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bentonite into rocks joints**

Roland Pusch

Högskolan i Luleå 1978-02-25

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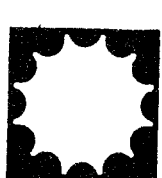
REPORT ON

SELF-INJECTION OF HIGHLY COMPACTED BENTONITE INTO ROCK JOINTS

Luleå 1978-02-25

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MASKINTEKNIK • GEOTEKNOLOGI • ARBETSVETENSKAP

SELF-INJECTION OF HIGHLY COMPACTED BENTONITE INTO ROCK JOINTS

DEFINITION OF PROBLEM

According to the HANNERZ / ASEA Atom concept the bore holes for deposition of radioactive canisters are filled with highly compacted block-shaped bentonite so that practically all the space between rock and canister is occupied (Fig. 1). Open joints formed or widened in the surrounding rock after the deposition will be sealed by "self-injecting" bentonite since water access through the joints will make the bentonite swell and move into the joints. Four important questions arise:

- How far will the bentonite go into the joints?
- How fast will it move?
- What will the mechanical and physical properties of the "self-injected" bentonite be like?
- Will the "self-injected" bentonite be dispersed and removed by the ground water flow?

FACTORS AFFECTING THE EXTRUSION OF BENTONITE INTO JOINTS

The problem which deals with the extrusion of bentonite into rock joints is essentially concerned with the driving and retaining forces in the system. The driving source is the swelling power of the highly compacted bentonite. Since this swelling power is known to drop with increasing water content, the driving source, expressed in terms of the

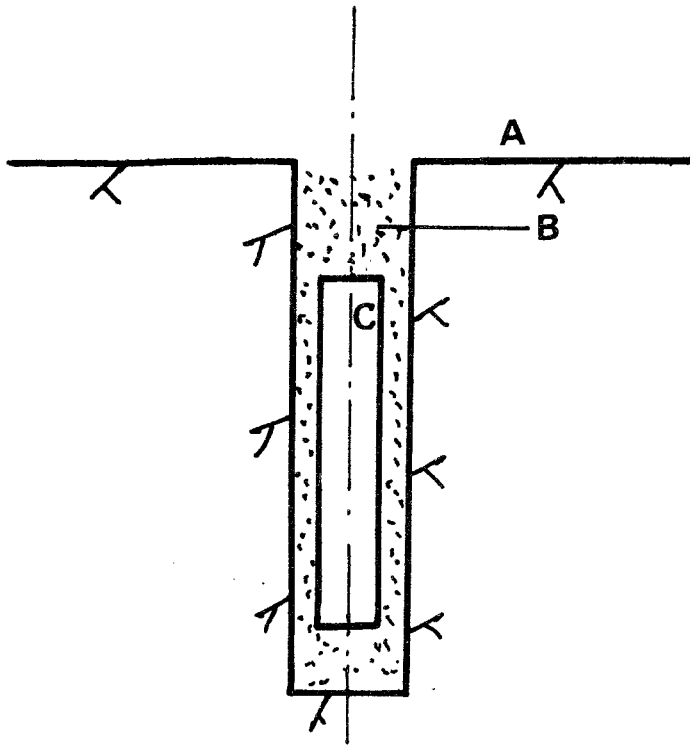


Fig. 1. Schematic picture of the deposition arrangement. A = tunnel floor (tunnel filling not shown), B = deposition hole with highly compacted bentonite, C = canister.¹⁾

gradient $\partial p_s / \partial x$, will drop in the direction of x in Fig. 2.

The other factors involved in the "self-injection" process are:

- The flow pattern and properties of the swelling bentonite
- The permeability of the extruded bentonite
- The viscosity of the extruded bentonite

¹⁾ There will be a space between the rock wall and the highly compacted bentonite body and between the canister and the bentonite body. The average density of the bentonite is considered in this report.

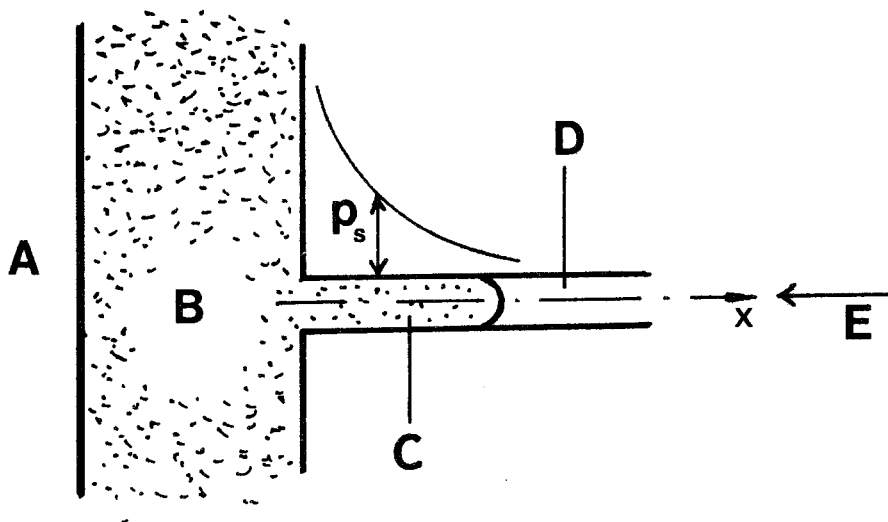


Fig. 2. Schematic section through canister/bentonite/rock joint. A = canister, B = highly compacted bentonite, C = "self-injecting bentonite", D = joint, E = water inlet, p_s = swelling pressure.

The importance of these factors is obvious: If the frictional resistance is very high at the clay/rock interface it retards the bentonite extrusion to a great extent and makes it non-uniform. The resistance against extrusion should be more important at decreasing width of the joints. The viscosity may play an important role in this context. The permeability of the extruded bentonite is of great importance since it determines the access of water to the swelling bentonite and therefore also the swelling rate.

We see that the derivation of a reasonable physical

model requires:

- The relationship between density and swelling pressure must be known
- The flow pattern and properties of extruding bentonite must be known
- The relationship between density and permeability must be known

a. Swelling pressure

The swelling pressure of Na-montmorillonite has been the subject of a large number of experimental as well as theoretical investigations. Classical papers by BOLT, WARKENTIN, and others deal with the application of electrical double layer theories. Their work has formed the basis for the derivation of a number of theories for calculation of swelling pressures. The method applied in this report presumes that clay surface-adsorbed water accounts for the first few water layers taken up on swelling and that further swelling results from osmotic pressure.

The swelling pressure is calculated as the osmotic pressure due to the difference in concentration of ions between clay particles and in the bulk pore water. This, of course, gives only the repulsive forces. Since we do not consider the attractive van der WAALS forces also in operation, the swelling pressure will therefore be too high but the error is known to be small at least at larger interparticle distances such as the ones corresponding to bulk densities lower than about 1.6 t/m^3 . The model assumed is that of charged, tabular particles in parallel arrangement with diffuse layers of exchangeable ions which overlap, resulting in a higher

ion concentration between particles than in bulk pore water. The required properties to make the calculation possible are: specific surface area, kind of exchangeable cations, concentration of ions in the pore water, and surface density of the clay.

For densities higher than about 1.6 t/m³ and pore water salt concentrations below 0.001 M, the concentration of anions between the clay particles can be neglected. The concentration C_c of cations at the midpoint between two interacting plates can be taken as:

$$C_c = \frac{\pi^2}{z^2 B(d+x_0)^2 10^{-16}} \quad (1)$$

where

C_c = concentration in moles/litre

z = valence of exchangeable cation

d = half-distance between two clay plates
in Å

x_0 = correction factor of 1-4 Å

B = 10^{15} cm/m mole

The swelling pressure p_s can then be calculated from the VAN'T HOFF equation which has the following form for monovalent ions:

$$p_s = RT(C_c - 2C_0) \quad (2)$$

where

R = gas constant

T = absolute temperature

C_0 = concentration of salt in the bulk pore
water, moles/litre

The relationship between water content w and inter-

particle spacing $2d$ is:

$$w = Sd/100 \quad (3)$$

where

w = water content in weight percent

S = surface area m^2/g

d = spacing in Å

It is interesting to see that these calculations adequately predict measured swelling pressures for very fine-grained sodium montmorillonite at low salt concentrations provided that the particles are oriented in a parallel fashion. The latter requirement is only fulfilled by preparing the clay paste by compressing a clay water slurry from the wet side. The prediction can then be excellent as illustrated by Fig. 3.

For highly compacted bentonite, produced by pressing air-dry clay powder to form dense bodies, there are two main deviations from the assumptions made so far in the text:

- The interparticle distance is so small that attractive van der WAALS forces will be important. At least for high bulk densities this means that the swelling pressure is over-estimated by the previous calculation.
- The particles are not in a parallel fashion. There will be differently oriented particle groups (domains, tactoids) with dead space in between.

