, T. Nishino, and I. Fujii. Oxford; New York: Pergamon Press. Vol. 2, 1433-1437.

Alther, G.R. 1982. "The Role of Bentonite in Soil Sealing Applications," *Bulletin of the Association of Engineering Geologists*. Vol. 19, no. 4, 401-409. (WPO#41474.)

American Colloid Company. 1995. "Technical Data Sheet, Volclay GPG 30." Arlington Heights, IL: American Colloid Company, Industrial Chemical Division. 1 p. (WPO#39636.)

Arrington-Webb, L.A. 1994. "Clays," *Mining Engineering*. Vol. 46, no. 6, 529-530. (WPO#41462.)

ASTM D 653 - 90. "Standard Terminology Relating to Soil, Rock, and Contained Fluids," *Annual Book of ASTM Standards, Volume 04.08, Soil and Rock; Dimension Stone; Geosynthetics*. Philadelphia, PA: American Society for Testing and Materials.

ASTM D 2487 - 93. "Standard Test Method for Classification of Soils for Engineering Purposes," *Annual Book of ASTM Standards, Volume 04.08, Soil and Rock; Dimension Stone; Geosynthetics*. Philadelphia, PA: American Society for Testing and Materials.

ASTM D 2488 - 93. "Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)," *Annual Book of ASTM Standards, Volume 04.08, Soil and Rock; Dimension Stone; Geosynthetics*. Philadelphia, PA: American Society for Testing and Materials.

Atabek, R., A. Lajudie, J. Lechelle, and R. Pusch. 1990. "Pilot Field Experiment with Canister-Embedding Clay Under Simulated Repository Conditions," *Engineering Geology*. Vol. 28, no. 3/4, 291-302. (WPO#41475.)

Bagchi, A. 1994. *Design, Construction, and Monitoring of Landfills*. 2nd ed. New York, NY: John Wiley & Sons. 361 p.

Barbour, S.L. 1987. "The Role of Physicochemical Effects on the Behavior of Clay Soils," *Geotechnique in Resource Development, Preprint Volume, 40th Canadian Geotechnical Conference, Regina, Saskatchewan, October 19-21, 1987.* [Rexdale, Ontario]: Canadian Geotechnical Society. 323-342.

Barbour, S.L., and N. Yang. 1993. "A Review of the Influence of Clay-Brine Interactions on the Geotechnical Properties of Ca-montmorillonitic Clayey Soils from Western Canada," *Canadian Geotechnical Journal.* Vol. 30, no. 6, 920-934.

Bear, J. 1972. *Dynamics of Fluids in Porous Media.* New York, NY: Elsevier Science Pub. Co. 764 p.

Benson, C.H., F.S. Hardianto, and E. Sabri Motan. 1994. "Representative Specimen Size for Hydraulic Conductivity Assessment of Compacted Soil Liners," *Hydraulic Conductivity and Waste Contaminant Transport in Soil, Proceedings of the Symposium, San Antonio, TX, January 21-22, 1993.* Eds. D.E. Daniel and S.J. Trautwein. ASTM Special Technical Publication 1142. Philadelphia, PA: American Society for Testing and Materials. 3-29. (WPO#38851.)

Berry, L.G., and B. Mason. 1959. *Mineralogy: Concepts, Descriptions, Determinations.* San Francisco, CA: W.H. Freeman and Company.

Berry, L.G., B.H. Mason, and R.V. Dietrich. 1983. *Mineralogy: Concepts, Descriptions, Determinations.* 2nd ed. San Francisco, CA: W.H. Freeman and Company. 561 p.

Börgesson, L., L-E. Johannesson, T. Sandén, and J. Hernelind. 1995. *Modelling of the Physical Behaviour of Water Saturated Clay Barriers. Laboratory Tests, Material Models and Finite Element Application.* SKB Technical Report 95-20. Stockholm: Swedish Nuclear Fuel and Waste Management Co. (Available from the NTIS, Springfield, VA as DE96617460/XAB.)

Bowders, J.J., D.E. Daniel, G.P. Broderick, and H.M. Liljestrand. 1985. "Methods for Testing the Compatibility of Clay Liners with Landfill Leachate," *Hazardous and Industrial Solid Waste Testing: Fourth Symposium, Arlington, VA, May 2-4, 1984.* Eds. J.K. Petros, Jr., W.J. Lacy, and R.A. Conway. ASTM Special Technical Publication 886. Philadelphia, PA: American Society for Testing and Materials. 233-250. (WPO#41466.)

Boynton, S.S., and D.E. Daniel. 1985. "Hydraulic Conductivity Tests on Compacted Clay," *Journal of Geotechnical Engineering.* Vol. 111, no. 4, 465-478. (WPO#41509.)

Brenner, R.P. 1988. *Bohrlochversiegelung: Materialeigenschaften von hochverditetem Bentonit mit Eignungsbeurteilung = Borehole Sealing: Material Properties of Highly Compacted Bentonite with a Judgment to its Suitability.* Technical Report NTB-88-04. Baden, Switzerland: NAGRA Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle. (In German.) 79 pp.

Brodda, B-G., and E. Merz. 1983. "Zur Wirksamkeit von Tonmineralen als Rückhaltebarriere bei der Endlagerung radioaktiver Abfälle in Salzgesteinen = Efficacy of Argillaceous Minerals used as a Hold-Back Barrier in the Final Disposal of Radioactive Wastes in Salt Rocks," *Zeitschrift der Deutschen Geologischen Gesellschaft*. Vol. 134, no. 2, 453-466. (In German with an English abstract.) (WPO#41478.)

Brodsky, N.S. 1994. *Hydrostatic and Shear Consolidation Tests With Permeability Measurements on Waste Isolation Pilot Plant Crushed Salt*. SAND93-7058. Albuquerque, NM: Sandia National Laboratories. (Available from the NTIS as DE94009980/XAB.) (WPO#10087.)

