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Water Uptake and Stress Development in Bentonites and Bentonite-Sand Buffer Materials

Apport d'eau et intensification des contraintes dans les bentonites et les matériaux tampons à base de bentonite et de sable

D.A. Dixon, A.W-L. Wan, M.N. Gray, S.H. Miller

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ABSTRACT

The development of swelling pressure and the transfer of pore water pressures through dense bentonite and bentonite-sand materials are examined in this report. Literature typically reports only the ultimate swelling pressure developed normal to the axis of compaction. To determine swelling pressure, specimens are typically percolated with water until full saturation is achieved and the swelling pressure is stable. Previous studies on water-saturated materials have established that the pressures developed by fully saturated materials can be described using the effective stress concept, that is, the total pressure exerted by the specimen on its confinement is the sum of the pore water pressure and the mechanical pressure developed by the swelling clay (swelling pressure).

This report focuses on the swelling pressure and total pressure developed in initially unsaturated specimens allowed access to free water on one end. The pressure measured normal to the axis of compaction develops rapidly as a result of a thin wetted "skin" present on the end closest to the water source. The bentonite in this wetted region rapidly develops its full swelling pressure and this pressure is transferred upwards through the specimen. Hence, the bentonite plug will exert a pressure approximately equivalent to the swelling pressure even though only a small region of the plug is actually saturated.

A number of specimens were tested with total pressure sensors mounted normal and parallel to the axis of compaction. Lateral pressures developed long before the wetting front reached sensor locations, suggesting stress transfer through the unsaturated portions of these specimens. On achieving saturation, specimens were found to have similar swelling pressures both normal to and parallel to the axis of compaction. This indicates that there is little or no specimen anisotropy induced by the compaction process. Tests were conducted on specimens allowed only to take on a limited quantity of water and it was found that density anisotropy was induced as the result of the swelling pressures generated by the buffer. The wetted skin of buffer developed a considerable pressure and compressed a region of buffer immediately above the wetted region. This resulted in a slightly higher density buffer being produced in the interior of the specimen and a slightly decreased density was developed in the region closest to the water source. Neither of these changes was sufficient to compromise the hydraulic performance of the buffer and they may in fact result in a slightly lower permeability envelope being developed in the buffer closer to the waste container.

These results suggest that the buffer material placed in a disposal vault will rapidly develop and transfer swelling pressures as a result of the saturation of a limited region or "skin" within the emplacement site. Thus unless other processes relieve the stresses generated by the buffer, it must be assumed that swelling pressure may be transferred, at least to some degree, to the waste container shortly after its emplacement. The total pressure ultimately present on the container surface should be the sum of the swelling and hydraulic components.

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APPORT D'EAU ET INTENSIFICATION DES CONTRAINTES DANS LES BENTONITES ET LES MATÉRIAUX TAMPONS À BASE DE BENTONITE ET DE SABLE

par

D.A. Dixon, A.W-L. Wan, M.N. Gray et S.H. Miller

RÉSUMÉ

L'intensification de la pression de gonflement et le transfert de la pression de l'eau interstitielle dans la bentonite et les matériaux à base de bentonite et de sable denses sont examinés dans le présent rapport. On ne trouve généralement dans la documentation que la pression limite de gonflement obtenue dans la direction perpendiculaire à l'axe de compaction. Afin de déterminer la pression de gonflement, la méthode type est de laisser de l'eau s'infiltrer par percolation dans des éprouvettes jusqu'à saturation complète et stabilisation de la pression de gonflement. Les études antérieures sur des matériaux saturés d'eau ont permis d'établir que le concept de tension effective représente bien les pressions que l'on observe dans les matériaux complètement saturés, c'est-à-dire que la pression totale exercée par l'éprouvette sur son enveloppe est la somme de la pression de l'eau interstitielle et de la pression mécanique exercée par le gonflement de l'argile (pression de gonflement).

Dans le présent rapport, on étudie en particulier la pression de gonflement et la pression totale exercées à l'origine dans des éprouvettes non saturées dont une extrémité a accès à l'eau libre. La pression mesurée perpendiculairement à l'axe de compaction augmente rapidement sous l'effet d'une mince «peau» humide qui se forme à l'extrémité la plus proche de la source d'eau. La bentonite, dans cette zone humide, exerce rapidement toute sa pression de gonflement et celle-ci est transférée vers le haut dans l'éprouvette. Pour cette raison, le bouchon de bentonite exerce une pression approximativement équivalente à la pression de gonflement, même si le bouchon n'est réellement saturé que dans une petite zone.

Les essais ont été effectués sur un certain nombre d'éprouvettes munies de capteurs de pression totale montés perpendiculairement et parallèlement à l'axe de compaction. Les pressions latérales ont été appliquées bien avant que le front d'humidité n'ait atteint les emplacements des capteurs, ce qui laisse supposer un transfert de contrainte dans les parties non saturées de ces éprouvettes. Lorsqu'elles sont saturées, les éprouvettes présentent des pressions de gonflement similaires de façon tant perpendiculaire que parallèle à l'axe de compaction. Cela indique que l'éprouvette manifeste peu ou pas d'anisotropie induite par le processus de compaction. Des essais ont été menés sur des éprouvettes dans lesquelles on limitait la quantité d'eau absorbée et on a trouvé que la pression de gonflement exercée par le tampon induisait une anisotropie de densité. La peau humide du tampon exerçait une pression considérable et comprimait une zone de tampon immédiatement au-dessus de la zone humide. Ce phénomène a produit un tampon d'une densité légèrement supérieure à l'intérieur de l'éprouvette, tandis que la densité a diminué légèrement dans la zone la plus proche de la source d'eau. Ni l'une ni l'autre de ces modifications n'a été suffisante pour compromettre le comportement hydraulique du tampon et celles-ci peuvent en réalité entraîner la formation dans le tampon d'une enveloppe de perméabilité légèrement moindre à proximité du conteneur de déchets.

Tous ces résultats sous-entendent que le matériau tampon mis en place dans une installation de stockage permanent exercera et transférera rapidement les pressions de gonflement produites par la saturation d'une zone circonscrite ou «peau» à l'intérieur de la zone de stockage. En conséquence, à moins que d'autres phénomènes n'interviennent pour relaxer les contraintes engendrées par le tampon, on doit supposer que la pression de gonflement peut être transférée, au moins jusqu'à un certain point, au conteneur de déchets peu après sa mise en place. La pression totale qui s'exerce finalement sur la surface du conteneur devrait représenter la somme des composantes des pressions hydraulique et de gonflement.

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CONTENTS

1. INTRODUCTION

Numerous reports have been published describing the ultimate (or maximum) swelling pressure developed by rigidly confined bentonite-based materials (buffer). These research results have provided valuable information about the saturated behavior of the buffer barriers being considered by a number of countries including Canada (Gray et al., 1984, 1985; Dixon, 1993), Sweden (Pusch, 1980, 1982, 1983) Switzerland (Bucher and Speigl, 1984, Bucher et al., 1986) and Japan (Kanno, 1995). However, many of these research programs have not reported on the stresses developed by a partially saturated or a saturating buffer, particularly as they may influence the pressures applied to the surrounding rock mass or the container.

Some of the difficulty in obtaining information on the relationship between pressure generated by and transmitted through buffer materials has been associated with the difficulty in monitoring water uptake in low permeability buffers. Water uptake (flux), under conditions of low hydraulic head (<100 kPa across a 30-mm specimen) can be lower than 1.3×10^{-11} $m^3/s/m^2$. The actual water uptake by the buffer will depend on a number of factors, including: initial degree of saturation, specimen density, time, and hydraulic head applied.

This report presents the results of several studies on the role of water uptake on the rate and magnitude of swelling pressure developed in bentonite-based buffer materials. These studies include investigations of the following:

(1) Role of initial degree of saturation on rate and magnitude of water uptake and swelling pressure developed by compacted bentonite-based materials,

(2) Role of specimen density on rate and magnitude of swelling pressure development,

(3) Moisture distribution within specimens which have reached "maximum" swelling pressure,

(4) Three-dimensional pressure distribution in specimens "wetted" on one end,

(5) Influence of a wetting "skin" on the density of buffer materials and the likely long-term swelling pressures exhibited.

2. DESCRIPTION OF MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 MATERIALS EXAMINED

The term Bentonite is commonly used as the trade name for a naturally occurring, swelling clay product sold commercially for use in a variety of applications. This product is composed predominantly of a layer silicate called montmorillonite, formed by alteration of a volcanic ash laid down in a brackish or marine environment. These clay-shales also contain smaller amounts of quartz, feldspar, illite and in some cases, gypsum and carbonate (Dixon and Miller, 1995). The age of such deposits vary with location but the main sources in Canada and the USA date from 80 Ma to 100 Ma (the Cretaceous age) (Dixon et. al, 1992; Dixon and Miller, 1995). The physical, chemical and mineralogical characteristics of bentonites from various sources depend on the initial ash composition, granularity and post-deposition conditions of each locality. The commercially mined bentonites considered in this report all have similar hydraulic and swelling characteristics (Dixon et. al, 1992; Dixon and Miller, 1995; Dixon, 1995). Based on previously established similarities in the behaviour of bentonites from Canada and the USA, the manner in which pressures are developed by and transmitted through them should be comparable.