The second point can be taken into consideration by reducing the assumed specific surface area value. This value is generally taken as $800 m^2/g$ for oriented dispersed Na montmorillonite particles. For

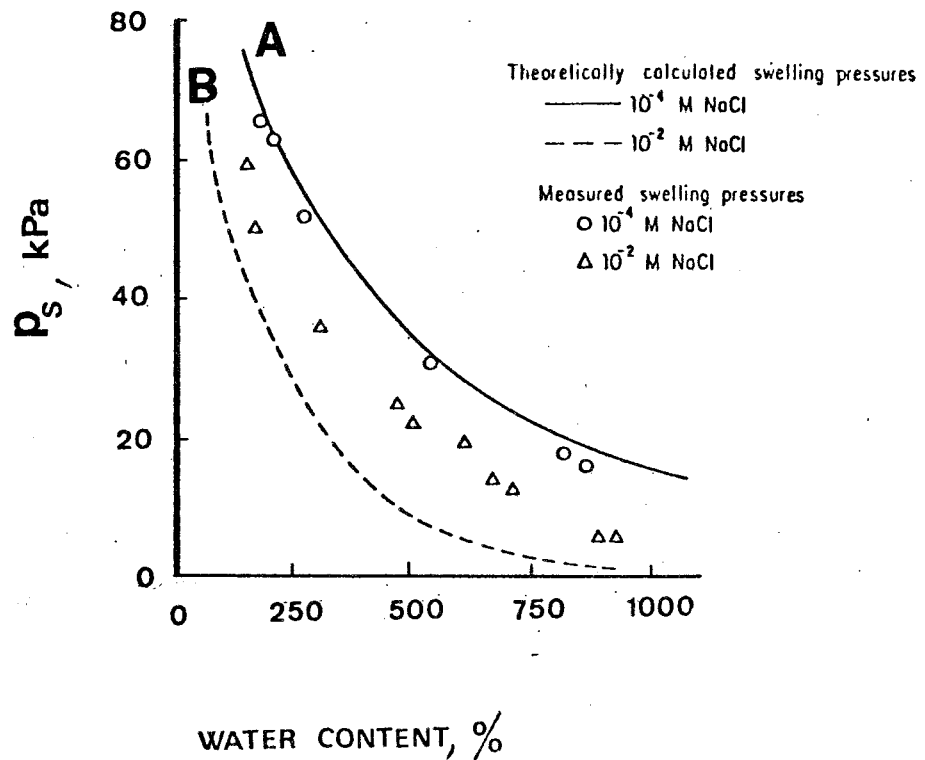


Fig. 3. Comparison of calculated and measured swelling pressures for sodium montmorillonite at two salt concentrations. (After WARKENTIN & SCHOFIELD).

A. Theoretical swelling pressure 10^{-4} M NaCl

B. Theoretical swelling pressure 10^{-2} M NaCl

Rings represent experimental values for 10^{-4} M NaCl.

tactoid-type Ca montmorillonite 80 m^2 has been suggested in literature but this value may be too low. One third of the value for oriented particles, i.e. about $270 \text{ m}^2/\text{g}$, should be plausible. This value yields $d = 0.37 w \text{ \AA}$ and $C_c = \frac{98.70}{(0.37w+2)^2} \text{ moles/l}$ while $800 \text{ m}^2/\text{g}$ specific surface area corresponds to $d = 0.125 w \text{ \AA}$ and $C_c = \frac{98.70}{(0.125w+2)^2} \text{ moles/l}$. For

$C_o = 3.4 \cdot 10^{-2}$ moles/l (corresponding to 2% NaCl solution) Eq (2) yields

$$p_s = 2.44 \cdot 10^3 \left(\frac{98.70}{(0.125w+2)^2} - 2 \cdot 3.4 \cdot 10^{-2} \right) \text{kPa} \quad (4)$$

for 800 m²/g specific surface area and

$$p_s = 2.44 \cdot 10^3 \left(\frac{98.70}{(0.37w+2)^2} - 2 \cdot 3.4 \cdot 10^{-2} \right) \text{kPa} \quad (5)$$

for 270 m²/g specific surface area.

The swelling pressure according to Eqs (4) and (5) are given in Fig. 4 where bulk density is used instead of water content. They are related as shown in Table 1 (page 13). In this figure curve A₁ represents the calculated swelling pressure according to Dr R TORRENCE MARTIN for the dry density (values given by ASEA Atom) while A₂ shows the author's recalculated bulk density values from A₁ for complete water saturation. Curve C shows the pressure actually measured by ASEA Atom in an experiment where highly compressed bentonite was exposed to external water under constant volume conditions¹⁾. This latter curve is located between the two curves representing the calculated swelling pressure for the extreme specific surface area values 800 m²/g (B) and 270 m²/g (D). The conclusion is that the applied way of calculating the swelling pressure in this report gives reasonable results and that ASEA Atom's curve C may well be used as a basis for selecting probable pressures in the deposition holes and tunnels. MARTIN's curve A₂ is fairly close to the B-curve which does not represent the actual condition.

¹⁾ The curve shows the author's recalculated relationship for complete water saturation.

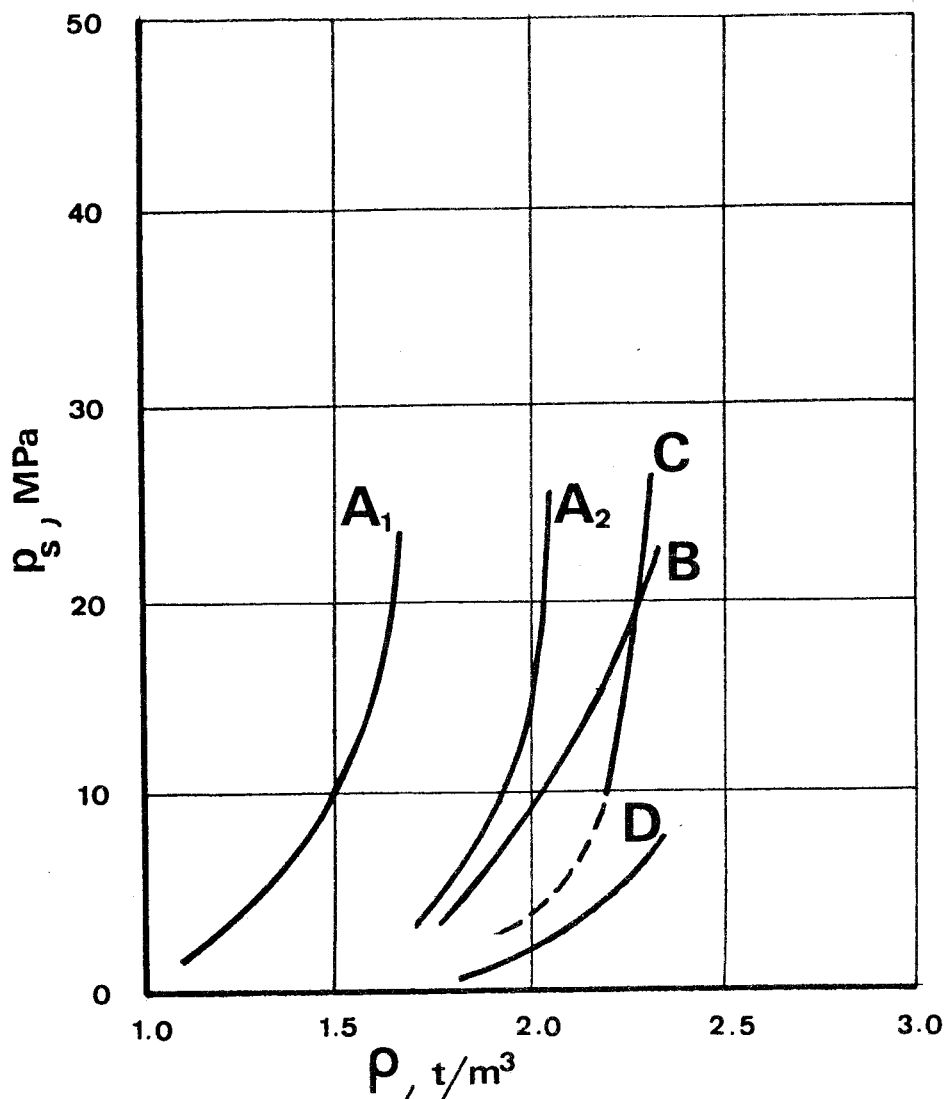


Fig. 4. Swelling pressure (p_s) versus bulk density (ρ) for water saturated Na montmorillonite.

b. The flow pattern and properties of extruding bentonite

The flow pattern of extruding bentonite has in fact been observed in a preliminary test (PUSCH, 1977). In principle it was of the type shown in Fig. 5 given by WEYMOUTH & WILLIAMSON in a report on microstructural effects caused by extrusion of clay through narrow openings.