Bucher, F., and P. Jedelhauser. 1985. *Verdichtungsversuche an quarzsand-bentonit-gemischen = Compaction Tests on Quartz Sand-Bentonite Mixtures*. Technical Report NTB-85-52. Baden, Switzerland: NAGRA Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle. (In German.) (Available from the NTIS as DE87900259/XAB.)

Bucher, F., P. Jedelhauser, and P.-A. Mayer. 1986. *Quell-, Durchlässigkeits- und Schrumpfversuche an Quarzsand-Bentonit-Gemischen = Swelling, Permeability and Shrinkage Tests on Quartz Sand-Bentonite Mixtures*. Technical Report NTB-86-13. Baden, Switzerland: NAGRA Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle. (In German.)

Butcher, B.M. 1994. "The Advantages of a Salt/Bentonite Backfill for Waste Isolation Pilot Plant Disposal Rooms," *Scientific Basis for Nuclear Waste Management XVII, Materials Research Society Symposium Proceedings, Boston, MA, November 29-December 3, 1993*. Eds. A. Barkatt and R.A. Van Konynenburg. Pittsburgh, PA: Materials Research Society. Vol. 333, 911-917. (Available from the NTIS as DE93013763/XAB.) (WPO#35921.)

Chapius, R.P. 1982. "Permeability Testing of Soil-Bentonite Mixtures," *Soil Mechanics and Foundation Engineering, Tenth International Conference, Stockholm, June 15-19, 1981*. Ed. N. Flodin. Rotterdam: A.A. Balkema; Salem, NH: M.B.S. Vol. 4, 744-745. (WPO#41510.)

Chapuis, R.P. 1990. "Sand-Bentonite Liners: Predicting Permeability from Laboratory Tests," *Canadian Geotechnical Journal*. Vol. 27, no. 1, 47-57. (WPO#41511.)

Coulon, H., A. Lajudie, P. Debrabant, R. Atabek, M. Jorda, and R. Andre-Jehan. 1987. "Choice of French Clays as Engineered Barrier Components for Waste Disposal," *Scientific Basis for Nuclear Waste Management X, Materials Research Society Symposium Proceedings, Boston, MA, December 1-4, 1986*. Eds. J.K. Bates and W.B. Seefeldt. Pittsburgh, PA: Materials Research Society. Vol. 84, 813-824. (WPO#41477.)

Daniel, D.E. 1984. "Predicting Hydraulic Conductivity of Clay Liners," *Journal of Geotechnical Engineering*. Vol. 110, no. 2, 285-300. (WPO#41513.)

Daniel, D.E. 1990. "Summary Review of Construction Quality Control for Compacted Soil Liners," *Waste Containment Systems: Construction, Regulation, and Performance, Proceedings of a Symposium, San Francisco, CA, November 6-7, 1990*. Geotechnical Special Publication No. 26. New York, NY: American Society of Civil Engineers. 175-189.

Daniel, D.E. 1993. "Clay Liners," *Geotechnical Practice for Waste Disposal*. Ed. D.E. Daniel. London; New York: Chapman & Hall. 137-163. (WPO#41512.)

D'Appolonia, D.J. 1980. "Soil-Bentonite Slurry Trench Cutoffs," *American Society of Civil Engineers, Journal of the Geotechnical Engineering Division*. Vol. 106, no. GT4, 399-417. (WPO#41514.)

Di Maio, C., and G.B. Fenelli. 1994. "Residual Strength of Kaolin and Bentonite: The Influence of Their Constituent Pore Fluid," *Geotechnique*. Vol. 44, no. 4, 217-226. (WPO#41516.)

Diamond, S. 1970. "Pore Size Distributions in Clays," *Clays and Clay Minerals*. Vol. 18, no. 1, 7-23.

Dixon, D.A., and M.N. Gray. 1985. "The Use of Bentonite in a Nuclear Fuel Waste Disposal Vault," *Preprints of Papers Presented at the First Canadian Engineering Technology Seminar on the Use of Bentonite for Civil Engineering Applications, Regina, Saskatchewan, March 18, 1985*. Regina, Saskatchewan: Ground Engineering Ltd. 64-73. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM as WPO#39637.)

Dixon, D.A., M.N. Gray, and A.W. Thomas. 1985. "A Study of the Compaction Properties of Potential Clay-Sand Buffer Mixtures for Use in Nuclear Fuel Waste Disposal," *Engineering Geology*. Vol. 21, no. 3/4, 247-255. (WPO#41480.)

Dixon, D.A., S.C.H. Cheung, M.N. Gray, and B.C. Davidson. 1987. "The Hydraulic Conductivity of Dense Clay Soils," *Geotechnique in Resource Development: Preprint Volume, 40th Canadian Geotechnical Conference, Regina, Saskatchewan, October 19-21, 1987*. [Rexdale, Ontario]: Canadian Geotechnical Society. 389-396.

Dixon, D.A., A.W.L. Wan, J. Graham, and B.H. Kjartanson. 1991. "Assessing Pressure-Volume Equilibrium in Bentonite-Based Materials," *44th Canadian Geotechnical Conference, Preprint Volume, Calgary, Alberta, September 29-October 2, 1991*. [Waterloo, Ontario]: Canadian Geotechnical Society. Pt. 2, 61/1 through 61/7.

Dixon, D.A., M.N. Gray, and D.S.J. Hnatiw. 1992a. "Critical Gradients and Pressures in Dense Swelling Clays," *Canadian Geotechnical Journal*. Vol. 29, no. 6, 1113-1119. (WPO#41479.)

Dixon, D.A., D.S.J. Hnatiw, and B.T. Walker. 1992b. *Bentonite Industry in North America. Suppliers, Reserves, Processing Capacity and Products*. AECL-10587; COG-92-80. Pinawa [Manitoba]: Atomic Energy of Canada Ltd., Whiteshell Nuclear Research Establishment. (Available from the NTIS as DE94614175/XAB.)