Bentonite clays have a long history of use in a wide range of applications, including in the foundry industry as a sand binder, in animal feed pelletizing, as an insecticide carrier, as a component in cosmetics, as drilling mud for the oil and gas industry, and as a general purpose sealant in water control applications. More recently bentonite has come into use as a component in many environmental engineering applications, such as slurry trenching and liners and covers for landfills.

Bentonite has also been identified for potential use as a component of engineered barriers in nuclear fuel waste disposal facilities (Gray et. al, 1984). Bentonite-based materials exhibit many of the characteristics deemed desirable in a sealant for such a facility. Among these desirable properties is the ability to swell on contact with free water thereby providing the barrier with a self sealing capacity should any cracks or fissures be induced in the barrier. Associated with the ability to swell on contact with free water is the capacity to generate considerable forces on any confinement to the bentonite (swelling pressure). Bentonites are also known to exhibit a very low hydraulic conductivity, and should therefore limit advective groundwater flow through a disposal site (Dixon and Miller, 1995; Dixon, 1995; Pusch, 1980, 1983).

Because of its ability to limit water movement, bentonite has been selected as a component in the sealing concepts of a number of nations. Those countries considering bentonite-based barriers as component(s) of a high level nuclear fuel waste disposal facility include Canada (Gray et al., 1984; Sweden (Pusch, 1983); Switzerland (Bucher and Speigl, 1984) and Japan (Kanno et al., 1995). In Canada, research has been directed towards the development of a clay-based sealant for use in isolating corrosion-resistant containers holding used nuclear fuel. This nuclear fuel waste disposal research has led to the selection of a mixture of bentonite clay and quartz sand (buffer material) to be used in waste container encapsulation.

The research project reported here has concentrated on the behaviour of sand - clay mixtures (equal dry weight proportions) and pure clay materials. The bentonites used for this study were from Wyoming USA and Saskatchewan Canada.

2.2 TESTING EQUIPMENT AND PROCEDURES

Testing was conducted using rigid-walled cells to confine compacted bentonite-based materials. These cells were constructed of stainless steel and a rigid steel piston was used to prevent vertical straining of the specimen. The vertical jacking force transmitted through the restraining ram was monitored by placing a load cell between the piston and the stiff steel reaction plate holding the piston in place. Cylindrical specimens were either trimmed and placed into, or compacted directly in the testing cells. In the walls of some cells were mounted miniature load cells which were to monitor swelling pressure normal to the axis of compaction of the specimens. These lateral pressure load cells were removed during the compaction process and replaced with plugs of the same size. After completion of specimen compaction, the load cells were installed, with a very minor initial contact pressure (10-50 kPa), being induced to ensure that the cell was in direct contact with the buffer or bentonite specimen. These lateral load cells were placed at various heights along the length of the specimens in order to determine what, if any, vertical differences would be present along the cell wall. The wetting of the specimens was accomplished by applying a source of porewater, under a nominal pressure (20 kPa), to the base of the specimen while maintaining atmospheric pressure at the top of the specimen. Later in the testing process the pore water pressure applied at the base was increased and the drainage line at the top of the cell was closed. This allowed the hydraulic conductivity of the specimens and total stress conditions within the cell to be monitored. Pore water pressure was monitored by means of a pressure transducer mounted on the reservoir for the inflow fluid and it was assumed that the effective stress concept is valid for this material when it is saturated.

3. RELATIONSHIP OF WATER UPTAKE, SWELLING PRESSURE AND TIME

3.1 SWELLING PRESSURE AND SPECIMEN DENSITY

In the course of this study a large body of data was collected on the relationship(s) between swelling pressure magnitude, time and the shape of a plot of swelling pressure and time where an unlimited supply of free water is supplied to one end of a rigidly confined specimen. Previous papers and reports have described the relationship between specimen density and the "ultimate"/saturated swelling pressure developed by bentonite-based specimens (Bucher and Speigl, 1984; Gray et. al, 1984, 1986; Oscarson et. al, 1990; Dixon and Miller, 1995; Pusch, 1980). The relationship between specimen density and saturated swelling pressure is presented in Fig. 1 and contains the literature data compiled by Dixon and Miller (1995). These data show that swelling pressure increases as the clay density increases. With this data base it is possible to examine the nature of the swelling pressure development with water uptake (Section 3.2), the manner in which pressures are transferred through bentonite-based materials that are wetting (Section 3.3) and the role of pore fluid salinity on swelling pressure (Section 3.3).

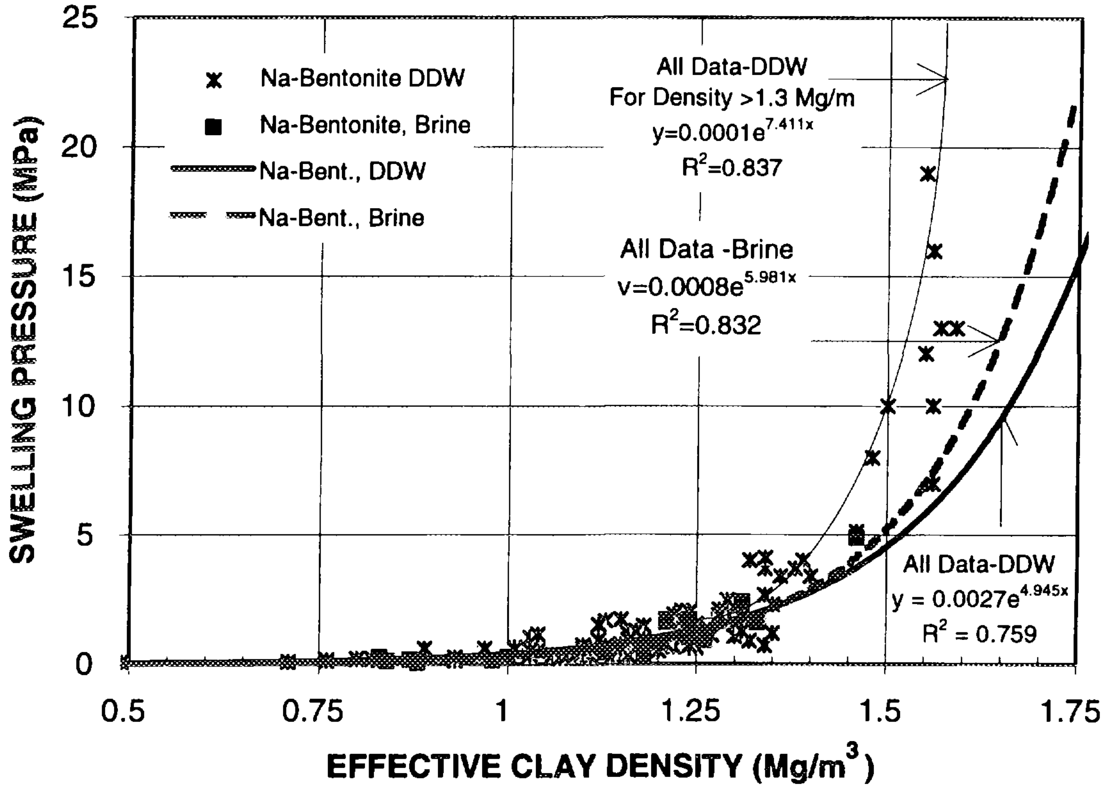

FIGURE 1: Swelling Pressure - Specimen Density Relationship

The early data collected at the Whiteshell Laboratories were used to develop an empirical relationship for use in predicting the swelling pressure which would be developed by a specimen of a particular clay density (Gray et. al, 1986). Specimens of bentonite clay and clay-sand mixtures were prepared at a wide range of initial densities and initial degrees of saturation. Tests were conducted using both deionized water as the wetting fluid and the highly saline Standard Canadian Shield Saline Solution (SCSSS) (Dixon et. al, 1987). Use of these different fluids permits extension of the data generated using fresh water and brine solutions into the groundwater conditions likely to be encountered at depth in the crystalline rocks of the Canadian Shield. The swelling pressure developed by densely compacted bentonite-based materials was found to be independent of the salinity of wetting fluid used (Dixon et. al, 1987) and is presented in Fig. 1 of this report. The ultimate swelling pressure developed by specimens was also found to be independent of the initial degree of saturation.

The regression lines shown in Fig. 1 show that there is little difference in the swelling pressures observed for specimens tested using either fresh water (distilled deionized water, DDW) or a brine solution when the effective clay dry density (ECDD) is in the range of 1.0 to 1.5 Mg/m3. The ECDD is defined as the mass of the clay component divided by the volume occupied by the clay and voids. The mass and volume occupied by non-clay solids are assumed to have no influence on the system and act only as inert filler(s). Since the reference buffer proposed in the Canadian Nuclear Fuel Waste Management Program has an effective clay density of 1.25 Mg/m3, its swelling pressure should not be influenced by the salinity of the permeating groundwater.

