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Borehole sealing with highly compacted Na bentonite

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1981-12-07

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BOREHOLE SEALING WITH HIGHLY COMPACTED Na BENTONITE

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LULEÅ 1981-12-07

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ABSTRACT

Nuclear waste repositories will be crossed by some boreholes extending from the ground surface and they have to be sealed effectively in order not to form passages for nuclides to the biosphere. This report describes the use of highly compacted Na bentonite for borehole plugging. Bentonites have an extremely low permeability and a low diffusivity, and a swelling ability which produces a non--leaching boundary between clay and rock if the initial bulk density of the bentonite is sufficiently high.

The suggested technique, which is applicable to long vertical, and inclined, as well as horizontal boreholes, is based on the use of perforated copper pipes to insert elements of compacted bentonite. Such pipe segments are connected at the rock surface and successively inserted in the hole. When the hole is equipped, the clay takes up water spontaneously and swells through the perforation, and ultimately forms an almost completely homogeneous clay core. It embeds the pipe which is left in the hole.

Several tests were conducted in the laboratory and one field test was run in Stripa. They all showed that a gel soon fills the slot between the pipe and the confinement which had the form of metal pipes in the laboratory investigations. Subsequently, more clay migrates through the perforation and produces a stiff clay filling in the slot. The redistribution of minerals, leading ultimately to a high degree of homogeneity, can be described as a diffusion process. The rate of redistribution depends on the joint geometry and water flow pattern in the rock. In rock with an average joint frequency of one per meter or higher, very good homogeneity and sealing ability of the clay are expected within a few months after the application of the plug.

INTRODUCTION

Terminal nuclear waste storage at great depths requires plug systems to prevent migration through boreholes and shafts of harmful amounts of radionuclides to the biosphere. This has long been realized and comprehensive work to help define the behavior of candidate materials, and to identify the most promising ones is being made in many countries.

The "KBS 2" concept implies the use of highly compacted bentonite as a plug substance for sealing shafts and tunnels (KBS, 1978). The excellent swelling properties of very dense sodium saturated bentonite and its ability to become "self-healed", leading ultimately to a practically homogeneous state, have also indicated that this material should be suitable as a borehole seal, and pilot tests run in early 1980 supported this idea (PUSCH 1980a, PUSCH & BERGSTRÖM, 1980). Since then, a number of laboratory experiments as well as field tests and practical applications, have been performed to such an extent that the technique is now sufficiently known to be applicable on a full scale.

SEALING PROPERTIES OF HIGHLY COMPACTED BENTONITE

General function, longevity

Effective sealing of boreholes and shafts requires a sufficient swelling potential to produce a perfect contact between the bentonite and the rock, so that no passages are created along this boundary. An additional criterion is that the clay plug must not be more permeable than the rock core which it replaces. These requirements imply that the ductile consistency and swelling ability are preserved during the entire period in which sealing is needed, which is many thousand years for a nuclear waste repository. Chemical stability is a necessary prerequisite for this and it can be affected or eliminated by a number of factors, mainly temperature, pressure, and pH. Their influence has been investigated (cf. KBS, 1978) and the conclusion is that smectite-rich clays, such as bentonites, are chemically stable for geological ages in the pH range and ground water composition which are characteristic of granite and gneiss bedrock, provided that the depth below ground surface is less than about one kilometer and that the temperature is lower than 100° C. It should be added that bentonite contacted with concrete, such as can be the case in the uppermost part of most boreholes, may cause smectite lattice alterations and loss of its barrier properties within some distance from the interface. Current research indicates that this distance is insignificant.

Permeability

The permeability is known to be very much dependent on the bulk density (Fig. 1) and it is also sensitive to the magnitude of the hydraulic gradient. Thus, dense bentonites do not obey Darcy's law in the sense that the permeability is a function of the hydraulic gradient. The very low gradients which will be operative some time after the sealing of a repository will, in practice, yield almost no flow through Na bentonite plugs with a bulk density of more than about 1.7 t/m^3. As to the influence of adsorbed ions, experience shows that complete ion exchange from Na to Ca, which possibly can take place in situ as a consequence of the transgression of a calcium-rich sea or estuary, increases the permeability 2-5 times at maximum. Since bentonite plugs with a bulk density exceeding 1.7 t/m^3 will have a net permeability coefficient of about $5 \cdot 10^{-12}$ m/s or less, they will almost always be less permeable than the surrounding rock.

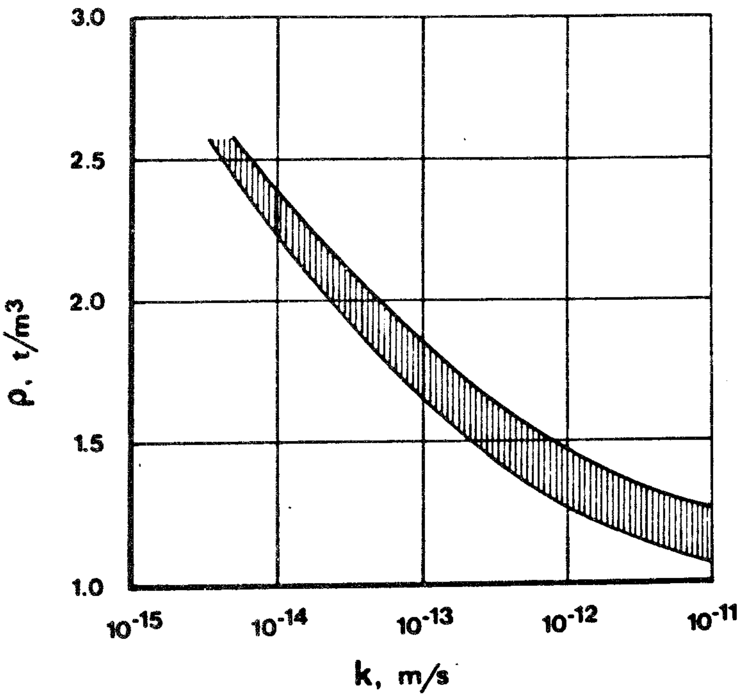


Fig. 1. Average relationship between coefficient of permeability (k) and bulk density (ρ) of Na bentonite. The hatched area accounts for scattering and for variations in the hydraulic gradient. (Water saturated conditions)

Diffusivity

Ion migration through borehole plugs must also be considered and the diffusion properties of dense bentonites have been investigated quite extensively for that purpose. The results from the experiments indicate that the traditional pore diffusion model is not valid for Na bentonite with bulk densities of the order of 2 t/m^3 (ERIKSEN, JACOBSSON, & PUSCH, 1981). The data seem to be better accomodated by a diffusion model where the positive ions can move within the crystal lattices, while negative ions, such as I^-, only move in continuous water passages. The mechanisms yield diffusion coefficients which are only a few percent or less, of the corresponding coefficients for diffusion in free water.

Rock/clay interaction

A non-leaching boundary between clay and rock is produced by the swelling pressure exerted by the expanding clay. This pressure is a function of the bulk density as shown by Fig. 2 (cf. PUSCH, 1980b). We see that the swelling pressure is considerable also when the bulk density drops to 1.7-1.8 t/m^3, which represents a practical lower limit of bentonite plugs in boreholes. For densities exceeding 2 t/m^3 changes in electrolyte composition and concentration do not affect p_s, while this effect is obvious for $\rho \leq 1.8$ t/m^3.

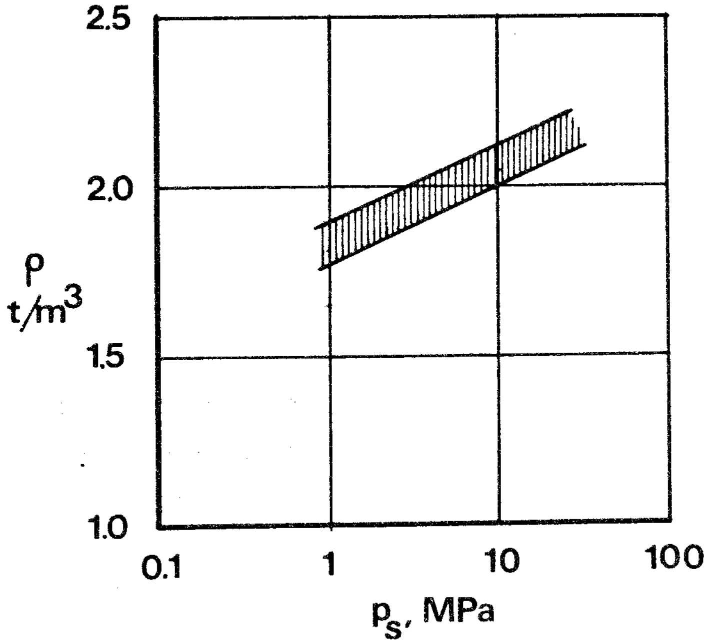


Fig. 2. Swelling pressure of water saturated Na bentonite. The hatched area accounts for scattering and variations in electrolytes in the pore water.

THE PLUGGING TECHNIQUE

Bentonite material

General

Inhomogeneities and large variations in density are expected if slurry injection techniques or simple filling of the boreholes with clay powder or pellets are applied. The most suitable condition of the bentonite is that of dense blocks produced by compacting granulated Na bentonite powder under high pressure, provided that the blocks can be applied with a minimum of voids. Using commercial powder, such as "Volclay MX-80", the bulk density of the blocks will be 2-2.15 t/m^3 if the compaction pressure is in the interval 50-100 MPa. The water content of the powder and hence of the manufactured blocks depends on the humidity of the atmosphere. It is usually of the order of 10%,which corresponds to about 50-60% degree of water saturation of the dense blocks. The high affinity of the bentonite to water means that the blocks take up additional water from the rock by which they get water saturated and swell to fill up the boreholes.

Granulometry and mineralogy

The American Colloid Co. Na bentonite "Volclay MX-80", which was used in this study, has a minus 2 µm content of approximately 85%, and a montmorillonite content of about 80-90% of this fraction. Silt is the dominant remaining fraction which mainly contains quartz and feldspars as well as some micas, sulphides, and oxides.

Spectrometric analyses show that the MX-80 material has a content of about 30 mg Ca, 15 mg Mg, and 70 mg Na per liter pore water.

Microstructure

The significant microstructural feature of granulated bentonite powders, compacted at their natural water contents, is a dominant anisotropy of the aggregates, which are characterized by a very small interparticle and interlamellar spacing in the original "air-dry" condition. The overall particle orientation is largely random at compaction pressures of the order of 50-100 MPa.

In the course of water saturation the aggregates expand and the larger interparticle voids successively get filled by a clay gel which emerges from the expanding aggregates (Fig. 3).

The technique for application of bentonite

The technique for application of the bentonite into boreholes should be so designed that:

1. ..steep as well as inclined and horizontal boreholes can be plugged. It must even be possible to plug steeply oriented holes extending upwards from a tunnel roof.

2. ..the bentonite will form a continuous or practically continuous,well fitting column at the application. No voids other than the intended, necessary slots required for bringing in the clay core can be accepted. A detailed documentation of the sealing operation, centimeter by centimeter,is required.

3. ..boreholes with diameters ranging from ϕ 35 mm and upwards, and lengths up to 1 000 m can be plugged.