DOE/WIPP. 1995. *Waste Isolation Pilot Plant Sealing System Design Report*. DOE/WIPP-95-3117. [Carlsbad, NM]: Waste Isolation Pilot Plant, U.S. Department of Energy. (WPO#29062.)

Dunn, I.S., L.R. Anderson, and F.W. Kiefer. 1980. *Fundamentals of Geotechnical Analysis*. New York, NY: John Wiley & Sons.

Edil, T.B., P.M. Berthouex, and K.D. Vesperman. 1987. "Fly Ash as a Potential Waste Liner," *Geotechnical Practice for Waste Disposal '87, Proceedings of a Specialty Conference, University of Michigan, Ann Arbor, MI, June 15-17, 1987*. Ed. R.D. Woods. Geotechnical Special Publication 13. New York, NY: American Society of Civil Engineers. 447-461.

EPA (Environmental Protection Agency). 1995a. "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," *Code of Federal Regulations 40, Part 191*. Washington, DC: U.S. Government Printing Office, Superintendent of Documents. (WPO#41461.)

EPA (Environmental Protection Agency). 1995b. "Land Disposal Restrictions," *Code of Federal Regulations 40, Part 268*. Washington, DC: U.S. Government Printing Office, Superintendent of Documents. (WPO#41481.)

Fagerström, H., and B. Lundahl. 1977. *Handling of Buffer Material Quartz — Bentonite = Hantering av buffermaterial av bentonit och kvarts*. KBS Technical Report 37. Stockholm: Kärnbränslesäkerhet. (Summary in English.) (WPO#41517.)

Fernandez, F., and R.M. Quigley. 1988. "Viscosity and Dielectric Constant Controls on the Hydraulic Conductivity of Clayey Soils Permeated with Water-Soluble Organics," *Canadian Geotechnical Journal*. Vol. 25, no. 3, 582-589. (WPO#41518.)

Garlanger, J.E., F.K. Cheung, and B.S. Tannous. 1987. "Quality Control Testing for a Sand-Bentonite Liner," *Geotechnical Practice for Waste Disposal '87, Proceedings of a Specialty Conference, University of Michigan, Ann Arbor, MI, June 15-17, 1987*. Ed. R.D. Woods. Geotechnical Special Publication No. 13. New York, NY: American Society of Civil Engineers. 488-499.

Gillott, J.E. 1987. *Clay in Engineering Geology*. Developments in Geotechnical Engineering 41. Amsterdam; New York: Elsevier.

Gipson, A.H., Jr. 1985. "Permeability Testing on Clayey Soil and Silty Sand-Bentonite Mixture Using Acid Liquor," *Hydraulic Barriers in Soil and Rock, A Symposium, Denver, CO, June 25, 1984*. Eds. A.I. Johnson, R.K. Frobel, N.J. Cavalli, and C.B. Pettersson. ASTM Special Technical Publication 874. Philadelphia, PA: American Society for Testing and Materials. 140-154. (WPO#41519.)

Gnirk, P. 1988. "State-of-the-Art Evaluation of Repository Sealing Materials and Techniques," *Scientific Basis for Nuclear Waste Management XI, Materials Research Society Symposium Proceedings, Boston, MA, November 30-December 3, 1987*. Eds. M.J. Apted and R.E. Westerman. Pittsburgh, PA: Materials Research Society. Vol. 112, 219-231. (WPO#41482.)

Goldman, L.J., L.I. Greenfield, A.S. Damle, G.L. Kingsbury, C.M. Northeim, and R.S. Truesdale. 1990. *Clay Liners for Waste Management Facilities—Design, Construction, and Evaluation*. Pollution Technology Review No. 178. Park Ridge, NJ: Noyes Data Corporation.

Grim, R.E. 1962. *Applied Clay Mineralogy*. New York, NY: McGraw-Hill Book Company, Inc.

Grim, R.E. 1968. *Clay Mineralogy*. 2nd ed. New York, NY: McGraw-Hill Book Company, Inc.

Grim, R.E., and N. Güven. 1978. *Bentonites: Geology, Mineralogy, Properties and Uses*. Developments in Sedimentology 24. Amsterdam; New York: Elsevier. 256 p.

Güven, N. 1990. "Longevity of Bentonite as Buffer Material in a Nuclear-Waste Repository," *Engineering Geology*. Vol. 28, no. 3/4, 233-247. (WPO#41483.)

Haile, J.P. 1985. "Construction of Underseals for the Key Lake Project, Saskatchewan," *Preprints of Papers Presented at the First Canadian Engineering Technology Seminar on The Use of Bentonite for Civil Engineering Applications, Regina, Saskatchewan, March 10, 1985*. Regina, Saskatchewan: Ground Engineering, Ltd. 74-86. (WPO#39638.)

Haug, M.D. 1985. "Design and Construction of Soil Bentonite Underseal for C-I-L Waste Storage Ponds, Becancour, Quebec," *Preprints of Papers Presented at the First Canadian Engineering Technology Seminar on The Use of Bentonite for Civil Engineering Applications, Regina, Saskatchewan, March 18, 1985*. Regina, Saskatchewan: Ground Engineering, Ltd. 87-97. (WPO#39639.)

Haug, M.D., S.L. Barbour, and P. Longval. 1988. "Design and Construction of a Prehydrated Sand-Bentonite Liner to Contain Brine," *Canadian Journal of Civil Engineering*. Vol. 15, no. 6, 955-963. (WPO#41484.)

Haug, M.D., S.L. Barbour, and R. Tang. 1990. "Hydraulic Performance of Slurry Trench Backfill in Brine Environments," *Proceedings of the Annual Conference and First Biennial Environmental Specialty Conference, Hamilton, Ontario, May 16-18, 1990*. Ed. D. Pufahl. Montreal, Quebec: Canadian Society for Civil Engineering. 250-269. (WPO#39641.)