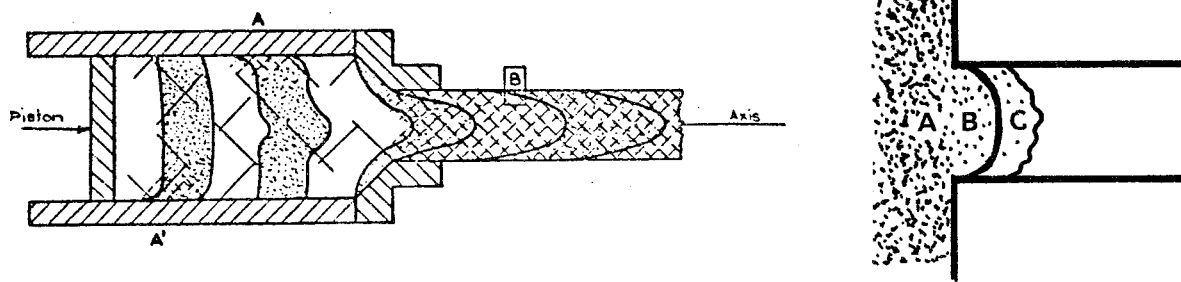


Fig. 5. Flow pattern of extruding bentonite.

a) WEYMOUTH & WILLIAMSON concept. b) Zones observed by PUSCH: A = highly compressed bentonite, B = dense extruded bentonite, C = soft bentonite gel.

The observed flow behaviour of the dense bentonite is of the POISEUILLE type implying the clay/wall friction to be sufficiently high to prevent or largely reduce flow along the walls.

The viscosity of water saturated bentonite is strongly dependent on the bulk density. Unfortunately, literature does not provide many experimental results. A few observations are plotted in Fig. 6. For bulk densities lower than about 1.5 t/m^3 the order of magnitude of the viscosity can be estimated although without any great accuracy. For highly compacted bentonite with a bulk density exceeding 1.8 t/m^3 , on the other hand, the viscosity is not known with any certainty. It increases very rapidly with increasing density and when ρ approaches 2.1 t/m^3 the bentonite behaves as soft rock. This means that the viscosity will exceed 10^{14} pois which is representative of young concrete. Preliminary creep tests indicate that a bulk density of 1.9 t/m^3 probably corresponds to 10^{10} - 10^{13} pois.

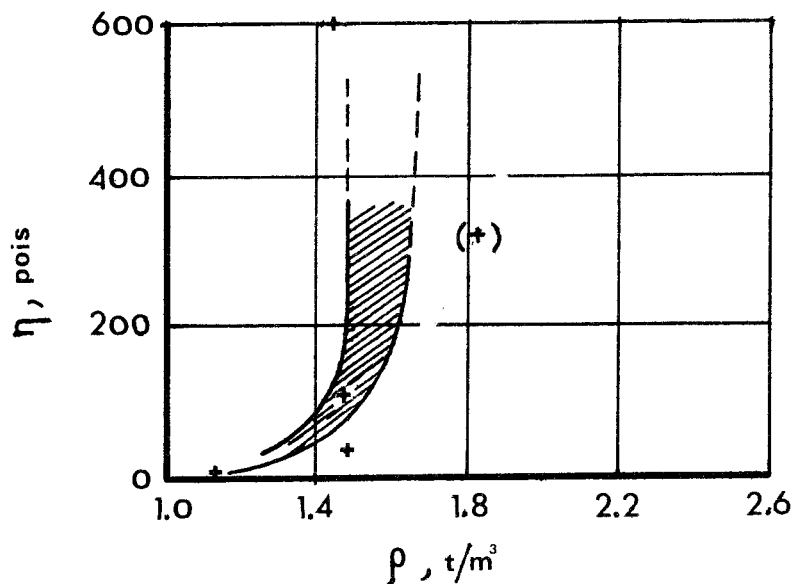


Fig. 6. Viscosity versus bulk density for Na bentonite. Hatched area represents probable zone of validity.

c. Permeability

The permeability of heavily compacted bentonite is known from a study by KHARAKA & SMALLEY (1976). These investigators compacted Wyoming Na bentonite to about 50 to 70 MPa and measured the permeability in a series of tests at very high hydraulic gradients. A compaction pressure of 50 MPa should correspond to a bulk density of about 2.2 t/m^3 at 100% water saturation.

The results, which are exemplified in Fig. 7, show that the coefficient of permeability k is less than $8 \cdot 10^{-15} \text{ m/sec}$. Also, the tests show that DARCY'S law does not apply to these very dense clays. There may very well be a threshold (critical) gradient below which flow does not take place at all.

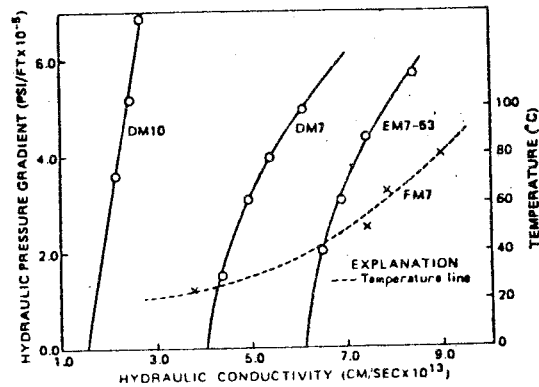


Fig. 7. KHARAKA's & SMALLEY's test results.

Less dense pure bentonite is of course more permeable. MESRI & OLSON (1971) determined the permeability of bentonite (Volclay) at various void ratios. The results of those tests which concerned Na bentonite are illustrated by Fig. 8.

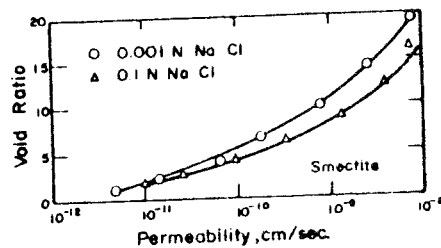


Fig. 8. Permeability of Na bentonite versus void ratio.

The influence of the electrolyte concentration is in agreement with electrical double layer theories and the FORSLIND (1953) water structure theory. This latter theory implies that cations of the electrolyte are attracted by the negatively charged clay particles and diffuse into the intercrystalline space where they, depending on the size and art of

ions, may disturb the water lattice. This partially compensates the repulsion between adjacent particles by which their approach is facilitated.

The void ratio is expressed as $\frac{V_p}{V_s}$ where V_p is the pore volume and V_s is the mineral volume. If the bulk density is ρ expressed in t/m^3 ($= g/cm^3$), $\frac{V_p}{V_s} = e$ and the specific weight of the montmorillonite is taken as $2.7 t/m^3$ we obtain:

$$\rho = \frac{1 + \frac{2.7}{e}}{\frac{1}{e} + 1} \quad (6)$$

The bulk density is given as a function of the void ratio and the water content in Table 1.

Table 1. Bulk density and water content (100% water saturation) versus void ratio

Void ratio e	Bulk density t/m^3 (g/cm^3)	Water content %
0.1	2.54	3.7 ¹⁾
0.2	2.42	7.4 ¹⁾
0.3	2.31	11.1 ¹⁾
0.4	2.21	14.8
0.5	2.13	18.5
0.6	2.06	22.2
0.7	2.00	25.9
0.8	1.95	29.6
0.9	1.90	33.3
1.0	1.85	37.0
1.5	1.68	55.5
2.0	1.57	74.1
3.0	1.43	111.1
4.0	1.34	148.1
5.0	1.28	185
10.0	1.15	370
20.0	1.08	741

¹⁾ These values do not correspond to a complete monolayer. Water saturation is probably achieved only for water contents larger than about 25%.

The MESRI & OLSON and KHARAKA & SMALLEY observations yield the required relationship between bulk density and permeability shown in Fig. 9.