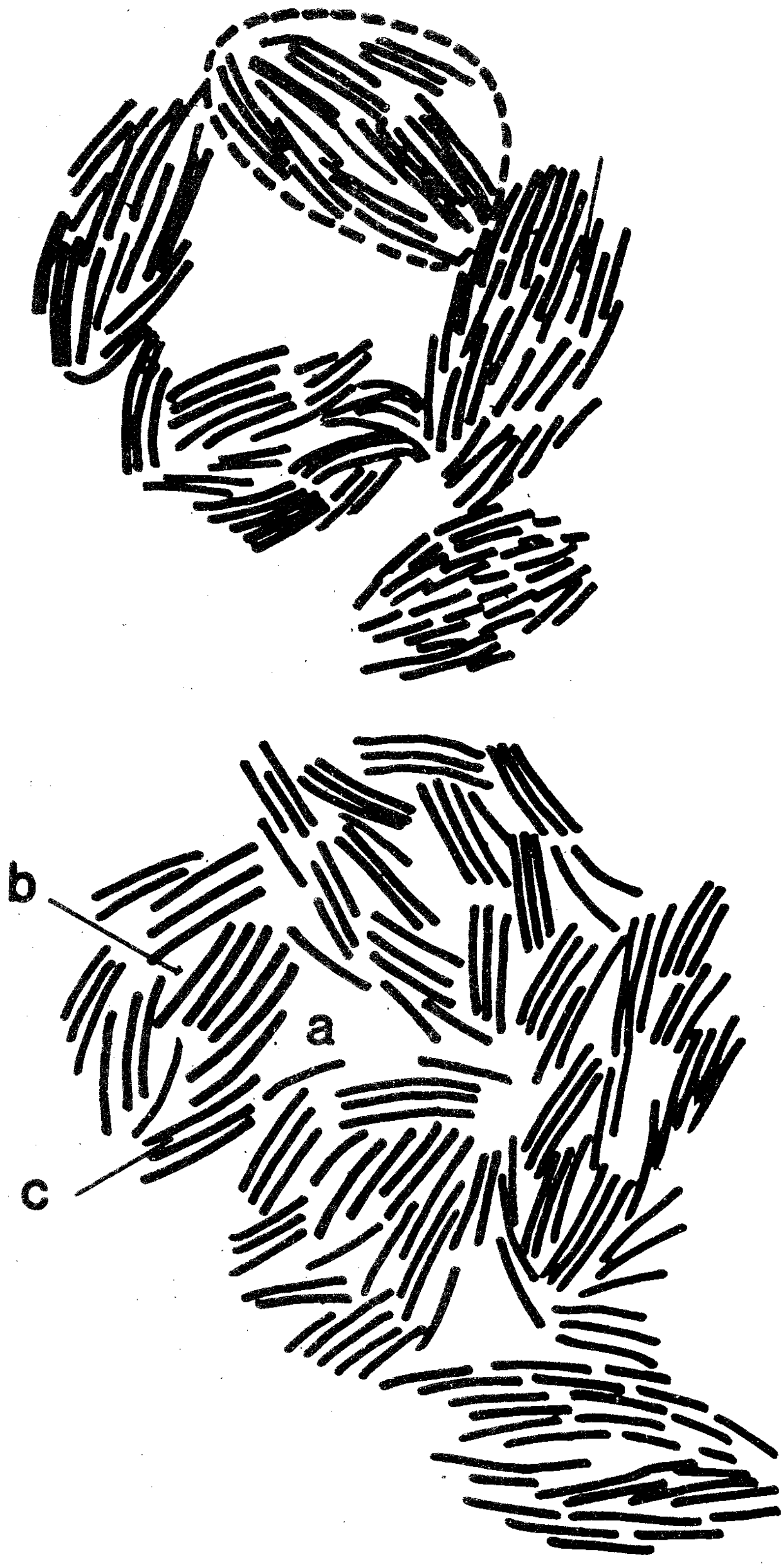


Fig. 3. Microstructural rearrangement of montmorillonite flakes in aging MX-80. Upper picture: freshly compacted. Lower picture equilibrium with largely uniform interparticle distance. a) Large void (≥10 μm), b) Small void (≤10 μm), c) Intra-aggregate (Inter-lamellar) space.

4. ..the time required for the plugging is less than 1 minute per meter (about 15 hours for a 1 km hole).

5. ..it can be handled by ordinary drilling teams (rugged, simple performance).

6. ..the bentonite takes up water from the rock and is allowed to swell and fill the hole completely.

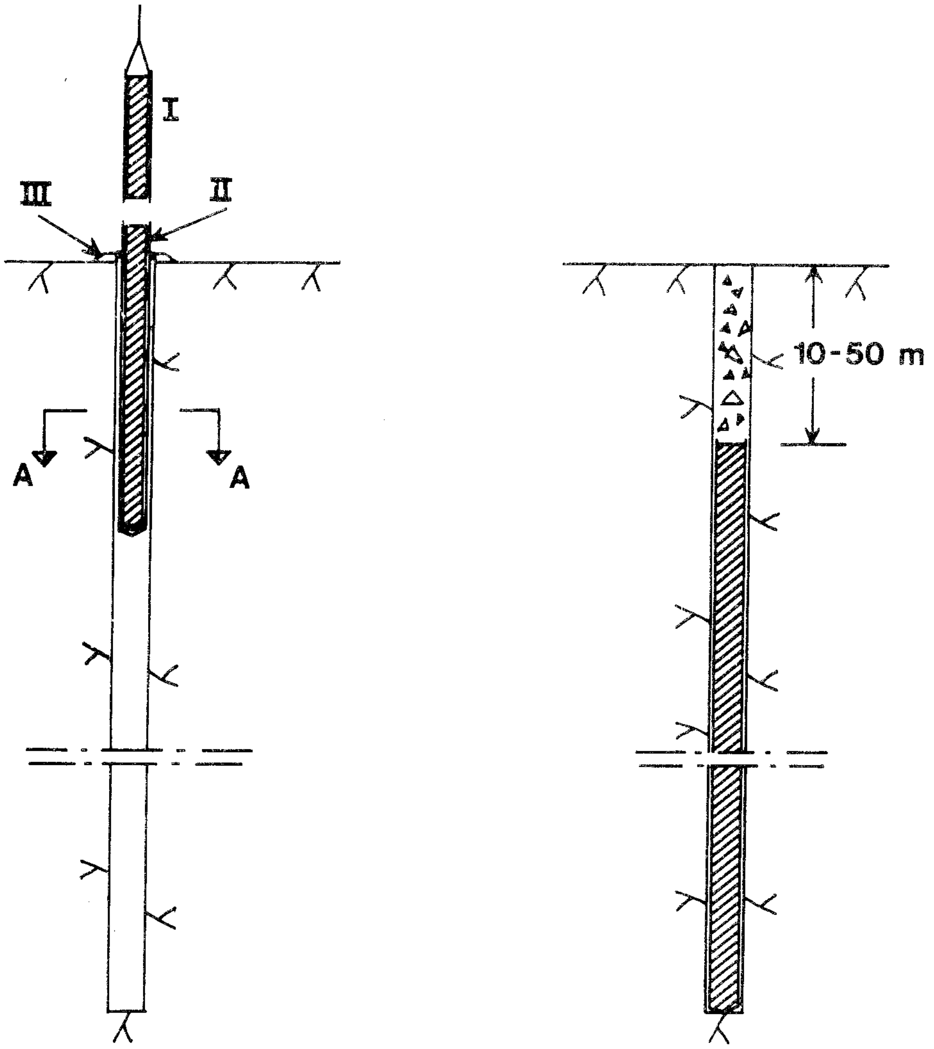
The main principle of the suggested technique, which fulfils these requirements, is to use a pipe to insert the compacted bentonite. The pipe consists of segments which are connected at the rock surface and successively lowered or pushed into the hole until the tip of the pipe reaches its end. The segments are filled with closely fitting, cylindrical blocks of highly compacted bentonite and they are richly perforated to let the clay expand through the holes of the pipe, which is left in the hole.

The use of pipes makes it possible to bring the bentonite into all kinds of boreholes, including those which are filled from below, and to make it form an almost continuous core of highly compacted bentonite in the hole.

The filling must be fairly complete, i.e. the slot between the rock and the pipe, and between the pipe and the clay, must be narrow in order to yield a sufficiently high final density, not only to get a low permeability but also to get a sufficient bearing capacity so that the clay column does not consolidate under its own weight. This can happen if the swelling pressure is lower than the effective vertical pressure. The bentonite will adhere to the borehole walls ("silo effect") which largely reduces the vertical pressure and a rough estimation suggests that a water saturated, homogeneous bentonite with an average bulk density of 1.7 t/m^3 or more will form a mechanically stable clay column in boreholes of practically any leng Initial inhomogeneities or density variations, which may appear in the course of the swelling, tend to be eliminated by the strong self--healing ability of the bentonite.

The pipe and the various bolts etc. which are needed to connect its segments, should be made of a material which is chemically fairly stable in the environment formed by the clay. Copper is suitable and recommended here since it is thermodynamically stable in water and does not react with the clay to form hazardous corrosion products. Slow corrosion may take place due to presence of oxygen, sulphides, and nitrates in the ground water, but since the metal pipe has no function after the plugging operation, its possible dissolution has no practical effect. If the corrosion is associated with a decrease in volume, the swelling power of the bentonite will yield self-healing.

The major components of the technical system are shown schematically in Figs. 4 and 5. It should be mentioned that practical difficulties may appear in the phase of insertion of the bentonite-filled pipe if the borehole crosses a zone of crushed rock since loose rock fragments may be displaced and form obstacles. Also, wide fractures represent difficulties in the sense that bentonite migrates into them, resulting in loss of clay and a low density of the remaining plug. These problems and possible ways of solving them are discussed later in this report.



CONNECTION OF PIPE SEGMENT (I) WHILE PREVIOUSLY LOWERED PIPE (II) IS ANCHORED AT THE GROUND SURFACE (III)

PLUGGING OPERATION FINISHED. THE UPPER PART IS SEALED WITH CEMENT MORTAR

SECTION A - A

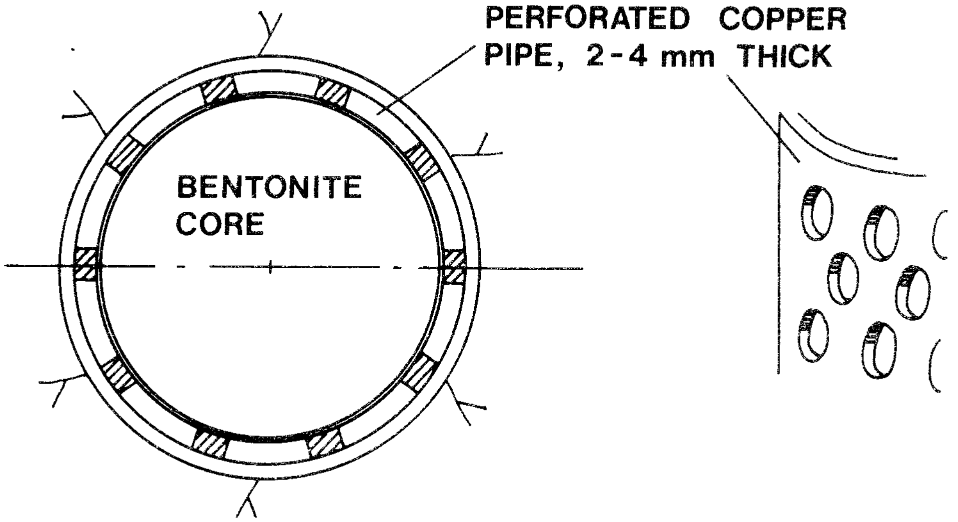


Fig. 4. Schematic picture of com ents and technique of the proposed plugging thod.