Haxo, H.E., Jr., R.S. Haxo, N.A. Nelson, P.D. Haxo, R.M. White, S. Dakessian, and M.A. Fong. 1985. *Liner Materials for Hazardous and Toxic Wastes and Municipal Solid Waste Leachate*. Pollution Technology Review No. 124. Park Ridge, NJ: Noyes Publications.

Hilf, J.W. 1975. "Compacted Fill," *Foundation Engineering Handbook.* Eds. H.F. Winterkorn and H-Y. Fang. New York, NY: Van Nostrand Reinhold Company. 244-311. (WPO#41520.)

Ho, Y.A. 1985. "The Effects of Brine Contamination on the Properties of Soils." M.Sc. thesis. Saskatoon, Saskatchewan: Department of Civil Engineering, University of Saskatchewan.

Ho, Y.A., and D.E. Pufahl. 1987. "The Effects of Brine Contamination on the Properties of Fine Grained Soils," *Geotechnical Practice for Waste Disposal '87, Proceedings of a Specialty Conference, University of Michigan, Ann Arbor, MI, June 15-17, 1987.* Ed. R.D. Woods. Geotechnical Special Publication No. 13. New York, NY: American Society of Civil Engineers. 547-561.

Holopainen, P. 1985. "Crushed Aggregate-Bentonite Mixtures as Backfill Material for Repositories of Low- and Intermediate-Level Radioactive Wastes," *Engineering Geology.* Vol. 21, no. 3/4, 239-245.

Hosterman, J.W., and S.H. Patterson. 1992. *Bentonite and Fuller's Earth Resources of the United States.* U.S. Geological Survey Professional Paper 1522. Reston, VA: U.S. Geological Survey.

Howard, C. L. 1989. "SSSPT Series D-Phase 2 Test Implementation Status." Memo to Distribution. Rapid City, SD: RE/SPEC Inc. 20 p. (WPO#5606.)

Howard, J.J., and D.M. Roy. 1985. "Development of Layer Charge and Kinetics of Experimental Smectite Alteration," *Clays and Clay Minerals.* Vol. 33, no. 2, 81-88. (WPO#41521.)

IAEA (International Atomic Energy Agency). 1990. *Sealing of Underground Repositories for Radioactive Wastes.* M. Gray, F. Gera, J.R. Wiley, Z. Dlouhy, and D. Squires. Technical Reports Series No. 319. Vienna: International Atomic Energy Agency; Lanham, MD: Unipub.

Janbu, N. 1963. "Soil Compressibility as Determined by Oedometer and Triaxial Tests," *European Conference on Soil Mechanics and Foundation Engineering, Wiesbaden, Germany.* Vol. 1, pp. 19-25.

Jessberger, H.L., W. Ebel, and R.A. Beine. 1985. "Bentonite Treated Colliery Spoil for Sealing Waste Disposals," *Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering, San Francisco, CA, August 12-16, 1985.* Rotterdam; Boston: A.A. Balkema. Vol. 3, 1193-1198. (WPO#41522.)

Kenney, T.C. 1967. "The Influence of Mineral Composition on the Residual Strength of Natural Soils," *Proceedings of the Geotechnical Conference Oslo 1967 on the Shear Strength Properties of Natural Soils and Rocks.* Oslo: Norwegian Geotechnical Institute. Vol. I, 123-129. (WPO#41487.)

Kenney, T.C., W.A. [Van] Veen, M.A. Swallow, and M.A. Sungaila. 1991. "Hydraulic Conductivity of Compacted Bentonite-Sand," *44th Canadian Geotechnical Conference: Preprint Volume, Calgary, Alberta, September 29-October 2, 1991*. Paper 63. Waterloo, Ontario: Canadian Geotechnical Society. 63/1 through 63/10

Kenney, T.C., W.A. Van Veen, M.A. Swallow, and M.A. Sungaila. 1992. "Hydraulic Conductivity of Compacted Bentonite-Sand Mixtures," *Canadian Geotechnical Journal*. Vol. 29, no. 3, 364-374. (WPO#41486.)

Kjartanson, B.H., N.A. Chandler, A.W.L. Wan, C.L. Kohle, and P.J. Roach. 1992. "Use of a Method Specification for In Situ Compaction of Clay-Based Barrier Materials," *High Level Radioactive Waste Management, Proceedings of the Third International Conference, Las Vegas, NV, April 12-16, 1992*. La Grange Park, IL: American Nuclear Society; New York, NY: American Society of Civil Engineers. Vol. 1, 1129-1136. (WPO#41488.)

Koorevaar, P., G. Menelik, and C. Dirksen. 1983. *Elements of Soil Physics*. Developments in Soil Science 13. New York, NY: Elsevier.

Krumhansl, J.L. 1986. *Observations Regarding the Stability of Bentonite Backfill in a High-Level Waste (HLW) Repository in Rock Salt*. SAND83-1293. Albuquerque, NM: Sandia National Laboratories. (Available from the NTIS as DE86005334/XAB.) (WPO#28368.)

Lundgren, T.Å. 1981. "Some Bentonite Sealants in Soil Mixed Blankets," *Soil Mechanics and Foundation Engineering, Tenth International Conference, Stockholm, June 15-19, 1981*. Rotterdam: A.A. Balkema; Salem, NH: M.B.S. Vol. 2, 349-354. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM as WPO#41523.) (WPO#41523.)

Meyer, D., and J.J. Howard, eds. 1983. *Evaluation of Clays and Clay Minerals for Application to Repository Sealing*. ONWI-486. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute. (Available from the NTIS as DE83017788.) (WPO#41547.)