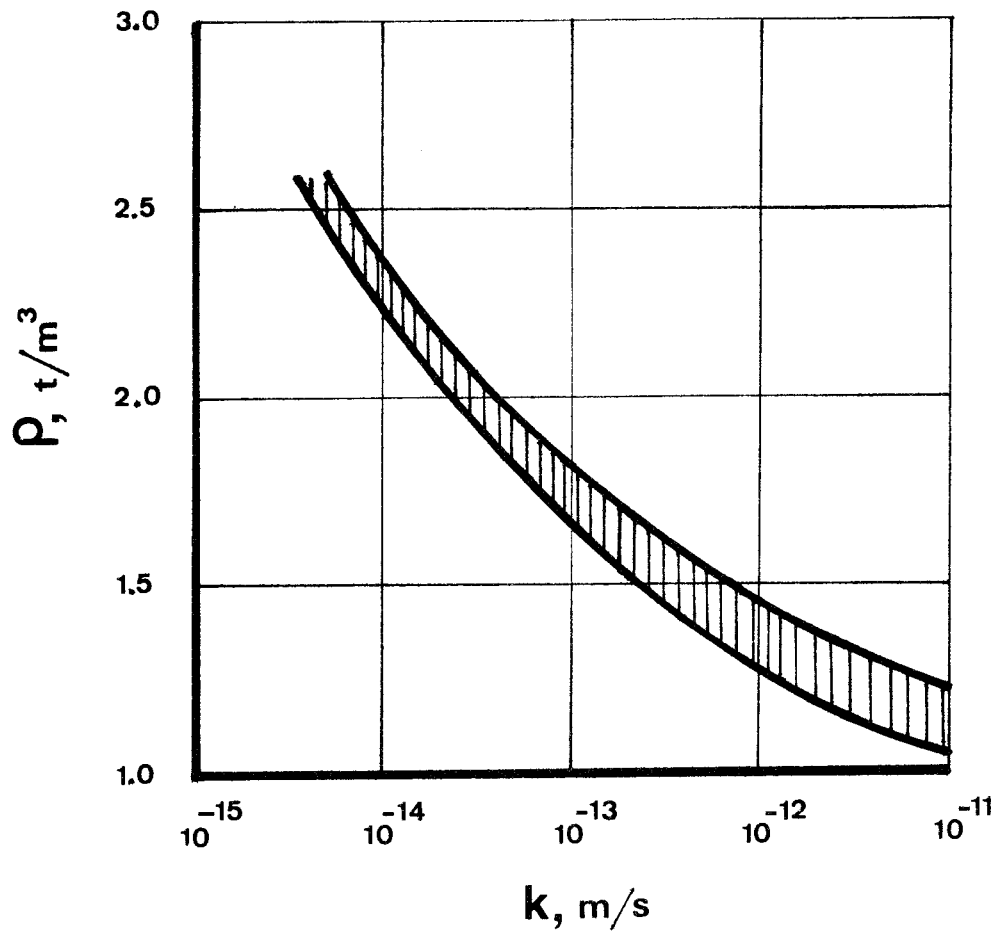


Fig. 9. General relationship between bulk density (ρ) and coefficient of permeability (k) for Na bentonite. The band shape is chosen here to take into account the influence of varying pore water salinity and scattering of experimental data.

It is obvious that bentonite compacted to 2 t/m³ or more is practically impervious and that also very soft, semi-liquid bentonite has an extremely low permeability.

The very low permeability of dense bentonite is easily understood. Thus, a density of 2 t/m³ of water saturated highly compacted Na bentonite means that the water content is 26%, which corresponds to an interparticle 3 Å water film only, if the specific surface area is taken as 800 m²/g. This implies that water transportation is a process which can hardly be explained in terms of ordinary flow in such dense clays. Yet, for practical purposes we can measure and describe this process by applying the concept of permeability.

The uptake of additional intra-lamellar water in the montmorillonite packages, which leads to swelling, requires that water molecules are removed from the pores adjacent to the packages. Although the process of bringing water molecules into a more or less regular intra-lamellar grouping may well be a very rapid process the governing time factor for the swelling is the rate with which external water is brought into the pores (external water is required since a redistribution of a inter-lamellar water does not produce any swelling). The external water does not pass through intra-lamellar space of the montmorillonite packages but through the more or less continuous pore system. The larger the swelling, the more flow-like will the water transport be, which means that the permeability is the governing parameter for the rate of swelling of bentonite.

PHYSICAL/MATHEMATICAL MODELLING

Let us now return to the three questions "How far will the bentonite go into the joints", "How fast

will the bentonite be extruded?", and "What will the mechanical and physical properties of the "self-injected" bentonite be like?"

The first two questions require the formulation of a physical model the mechanical and physical properties of which are derived from the previous text. For this purpose attention is called again to Fig. 1 and to the hypothesis that the extruding bentonite can be regarded as a viscous fluid affected by a pressure gradient. The density and therefore also the viscosity are both decreasing with increasing distance from the rock wall (Fig. 10). The permeability, on the other hand, is changed in the opposite manner.

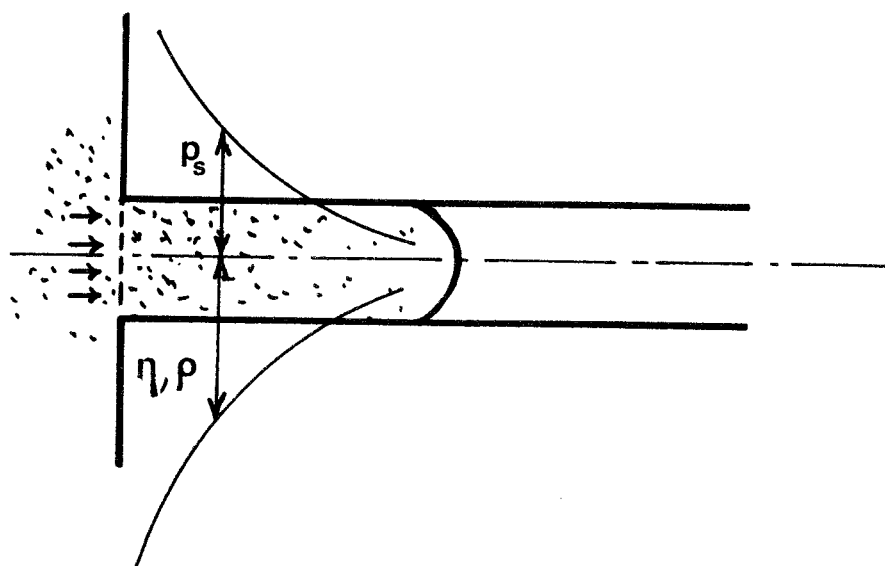


Fig. 10. Schematic picture of the influence of extrusion depth on swelling pressure (p_s), viscosity (η) and bulk density (ρ).

The water uptake

It is obvious that the driving force to bring water into the highly compacted bentonite and to extrude it through opening joints is the swelling power of the bentonite. Considering the previous conclusion that the permeability is the governing factor for the rate of water uptake, a hydraulic gradient must hence be responsible for the water transport. The question is therefore: What is the cause and magnitude of this gradient?

Firstly, let us assume that the highly compacted bentonite has been water saturated by the uptake of ground water before the joint formation or widening takes place. This means that the water pressure in inter-lamellar space (pores) in the clay and in adjacent joints or pores in the confining rock are equal (5 MPa). We know that the highly compacted bentonite has a very strong affinity to water as is demonstrated by the suction (pore water underpressure) which can in fact be measured in the course of swelling. Suction, which is a function of the water content, is an equivalent to consolidation pressure (BRACKLEY, 1973). Since, in the case of Na montmorillonite, the consolidation pressure is practically the same as the swelling pressure (MEADE 1964 and several others) it is reasonable to believe that the suction is of the same order as the swelling pressure (with the opposite sign). Thus, the driving force to bring water into the highly compacted water saturated bentonite is assumed to be the hydraulic gradient caused by the suction.

When the highly compacted water saturated bentonite is exposed to a formed or widened joint the suction in the bentonite with a bulk density of about 2.2 t/m^3 ¹⁾ will be of the order of 10 MPa in the very first moment of exposure. Thus, the pressure difference 10 MPa acts over an extremely small distance in this initial state and at first water enters the bentonite very rapidly. Let us now assume that the extrusion rate is governed by the flow resistance (viscosity) and not by the rate of water uptake. Thus, it is assumed that the expansion is so slow that sufficient time is available for water to be transported far into the highly compacted clay. The swelling and extrusion can then be estimated by considering the one-dimensional case shown in Fig. 11.

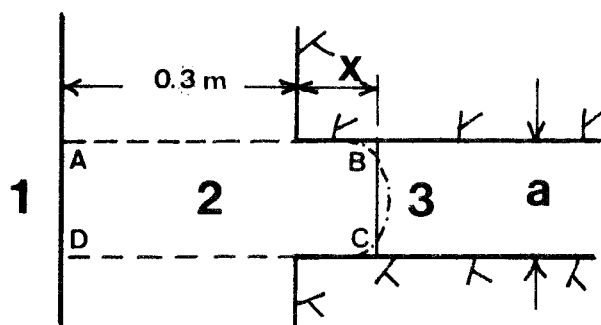


Fig. 11. Model of swelling body. 1) Canister, 2) Swelling body ABCD, 3) Joint. X is the extrusion depth.

It is implied that the body ABCD takes up water through the opened joint and that the swelling body enters the joint. If the depth of extrusion is x we obtain for the average bulk density:

¹⁾ Due to the fairly loose bentonite powder which fills certain minor parts of the deposition hole, the average bulk density of the water saturated bentonite will probably drop from 2.2 t/m^3 to about 2.15 t/m^3 . This reduction is neglected here.

$$\rho = \frac{0.66 + x}{0.3 + x} \quad (7)$$

provided that ρ is taken as 2.2 t/m^3 for the highly compacted bentonite before swelling takes place.

For various extrusion depths the values obtained from Eq (7) can be used to calculate the average swelling pressure (Fig. 12).