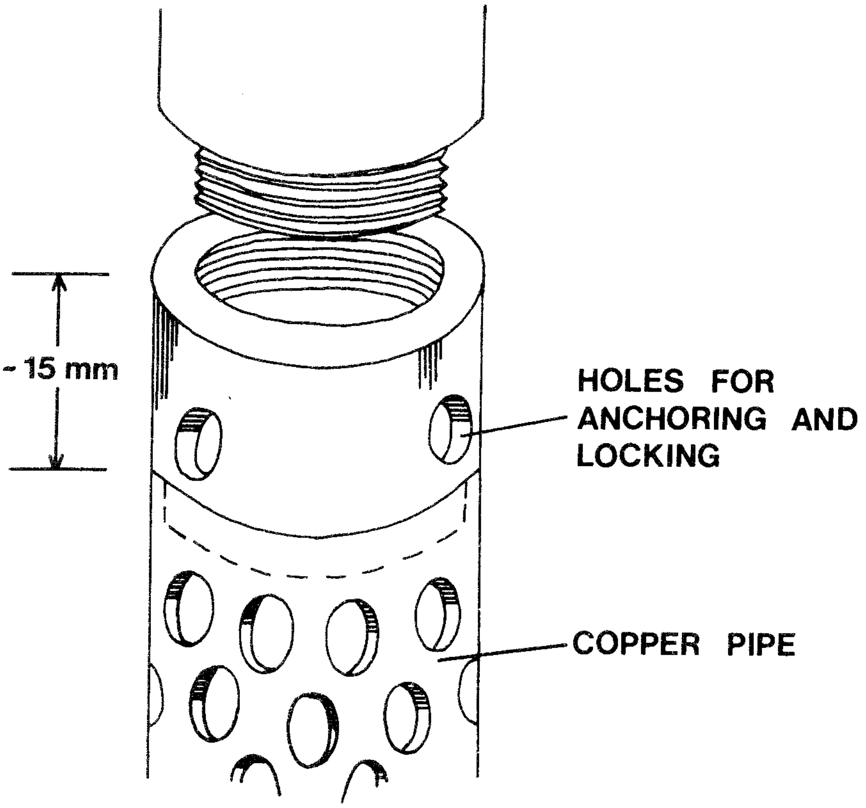


Fig. 5. Example of connection of pipe segments.

TEST REPORT

General

A pilot test was conducted in early 1980 in which the general validity of the plugging principle was confirmed. In December the same year, a systematic laboratory test was initiated in which long metal pipes were used to simulate boreholes. Field experiments were run in the Stripa mine in 1981.

Pilot laboratory test

A pilot test was made to investigate the character and homogeneity of the bentonite in a simulated ϕ 56 mm borehole approximately 10 days after filling it with Na bentonite cylinders and distilled water. The actual inner diameter was 53 mm, and the outer diameter of the perforated pipe and the bentonite cylinders 51 mm and 45 mm, respectively. The bentonite had an initial water content of 10% by weight and a bulk density of 1.85 t/m^3. The thickness of the perforated pipe was 2 mm and its total volume 60 cm^3. Theoretically, the bulk density and water content after complete redistribution of solid matter and water should thus become 1.5 t/m^3 and 75% respectively. The device was equipped with a local water inlet for the uptake of additional water by which the non-uniform conditions for water take-up in a real borehole in rock were simulated. Fig. 6 shows the application of the bentonite in the perforated pipe, and Fig. 7 the test device before applying the lid.

An electronic pressure gauge at mid-height of the cylinder showed that the swelling pressure was built up fairly rapidly. 24 hours after the start of the test the recorded pressure was about 60 kPa. 48 hours after the start it was 80 kPa, and after 1 week it had reached a value of 180 kPa. This indicates a rather fast migration of the bentonite through the perforation. After 10 days the device was dismantled and it was confirmed that bentonite had formed a fairly continuous clay skin outside the perforated pipe (Fig. 8) and that the entire interior of this pipe was filled with clay. The water content of the extruded bentonite ranged between 58 and 77%, while the interior had a water content of 31-35%. These values show that there are voids in the outer slot but that redistribution of water and solid matter is fairly rapid. No free water was observed when the test device was opened.

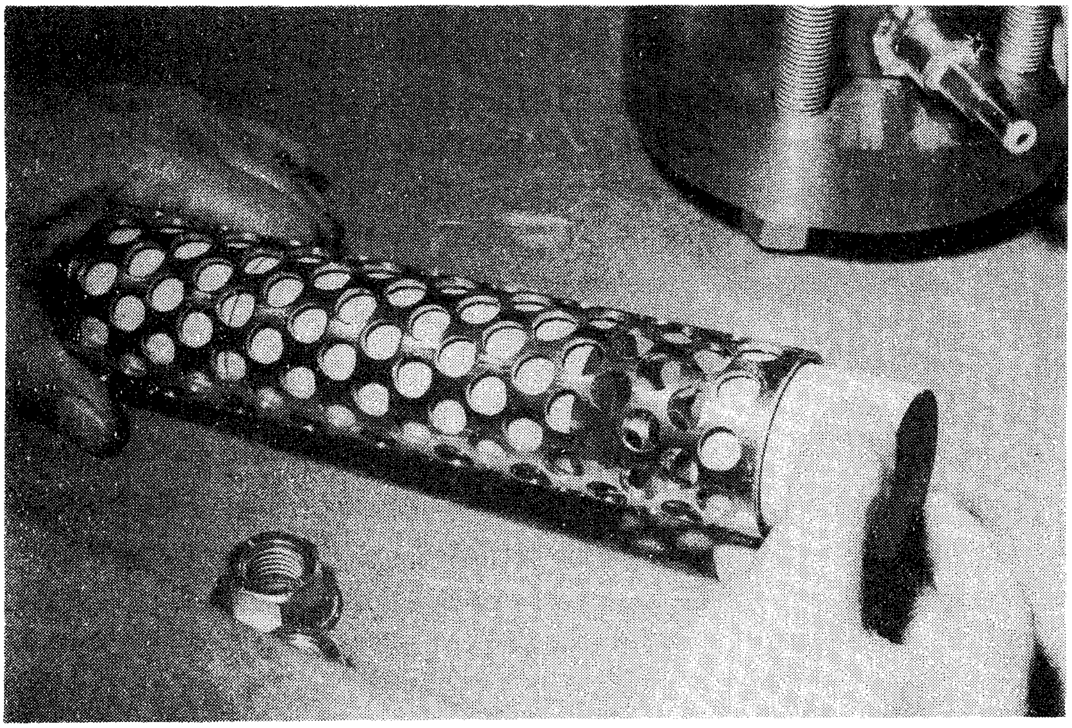


Fig. 6. Filling of the perforated pipe with "air-dry" bentonite.

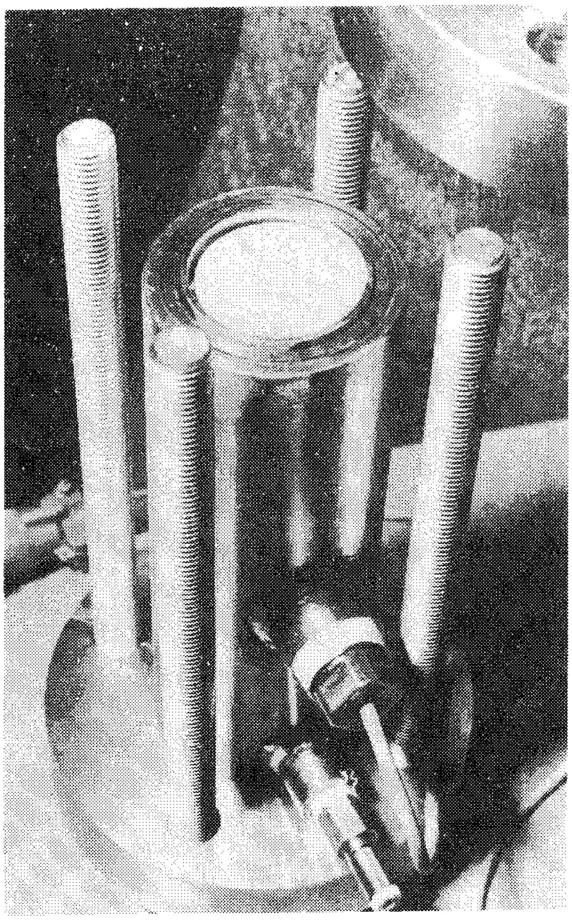


Fig. 7. Pipe device with water inlet seen at lower end and pore pressure gauge at mid-height. The device is turned upside down here.

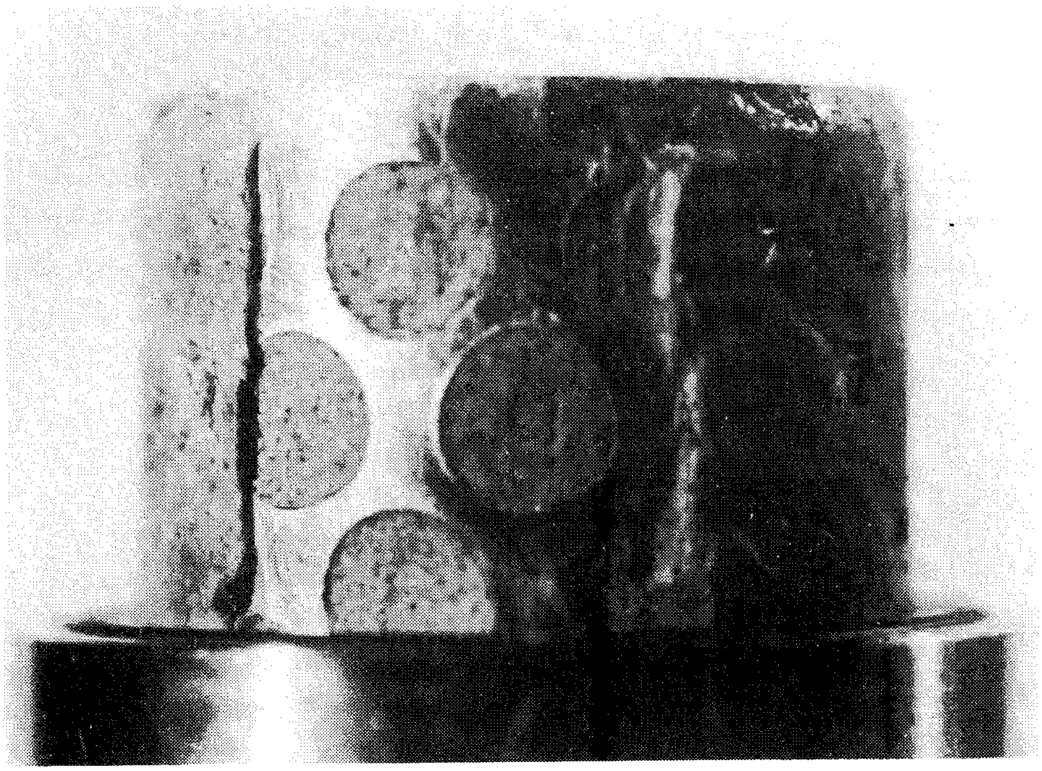


Fig. 8. Top part of the perforated pipe jacked out of the outer cylinder after the test. Notice the formation of a largely continuous clay skin which covers the inner pipe. As can be seen part of it was removed before taking the photo in order to examine the homogeneity of the clay extruded through the perforation.

Systematic laboratory tests

Applying the same basic test principle as in the pilot test, an experimental study was run on a larger scale in 1981. Three 4 m long brass pipes with an outer diameter of 60 mm and an inner diameter of 54 mm, were filled with 25 cm long perforated brass pipe segments with an outer diameter of 50 mm, and an inner diameter of 47 mm. The perforated segments, of which approximately 50% consisted of solid substance, contained cylindrical blocks of MX-80 bentonite with 50 mm length and 46 mm diameter. The bulk density of the blocks was 1.99 t/m^3, and the water content 9%, which yields an ultimate average bulk density of about 2 t/m^3, and a water content of about 30%. At each 0.9 m interval two opposite water inlets were installed with stainless steel filters (5 pairs per pipe) through which "Allard" water[1] was let in, the flow into each individual inlet being measured. The general test arrangement is illustrated by Fig. 9. The ambient temperature was $20 \pm 3^{\circ}$ in the laboratory hall throughout the test period.