At densities >1.5 Mg/m3 the regression lines generated using the entire database do not accurately predict the swelling pressure observed, this can be attributed to the paucity of data in the higher density range which allows the regression lines to be dominated by the data collected at lower densities. A separate regression line for materials compacted to very high density (>1.3 Mg/m3), was developed, its equation is 0.0001e7.411x with an R2 value of 0.837. For highly compacted bentonite, this equation provides a more representative prediction of the swelling pressures that will be developed by rigidly confined materials.

3.2 SWELLING PRESSURE DEVELOPMENT IN SATURATING BENTONITE SPECIMENS

The rapid rate of swelling pressure (PS), observed in densely compacted bentonite-based materials raises a number of questions about the nature of swelling pressure and its relationship to the water present in the specimen. In order to better understand these relationships, a series of tests were conducted to determine the relationship between swelling pressure and testing time in specimens of various initial degrees of saturation. The shape of the swelling pressure versus wetting time curves has been broken down into four basic types and two subtypes for a total of 6 classifications, as shown in Figure 2 and these were used in classifying the behaviour of the specimens examined.

The results of the swelling pressure - initial moisture content experiments conducted at Whiteshell Laboratories is presented as Appendix 1 and summarized in Table 1.

Data on swelling pressure classification, by type of material and fluid used in testing are presented and the swelling curve for each is classified in one of the six categories. There were a number of specimens whose swelling pressure development was indeterminate and they were given two classification codes to allow them to be included in the data base. Hence, there are 131 observations (n=131) made on 110 specimens.

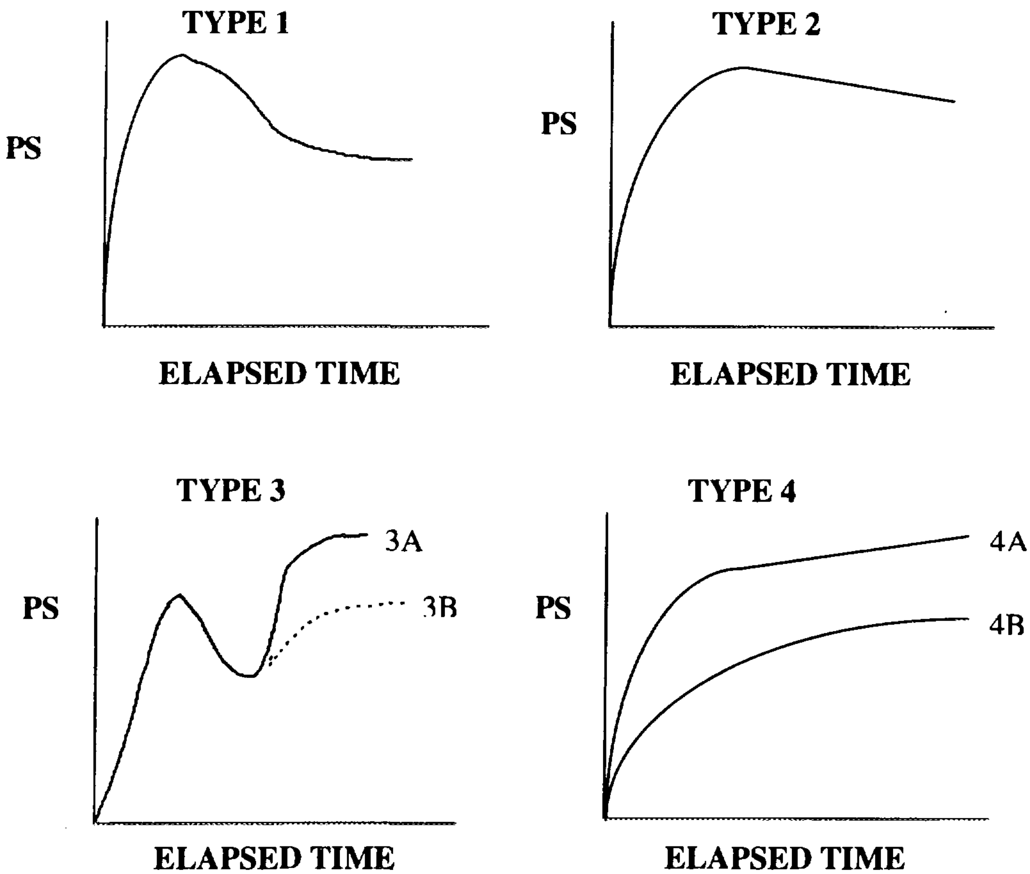

FIGURE 2: Types of Curves Observed for Plot of Swelling Pressure (PS) Versus Wetting Time

TABLE 1

TYPE OF SWELLING PRESSURE DEVELOPMENT IN BENTONITE SPECIMENS

INITIAL DEGREE OF WATER SATURATION (%)

Swelling Type	0	<20	21-40	41-50	51-60	61-80	81-90	>90	n
1	2	3	1	3	0	3	1	2	15
2	13	0	2	5	3	14	3	3	43
3A	5	2	3	2	1	1	0	0	14
3B	2	0	0	0	0	0	1	0	3
4A	11	1	1	6	6	22	2	4	53
4B	0	0	1	0	1	1	0	0	3
n	33	6	8	16	11	41	7	9	131

The data in Table 1 show that there are relatively few occasions where swelling types 3B or 4B were observed (3 each in 131 observations) and there is no particular moisture content range where they are observed. This indicates that these two types are more likely aberrations in the swelling pressure-time plots and that swelling pressure is most likely to develop in one of the four other manners. The majority of the specimens exhibited either type 2 (44 of 131 observations) or 4A (54 of 131 observations) swelling pressure. That is, the specimen rapidly developed near-full swelling pressure and then either relaxed slightly or very gradually increased its swelling pressure with time. The swelling pressure versus time data summarized in Table 1 show no clear separation of swelling pressure type with initial degree of saturation.

Throughout each of these tests, an unlimited supply of water was supplied at the base of the specimen. Hence, the degree of saturation determined for the overall specimen at the end of the testing may not accurately reflect the moisture conditions present locally in the specimens. The issue of moisture distribution within specimens is discussed in Section 3.3 of this report.

3.3 MOISTURE DISTRIBUTION WHEN FULL VERTICAL SWELLING PRESSURE IS PRESENT

Thirteen specimens were prepared to investigate the relationship between moisture distribution within specimens and the swelling pressure developed. Initial degrees of saturation of these specimens ranged from 0% to 90%. Unlimited access to water under a nominal pressure (approximately 100 kPa) was allowed to each specimen tested. The vertical jacking pressure developed by these specimens was monitored until either full swelling pressure (no further increase in pressure with time), was developed (8 specimens) or, approximately 120 hours had elapsed (5 specimens). Where the swelling pressure had not yet reached its "full" value before testing was terminated, the swelling pressure and time to develop full swelling pressure is denoted as being greater than (>) in Table 2. Testing was terminated at 120 hours for selected specimens in order to section them and obtain a saturating moisture content distribution for bentonites. Data from the tests are presented in Table 2 and include the average moisture content of each specimen at the end of testing.

At the end of each test the specimen was sliced into a number of layers and the gravimetric moisture content of each layer was determined as a function of the distance from the distance from the source of water (Table 3). The number of layers obtained varied among the specimens, shorter specimens (25-mm nominal height), only provided 5 or 6 disks while longer (50-mm nominal height) specimens could provide from 6 to 10 disks. The location, thickness, mass and moisture content of each disk was recorded and used to determine the moisture content and density distribution within bentonitic specimens. Table 3 presents the results of the moisture content analyses conducted.

Tables 2 and 3 clearly show that there is no relationship between the initial degree of saturation, the average specimen saturation and ultimate vertical swelling pressure.