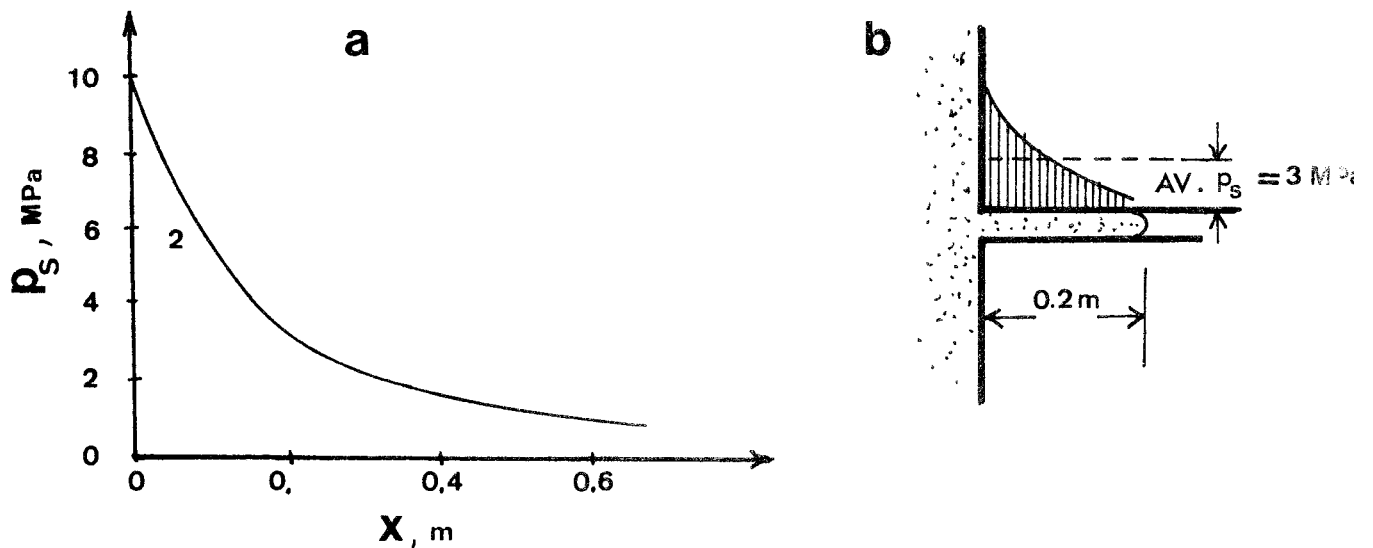


Fig. 12. a) Average swelling pressure p_s in extruded bentonite versus extrusion depth x .
b) Example for $x = 0.2 \text{ m}$ showing probable distribution of swelling pressure.

The swelling pressure given by Fig. 12a is conservative (too high) as concerns the possible influence on the stress situation in the surrounding rock. This is because the calculation implies a uniform swelling pressure within the whole body while the real distribution must follow some power

law with the maximum pressure at the rock wall (Fig. 12 b).

Let us now, in order to illustrate the general importance of the permeability, assume that bentonite has been extruded 0.1 m into a joint, that the differential water pressure is still 10 MPa (corresponding to a 1000 m water column) over the distance from AD to BC in Fig. 11 and that the gradient is constant. We then find for the rate of water flow v :

$$v = k \cdot \frac{1000}{0.4} = 2.5 \cdot 10^3 k \quad (8)$$

It should be remarked here that it is reasonable to assume that a suction of 10 MPa is maintained at the AD-border for very long periods of time due to the action of the adjacent clay mass. If k is taken as the average permeability at $\rho = 1.9 \text{ t/m}^3$ (cf. Eq 7) we obtain $v \approx 3 \cdot 10^{-10} \text{ m/s}$. This means that about 100 years are required to pass water the 0.4 m distance from the outer end of the bentonite body to the canister periphery and thus to supply water to complete the swelling of the whole body. If we repeat the calculation and assume the extruded bentonite body to be 1 m we find $v = 8 \cdot 10^2 k$. Taking the average k -value as 10^{-13} m/s , $v \approx 10^{-10} \text{ m/s}$ which means that about 400 years are required to pass water through the 1.3 m bentonite body. Similarly using the same average k -value, 30 000 years would be required to let water through a 10 m body. These calculations are very conservative because DARCY'S law is assumed to be valid. Also, the gradient will in fact be smaller, in the outermost part of the extruded bentonite even much smaller than assumed in the calculation, while the permeability is still extremely low. The rate of water transportation through extruded bentonite bodies will therefore probably be very much lower than indicated by

the given values. There is no need, however, to derive any refined time/swelling relationship because the required time for water to be transported and taken up in the clay determines the maximum swelling rate while in reality the wall friction and internal friction (viscosity) of the clay govern the rate of extrusion in those narrow joints which are of interest in this context.

Extrusion as a flow process

In principle, the flow of bentonite in plane joints with a large extension and a constant width can be described by applying POISEUILLE'S law. The flow rate is easily derived from Fig. 13 which shows a bentonite element with the length dx in the flow direction.

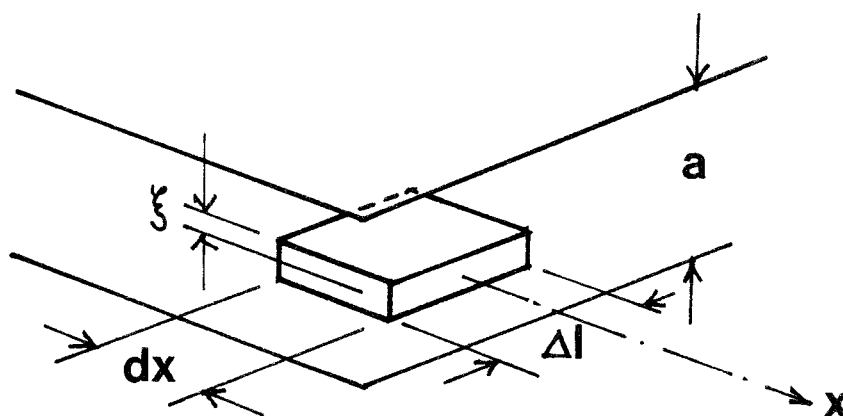


Fig. 13. Element of flowing bentonite.

The driving force is the swelling pressure gradient $\partial p/\partial x$ which acts in the direction of flow while the counteracting force is due to viscosity. We obtain for force equilibrium in the direction of

flow (x):

$$2\Delta l \cdot \xi \cdot \frac{\partial p}{\partial x} dx = \eta \frac{\partial u}{\partial \xi} dx \cdot 2(2\xi + \Delta l) \quad (9)$$

where

u = flow velocity

η = average viscosity

For $\Delta l \rightarrow \infty$ we find

$$u = \frac{\xi^2}{2\eta} \frac{\partial p}{\partial x} + C \quad (10)$$

If $u = 0$ for $\xi = \frac{a}{2}$

$$C = -\frac{a^2}{8\eta} \frac{\partial p}{\partial x} \quad (11)$$

Then, by considering the flow rate to be positive in the flow direction, the maximum rate will be:

$$u_{\max} = \frac{a^2}{8\eta} \frac{\partial p}{\partial x} \quad (12)$$

while the average rate is:

$$u_m = \frac{a^2}{12\eta} \frac{\partial p}{\partial x} \quad (13)$$

The flow rate can be roughly estimated by applying this expression but it is required that the viscosity of the mass is uniform and that the gradient is constant. This is not the case for the extruding bentonite body (Fig. 11). However, the order of magnitude of the flow rate can be estimated by applying reasonable viscosity and gradient values.

Let us consider, as previously, the case where the extrusion depth is 0.1 m. The average swelling pressure of the ABCD-body is then about 5 MPa. However, analogous to what was assumed for the water suction it is reasonable to believe that the swelling

pressure 10 MPa is maintained almost permanently at the AD-border in Fig. 11 and that the pressure gradient can be approximated to be linear and, thus, equal to $2.5 \cdot 10^4$ kN/m³. Since the average bulk density according to Eq (7) is 1.9 t/m³ for the assumed extrusion an approximate value of η would be about 10^{10} to 10^{13} pois. Using the average $\eta = 5 \cdot 10^{11}$ we obtain the values given in Table 2 for the flow or extrusion rate u_m .

Table 2. Extrusion rate of swelling of highly compacted bentonite in rock joints at 0.1 m extrusion depth

Joint width mm	Extrusion rate	
	m/s	mm/year
0.1	$4 \cdot 10^{-13}$ m/s	$1.3 \cdot 10^{-2}$
1.0	$4 \cdot 10^{-11}$ m/s	1.3
10	$4 \cdot 10^{-9}$ m/s	130
100	$4 \cdot 10^{-7}$ m/s	$1.3 \cdot 10^4$
1000	$4 \cdot 10^{-5}$ m/s	$1.3 \cdot 10^6$

This example illustrates the importance of the joint width. When comparing the results with the previously deduced water transport rates we find, however, that only the extrusion rates for 0.1 and possibly 1.0 mm joints are relevant. Thus, for wider joints the water will not have sufficient time to enter more than a very small part of the extruding clay body at higher extrusion rates. Obviously, the flow law for estimating the extrusion rate can be applied only for narrow joints.