Miles, W.J. 1995. "Wyoming Bentonite - Chemistry, Mineralogy & Markets," *1995 Denver Annual Meeting*. SME Preprint 95 242. Littleton, CO: Society of Mining Engineers. (WPO#39642.)

Mingarro, E., P. Rivas, L.P. del Villar, B. de la Cruz, P. Gomez, A. Hernandez, M.J. Turrero, M.V. Villar, R. Campos, and J. Cozar. 1991. *Characterization of Clay (Bentonite)/Crushed Granite Mixtures to Build Barriers Against the Migration of Radionuclides: Diffusion Studies and Physical Properties*. Technical Report EUR 13666 EN. Luxembourg: Commission of the European Communities.

Mitchell, J.K. 1976. *Fundamentals of Soil Behavior*. New York, NY: John Wiley & Sons. 422 p.

Mitchell, J.K. 1993. *Fundamentals of Soil Behavior*. 2nd ed. New York, NY: John Wiley & Sons. 437 p.

Mitchell, J.K, D.R. Hooper, and R.G. Campanella. 1965. "Permeability of Compacted Clay," *Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers*. Vol. 91, no. SM4, 41-65. (WPO#41524.)

Nilsson, J. 1985. "Field Compaction of Bentonite-Based Backfilling," *Engineering Geology*. Vol. 21, no. 3-4, 367-376. (WPO#41489.)

Olson, R.E., and D.E. Daniel. 1981. "Measurement of the Hydraulic Conductivity of Fine-Grained Soils," *Permeability and Groundwater Contaminant Transport, A Symposium, Philadelphia, PA, June 17-23, 1979*. Eds. T.F. Zimmie and C.O. Riggs. ASTM Special Technical Publication No. 746. Philadelphia, PA: American Society for Testing and Materials. 18-64. (WPO#41490.)

Oscarson, D.W., D.A. Dixon, and M.N. Gray. 1990. "Swelling Capacity and Permeability of an Unprocessed and a Processed Bentonite Clay," *Engineering Geology*. Vol. 28, no. 3/4, 281-289.

Peterson, E., and S. Kelkar. 1983. *Laboratory Tests to Determine Hydraulic and Thermal Properties of Bentonite-Based Backfill Materials*. SAND82-7221. Albuquerque, NM: Sandia National Laboratories. (Available from the NTIS as DE84001143.) (WPO#24739.)

Pfeifle, T.W. 1990. *Consolidation, Permeability, and Strength of Crushed Salt/Bentonite Mixtures with Application to the WIPP*. SAND90-7009, Topical Report RSI-0357. Albuquerque, NM: Sandia National Laboratories. (Available from the NTIS as DE91007251/XAB.) (WPO#25750.)

Pfeifle, T.W., and N.S. Brodsky. 1991. *Swelling Pressure, Water Uptake, and Permeability of 70/30 Crushed Salt/Bentonite*. SAND91-7070. Albuquerque, NM: Sandia National Laboratories. (Available from the NTIS as DE92040647/XAB.) (WPO#25438.)

Pusch, R. 1978. *Small-Scale Bentonite Injection Test on Rock*. KBS Teknisk Rapport 75. Stockholm: Kärnbränslesäkerhet. (Available from the NTIS as KBS-TR-75.) (WPO#41501.)

Pusch, R. 1979. "Highly Compacted Sodium Bentonite for Isolating Rock-Deposited Radioactive Waste Products," *Nuclear Technology*. Vol. 45, 153-157. (WPO#41504.)

Pusch, R. 1980. *Swelling Pressure of Highly Compacted Bentonite*. Technical Report SKBF/KBS-TR-80-13. Stockholm: Svensk Kärnbränsleförjning AB. (Available from the NTIS as SKBF/KBS-TR-80-13.)

Pusch, R. 1982. "Mineral-Water Interactions and Their Influence on the Physical Behavior of Highly Compacted Na Bentonite," *Canadian Geotechnical Journal*. Vol. 19, no. 3, 381-387. (WPO#41505.)

Pusch, R. 1994. *Waste Disposal in Rock*. Developments in Geotechnical Engineering 76. Amsterdam; New York: Elsevier. 490 p.

Pusch, R., and G. Alstermark. 1985. "Experience from Preparation and Application of Till/Bentonite Mixtures," *Engineering Geology*. Vol. 21, no. 3/4, 377-382. (WPO#41494.)

Pusch, R., and A. Bergström. 1980. "Highly Compacted Bentonite for Bore-hole and Shaft Plugging," *Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, May 7-9, 1980*. Paris, France: Organisation for Economic Co-Operation and Development. 161-168. (WPO#41502.)

Pusch, R., and T. Carlsson. 1985. "The Physical State of Pore Water of Na Smectite Used as Barrier Component," *Engineering Geology*. Vol. 21, no. 3/4, 257-265. (WPO#41497.)

Pusch, R., and N. Güven. 1990. "Electron Microscopic Examination of Hydrothermally Treated Bentonite Clay," *Engineering Geology*. Vol. 28, no. 3/4, 303-314. (WPO#41493.)

Pusch, R., and H. Hökmark. 1990. "Basic Model of Water- and Gas-Flow Through Smectite Clay Buffers," *Engineering Geology*. Vol. 28, no. 3/4, 379-389. (WPO#41492.)

Pusch, R., and O. Karnland. 1990. *Preliminary Report on Longevity of Montmorillonite Clay Under Repository-Related Conditions*. Technical Report SKB-TR-90-44. Stockholm: Swedish Nuclear Fuel and Waste Management Co. (Available from NTIS as DE92600928.) (WPO#41498.)

Pusch, R., L. Borgesson, and J. Nilsson. 1982. *Buffer Mass Test - Buffer Materials*. Technical Report TR 82-06. Stockholm: Svensk Kärnbränsleförsorjning AB. (WPO#41546.)