TABLE 2

MOISTURE DISTRIBUTION WITHIN SPECIMENS EXHIBITING FULL VERTICAL SWELLING PRESSURE

Specimen Name	Dry Density (Mg/m^3)	Clay Density (Mg/m^3)	Initial Water Content (%)	Initial Saturation (%)	Full Swelling Pressure (kPa)	Test Duration (Hrs)	Time to Full Swelling Pressure (Hrs)	Final Average Water Content (%)	Final Average Saturation (%)	Shape of Swelling Pressure Curve (Fig. 2)
URL-40%	1.16	1.16	39.9	78	300	336	225	47	96	2/4A
URL-40%-2	1.25	1.25	39.9	89	1300	120	120	40	89	2/4A
URL-40%-3	1.10	1.10	39.8	71	450	550	200	41	74	2/4A
URL-30%	1.31	1.31	30	73	1250	312	225	37.8	92	2/4A
URL-30%-2	1.24	1.24	30.1	66	>700	120	>120	35	77	2/4A
URL-20%	1.15	1.15	20	39	600	336	300	48.9	94	2/4A
URL-20%-2	1.20	1.20	20	42	>800	120	>120	30	62	4A
URL-10%	1.16	1.16	10	20	900	390	300	46.7	92	4B
URL-10%-2	1.22	1.22	10.6	23	>650	120	>120	26	56	3A
URL-0%-2	1.18	1.18	0	0	450	336	200	41.6	84	3B
URL-0%-3	1.21	1.21	0	0	750	120	30	18	38	2/4A
URL-0%-Buf	1.54	1.10	0	0	575	550	400	18.6	65	2/4A
Buffer-17%	1.56	1.11	17	61	600	2250	2000	25.2	91	2/4A

TABLE 3

MOISTURE DISTRIBUTION WITHIN SPECIMENS

Specimen	**Layer #**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
URL-40%: 1.16 Mg/m^3										
Top of Layer (mm)	5.4	8.5	11.6	18	21.9	25.1				
Moisture Content (%)	56.7	45.6	44.2	44.4	44.5	46				
Saturation (%)	111.1	89.4	86.6	87	86.9	90.1				
URL-40%-2: 1.25 Mg/m3										
Top of Layer (mm)	8.9	16.1	22.3	33.2	40.9	49.5				
Moisture Content (%)	42.1	41.6	40.2	39.2	38.9	38				
Saturation (%)	94	93	89.8	87.5	86.9	84.9				
URL-40%-3: 1.10 Mg/m^3										
Top of Layer (mm)	5.8	12.5	19.6	25.6	31.2	41.3	48.7	54.9		
Moisture Content (%)	45.3	42.7	40.7	38.5	39.5	39.9	40.1	39.9		
Saturation (%)	81.3	76.6	73	69.1	70.9	71.6	72	71.6		
URL-30%: 1.31 Mg/m^3										
Top of Layer (mm)	8.4	16.4	23.3	31.9	43.1	47.4				
Moisture Content (%)	39.4	37.3	36.8	38.2	37.9	35.7				
Saturation (%)	95.8	90.7	89.5	92.9	92.2	86.8				

continued.....

TABLE 3 (continued)

MOISTURE DISTRIBUTION WITHIN SPECIMENS

Specimen	**Layer #**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
URL-30%-2: 1.24 Mg/m^3										
Top of Layer (mm)	6.9	13.5	19.1	29.6	44.4	50.2				
Moisture Content (%)	46.9	40.0	36.8	33.1	30.7	28.9				
Saturation (%)	103.3	88.1	81.1	72.9	67.6	63.7				
URL-20%: 1.15 Mg/m^3										
Top of Layer (mm)	6.1	12.2	18.3	21.9	26.8					
Moisture Content (%)	52.2	47.7	46.8	46.6	47.4					
Saturation (%)	100.9	96.4	90.5	90.1	91.6					
URL-20%-2: 1.20 Mg/m^3										
Top of Layer (mm)	7.0	16.0	20.5	28.1	36.3	49.5				
Moisture Content (%)	46.5	35.8	29.1	27.5	24.2	22.1				
Saturation (%)	96.9	74.6	60.6	57.3	50.4	46.1				
URL-10%: 1.16 Mg/m^3										
Top of Layer (mm)	4.5	8.7	15.0	20.8	24.5	30.7				
Moisture Content (%)	55.3	47.2	44.6	44.1	43.4	44.2				
Saturation (%)	108.0	92.5	87.4	86.4	91.7	86.7				
URL-10%-2: 1.22 Mg/m^3										
Top of Layer (mm)	8.0	15.5	23.9	33.7	42.3	50.0				
Moisture Content (%)		33.5	24.3	18.2	14.7	13				
Saturation (%)	108.5	71.7	51.6	38.6	31.2	27.6				

continued.....

TABLE 3 (concluded)

MOISTURE DISTRIBUTION WITHIN SPECIMENS

Specimen	**Layer #**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
URL-0%-2: 1.18 Mg/m^3										
Top of Layer (mm)	5.4	11.1	16.1	21.5	26.4	33.9				
Moisture Content (%)	50.3	44.2	41.9	39.8	38.9	36.9				
Saturation (%)	101.5	89.2	84.5	80.3	78.5	74.5				
URL-0%-3: 1.21 Mg/m^3										
Top of Layer (mm)	4.9	13.8	23.2	49.7						
Moisture Content (%)	48.8	32.8	20.4	6.9						
Saturation (%)	102.9	61.9	43	14.5						
URL-0%-Buffer: 1.54 Mg/m^3										
Top of Layer (mm)	1.8	6.5	12.6	19.5	24.4	30.6	28.4	41.5	50.2	
Moisture Content (%)	32.7	26.4	21.8	18.8	17	15.7	13.7	13	12.5	
Saturation (%)	117.8	105.1	78.5	67.7	61.2	56.6	49.4	46.8	45	
Buffer 17 %: 1.56 Mg/m^3										
Top of Layer (mm)	4.3	12.8	19	23.7	29.4	36.2	43.1	49.7	56.7	66.1
Moisture Content (%)	31.5	26.9	27	26	26.6	24.8	24.7	23.8	23.4	22.7
Saturation (%)	113.5	103.2	97	93.7	95.8	89	89	86	84	82

These data also show that there is no need for the specimen to be entirely saturated for its full vertical swelling pressure to be observed. One potential explanation for this lack of association between overall specimen saturation and observed swelling pressure could be that the thin layer of the clay immediately in contact with the free water source becomes fully saturated generating a vertical force which is of a magnitude similar to that of the "full" swelling pressure of a completely saturated specimen.. This suggests that it is not necessary to run swelling pressure tests for the thousands of hours necessary to ensure full specimen saturation.

The vertical transfer of force through the unsaturated specimen raises two major questions: Firstly, does the moisture distribution within a specimen which has just achieved "full" vertical swelling pressure support a wetted skin concept? Secondly, is there is a difference between the forces acting vertically and against the side walls of the confinement?

Tables 2 and 3 also show that there has been significant water uptake in all the specimens examined. The end-of-testing average degree of saturation ranged from 38% to 96%, compared to an initial degree of saturation which ranged from approximately 0% to 90% (Table 2). More important than the somewhat misleading final overall degree of saturation (which only provides an average saturation for the entire specimen), was the distribution of moisture within each of the specimens. The data contained in Table 3 show that full specimen saturation is not necessary for full "swelling pressure" to be exerted by the specimen. While one end of each specimen was allowed unlimited access to free water, it would appear than only a very thin layer at this location achieved saturation. The clay dry density of all but one of the specimens examined ranged from 1.10 Mg/m^3 to 1.25 Mg/m^3, and so these specimens should exhibit fairly similar hydraulic conductivities (Dixon, 1995). Although they were constructed at very different initial moisture contents it would appear that this parameter has little influence on either the rate of swelling pressure development or the proportion of the specimen that has achieved full saturation. The specimens examined typically developed "full" swelling pressure within 120 hours to 300 hours.

A further point of interest in Table 3 is the calculated degree of saturation present at the base of the specimens. Degree of saturation was calculated based on the overall specimen mass and volume, and assumes a uniform density of the specimen. The presence of many specimens with degrees of saturation well above 100% is indicative of a material that is not of uniform density but rather a material with a lower density at its base. This lower density is consistent with a material that has swelled on water uptake and compressed the material above it.

Also presented in Table 3 and shown in Figure 3 is the thickness of the saturated portion of these specimens. This zone was only some 6mm to 8mm thick at the end of 120 hours of testing, and was not much further developed at the end of approximately 300 hours of testing. The two specimens (URL-40%-3 and URL-0%-Buff), that were tested for 550 hours before sectioning showed saturated zones that were between 5-mm and 8-mm thick,

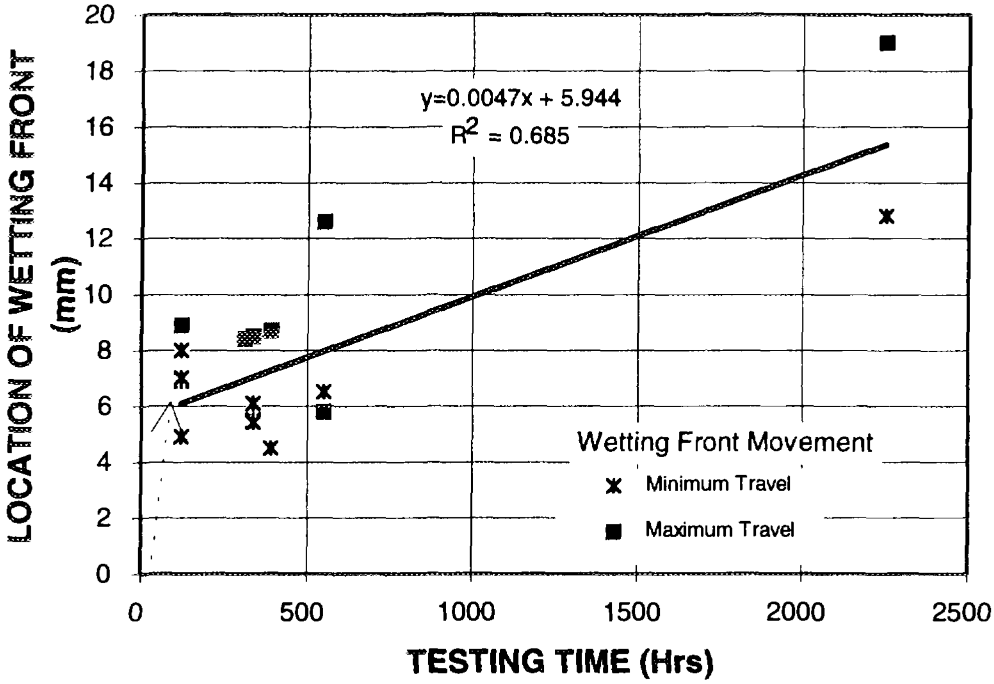

FIGURE 3: Relationship Between Thickness of Saturated Soil Layer and Wetting Time (at 20 kPa to 100 kPa Hydraulic Head)