The 6 week test

One of the tests was stopped 6 weeks after the start and ocular inspection showed that the bentonite had filled the perforated pipe segments, passed through the perforation and formed clay columns with a close contact with the outer pipe. At and close to the water inlets these columns had swelled to form a continuous clay skin as in the pilot test, while small, regularly distributed and isolated voids were frequent in the rest of the pipe. No continuous voids or passages and no free water were observed (Fig. 10).

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[1] Allard water is the standard artificial ground water (cf. KBS Report 98) which is assumed to be representative of the water in Swedish crystalline rock at 500 m depth.

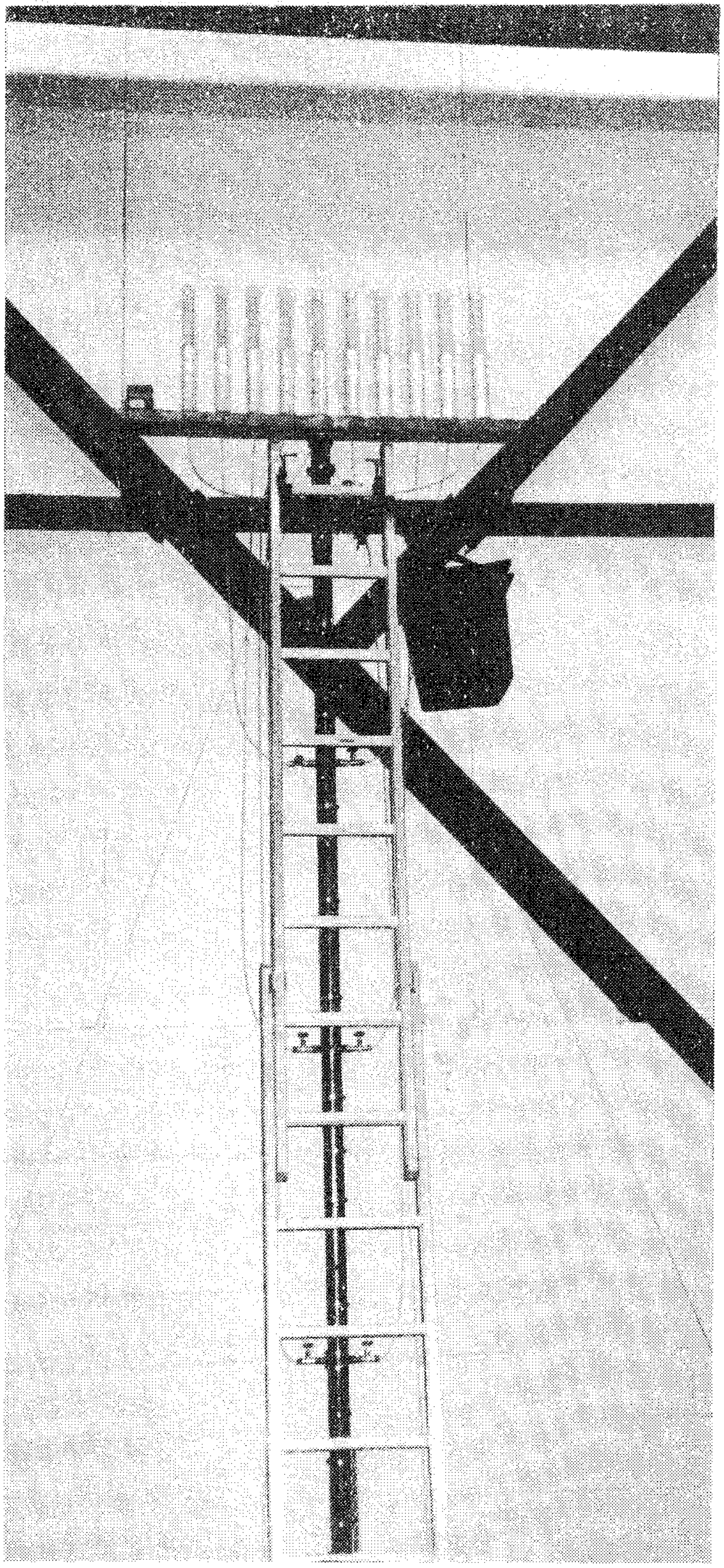
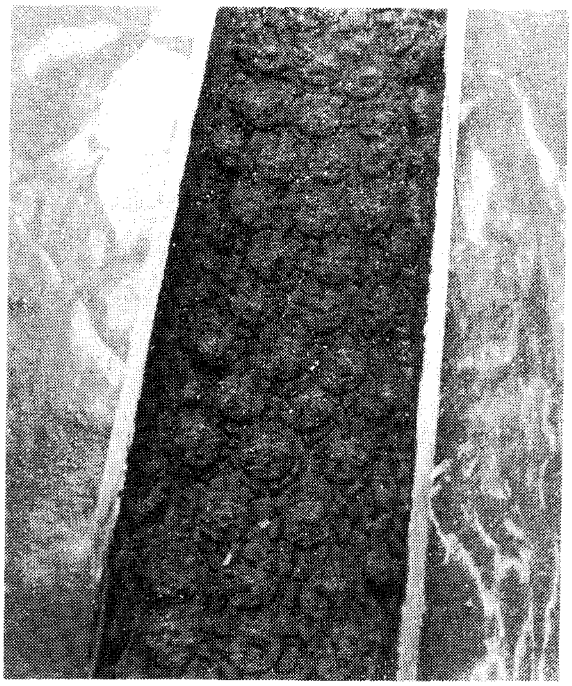


Fig. 9. Test arrangement in the test hall with one of the 4 m long brass pipes simulating boreholes in rock. The vessels with water, one for each inlet, are seen on top of the pipe.



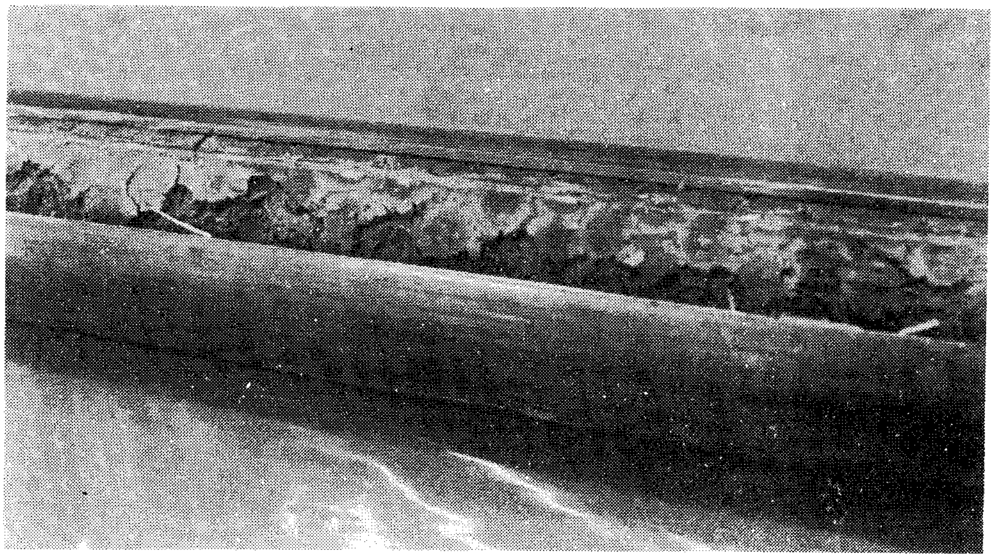


Fig. 10. Upper picture: Split pipe showing dense clay columns grown out from the perforation of the inner pipe (covered by clay).

Lower picture: At and close to the water inlets a continuous clay skin had formed between the pipes. (Outer pipe removed by which some adhering clay was ripped off.

The water content was determined of the clay which had swelled to form a more or less homogeneous filling of the outer slot (Zone III in Table 1), as well as of two inner zones within the pipe segments. One of these (Zone I) formed the "nucleus", i.e. a cylinder with 14 mm diameter, while the other one (Zone II) formed the intermediate material between the two previously mentioned zones. A hydraulic jack, producing an axial force of more than 1 kN, was required to overcome the bond strength at the extrusion of the 25 cm long clay samples from the perforated pipes.

The result of the water content determination shows that the distribution of water was surprisingly uniform in the axial direction and that also the "nucleus" had absorbed water and contributed to the swelling. This suggests that the water uptake and swelling will be fairly uniform also in rock with a low fracture or joint frequency. Actually, the difference between the theoretically deduced ultimate water content 30% and the observed contents is so small that we can consider the major part of the clay core to be fairly close to equilibrium. The observation that there were still voids in the outer space shows, however, that considerable redistribution of particles and water will take place in the peripheral parts.

The 6 month test

The second pipe was opened after 6 months and in this case an apparently continuous clay matrix without visible voids was observed between the two pipes. A clear difference in density and, thus, in water content was noticed, however, between the columns and the secondarily swelled clay separating the columns (cf. Fig. 11). The average water content was determined using the same zone division as in the 6 week test, the result of the determination being summarized in Table 2.

Table 1. Distribution of the water content in the 6 week test (w in weight percent).

	Zone I	Zone II	Zone III	
	30	31		0
	26	27	27	
Inlet ●	-	-		
	24	26		
	24	25	29	
	26	28		
	25	27		
	24	26	32	
	25	28		
	25	28		
	24	28	33	
Inlet ●	25	27		1
	24	27		
	26	28	36	
	27	28		
	26	29		
	24	28	34	
	24	26		
	25	27		
	23	25	35	
	23	27		
	31	34		
Inlet ●	25	27	39	
	26	27		2
	27	-		
	25	26	37	
	28	29		
	28	30		
	25	27	31	
	26	27		
	27	29		
	25	27	32	
	26	28		
	27	29		
Inlet ●	29	31	36	
	26	28		3
	27	26		
	25	27	31	
	26	27		
	27	29		
	25	27	31	
	26	29		
	24	25		
	23	25	32	
	24	29		
Inlet ●	13	14		
	17	19	40	
	26	27		4
Mean value	25	27	33	

4 m

Table 2. Distribution of the water content in the 6 month test (w in weight percent).

	Zone I	Zone II	Zone III		
	22	21	-	0	
Inlet ●	23	23	23		
	28	29	31		
	30	31	38		
	28	29	37		
	25	32	37		
	28	29	37		
	30	31	37		
	30	31	38		
	30	31	37		
Inlet ●	35	36	38	1	
	30	38	41		
	29	30	36		
	27	28	36		
	27	29	33		
	30	32	32		
	28	30	39		
	30	30	40		
	30	31	42		
	30	31	41		
Inlet ●	36	38	48	2	4 m
	31	32	44		
	31	33	-		
	30	31	41		
	30	31	37		
	29	30	41		
	29	31	43		
	31	33	-		
	30	31	37		
	31	32	41		
Inlet ●	31	34	43		
	29	30	42	3	
	32	33	37		
	30	31	42		
	30	31	39		
	32	33	41		
	30	31	41		
	30	34	40		
	33	34	45		
Inlet ●	29	30	41		
	29	30	40		
	-	-	-	4	
Mean value	30	31	38		

1) Notice that the axial division at the water content determination differs somewhat from that of Table 1.

The water content in all three zones is higher (by approximately 5 percent units) than in the 6 week test. While the uniformity in the axial direction is again very obvious despite the fact that water entered through separated, local inlets, the radial distribution gradient is only slightly diminished from the 6 week state. The major part of the core (Zones I & II) are very close to complete equilibrium, while the peripheral zone will still require some mass redistribution to reach this state. Hence, it is obvious that a complete homogeneity of the clay may require a very long time, at least in rock with few fractures. On the other hand, the average water content 38%, which corresponds to a bulk density of water saturated clay of about 1,85 t/m^3, tells us that its sealing effect is tremendous, the permeability being less than 10^{-13} m/s.