An interesting question is whether the extrusion is accelerating or not? Applying the same reasoning as in the previous example and considering the extrusion depths 0.02 m and 0.05 m we find higher extrusion rates than for the 0.1 m depth if the viscosity

is assumed to be the same (cf. Fig. 14). A constant extrusion rate is obtained, however, if the viscosity is about 10 times higher for the smallest extrusion depth than for the 0.1 m depth. Since the viscosity is not known with any certainty and the flow and water uptake processes are much more complex than assumed here, the theoretical treatment of the extrusion process needs much more consideration to yield safe conclusions. It is interesting to see, however, that an experimental study and geological evidence yield values which are in reasonable agreement with the trend of the curves in Fig. 14 (cf. next chapter).

It is obvious in this context that the risk of a rapid loss of large quantities of bentonite through opened joints must be considered. This requires an estimation of the possible width and extension of joints formed or widened in the surrounding rock after deposition. Following PUSCH (1977b) and many others it is reasonable to believe that displacements induced by tectonic deviator stresses in rock will take place along already existing joints or weak zones which can be avoided in the choice of suitable rock volumes for deposition purposes. Shear strain along pre-existing irregular joints may involve a slight increase in width due to dilatancy. Possibly, certain delayed stress transfer processes initiated by the excavation of tunnels and bore holes may involve a slight opening of pre-existing joints. Finally, temperature gradients in connection with the previously mentioned processes may create fissures. It is the author's belief, however, that such an increased width of pre-existing joints or the width of formed fissures will be very small, probably much less than a millimeter. Even if such fissures will be numerous and filled with dense extruded bentonite to a depth of several meters the bentonite loss will be insignificant (cf. PUSCH, 1978).

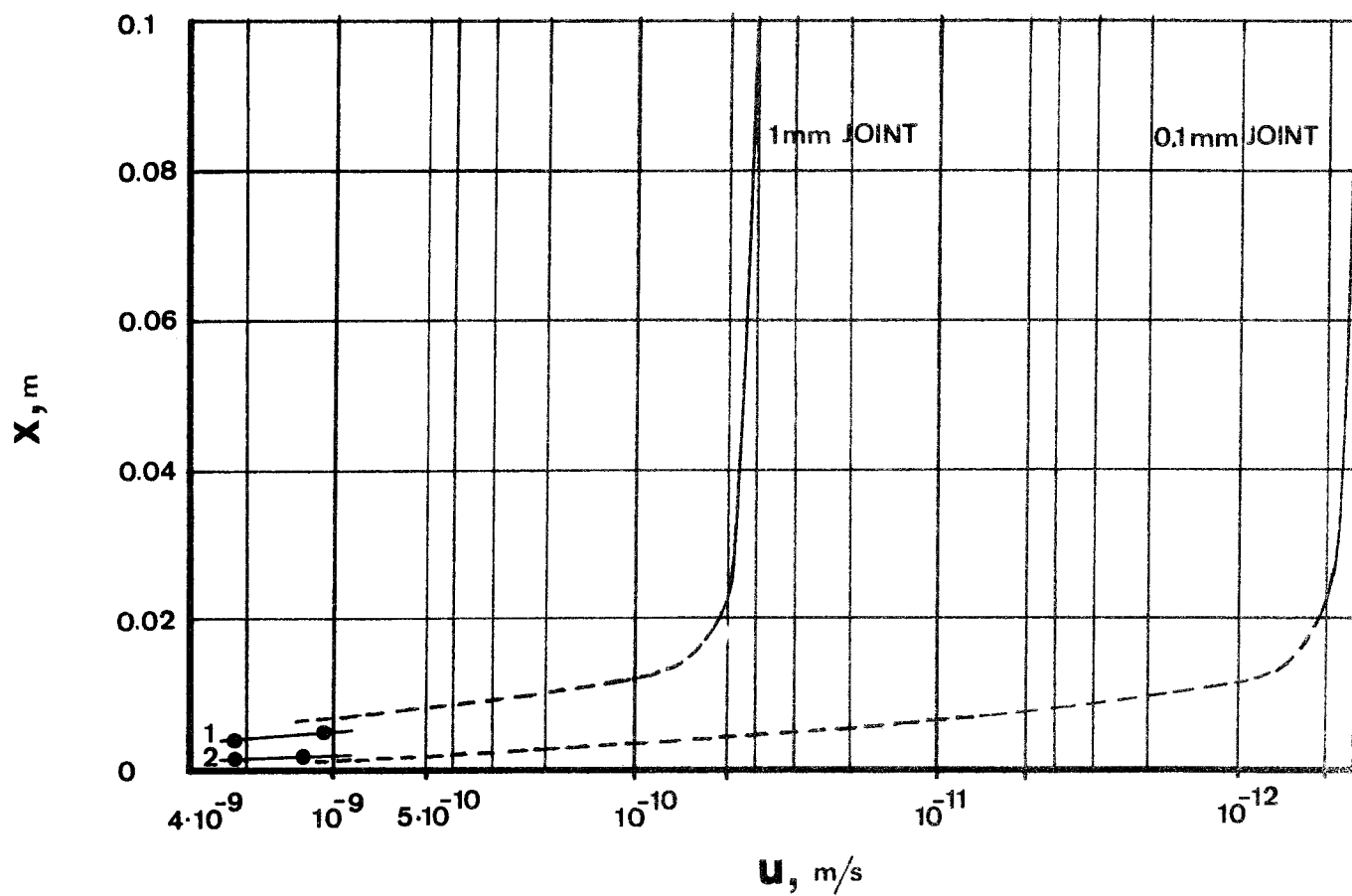


Fig. 14. Extrusion rate (u) versus depth (x). The experimental values (●) concern the outer border of the fairly stiff bentonite zone in Fig. 5. Curve 1 represents a 0.5 mm joint and Curve 2 a 0.3 mm joint.

LABORATORY AND FIELD EXPERIENCE

Laboratory experiments

The application of the model derived in the preceding chapter indicates that the swelling and extrusion processes are extraordinarily slow in narrow joints. This is also strongly supported by laboratory experiments where highly compressed (50 MPa) bentonite was confined in a rigid steel container with slots which simulate joints in the surrounding rock. The device has been described in detail in an earlier report (PUSCH, 1977).

As shown in Figs. 15 and 16 the container consists of a series of rings which have notches with various depth so that the pack of rings form a cylinder with slots, 0.5, 0.3, 0.15, 0.10 and 0.05 mm wide, through which water was allowed to enter and through which the swelling bentonite could be extruded.

The extrusion of bentonite was determined at various time intervals by means of thin metal blades which were pushed through the slots. The typical pattern of a fairly stiff and a soft region shown in Fig. 5 was observed in all the tests. Fig. 17 shows the rate of movement of the outer border of the fairly stiff region for two test series, one where the water was a 2% NaCl solution, and one where a synthetic ground water ("ORRJE" solution) was used.

We can see from Fig. 17 that the extrusion rate is a function of the joint width. The two investigated water compositions gave approximately the same values. The influence of the width confirms that the extrusion is a flow process governed by the viscosity of the extruded mass. The conclusion

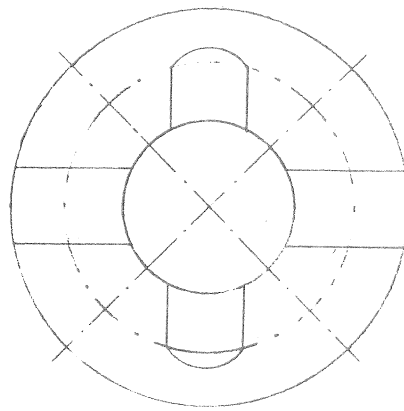
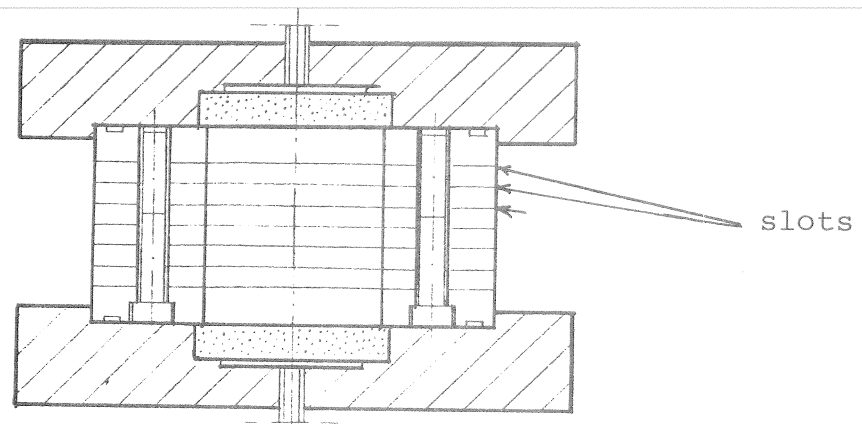


Fig. 15. ASEA Atom's device for determination of extrusion rates.