not much different than was observed for the tests terminated at shorter expired time. The longest running specimen (2250 hours), was among the lowest density specimens (clay density 1.11 Mg/m^3) but still showed full saturation only to a distance of 16 mm from the water source. The distance given for the movement of the wetting front is determined as being somewhere within the layer above the uppermost region showing full saturation (see Table 3). For example in Table 3 specimen "Buffer 17%" showed full saturation to a distance of at least 12.8 mm from the base and the layer above this level extends to 19 mm from the specimen base. Hence, the wetting front has travelled a minimum of 12.8 mm and less than 19 mm. From this information the minimum and maximum distance of water movement was plotted in Figure 3 and regression lines were calculated. The regression line plotted in Figure 3 is that generated by combining the minimum and maximum travel distances.

It appears that the rate of specimen saturation depends on the hydraulic conductivity of the specimen (approximately 10^{-12} m/s) and so water movement into the specimen is limited by the ability of the wetted zone to transmit moisture. The rate of moisture movement through the wetted zone can be described using the Darcian model for flow (Dixon, 1995). However, it is difficult to use this model because the gradient actually acting across the specimen is unknown. The effective gradient across the specimen is a combination of both the applied hydraulic head as well as the presence of suction forces pulling the water into the specimen. While the applied hydraulic head is measurable, the suction forces are not readily quantified. It is the suction that is likely to be the dominating factor in the water movement process, especially in the early stages of water uptake.

The development of swelling pressure and vertical transfer of force to a restraint requires only the presence of a thin wetted zone in contact with a source of free water. The swelling pressure developed by the wetted skin is almost immediately transferred vertically as a jacking force. The advancement of the wetting front in the specimen has little or no influence on the swelling pressure measured by the restraining ram. The specimens tested and sectioned in this study showed little change in the swelling pressure with time once the full swelling pressure was developed shortly after test initiation (120 hours - 300 hours). There was perhaps a slight tendency for the pressure to relax in some cases or increase very slightly in others. Relaxation can be attributed to material compression in the unsaturated regions and an associated swelling and reduction in the swelling pressure generated in the saturated regions. Slight increase in swelling pressure may be associated with the formation of a more fully saturated region near the base of the specimens as time passed.

While the majority of the swelling pressure versus time behaviours recorded were of Types 2 and 4 (99 of 131 observations), remaining specimens exhibited different swelling pressure development patterns. In these specimens swelling pressure developed rapidly, followed by a significant stress relaxation (Figure 2, swelling types 1 and 3). In some cases the swelling pressure observed increased again following the initial relaxation and in others no recovery was observed (Figure 2). This relaxation behaviour may be attributed to reseating of the filterstones, restraining ram or clay plug within the test cell as the result of initially non-rigid specimen confinement. Once all possible internal straining occurred, swelling pressure equilibrated. Even in the specimens showing "non-typical" swelling pressure development, full swelling pressure was achieved within a few hundred hours of testing, much more rapidly than it would be possible to achieve full specimen saturation. Use of a term such as "Swelling-Induced Pressure" rather than Swelling Pressure might be more appropriate to describe the pressures developed by saturating specimens.

The rapid development of the full swelling-induced pressure for all specimens can be attributed to a rapid upwards transfer of the swelling pressure developed in the wetted zone on the bottom of the specimen. The relaxation of the stress applied to the restraining ram can be explained by a gradual compression of the unsaturated regions of the specimen under the force applied by the saturated regions of the specimen. Compression allows the saturated region to gradually swell and decrease in density, thereby gradually decreasing the swelling-induced pressure. Once the full compression possible under the applied (swelling pressure) load has occurred, the stress on the restraining ram could be expected to ultimately increase slightly as the wetting front penetrates into the previously consolidated portion of the specimen. As wetting of the higher density consolidated region proceeds, the increased swelling pressure generated in these regions could compress the lower-density regions at the base of the specimen. Ultimately, the specimen achieves full saturation and the specimen would gradually strain until stresses were redistributed and density isotropy was regained. Given the low permeability of bentonite-based materials, steady-state stress conditions may take a very long time to be achieved.

3.4 SUCTION FORCES WITHIN SATURATING BENTONITE-BASED MATERIALS

The suction properties of compacted sand-bentonite materials were measured by Wan et al. (1995) using the psychrometer, filter paper and vapour techniques. Figure 4 shows the relationship between total suction and water content for compacted sand-bentonite material. Due to the presence of active clay minerals and small capillary pores, relatively high suctions exist in these materials. For the gravimetric water content (w) range of 1% to 26%, the total suction increases logarithmically from 1 MPa at w=26% to 600 Mpa at w=1%. The majority of this change in total suction arises from the matric component and is attributed to the capillary phenomena within the soil microstructure in the clay phase (Wan et al., 1995). In contrast to the matric suction, the osmotic suction in unsaturated sand-bentonite material is generally insensitive to changes in water content. For the water content range of 10 to 24%, the osmotic suction generally varies from 0.5 MPa to 1.5 Mpa (Wan et al. 1995).

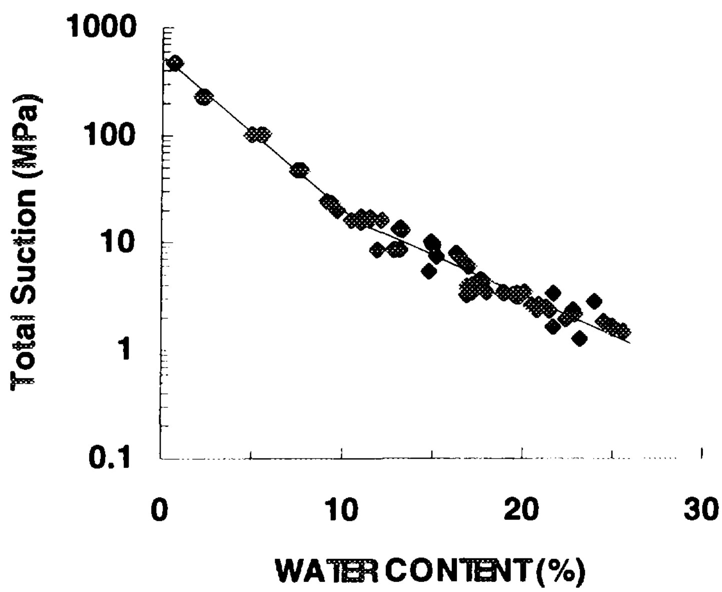

FIGURE 4: Total Suction - Water Content Relationship For Sand-Bentonite Material (Wan et al., 1995)

Most of the test specimens used in this study were formed at an initial water content of 10% to 20%, with corresponding total suctions of 20 MPa to 2 MPa respectively. These high suctions, combined with externally-applied positive pore water pressures produce high hydraulic gradients across the specimen. Thus water uptake in these unsaturated sand-bentonite specimens would be rapid during the initial stages of testing. With time, as water moved into the specimens, the total suction, and hence the hydraulic gradients, decreased. Under these conditions, the rate of water uptake by the specimens once a saturated region was developed, should be governed by the hydraulic conductivity of the saturated material.

3.5 RADIAL PRESSURES DEVELOPED BY SATURATING BENTONITE-BASED MATERIALS

In addition to tests monitoring of the vertical jacking forces developed during water uptake a number of tests were conducted in which both the vertical and lateral swelling were monitored. The cells used to monitor development of lateral pressure were 50mm internal diameter versions of the 32mm swelling pressure cells used in the water uptake studies (Section 3.9). Load cells (diameter approximately 7mm), were mounted at a number of locations in the walls of the swelling pressure cells. The sensing surface of each of these cells was mounted flush with the inside wall of the swelling pressure cells following placement of the specimens. This ensured that there were no compaction-induced stresses initially present on the load cells and that all pressures measured were the result of swelling pressure and/or applied pore water pressures.