Electronic pressure gauges were installed in all three pipes but only the two long term tests have yielded swelling pressures. In the 6 month test such a pressure began to build up after approximately 4 months and it reached a value of about 0.5 MPa at the end of the test. This is much lower than the expected value for 2 t/m^3 bulk density, which indicates that complete swelling to fill up all original voids had not yet taken place.

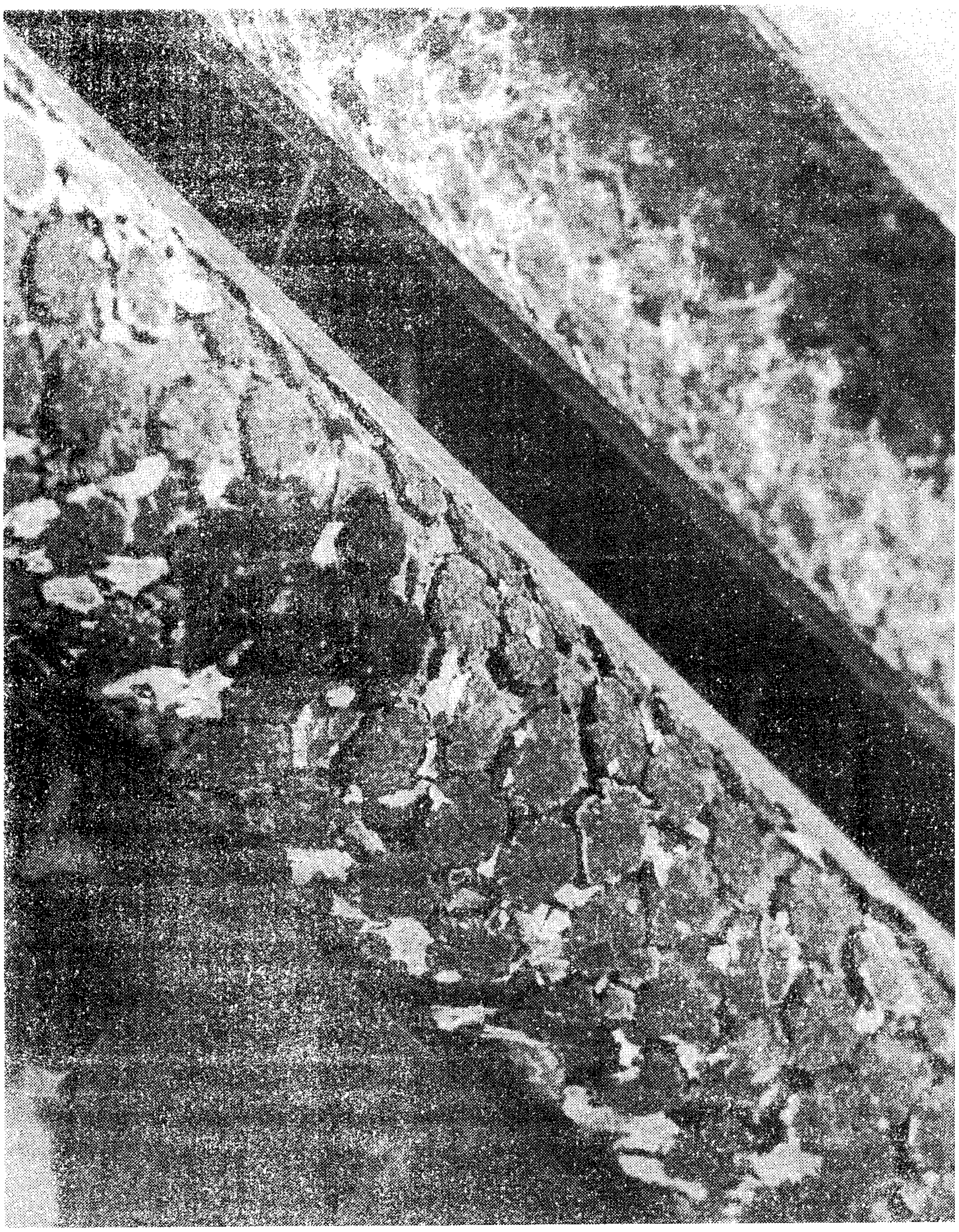


Fig. 11. The two pipe halves separated to show the appearance of the clay which had swelled out through the perforation after 6 months. The rather dense clay "columns" stick to the perforated pipe, while the softer, secondary clay filling in between, sticks to the outer pipe (upper half seen in the picture). Some drying took place before the photo was taken.

The 1 year test

The third pipe was opened after approximately 12 months. As in the 6 month test, an apparently continuous clay skin had formed between the outer pipe and the perforated one. The water content distribution is given in Table 3, the zone division being the same as in Tables 1 and 2. Only two 2 m long segments were analyzed in the 1-year test since ocular inspection indicated that the consistency of the clay was rather constant in the axial direction. We see that the average water content has increased insignificantly only, during the last half year. It also appears that there is still some difference in stiffness and therefore in water content between the extruded clay columns and the secondarily expanded clay between them.

The measurement of the net water flow into the pipes through the inlets shows large variations; the recorded amounts ranging between 23 and 134 cm^3 in one year with an average of 45 cm^3 per year and inlet. The theoretical porosity of the bentonite core is 45%, which corresponds to a total pore volume of approximately 3 000 cm^3, some 60% of which was filled with water from the start. This yields an initial air--filled volume of 1 200 cm^3 which was reduced to about 450 cm^3 by the uptake of the original water in the outer pipe and of the water adsorbed from the vessels. The degree of water saturation was therefore about 85% at the end of the test, which shows that the uptake of additional water (450 cm^3) to reach complete water saturation, requires several years with this particular test geometry.

Table 3. Distribution of the water content in the 1 year test
(w in weight percent)

	Zone I	Zone II	Zone III	
Inlet ●				0
	28 30 28	28 31 29	35 36 37	
Inlet ●	29 31 30	30 32 31	37 43 41	1
	29 29 29	31 29 30	38 36 38	
	31	32	41	
Inlet ●				2
	31 30 30	32 32 32	39 40 39	
Inlet ●	33 30 31	34 31 32	42 40 39	3
	31 30 31	33 31 32	42 37 39	
	30	31	40	
Inlet ●				4
Mean value	30	31	39	

4 m

Field tests (Stripa)

General

Two 6 m long boreholes in the Stripa mine were used for a field test. The water inflow into the $\phi38$ mm holes had been recorded for a long period of time and was found to be 12, and 24 cm^3/hour, respectively. In the first week of March 1981 the boreholes were equipped with MX-80 bentonite plugs and sealed with cement mortar in the upper 0.5 m part. The bentonite cylinders had a water content of 10%, and a bulk density of 2.15 t/m^3. Their height and diameter were 40 mm and 30 mm, respectively, while the outer and inner diameter of the perforated copper pipe were 35 and 32 mm, respectively. The expected, ultimate, average bulk density was 1.78 t/m^3 and the corresponding water content about 43%.

Both plugs were equipped with moisture sensors of the type used in the deposition holes of the "Buffer Mass Test" in Stripa. They were located at 0.5 m, 1.5 m, and 2.5 m from the upper end and were connected to the ground surface (tunnel floor at 360 m depth) by cables passing through the center of the bentonite core. The borehole with the smaller inflow was overcored in August, almost 6 months after the plugging, and investigated in detail with respect to the water uptake and swelling.

The water uptake

The overcoring offered a clear picture of the pattern of fractures and joints of the rock. It is shown, together with the water content distribution, in Figs. 12 and 13 for those parts of the core which have been examined so far, and which were located below the surface-near, somewhat disturbed upper 1 m segment. "I", "Ay" and "By", respectively, denote different zones in which the core was divided for the water content determination (cf. Fig. 12).

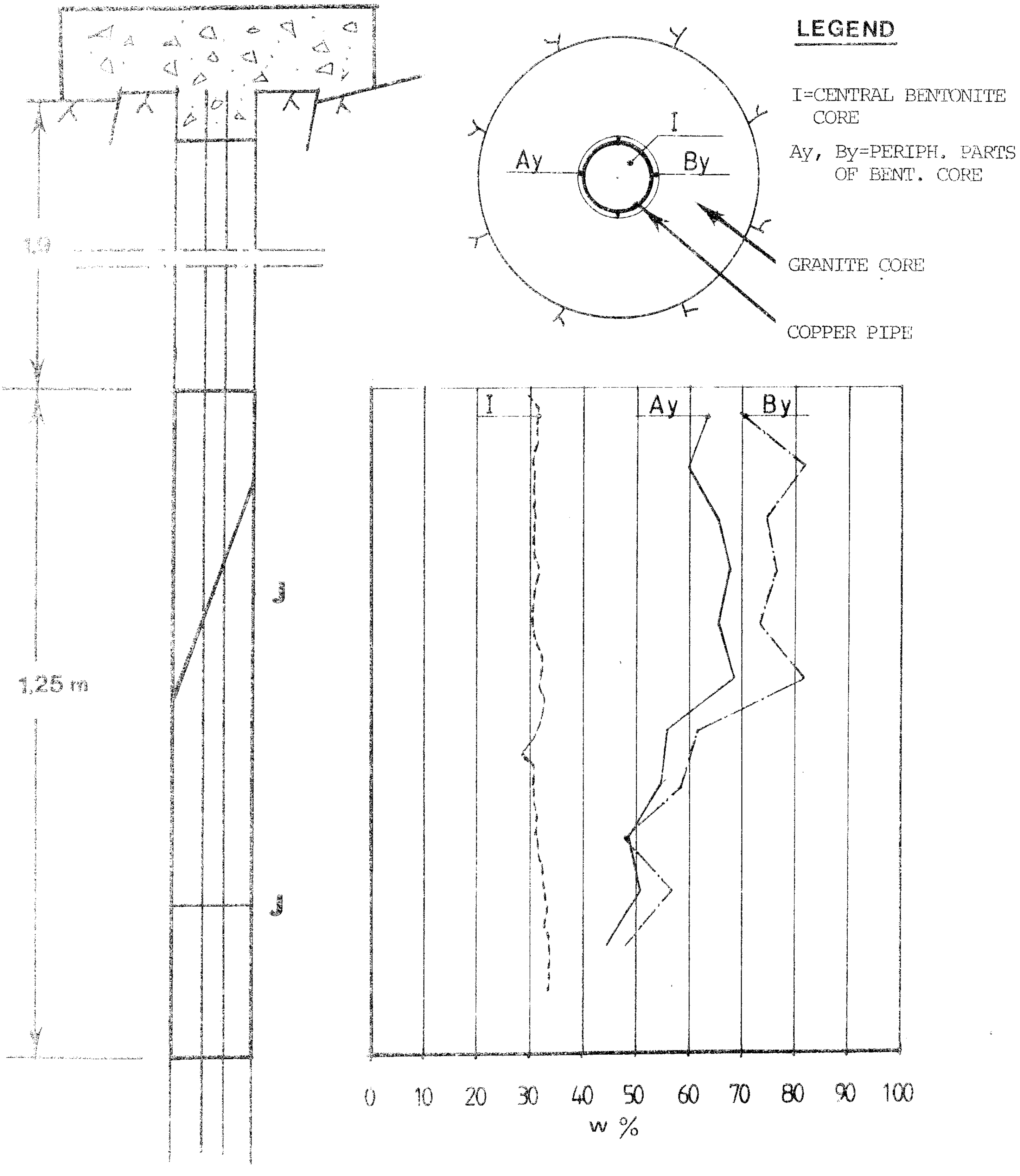


Fig. 12. Fractures and joints as observed in the upper part of the overcored rock. Water content distribution (cf. Legend). "J"=open joint.