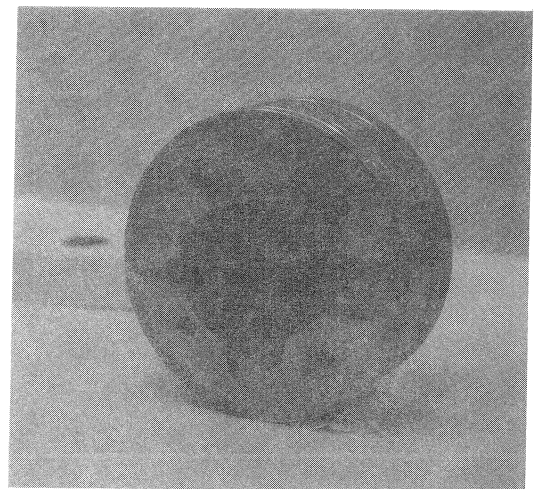
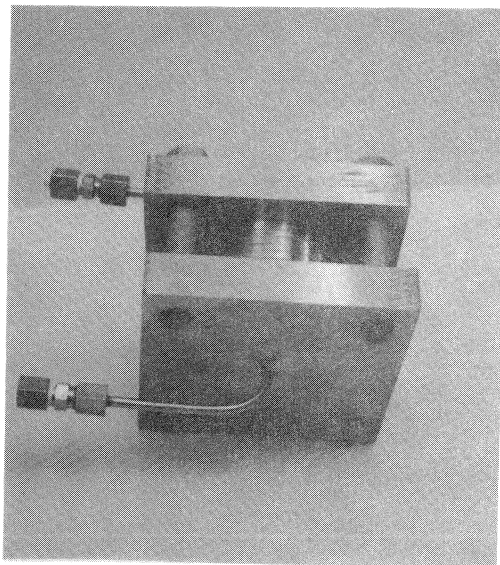


Fig. 16. View of closed and open device.

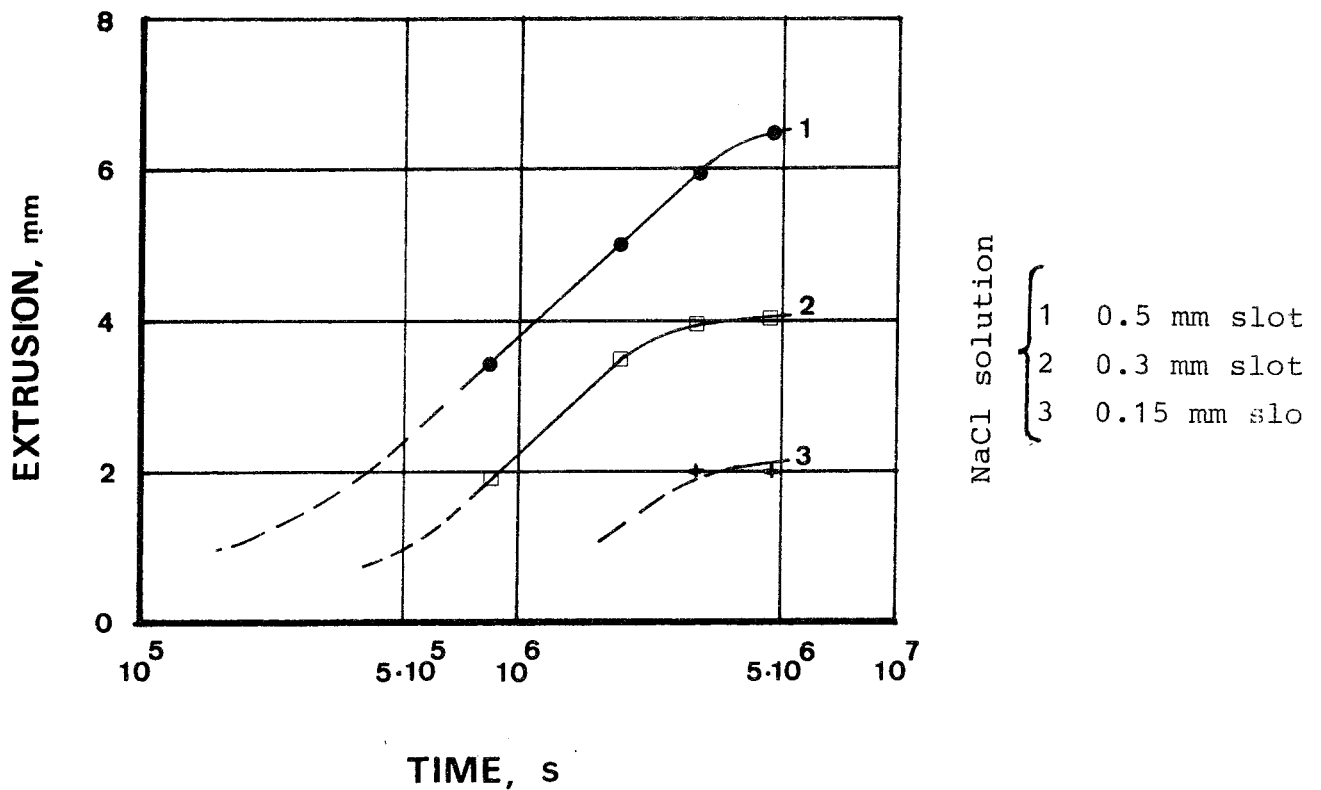


Fig. 17. Experimental investigation of bentonite extrusion versus time.

is therefore that the rate of water uptake, which is governed by the permeability and the hydraulic gradient, is not a limiting factor for the rate of extrusion through these narrow slots for small x-values.

Geological evidence

Montmorillonite-bearing zones in crystalline rock provide valuable evidence of the swelling and extrusion behaviour in nature. In Sweden, a series of glaciations removed old weathered rock material so that high quality pre-Cambrian rock is found today below Quaternary soils. This bedrock contains steeply oriented weathered zones of pre-Quaternary origin which are now found immediately below a fairly thin cover of clay, sand and till. The inter-



Fig. 18a. Apparently stable rock slope a couple of months after blasting and excavation. Several weeks afterwards when the building was partly finished, steep zones of clay-weathered rock moved out in a semi-liquid condition (18b).



Fig. 18 b. White squares applied for photographic recording of the flow.

esting fact is that although such zones may contain a large amount of Na montmorillonite and have densities higher than 2.3 t/m^3 they have not swollen noticeably. They have stayed undisturbed in the confining rock for more than 10 000 years despite their immense swelling potential and despite the fact that the overburden pressure is only a very small fraction of the swelling pressure. There is no sign of swelling or uplift of the overlying beds. The only plausible explanation for the absence of swelling is that the extremely low permeability prevents such zones to take up water. It is a well-known experience, however, that if such rock is excavated by blasting which releases the confining pressure and gives access to free ground water through various openings, shallow parts of the montmorillonite-bearing zones turn into a semi-liquid condition and tend to flow out of the rock (cf. Fig. 18). Also, it is a common experience that the disintegration of narrow weathered zones is very much slower than that of wide zones.

All these observations support the assumption concerning the importance of permeability and swelling potential with special reference to their interaction in joints with various width.

STATE AND BEHAVIOUR OF EXTRUDED BENTONITE

The main consequence of the suggested physical model is that the viscosity of the main body of extruded bentonite is fairly high. It is reasonable to believe that this idea is valid only for narrow joints where rock wall friction provides a large resistance against extrusion. Geological evidence, such as the slower disintegration rate of narrow than of wider weathered zones in rock, support this hypothesis. Experience from rock excavation work confirms that wide, montmorillonite-rich zones rapidly become soft in their shallow parts when

free space for expansion and access of ground water is provided. Also, the process of softening proceeds fairly rapidly into the interior of such wide zones.

One important question concerns the possibility of dispersion and removal of extruded bentonite by the regional ground water flow, which has been estimated to be of the order of 0.1 mm per second. It is true that there is a spontaneous dispersion of bentonite exposed to water. This dispersion is the manifestation of the swelling process which successively brings more water into the softening clay. There are two basic questions in this context:

- How fast will water be taken up in a dilute, but still swelling montmorillonite gel?
- Will the water uptake proceed to transfer the clay-water system from a gel state to a sol?

The first question is intimately connected with the previously discussed permeability. Fig. 9 tells us that the permeability is extremely low even when the bulk density drops to slightly more than that of pure water. Thus, a bulk density of 1.08 to 1.15 t/m³, which corresponds to a water content of about 740 and 370 percent, respectively, still corresponds to a permeability of less than 10⁻⁹ to 10⁻¹⁰ m/s. This means that in the very dilute front part of the extruded bentonite (zone C in Fig. 5) where the hydraulic gradient (suction gradient) must be small, water is transported very slowly only, into the softening gel. Very probably, however, the swelling rate of this front part is higher than the rate of extrusion of the denser bentonite body. It may even be that the first-mentioned rate is

very much higher, 10 or 100 or even a 1000 times higher than the rate of extrusion of the denser body. Yet, this does not accelerate the water uptake in the denser bentonite. On the contrary, it provides an increasing zone of low permeability through which any water taken up by the dense bentonite has to pass. It does, on the other hand, successively transfer the outer part of the dense bentonite zone to a soft state whereby the border between zones B and C in Fig. 5 will soon be stationary as indicated by Fig. 17.