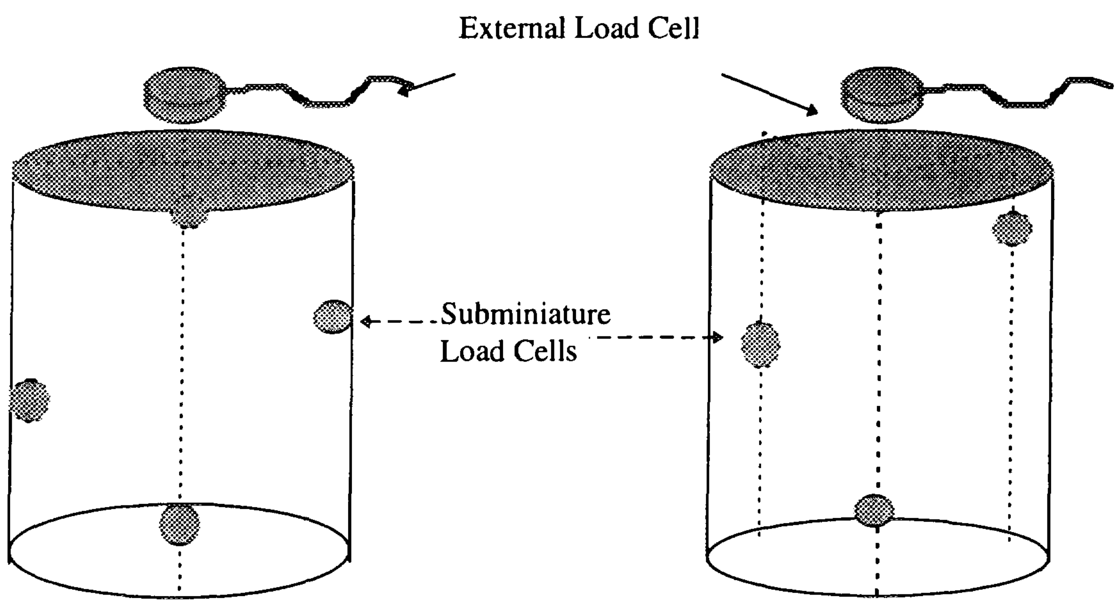

FIGURE 5: Cells Used To Monitor Lateral Pressure Development

Figure 5 shows a sketch of the locations of the subminiature load cells mounted in the walls of the two cells used for the investigation of lateral swelling pressure development. Seven lateral stress development tests were conducted. Each test each lasted from 4000 to 7000 hours (167-292 days). A summary of the properties of these specimens is

TABLE 4

PROPERTIES OF SPECIMENS MONITORED FOR LATERAL STRESS DEVELOPMENT

Test	Dry Density (Mg/m^3)	Dry Density (Mg/m^3)	Initial Water Content (%)	Initial Saturation (%)	Testing Time (Hrs)	Final Water Content (%)	Final Saturation (%)	Transducer Location	Maximum Swelling Pressure (kPa)
LatPress1	1.49	1.04	0	0	4200	28.5	93	Top Ram	300
								Mid Lateral	375-475
LatPress2	1.35	0.92	17	45	7500	36.5	97	Top Ram	200
								Top Lateral	175
								Mid Lateral	175
								Btm Lateral	325
LatPress3	1.37	0.93	17	46	5700	35.6	97	Top Ram	225
								Top Lateral	250
								Btm Lateral	225
LatPress4	1.62	1.16	17.7	67	4100	24.9	98		
								Top Ram	500
						25.5	100	Top Lateral	550
						23.8	94	Mid Lateral	550
								Mid Lateral	550
						25.6	101	Btm Lateral	325leak
								Btm Lateral	325leak

continued.....

TABLE 4 (concluded)

PROPERTIES OF SPECIMENS MONITORED FOR LATERAL STRESS DEVELOPMENT

Test	Dry Density (Mg/m^3)	Dry Density (Mg/m^3)	Initial Water Content (%)	Initial Saturation (%)	Testing Time (Hrs)	Final Water Content (%)	Final Saturation (%)	Transducer Location	Maximum Swelling Pressure (kPa)
LatPress5	1.60	1.15	17.5	67	4500	26.0	100		
								Top Ram	475
						24.8	95	Top Lateral	250 leak
						23.1	89	Mid Lateral	150 leak
						25.9	99	Btm Lateral	150 leak
						30.3	116	Base	
LatPress6	1.60	1.15	17.5	67	3500	24.8	95		
								Top Ram	400
						25.7	99	Top Lateral	450
						22.8	87	Mid Lateral	600
						24.9	95	Mid Lateral	450
						24.9	112	Btm Lateral	500
LatPress7	1.56	1.11	17.1	62	3500	27.9	101		
								Top Ram	300
						29.0	104	Top Lateral	350
						25.8	93	Mid Lateral	350
						26.9	97	Btm Lateral	475
						33.1	116	Base	

presented in Table 4. Water uptake was monitored constantly throughout the test to provide an estimate of the average moisture content present as the swelling pressure developed. However, based on the results of the water uptake - swelling pressure relationships reported in Section 3.3 of this report, it is unlikely that there was a uniform moisture content distribution within these specimens during the early stages of testing. A "saturated skin" likely developed and the pressures monitored in both the vertical and lateral directions are the result of stress transfer through an unsaturated material.

Figures 6 through 8 present the results of three of the lateral stress monitoring tests. A number of the tests developed leaks at the locations of the laterally mounted load cells, making it difficult to determine the proportion of the total pressure resulting from pore water versus swelling pressure. When leakage was identified, an attempt was made to stop the leakage and if this was unsuccessful, the data obtained from that transducer were discarded. The transducer was removed and a steel plug was placed in its location. Thus, a number of the tests have data that are not complete from test initiation to completion. The manner in which stresses induced by development of swelling pressure at the wetted end of the specimens were transferred upwards and laterally provide a measure of the manner in which a buffer that is wetting along one side, or one end, would transfer swelling pressures within a borehole environment.

The effective stresses developed vertically and laterally by three of the saturating buffer specimens (Figures 6 through 8), show that ultimately the vertical and lateral pressures equilibrated to similar magnitudes. In these tests the pore water pressure was stepwise increased and the response of the load cells located was monitored. However, there are some differences between the pressures recorded at the various locations. These differences are attributable to the presence of local arching or locked-in stresses originating from the compaction of the specimens into the cells, local differences in clay density, or the accuracy of the loadcells (±10%). Differences in observed pressure were greatly reduced once the drainage through the specimens was closed and saturation was approached. As shown in Figure 6 through 8, part way through the test the top drainage was closed and the influence of changes in pore water pressure on the total pressure measured. The effective stress principle states that the total stress on the walls of the containment should be the sum of the stresses induced by the pore fluid and that transferred through, or developed by, solid particles (swelling pressure). In a completely isotropic specimen the stresses in all directions should be uniform and this condition was ultimately closely approached in many of the specimens examined.

In a fully saturated system, altering of pore water pressure should rapidly result in an equal change in the total pressure exerted by that specimen. The presence of a gradual response in the total pressure exerted (under conditions of no drainage, such as in Figures 6 through 8) can be interpreted as evidence of incomplete specimen saturation (see Table 4). The specimens presented in Figures 6 thrugh 8 were at or near full saturation at the end of testing and this is reflected by the rapid response of the total pressure of the system to closure of the top drain. Were there any air present within the specimen, it must be compressed by the movement of fluid into the specimen. As this

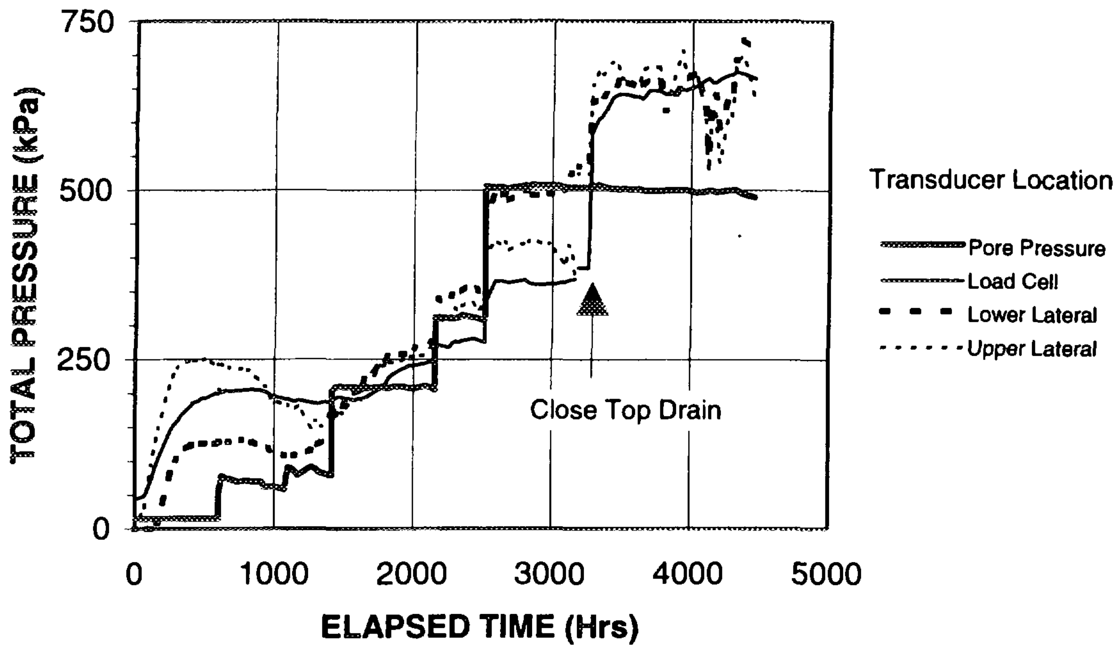

FIGURE 6: Vertical and Lateral Swelling Pressures Developed by Buffer (Specimen LatPress 3)