Pusch, R., L. Ranhagen, and K. Nilsson. 1985. *Gas Migration through MX-80 Bentonite. Final Report*. NAGRA Technical Report 85-36. Baden, Switzerland: NAGRA Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle. 29 pp. (WPO#41495.)

Radhakrishna, H.S., and H.T. Chan. 1982. "Laboratory Study of Physical Properties of Clay Buffers for a Nuclear Fuel Waste Vault," *International Conference on Radioactive Waste Management, Conference Proceedings, Winnipeg, Manitoba, September 12-15, 1982*. Ed. M.A. Feraday. Toronto, Ontario: Canadian Nuclear Society. 84-90.

Ran, C. 1993. "Performance of Fracture Sealing with Bentonite Grouting." Ph.D. dissertation. Tucson, AZ: University of Arizona. 402 p.

Ran, C., and J.J.K. Daemen. 1991. *Effectiveness of Fracture Sealing with Bentonite Grouting*. Technical Report NUREG/CR-5686. Washington, DC: U.S. Nuclear Regulatory Commission. (Available from the NTIS as NUREG/CR-5686/XAB.) (WPO#41548.)

Ran, C., and J.J.K. Daemen. 1992. "Fracture Grouting with Bentonite Slurries," *Grouting, Soil Improvement and Geosynthetics, Proceedings of the Conference, New Orleans, LA, February 25-28, 1992.* Eds. R.H. Borden, R.D. Holtz, and I. Juran. Geotechnical Special Publication No. 30. New York, NY: American Society of Civil Engineers. Vol. 1, 360-371. (WPO#41500.)

Rath, D.L. 1986. "Origin and Characteristics of Wyoming Bentonite Deposits," *Metallic and Nonmetallic Deposits of Wyoming and Adjacent Areas, 1983 Conference Proceedings, Laramie, WY, April 28-30, 1983.* Ed. S. Roberts. Public Information Circular No. 25. Laramie, WY: Geological Survey of Wyoming. 84-90

Ridley, K.J.D. 1985. "The Impact of a NaCl Brine on the Behaviour of Compacted Fine Grained Soil - A Laboratory Study." Ph.D. dissertation. Windsor, Ontario: University of Windsor, Department of Civil Engineering. 360 p.

Ridley, K.J.D., J.K. Bewtra, and J.A. McCorquodale. 1983. "Behaviour of Compacted Fine-Grained Soil in a Brine Environment," *Canadian Journal of Civil Engineering.* Vol. 11, no. 2, 196-203.

Rowe, R.K., R.M. Quigley, and J.R. Booker. 1995. *Clayey Barrier Systems for Waste Disposal Facilities.* London: E & FN Spon; New York, NY: Routledge, Chapman & Hall, Inc.

Seed, H.B., and C.K. Chan. 1959. "Structure and Strength Characteristics of Compacted Clays," *Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers.* Paper 2216. Vol. 85, no. SM5, 87-128. (WPO#41506.)

Sego, D.C., J.P.A. Hettiaratchi, and D.W. Smith. 1987. "Low Gradient Direct Permeability Testing for Waste Disposal Facility Design," *Geotechnique in Resource Development, 40th Canadian Geotechnical Conference, Preprint Volume, Regina, Saskatchewan, October 19-21, 1987.* Waterloo, Ontario: Canadian Geotechnical Society. 423-429.

Sridharan, A., S.M. Rao, and N.S. Murthy. 1986. "Liquid Limit of Montmorillonite Soils," *ASTM Geotechnical Testing Journal.* Vol. 9, no. 3, 156-159. (WPO#41507.)

Stockmeyer, M.R. 1992. "Organophilic Bentonites in Composite Liner Systems," *71st Annual Meeting of the Transportation Research Board, Washington, DC, January 12-16, 1992.* Paper No. 920180. Washington, DC: Transportation Research Board, National Research Council.

Taylor, C.L., G.J. Anttonen, J.E. O'Rourke, and D. Allirot. 1980. *Preliminary Geochemical and Physical Testing of Materials for Plugging of Man-Made Accesses to a Repository in Basalt.* RHO-BWI-C-66. Richland, WA: Rockwell International, Rockwell Hanford Operations, Energy Systems Group. (Available from the NTIS as RHO-BWI-C-66.)

Terzaghi, K. 1936. "The Shearing Resistance of Saturated Soils and the Angle Between the Planes of Shear," *Proceedings of the International Conference on Soil Mechanics and Foundation Engineering, Graduate School of Engineering, Harvard University, Cambridge, MA, June 22-26, 1936*. No. D-7. Reprinted by Harvard Printing Office (with corrections) October 1965. Vol. 1, 54-56. (WPO#41508.)

Virta, R.L. 1994. *Clays. 1993 Annual Report*. [Washington, DC]: U.S. Department of the Interior, Bureau of Mines. 32 pp. (WPO#41468.)

Westsik, J.H., Jr., L.A. Bray, F.N. Hodges, and E.J. Wheelwright. 1982. "Permeability, Swelling and Radionuclide Retardation Properties of Candidate Backfill Materials," *Scientific Basis for Nuclear Waste Management, Proceedings of the Materials Research Society Annual Meeting, Boston, MA, November 16-19, 1981*. Ed. S.V. Topp. New York, NY: North-Holland. Vol. 6, 329-336. (WPO#41496.)

Wheelwright, E.J., F.N. Hodges, L.A. Bray, J.H. Westic, and D.H. Lester. 1981. *Development of Backfill Material as an Engineered Barrier in the Waste Package System. Interim Topical Report*. PNL-3873. Richland, WA: Pacific Northwest Laboratory. (Available from the NTIS as DE82000937.)

Yang, N., and S.L. Barbour. 1992. "The Impact of Soil Structure and Confining Stress on the Hydraulic Conductivity of Clays in Brine Environments," *Canadian Geotechnical Journal*. Vol. 29, no. 5, 730-739.