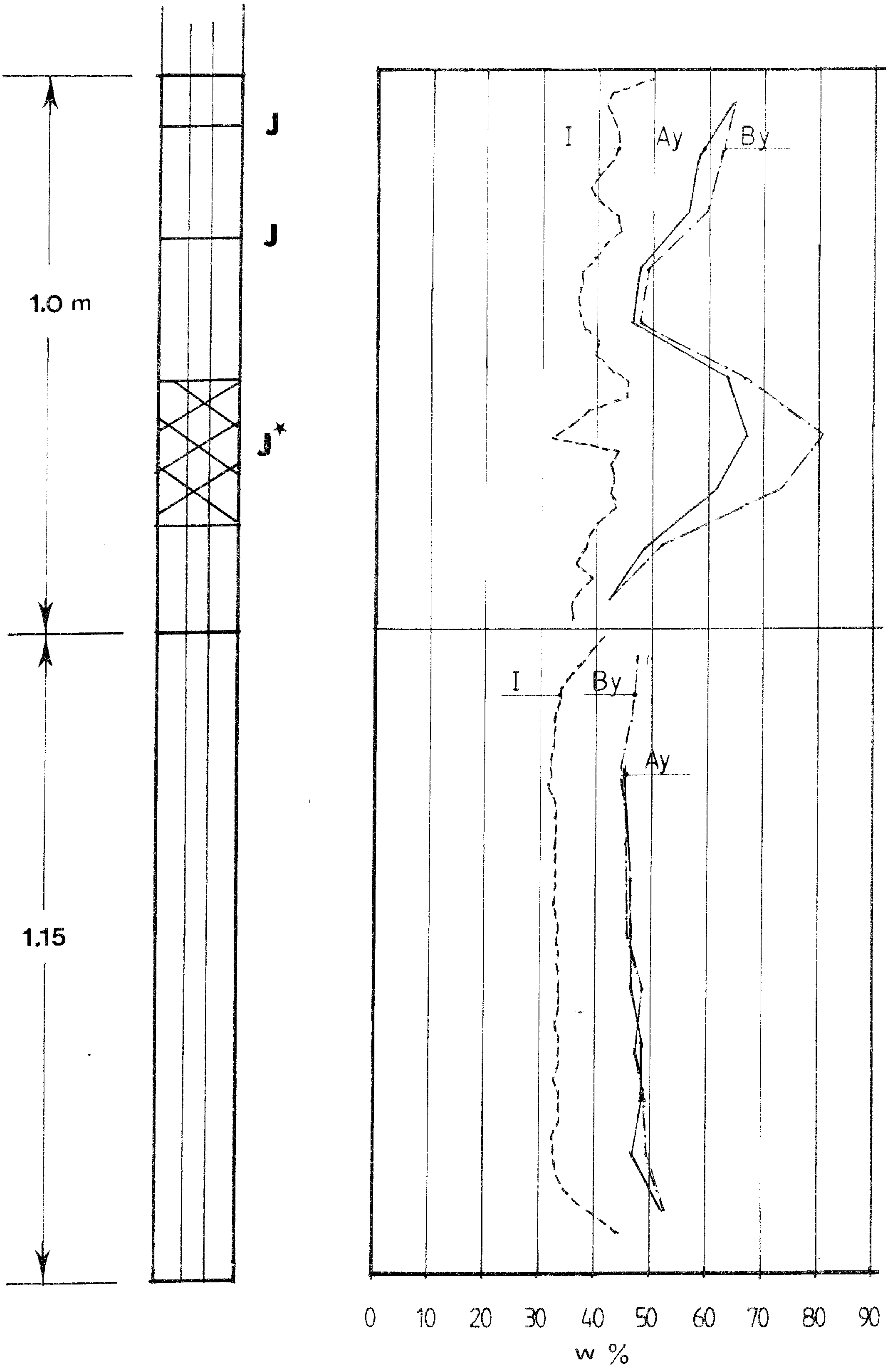


Fig. 13. Fractures and joints as observed in the lower part of the overcored rock. Water content distribution (cf. Fig. 12). "J"=open joint; J* crushed zone.

The sampling of the clay was made after splitting of the 1-1.25 m long segments into which the core was divided. The splitting operation was conducted by cutting longitudinal slots located diametrically from the outer periphery to a few millimeters from the borehole periphery (Figs. 14, 15 and 16). The clay adhered strongly to the rock so that the separation of the core halves after splitting required a considerable tension force. Inspection showed that the slot between the copper pipe and the surrounding rock was completely filled with clay that had migrated from the interior out through the perforation (Fig. 17).

The field test is of particular interest since it illustrates the water uptake process in rock with different structural patterns. It must be noticed, however, that the water distributions are somewhat affected by the cutting operations, which required pressurized flushing water for cooling purposes. Thus, the ends of each plug segment absorbed cooling water and do therefore show too high water contents within 10-20 cm from the cuttings. Similarly, the overcoring caused water content anomalies at and close to the open joints. This is particularly obvious for the Ay and By values of the central 1 m long core segment. The Ay:s and By:s of the upper 1.25 m segment are surprisingly high, on the other hand, since there are just two joints in that part of the core. The anomaly is explained by the inclination of the joint at the top by which the larger part of the segment periphery was exposed to the flushing water. It may also be that the upper joint was very wide.

We see that the redistribution of water and minerals, which will finally yield a high degree of homogeneity, has proceeded very far in the central part of the 1 m core segment which is rich in joints and fractures. Here, the average water content of the bentonite is 43%, i.e. the same as the expected ultimate

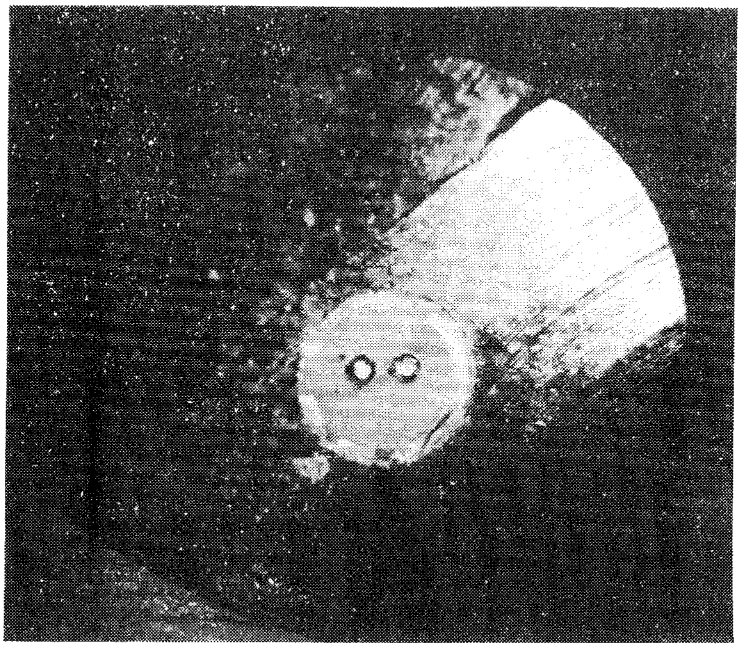


Fig. 14. End face of sectioned core. Notice the copper pipe which contains two moisture gauge cables.

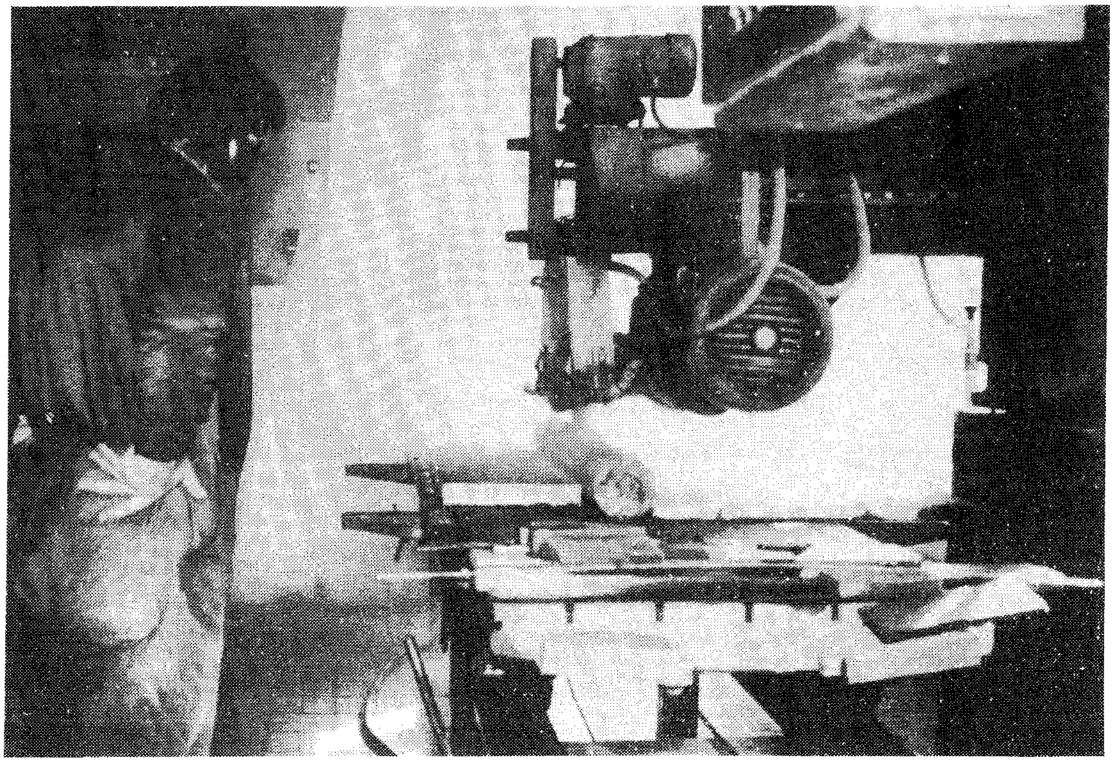


Fig. 15. Cutting of slots (Grythyttans stenindustri H.B.)

Fig. 16. Core with slot. Separation into two halves being prepared.