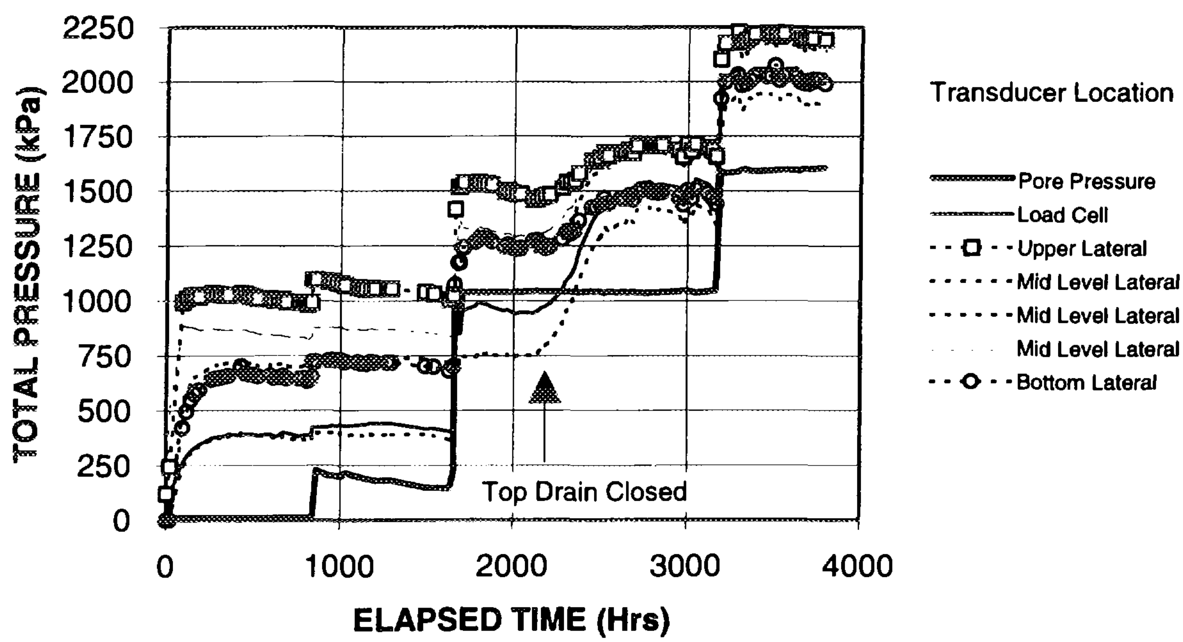

FIGURE 7: Vertical and Lateral Swelling Pressures Developed by Buffer (Specimen LatPress 4)

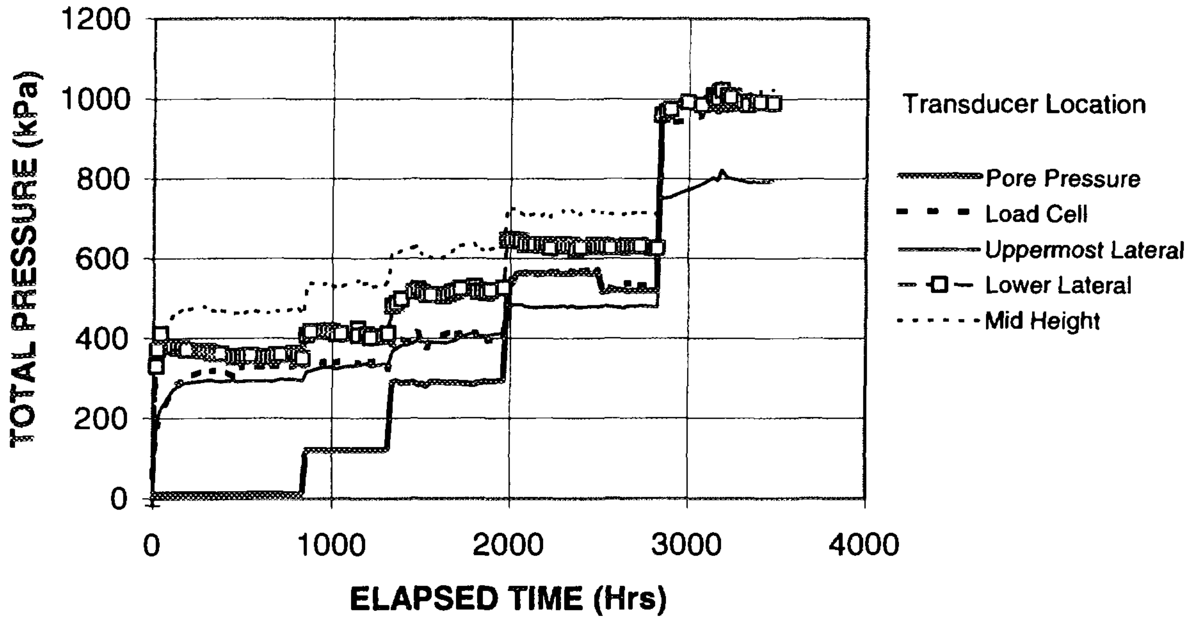

FIGURE 8: Vertical and Lateral Swelling Pressures Developed by Buffer (Specimen LatPress 7)

moisture movement is limited to that possible by advective flow through the saturated zone, the low permeability materials considered in this study (approximately 10^{-12} m/s) will not see the development of a "full" pressure for a long time. What is observed following increase in the pore water pressure supplied to one end of an unsaturated specimen, is a gradual increase in the total pressure of the system and development of differences in the total pressure present at various locations within the specimen. Some density anisotropy was evident in the specimens in which moisture content distribution was determined. Specimens LatPress 5, 6, and 7 showed high moisture content / low density in the region closest to the water source (saturation >100% based on average density of entire specimen). As can be seen in Table 4, the specimens were not completely saturated at the end of testing (with the possible exception of specimen LatPress7). The final degree of saturation ranged from 92% to 100% but, as is illustrated by the data in Table 4, this moisture was not uniformly distributed. This may be the cause of anisotropic stress distribution, or localized consolidation which would be reflected in intermediate-term variability in the stress applied to the walls of the confining cell.

As observed in the water uptake portion of this study (Section 3.3), it is evident that high stresses can rapidly develop at the interface of the specimen and its confinement. It is not necessary for the specimen to develop full or nearly full saturation for "full" swelling pressure to be transferred to the walls of the clay's confinement. This "swelling" pressure is explained by the mechanical forces developed by a thin layer of saturated material at the base of the specimen. This force developed by the swelling clay is transferred directly upwards to the restraining piston and laterally to the cell walls as the specimen is compressed. This is not unlike an undrained triaxial compression test of a saturated specimen or, the stresses developed on a retaining wall following loading of the soil adjacent to the wall.

4. SUMMARY

The relationship between swelling pressures and saturation in confined bentonite-based materials has been investigated. It is not necessary for full specimen saturation to be achieved for the full swelling pressure to be developed and transferred through the unsaturated regions to the confining medium. Only a thin layer of saturated material (perhaps a few mm), developed by contact with a source of free water, is necessary for generation of a full swelling pressure.

When provided with an unlimited supply of free water, water uptake in bentonite-based materials is initially very rapid as the bentonite seeks to satisfy its high suction potential. However, on formation of a thin layer of saturated clay, this rapid water uptake is quickly reduced. The rate of water movement into the clay is relatively constant, changing only with the hydraulic gradient applied across the specimen.

Hence, for clay buffers emplaced for waste management purposes, it may be expected that buffer resaturation will be gradual and controlled by the balance between water supply and the ability of the buffer to transmit the groundwater inwards from its wetted surface. Once sufficient water uptake occurs to provide a wetted layer or region on the buffer surface, the pressures caused by the resaturation of this region could be tranferred through the buffer mass within a short time of material emplacement. This pressure transfer would be present provided that other mechanisms were not acting to reduce the effectiveness of this process (for example, shrinkage occurring as a result of the presence of a desiccated region closest to a relatively hot waste container).