Yin, J.-H., F. Saadat, and J. Graham. 1990. "Constitutive Modelling of a Compacted Sand-Bentonite Mixture Using Three-Modulus Hypoelasticity," *Canadian Geotechnical Journal*. Vol. 27, no. 3, 365-372. (WPO#41544.)

Yong, R.N., and A.R. Cabral. 1992. "A Clay-Heavy Metal Compatibility Analysis Using Permeability Testing," *45th Canadian Geotechnical Conference: Innovation, Conservation, and Rehabilitation, Preprint Volume, Toronto, Ontario, October 26-28, 1992*. Paper 76. Waterloo, Ontario: Canadian Geotechnical Society. 76/1 through 76/10.

Yong, R.N., P. Boonsinsuk, and G. Wong. 1986. "Formulation of Backfill Material for a Nuclear Fuel Waste Disposal Vault," *Canadian Geotechnical Journal*. Vol. 23, 216-228. (WPO#41545.)

Federal Agencies

US Department of Energy (4)
Office of Civilian Radioactive Waste Mgmt.
Attn: Deputy Director, RW-2
        Acting Director, RW-10
            Office of Human Resources & Admin.
        Director, RW-30
            Office of Program Mgmt. & Integ.
        Director, RW-40
            Office of Waste Accept., Stor., & Tran.
Forrestal Building
Washington, DC 20585

Attn: Project Director
Yucca Mountain Site Characterization Office
        Director, RW-3
        Office of Quality Assurance
101 Convention Center Drive, Suite #P-110
Las Vegas, NV 89109

US Department of Energy
Albuquerque Operations Office
Attn: National Atomic Museum Library
P.O. Box 5400
Albuquerque, NM 87185-5400

US Department of Energy
Research & Waste Management Division
Attn: Director
P.O. Box E
Oak Ridge, TN 37831

US Department of Energy (5)
Carlsbad Area Office
Attn: G. Dials
        D. Galbraith
        M. McFadden
        R. Lark
        J. A. Mewhinney
P.O. Box 3090
Carlsbad, NM 88221-3090

US Department of Energy
Office of Environmental Restoration and
    Waste Management
Attn: J. Lytle, EM-30
Forrestal Building
Washington, DC 20585-0002

US Department of Energy (3)
Office of Environmental Restoration and
    Waste Management
Attn: M. Frei, EM-34, Trevion II
Washington, DC 20585-0002

US Department of Energy
Office of Environmental Restoration and
    Waste Management
Attn: S. Schneider, EM-342, Trevion II
Washington, DC 20585-0002

US Department of Energy (2)
Office of Environment, Safety & Health
Attn: C. Borgstrom, EH-25
        R. Pelletier, EH-231
Washington, DC 20585

US Department of Energy (2)
Idaho Operations Office
Fuel Processing & Waste Mgmt. Division
785 DOE Place
Idaho Falls, ID 83402

US Environmental Protection Agency (2)
Radiation Protection Programs
Attn: M. Oge
ANR-460
Washington, DC 20460

Boards

Defense Nuclear Facilities Safety Board
Attn: D. Winters
625 Indiana Ave. NW, Suite 700
Washington, DC 20004

Nuclear Waste Technical Review Board (2)
Attn: Chairman
        S. J. S. Parry
1100 Wilson Blvd., Suite 910
Arlington, VA 22209-2297

State Agencies

Attorney General of New Mexico
P.O. Drawer 1508
Santa Fe, NM 87504-1508

Environmental Evaluation Group (3)
Attn: Library
7007 Wyoming NE
Suite F-2
Albuquerque, NM 87109

NM Energy, Minerals, and Natural
Resources Department
Attn: Library
2040 S. Pacheco
Santa Fe, NM 87505

NM Environment Department (3)
Secretary of the Environment
Attn: Mark Weidler
1190 St. Francis Drive
Santa Fe, NM 87503-0968

NM Bureau of Mines & Mineral Resources
Socorro, NM 87801

NM Environment Department
WIPP Project Site
Attn: P. McCasland
P.O. Box 3090
Carlsbad, NM 88221

Laboratories/Corporations

Battelle Pacific Northwest Laboratories
Attn: R. E. Westerman, MSIN P8-44
Battelle Blvd.
Richland, WA 99352

INTERA, Inc.
Attn: G. A. Freeze
1650 University Blvd. NE, Suite 300
Albuquerque, NM 87102

INTERA, Inc.
Attn: J. F. Pickens
6850 Austin Center Blvd., Suite 300
Austin, TX 78731

INTERA, Inc.
Attn: W. Stensrud
P.O. Box 2123
Carlsbad, NM 88221

Los Alamos National Laboratory
Attn: B. Erdal, INC-12
P.O. Box 1663
Los Alamos, NM 87544

RE/SPEC, Inc
Attn: Angus Robb
4775 Indian School NE, Suite 300
Albuquerque, NM 87110-3927

RE/SPEC, Inc
Attn: J. L. Ratigan
P.O. Box 725
Rapid City, SD 57709

Tech Reps, Inc. (3)
Attn: J. Chapman (1)
Loretta Robledo (2)
5000 Marble NE, Suite 222
Albuquerque, NM 87110

Westinghouse Electric Corporation (5)
Attn: Library
J. Epstein
J. Lee
B. A. Howard
R. Kehrman
P.O. Box 2078
Carlsbad, NM 88221

S. Cohen & Associates
Attn: Bill Thurber
1355 Beverly Road
McLean, VA 22101

National Academy of Sciences, WIPP Panel

Howard Adler
Oxyrase, Incorporated
7327 Oak Ridge Highway
Knoxville, TN 37931

Bob Andrews
Board of Radioactive Waste Management
GF456
2101 Constitution Ave.
Washington, DC 20418