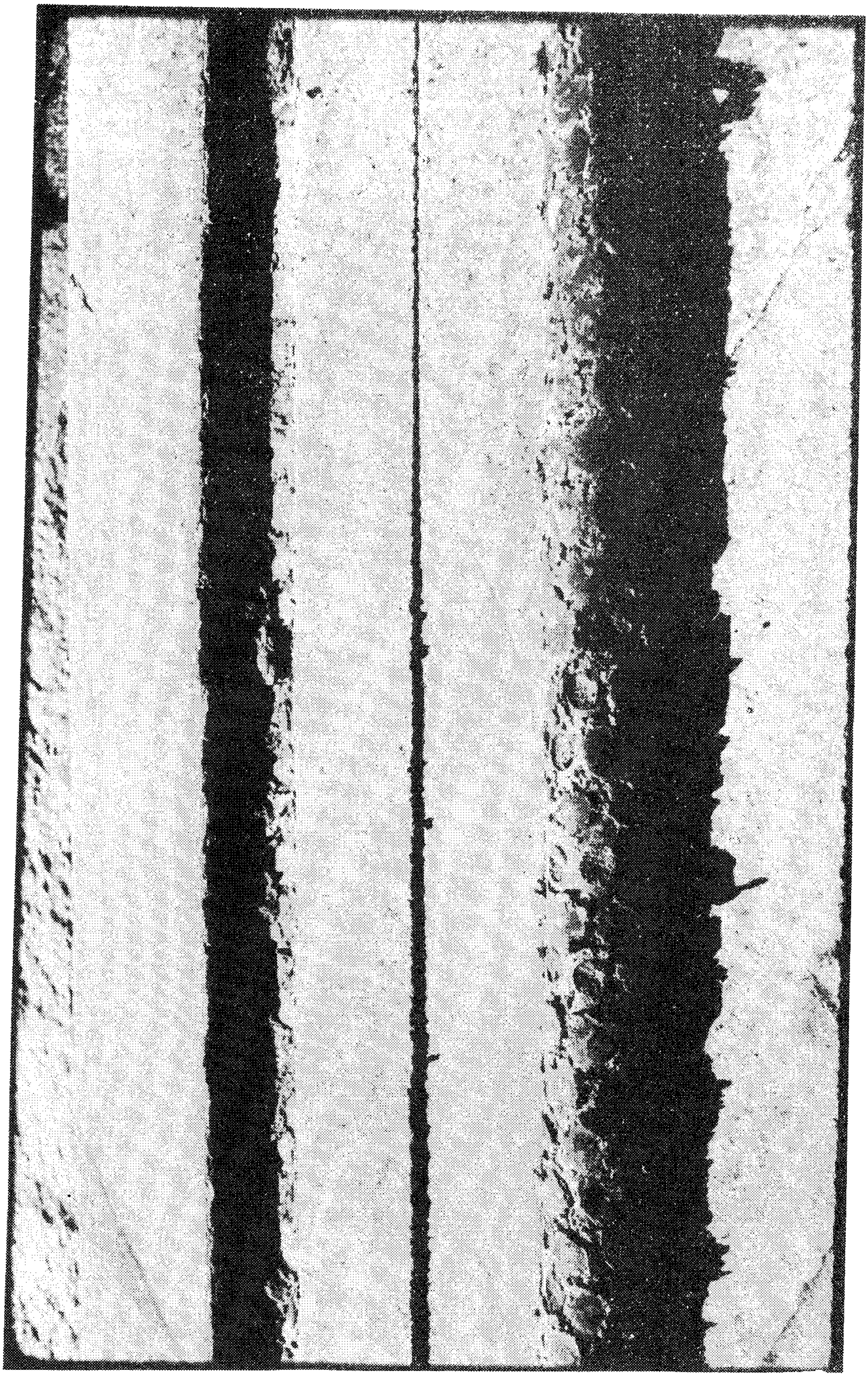


Fig. 17. Typical appearance of the exposed plug. Notice that practically all the clay sticks to the perforated pipe in the upper part of the picture while more clay sticks to the rock in the lower part. Only one single fracture, partly sealed by crystalline matter, is seen in the core and here is where the homogeneity of the clay is best developed.

water content. It should be mentioned here that the theoretically derived values are based on an assumed compact mineral density of 2.70 t/m^3. Slight deviations from this value yield slightly different ultimate water contents and bulk densities, the maximum deviation probably being of the order of ±5%.

The average water content of the upper and lower segments is 37 and 35%, respectively, which clearly shows that the development of a homogeneous state of the bentonite requires a longer period of time when the rock is poor in joints than in heavily fissured rock.

Moisture gauges

The moisture gauges were expected to show a slow rate of water uptake since it was assumed that self-healing of the joints between the bentonite blocks would prevent water from entering the interior of the bentonite core at a high rate. This was confirmed with the exception of two of the six gauges which reacted immediately after the plugging operation. They were both located high up in the top segments of the two boreholes, where the bentonite core contained three moisture gauge cables, and therefore probably some passages for rapid initial water flow.

The gauges were used here only to indicate when the water uptake into the inner zone of the bentonite core started. For practical reasons the readings had to be taken with considerable intervals so no actual information on the rate of water uptake was obtained.

Permeability test

A segment of the overcored plug from Stripa was sectioned into a number of 10 cm thick discs, one of which was used in a pilot permeability test. The disc was placed in a strong steel cylinder with bolted lids. The slot between the cylinder and the rock was sealed with plastic while there was an open space between the end surfaces of the specimen and the lids to distribute the water evenly over the pressurized end and to allow for free drainage to the outflow end. The clay plug was covered by a sintered filter of stainless steel of the type used in the swelling pressure oedometers.

Allard water was used for the percolation, which was run at a constant pressure of 500 kPa. The flow was recorded by measuring the rate of displacement of a water meniscus in a calibrated capillary connected to the outflow end of the device (PUSCH, 1981)

The test was first run with the steel filter at the inflow end covered by rubber membranes so that only rock was permeated. The flow stabilized soon after the application of the water pressure (cf. Table 4), and after 3 weeks the filter cover was removed and the test continued. As shown by Table 4 the flow was then initially higher than when only rock was permeated. It dropped successively, however, and approached a lower value after 6 weeks than the original one, which indicates that clay migrated from the clay core into adjacent joints which were partly sealed off.

The entering of clay into rock joints which extend to the borehole, is amply illustrated by Fig. 18 which is an autoradiogram of one of the rock surfaces of an approximately 0.2 mm wide joint. The clay gel had obviously moved some 5-7 mm into the joint in 6 months which is in reasonable agreement with the author's predictions (PUSCH, 1980a).

Table 4. Flow through overcored bentonite plug[1)]

Test type	Time after onset of pressure, days	Flow rate in capillary m/s
Rock permeated	0-7	$2.2\cdot10^{-7}\rightarrow10^{6}$
(149 cm^2 cross section)	8-15	$0.9\cdot10^{-6}\rightarrow1.1\cdot10^{-6}$
	16-21	$1.1\cdot10^{-6}\rightarrow1.2\cdot10^{-6}$
Rock & clay permeated	0-4	$\sim3\cdot10^{-6}$
(160 cm^2 cross section)	5-15	$\sim2\cdot10^{-6}$
	16-21	$\sim1.3\cdot10^{-6}$
	22-31	$\sim10^{-6}$
	32-40	$\sim1.5\cdot10^{-6}$
	41-53	$\sim4\cdot10^{-7}$
	54-58	$\sim6\cdot10^{-7}$

[1)] Permeability values were not derived since the complex flow patterns make that sort of conductivity data irrelevant. If the rock is considered to represent a porous medium the recordings yield a coefficient of permeability of about $5\cdot10^{-13}$ m/s.

When the percolation test was stopped, the clay core was extruded by applying an axial force of 0.7 kN. This shows that the "bond strength" (shear strength along the clay/rock interface) was approximately 70 kPa. The water content of the peripheral clay zone, situated between the rock and the perforated pipe, was found to be approximately 56%, while it was about 42% in the clay inside the pipe. It is obvious that the large majority of the clay core had reached the expected ultimate water content in the course of the permeation.

The higher moisture of the slot filling is explained by the migration of clay into rock joints which caused a loss in solid mass. This effect was probably much stronger due to the high external pressure in the test than if only self-injection had taken place as will usually be the case in practical applications.

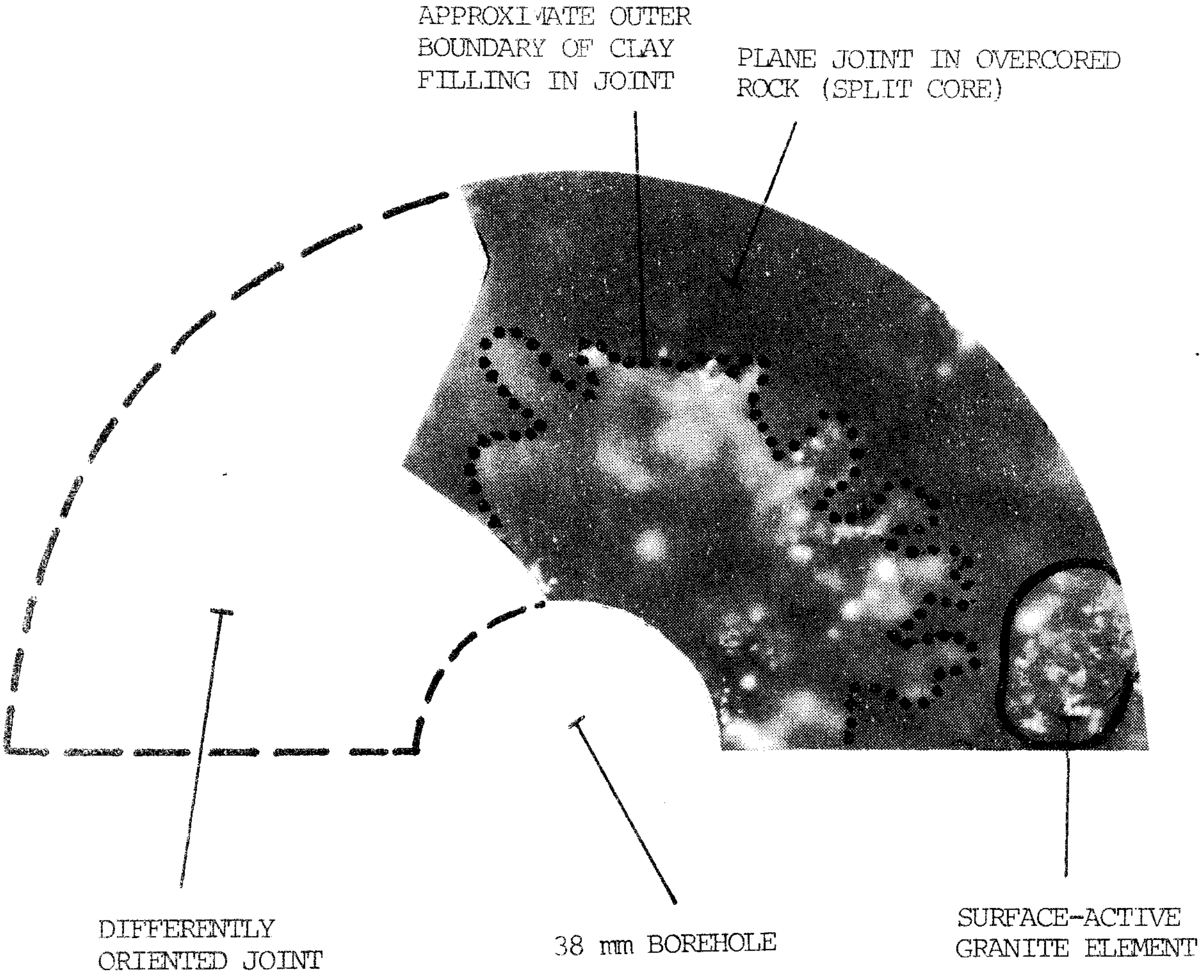


Fig. 18. Autoradiogram of a rock surface with attached clay. The radiogram was taken after splitting an approximately 0.2 mm wide joint into which the clay had been self-injected. The entire surface was saturated with a radioactive Ca solution and then sprayed with distilled water so that only the ion-adsorbing clay retained the tracer.

The general appearance of the device used for permeation of the overcored clay plug is illustrated by Fig. 19.