The second question depends on the chemical environment, i.e. the composition of the ground water. Colloid chemistry literature dealing with clay-water-electrolyte systems provides many examples of the gel nature of extremely dilute montmorillonite/water systems. The conventional theory of dispersion and flocculation of clay colloid systems has been forwarded by van OLPHEN. According to this theory, stable suspensions (sols) are formed if sufficient repulsive forces are present to overcome the interparticle LONDON-VAN DER WAALS attraction. In electrolyte-free aqueous systems the exchangeable ions are dissociated and form electrical double layers which cause a net repulsion between particles with parallel basal planes. There is, however, a small positive net charge on the edges of montmorillonite particles (due to broken bonds) which may create edge-to-face coupling and therefore a strength ("viscosity") which preserves the gel state and largely withstands the erosive effect of the (slow) ground water flow.

In the presence of a few milliequivalents of NaCl per liter the effective charge of the basal plane double-layers is reduced and dispersion is obtained. As more electrolyte is added the balance changes, attraction predominates, and edge-to-face bonds develop again. At very high electrolyte levels the basal plane double-layers are so much compressed that face-to-face association occurs by the dominating attractive LONDON-VAN DER WAALS forces.

According to van OLPHEN the sol state of very dilute Na montmorillonite suspensions (conc. 1/4 percent) is reached when the salinity of the water is less than that corresponding to 12-16 meq NaCl per liter or 2-3 meq CaCl_2 per liter. This electrolyte content induces flocculation which involves a continuous microstructural system with edge-to-face particle association and gel formation. Such gels appear to behave as Bingham systems (see Fig. 19).

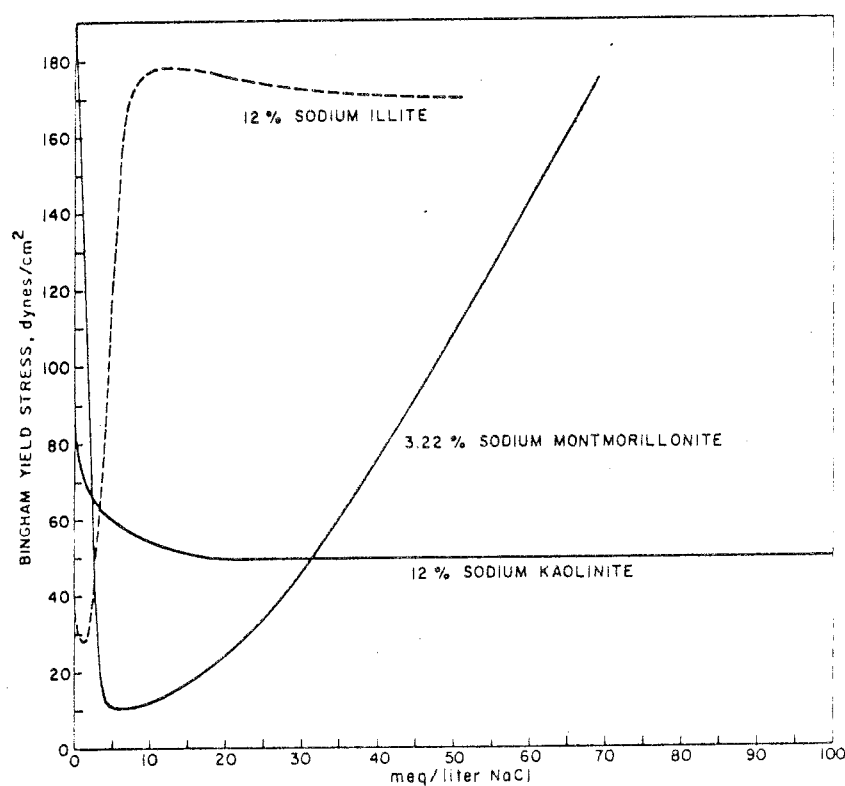


Fig. 19. Bingham yield stress of clay suspensions as a function of the salt concentration (after van OLPHEN).

The essential thing is that flocculation must be discussed in terms of concentration of the suspension. Thus, van OLPHEN's example with a 1/4 percent concentration means that, assuming the base exchange capacity to be 100 meq per 100 g dry clay, the suspension can take 2.5 meq per liter from the solution in forming a calcium clay. This Ca montmorillonite

sol then requires only 0.17-0.23 additional meq/liter of CaCl_2 to flocculate. If the concentration of the suspension had been 2.5 percent the same reasoning had yielded 25 meq per liter to complete the ion exchange and some minor additional CaCl_2 to flocculate. Similarly, a lower concentration of the suspension would require lower ion contents to flocculate.

Considering the composition of the synthetic "ORRJE" solution, which is assumed to be representative of real rock ground water (salinity about 0.8 ‰, amount of Na, Ca and Cl, 100 mg, 40 mg, and 40 mg per liter, respectively), dispersed sodium montmorillonite should flocculate in this water when the concentration of the suspension is reduced to a fraction of 1 percent. The consequence is that the swelling and dispersion of the front part of the Na bentonite will not lead to complete dispersion and individual particle behaviour. Possibly, a minor amount of flocs consisting of tens, hundreds, or thousands of montmorillonite sheets may be loosened by the erosive action of the slow ground water movement.

It must be remarked here that the conventional theory referred to gives a too simplified picture of the coagulation process. Thus, the stabilizing effect of ordered water molecules (hydrogen bonds) in regular water lattices is totally ignored. HAUSER's classical study of the mobility of montmorillonite particles in very dilute suspensions convincingly indicates that water contributes to the coupling of adjacent clay particles. We also have to pay attention to long range forces, Thus, it is an important fact that there is definite evidence of the existence of long range attractive forces which produce tactoids (groups of parallel and equidistant flakes behaving like units and other stable grouping of particles). This means that even

if a gel-sol transition occurs as a consequence of unlimited swelling, there may still be sufficient attraction between particles to form fairly big particle groups. The consequence of this is important. Thus, joints which may be formed or widened and which may therefore make possible an escape of swelling bentonite, will not have an infinite extension. Their width will be varying and their extension limited. Thus, groups of montmorillonite particles transported by the ground water flow will be stuck when the passages are getting narrow. Islands of particle aggregates will form and they may grow and finally fill the space with a dilute but nevertheless fairly impervious and very surface active clay/water system, i.e. a system with a large specific area and a high ion exchange capacity.

CONCLUSIONS


Although much work remains to be done in order to obtain relationships of general validity, a few statements can be made here:

- In the narrow joints (width smaller than 1 mm) that can possibly be opened by various processes, the rate of bentonite extrusion will be very slow except for the first few centimeter move which may take place in a few months.
- Even after several thousand years the extrusion of fairly dense bentonite will probably not exceed one or a few decimeters in such narrow joints.
- In the outer part of the bentonite zone there will be a successive transition to a very soft, diluted bentonite suspension. The suspension will probably be a gel. However

even if there will be a sol transition it will not consist of individual 10 Å montmorillonite sheets but of fairly large particle aggregates which will be stuck where the joint width decreases. Here, such aggregates will collect, thus forming a dilute, but fairly impervious and very surface-active fill.

- The loss of bentonite extruded through such narrow joints is negligible.
- The reduction of swelling pressure in the highly compacted bentonite which is still in the deposition hole will be insignificant
- The swelling pressure of the extruded bentonite will decrease rapidly with the distance from the deposition hole. Already at a distance of one or two decimeters it will be less than 3 MPa while the pressure is still 10 MPa in the deposition hole.

Luleå 1978-02-22



Roland Pusch

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- 72 Värmeledningsförsök på buffertsubstans av kompakterad bentonit
Sven Knutsson
Högskolan i Luleå 1977-11-18
- 73 Self-injection of highly compacted bentonite into rock joints
Roland Pusch
Högskolan i Luleå 1978-02-25
- 74 Highly compacted Na bentonite as buffer substance
Roland Pusch
Högskolan i Luleå 1978-02-25
- 75 Small-scale bentonite injection test on rock
Roland Pusch
Högskolan i Luleå 1978-03-02
- 76 Experimental determination of the stress/strain situation in a sheared tunnel model with canister
Roland Pusch
Högskolan i Luleå 1978-03-02
- 77 Nuklidvandring från ett bergförvar för utbränt bränsle
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Kemakta konsult AB, Stockholm
- 78 Bedömning av radiolys i grundvatten
Hilbert Christenssen
AB Atomenergi 1978-02-17