Rodney C. Ewing
Department of Geology
University of New Mexico
Albuquerque, NM 87131

Charles Fairhurst
Department of Civil and Mineral Engineering
University of Minnesota
500 Pillsbury Dr. SE
Minneapolis, MN 55455-0220

B. John Garrick
PLG Incorporated
4590 MacArthur Blvd., Suite 400
Newport Beach, CA 92660-2027

Leonard F. Konikow
US Geological Survey
431 National Center
Reston, VA 22092

Carl A. Anderson, Director
Board of Radioactive Waste Management
National Research Council
HA 456
2101 Constitution Ave. NW
Washington, DC 20418

Christopher G. Whipple
ICF Kaiser Engineers
1800 Harrison St., 7th Floor
Oakland, CA 94612-3430

John O. Blomeke
720 Clubhouse Way
Knoxville, TN 37909

Sue B. Clark
University of Georgia
Savannah River Ecology Lab
P.O. Drawer E
Aiken, SC 29802

Konrad B. Krauskopf
Department of Geology
Stanford University
Stanford, CA 94305-2115

Della Roy
Pennsylvania State University
217 Materials Research Lab
Hastings Road
University Park, PA 16802

David A. Waite
CH$_2$ M Hill
P.O. Box 91500
Bellevue, WA 98009-2050

Thomas A. Zordon
Zordan Associates, Inc.
3807 Edinburg Drive
Murrysville, PA 15668

Universities

University of New Mexico
Geology Department
Attn: Library
141 Northrop Hall
Albuquerque, NM 87131

University of Washington
College of Ocean & Fishery Sciences
Attn: G. R. Heath
583 Henderson Hall, HN-15
Seattle, WA 98195

Libraries

Thomas Brannigan Library
Attn: D. Dresp
106 W. Hadley St.
Las Cruces, NM 88001

Government Publications Department
Zimmerman Library
University of New Mexico
Albuquerque, NM 87131

New Mexico Junior College
Pannell Library
Attn: R. Hill
Lovington Highway
Hobbs, NM 88240

New Mexico State Library
Attn: N. McCallan
325 Don Gaspar
Santa Fe, NM 87503

New Mexico Tech
Martin Speere Memorial Library
Campus Street
Socorro, NM 87810

WIPP Public Reading Room
Carlsbad Public Library
101 S. Halagueno St.
Carlsbad, NM 88220

Foreign Addresses

Atomic Energy of Canada, Ltd.
Whiteshell Laboratories
Attn: B. Goodwin
Pinawa, Manitoba, CANADA R0E 1L0

Francois Chenevier (2)
ANDRA
Route de Panorama Robert Schumann
B. P. 38
92266 Fontenay-aux-Roses, Cedex
FRANCE

Claude Sombret
Centre d'Etudes Nucleaires de la Vallee Rhone
CEN/VALRHO
S.D.H.A. B.P. 171
30205 Bagnols-Sur-Ceze, FRANCE

Commissariat a L'Energie Atomique
Attn: D. Alexandre
Centre d'Etudes de Cadarache
13108 Saint Paul Lez Durance Cedex
FRANCE

Bundesanstalt fur Geowissenschaften und
Rohstoffe
Attn: M. Langer
Postfach 510 153
D-30631 Hannover, GERMANY

Bundesministerium fur Forschung und
Technologie
Postfach 200 706
5300 Bonn 2, GERMANY

Institut fur Tieflagerung
Attn: K. Kuhn
Theodor-Heuss-Strasse 4
D-3300 Braunschweig, GERMANY

Gesellschaft fur Anlagen und Reaktorsicherheit
(GRS)
Attn: B. Baltes
Schwertnergasse 1
D-50667 Cologne, GERMANY

Shingo Tashiro
Japan Atomic Energy Research Institute
Tokai-Mura, Ibaraki-Ken, 319-11
JAPAN

Netherlands Energy Research Foundation ECN
Attn: J. Prij
3 Westerduinweg
P.O. Box 1
1755 ZG Petten
THE NETHERLANDS

Svensk Karnbransleforsorjning AB
Attn: F. Karlsson
Project KBS (Karnbranslesakerhet)
Box 5864
S-102 48 Stockholm
SWEDEN

Nationale Genossenschaft fur die Lagerung
Radioaktiver Abfalle (2)
Attn: S. Vomvoris
       P. Zuidema
Hardstrasse 73
CH-5430 Wettingen
SWITZERLAND

AEA Technology
Attn: J. H. Rees
D5W/29 Culham Laboratory
Abington, Oxfordshire OX14 3DB
UNITED KINGDOM

AEA Technology
Attn: W. R. Rodwell
044/A31 Winfrith Technical Centre
Dorchester, Dorset DT2 8DH
UNITED KINGDOM

AEA Technology
Attn: J. E. Tinson
B4244 Harwell Laboratory
Didcot, Oxfordshire OX11 ORA
UNITED KINGDOM

Internal

MS	Org.	
1324	6115	P. B. Davies
1320	6831	E. J. Nowak
1322	6121	J. R. Tillerson (2)
1328	6849	D. R. Anderson
1328	6848	H. N. Jow
1335	6801	M. Chu
1341	6832	J. T. Holmes
1395	6800	L. Shephard
1395	6821	M. Marietta
1395	6841	V. H. Slaboszewicz
1322	6121	F. Hansen (3)

1322	6121	K. Knowles (2)
1395	6743	Schuhen (18)
1322	6121	A. Dennis
1322	6121	E. Arhens
1337	6000	W. Weart
1395	6742	A. Orrell
1395	6743	C. Howard
1330	6811	K. Hart (2)
1330	4415	NWM Library (20)
9018	8523-2	Central Technical Files
0899	4414	Technical Library (5)
0619	12630	Review and Approval Desk,(2)
		For DOE/OSTI