ACKNOWLEDGEMENTS

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APPENDIX 1

SUMMARY OF SWELLING PRESSURE DATA

Name	Dry Density (Mg/m³)	Clay Density (Mg/m³)	Initial Moisture Content (%)	Initial Saturation (%)	Full Swelling Pressure (kPa)	Time to Est. Full Swelling Pressure (Hrs)	Final Moisture Content (%)	Final Degree Saturation (%)	Swelling Pressure Type
BAR115	1.35	1.35	8.4	22.7	2400	600	38.1	100	3A
BAR130	1.3	1.3	8.4	22.8	1080	1100	41.7		3A
BUF 0%	1.54	1.09	0	0	590	400	18.9	65	2
BUF17%	1.58	1.1	17	63	600	2000	25.2	94	4B
RBMLH01	1.49	1.04	21.7	68.1	500	6000	----	----	1/2
URL115	1.13	1.13	10.3	19.4	500	1200	47.1	98.5	1/3A
URL125	1.2	1.2	9.1	18.9	850	1800	45.2	94	1/3A
URL135	1.31	1.31	9	21.9	2250	1200	27.3	66	3A
SSB40A	1.81	1.31	0	0	1050	640	19.9	102	2/4A
DW50.15T	1.7	1.32	16.4	84	3900	150	18.1	97	4A
T90TA	1.14	1.14	0	0	300	100	53.5	100	3A
T90TB	1.17	1.17	0	0	300	125	49.3	98	3A
T90T3	1.14	1.14	47.9	94	300	24	48.8	95	1
T90T4	1.18	1.18	47.9	95	400	----	----	----	1
TS150A	1.18	1.18	5	10	500	660	----	----	3A
TD150A	1.27	1.27	0	0	700	150	----	----	1
P-014-2-AL	1.54	1.09	17.1	59.9	350	300	26.9	94.2	4A

continued....

SUMMARY OF SWELLING PRESSURE DATA (continued)

Name	Dry Density (Mg/m^3)	Clay Density (Mg/m^3)	Initial Moisture Content (%)	Initial Saturation (%)	Full Swelling Pressure (kPa)	Full Swelling Pressure (Hrs)	Final Moisture Content (%)	Final Degree Saturation (%)	Swelling Pressure Type
TS150B	1.23	1.23	0	0	2000	200	44	96	3A
SHC75	1.9	1.03	11	71	1125	200	14.5	83	4A
S50MC7	1.86	1.34	7	40	3375	400	15.9	91	4A
S50MC11	1.74	1.12	11	52	865	400	19.9	94	4A
S50MC15	1.75	1.18	15	72	1700	400	19.2	92	4A
S50MC17	1.72	1.24	17	78	950	250	20.1	92	4A
SHC25	1.58	1.39	26.5	98	4000	100	27	100	4A
SC50.20D	1.64	1.15	20	76	1700	----	----	----	4A
DW50.20W	1.75	1.28	20.3	98	2080	100	----	----	4A
DW100.42	1.22	1.22	42.8	80	1900	150	45.9	98	4A
DW100.LL	0.39	0.39	221	100	250	<24	221	100	2
BARCG04B	0.79	0.79	84.9	93	150	100	104.9	115	1
BARCG03B	0.93	0.93	49.8	69	250	<100	----	----	1
T125C2	1.44	0.99	0	0	300	700	31.5	92	3
TS125C	1.14	1.14	22	42	425	250	50.7	97	4A
FILE6A	1.47	1.0	14.2	43	250	50	----	----	1
TC125C1	1.20	1.20	22	46	650	200	40.5	84	4A
TC125C2	1.16	1.16	22	43	400	50	51.6	101	4A
1-014-AL	1.53	1.08	19.3	66.5	310	150	28.9	99.6	2

continued.....

SUMMARY OF SWELLING PRESSURE DATA (continued)

Name	Dry Density (Mg/m^3)	Clay Density (Mg/m^3)	Initial Moisture Content (%)	Initial Saturation (%)	Full Swelling Pressure (kPa)	Full Swelling Pressure (Hrs)	Final Moisture Content (%)	Final Degree Saturation (%)	Swelling Pressure Type
TFILE2	1.69	1.24	19	86	1250	---	21.1	96	---
RBMLHPS	1.49	1.04	20.3	48	475	275	29.9	97	2
RBMLH02	1.65	1.20	18.9	80	600	400	22.8	98	1?
THS150A	1.18	1.18	----	----	700	660	----	----	3A
THS150B	1.19	1.19	24	50	350	830	48.4	99	
TD150B	1.13	1.13	0	0	1100	660	44	83	3A
T200C	1.68	1.24	15	62	650	300	20.8	86	3A
THS90A	1.07	1.07	28	48	550	<300	57	98	3A
THS90B	1.25	1.25	23	51	450	300	46.1	103	3A/2
TS125C	1.14	1.14	22	42	425	125	50.7	97	4A
T125C1	1.48	1.03	----	----	250	700	29.8	96	3B
T125C3	1.18	1.18	23.7	48	700	200	47.5	96	2
BARCGEX	1.46	1.46	0	0	5750	800	25.8	78	2
URL	1.17	1.17	0	0	500	300	55.5	100	2
TSAT125A	1.19	1.19	38	78	400	24	34.4	71	3B
RSS01	1.49	1.04	0	0	1800	700	22.5	103	2
I-098-AL	1.65	1.20	14	61.5	500	900	22.4	90	4A
TS125B	1.07	1.07	38	65	350	250	55.2	95	3B
ACCS200	1.06	1.06	0	0	750	24	58.8	99	

continued.....

SUMMARY OF SWELLING PRESSURE DATA (continued)

Name	Dry Density (Mg/m3)	Clay Density (Mg/m3)	Initial Moisture Content (%)	Initial Saturation (%)	Full Swelling Pressure (kPa)	Full Swelling Pressure (Hrs)	Final Moisture Content (%)	Final Degree Saturation (%)	Swelling Pressure Type
ACMX80	1.31	1.31	0	0	2000	250	40.3	98	2A/4
BC-ES	1.25	1.25	0	0	700	100	48.2	108	4A
FILE4R	1.60	1.15	16.3	62	350	30	26.6	102	3A/1
BHB-P204	1.17	1.17	0	0	400	400	50	100	4A
MI-FJ	1.15	1.15	0	0	1300	1000	50	97	2
MI-FS200	1.18	1.18	0	0	950	50			2
R-API	1.19	1.19	0	0	400	750	50.5	103	4A
R-SS	1.37	1.37	0	0	700	1000	39	103	2
TMP-CS	1.12	1.12	0	0	1450	>400	51.7	96	2
WB-UNTR	1.22	1.22	0	0	700	300			4A
I-014-AL	1.53	1.08	19.3	67	150	310	28.9	99.6	2
N-064-AL	1.70	1.25	12.3	60	650	1000	20.9	93	4A
P-014-AL	1.62	1.17	17.1	67	450	1000	25.4	100	4A
L-064-AL	1.65	1.20	13	54	600	125	25	103	2/4A
P-106-AL	1.58	1.13	16.4	61	500	125	25.2	94	2/4A
H-014-AL	1.33	0.89	18.1	47	600	350	33.1	85	2/4A
G-098-AL	1.63	1.18	16.9	68	550	100	23.5	94	4A
H-064-2-AL	1.60	1.15	17.5	62	600	200	24.8	95	2/4A
H-064-AL	1.55	1.10	17.5	62	500	----	26	92	----

continued.....

SUMMARY OF SWELLING PRESSURE DATA (concluded)

Name	Dry Density (Mg/m3)	Clay Density (Mg/m3)	Initial Moisture Content (%)	Initial Saturation (%)	Full Swelling Pressure (kPa)	Full Swelling Pressure (Hrs)	Final Moisture Content (%)	Final Degree Saturation (%)	Swelling Pressure Type
TS125A	1.17	1.17	38	76	400	250	34.3	68	3B
L-014-AL	1.60	1.15	17.4	67	550	200	24.9	95	4A
SALINE									
C50/20W/D	1.72	1.24	9.8	45	1500	300	----	----	4A
SC100.44	1.24	1.24	43	95	1150	200	43.3	96	4A
SC100.9175	1.33	1.33	8.9	23	1600	250	36.9	87	3B/1
SC50.20	1.71	1.25	19.9	93	1160	200	20.8	94	4A
SC100.28	1.46	1.46	27.5	85	5000	400	32.1	96	2
SC50.15146	1.58	1.13	15	58	525	200	24.9	93	4A
FILE5	1.67	1.21	15	46	1500	200	23.7	101	3A
SC50.1.5T	1.67	1.21	19	87	1400	300	21.1	90	1
FILE3	1.60	1.18	31	93	350	500	25.2	96	4A
SC50.32	1.3	0.86	32	53	175	<50	45.9	113	4A
SC100.85	0.88	0.88	84.6	90	50	50	73.2	93	3B
SC50.38	1.27	0.84	38	90	100	50	39.3	93	2
FILE5A	1.44	0.98	14.2	46	125	90	>29.6	>90	1
FILE6A	1.47	1.00	14.2	49	250	50	>28	>90	1
SC100.42	1.26	1.26	42.8	92	835	150	41.9	95	2
SC50.15	1.27	0.83	15	35	300	125	----	----	2

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