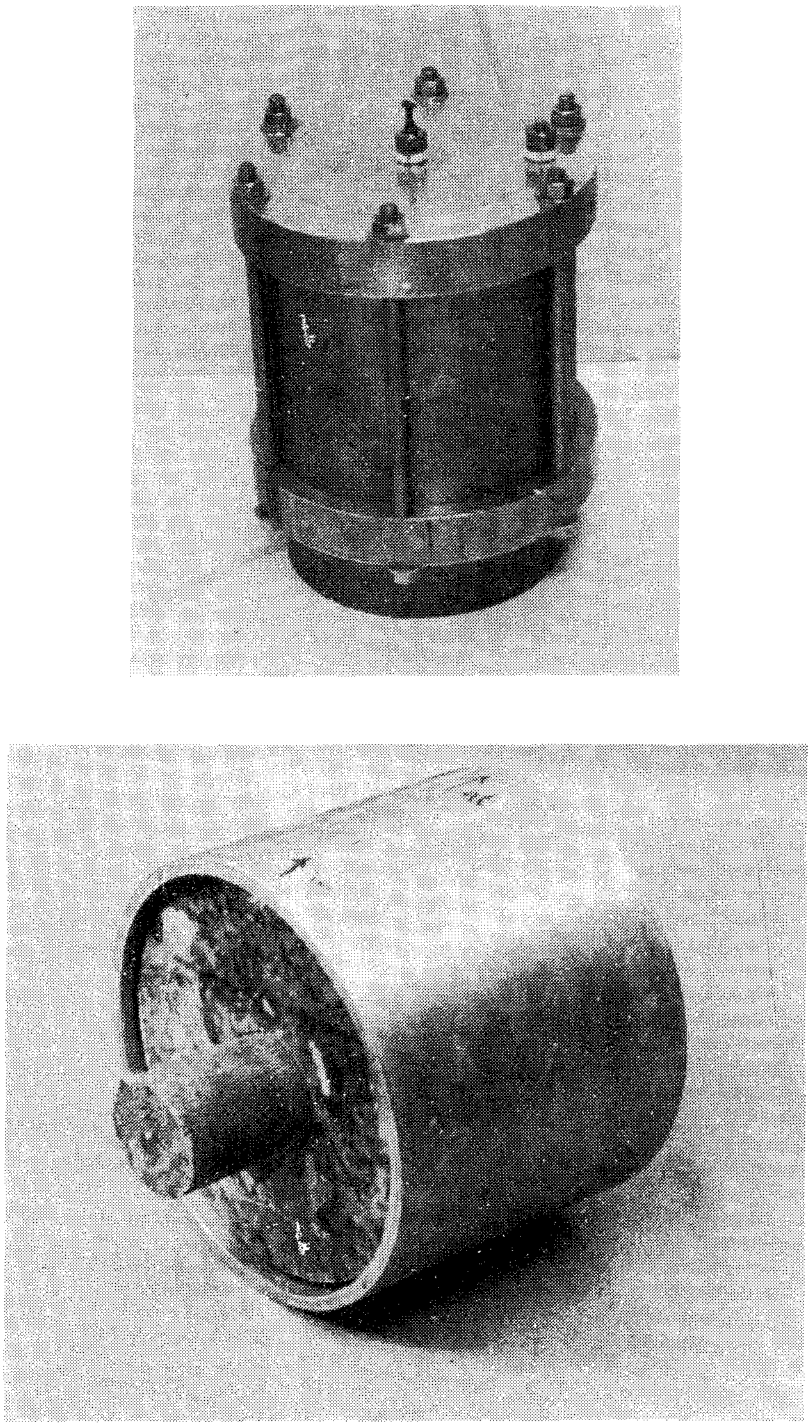


Fig. 19. Assembled permeameter and opened cylinder with partly extruded clay core.

THEORY

General

For certain practical applications it is probably sufficient to know that the water uptake yields swelling and acceptable sealing of the slot between the rock and the perforated pipe within some weeks after the plugging. Other applications demand more reliable predictions of the behavior and function of borehole plugs, which requires derivation of a relevant physical model and a mathematical equivalent. A first attempt to achieve this is made in the subsequent text.

Synthesis of observations

Laboratory tests

No free water was found when the tests were stopped and the pipes simulating boreholes were opened. This observation and the fact that the slot between the outer and inner pipes was first filled with clay at the water inlets, indicates that the slot was blocked by swelling clay at the inlets shortly after each test start. Water then migrated into the rest of the respective clay core through the primarily swelled zones, by which clay "columns" grew through the perforations. The pilot test showed that this stage was reached in 10 days in a 30 cm long pipe, while the first of the tests with 0.9 m spacing of the point-shaped inlets demonstrated that the larger part of the maturing processes had taken place in 6 weeks.

The radial distribution of the water content showed the same pattern in all the tests: The clay in the slot was the wettest, while the central core was the driest. The short-term test naturally gave the highest water content at the periphery since the successive swelling of the interior of the core produced consolidation of the outer zone at later stages.

As to the axial distribution of water, it was found to be remarkably uniform in all the tests. This indicates that water spread rather rapidly from the inlets all over the peripheral slots, which contained rather soft, water saturated inhomogeneous clay gels in the first phase, and non-saturated "column"-type clay in a second phase. Still, water seems to have been transported through this inhomogeneous zone, so that it was constantly available for radial migration into the denser, central clay core which obtained a high degree of water saturation after a few days already.

The fact that the water content tended to be higher in the lower than in the upper parts of the plug periphery in the long term tests, indicates that the water head is of considerable importance. Thus, while water uptake in highly compacted bentonite is almost entirely caused by suction, external pressure will contribute to the rate of uptake in less dense bentonite.

Field test

Two observations are of primary interest. One concerns the lowest segment (Fig. 13) where the very uniform axial water content distribution inside and outside the perforated pipe, respectively, confirm the conclusion from the laboratory tests that water was available over the entire periphery throughout the test even if it entered the hole only through discrete, widely separated joints.

The other finding concerns the upper segment in the same figure, and the outcome of the permeation test. It shows that the water content inside the perforated pipe is approximately 40%, which tells us that highly compacted bentonite swells spontaneously to at least twice its original volume.

Physical and mathematical modelling, first approach

A simplified model based on the preceeding synthesis would involve an early formation of a soft clay gel in the slot between the rock (A in Fig. 20) and the perforated pipe, and a fast water saturation of the core (B), as well as a successive radial redistribution of water and solid matter due to water content gradients (cf. Fig. 20). Assuming, for the sake of simplicity, that I is originally 100% water, and that II represents highly compacted bentonite which is rapidly water saturated at its outer periphery, the rate of redistribution can be roughly estimated if the perforation (50% of total pipe surface area) is omitted.

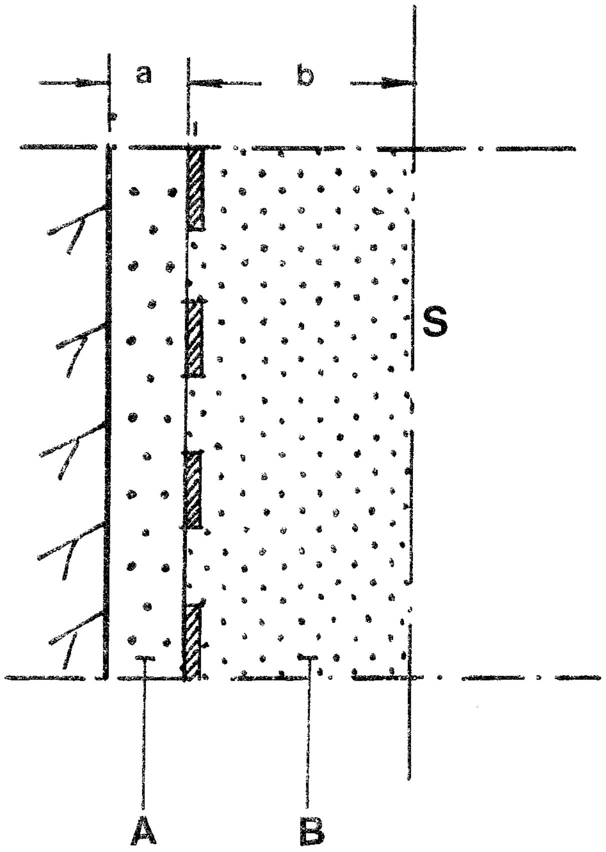


Fig. 20. Schematic picture of the initial distribution of clay and water. A) soft clay gel, and B) dense clay core. S is axis of symmetry.

The calculation can be performed by applying a simple stepwise calculation analoguous to that used for estimation of the rate of expansion of a clay plug (PUSCH, 1979). The driving force is the water suction of the bentonite which is taken as the swelling pressure (with opposite sign). Fig. 21 illustrates, in principle, the procedure.

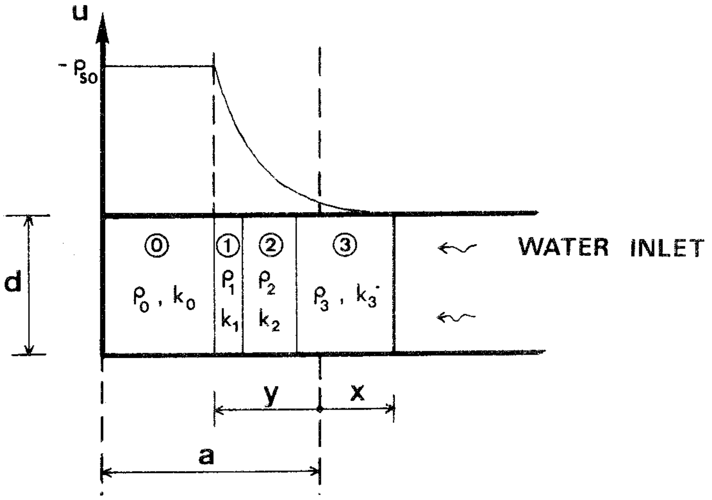


Fig. 21. Expansion of a clay element. Notice that when the bulk density ρ is reduced through swelling, the swelling pressure and thus the suction (u) is decreased, while the permeability (k) is increased (cf. Table 5).

Taking as an example the ϕ 38 mm Stripa borehole with a=4 mm and b=15 mm, an initial bulk density of 2.15 t/m^3, and the parameters in Table 5, we arrive at the following scenario.

Table 5. Suction (u) and permeability (k) of highly compacted Na bentonite

ρ_m t/m^3	$u=p_s$ MPa	k m/s
2.1	30	$1.5\cdot10^{-14}$
2.0	7	$2\cdot10^{-14}$
1.9	2.5	$4\cdot10^{-14}$
1.8	1.0	$8\cdot10^{-14}$
1.7	0.4	10^{-13}
1.6	0.3	$2\cdot10^{-13}$
1.5	0.2	$5\cdot10^{-13}$
1.4	0.15	10^{-12}
1.3	0.10	$3\cdot10^{-12}$

The formation of a soft clay gel, in the "A-zone", i.e. with a bulk density of the order of 1.2 t/m^3, takes place in approximately 2 days. It is formed on the expense of the outer 1.5 mm part of the dense core, the bulk density of which drops to about 1.5 t/m^3. The "A-zone", which is initially soft, is then consolidated by the continued expansion of the denser central clay core until equilibrium is finally developed. The latter process, which governs the maturing of the clay core, can be described as one of diffusion, the driving force being the particle concentration gradient. The mathematical form of the diffusion-type redistribution of solid matter for the uniaxial case is:

$$\partial m_s/\partial t = D\partial^2 m_s/\partial x^2$$

where m_s = mass of minerals per unit volume.
D = diffusion coefficient

A reasonably correct diffusion coefficient for the description of the expansion of non-saturated dense clay with simultaneous water uptake, can be derived from earlier swelling oedometer tests, in which highly compacted specimens were allowed to swell in one direction and fill up a given space, i.e. the same process as we deal with here (PUSCH, 1980a). A finite element analysis$^{1)}$ was run on some of the tests and it yielded a diffusion coefficient of the order of $5\cdot 10^{-11}$ m^2/s (cf. Fig. 22).

If the same analysis is applied to the Stripa borehole (lower part in Fig. 13) we find, by considering the relevant geometry (radial diffusion), that the diffusion coefficient is lower ($\sim 10^{-12}$ m^2/s). This is due, to some minor extent, to the retarding effect of the perforation. The major reason is probably the large spacing of the joints, but it may also be that the flow capacity of the rock joints was a limiting factor. The conclusion is therefore that the rate of maturing is a function of the frequency and width of the water-bearing rock joints.

$^{1)}$The analysis was performed by Sven Knutsson, Div. Soil Mechanics, University of Luleå.

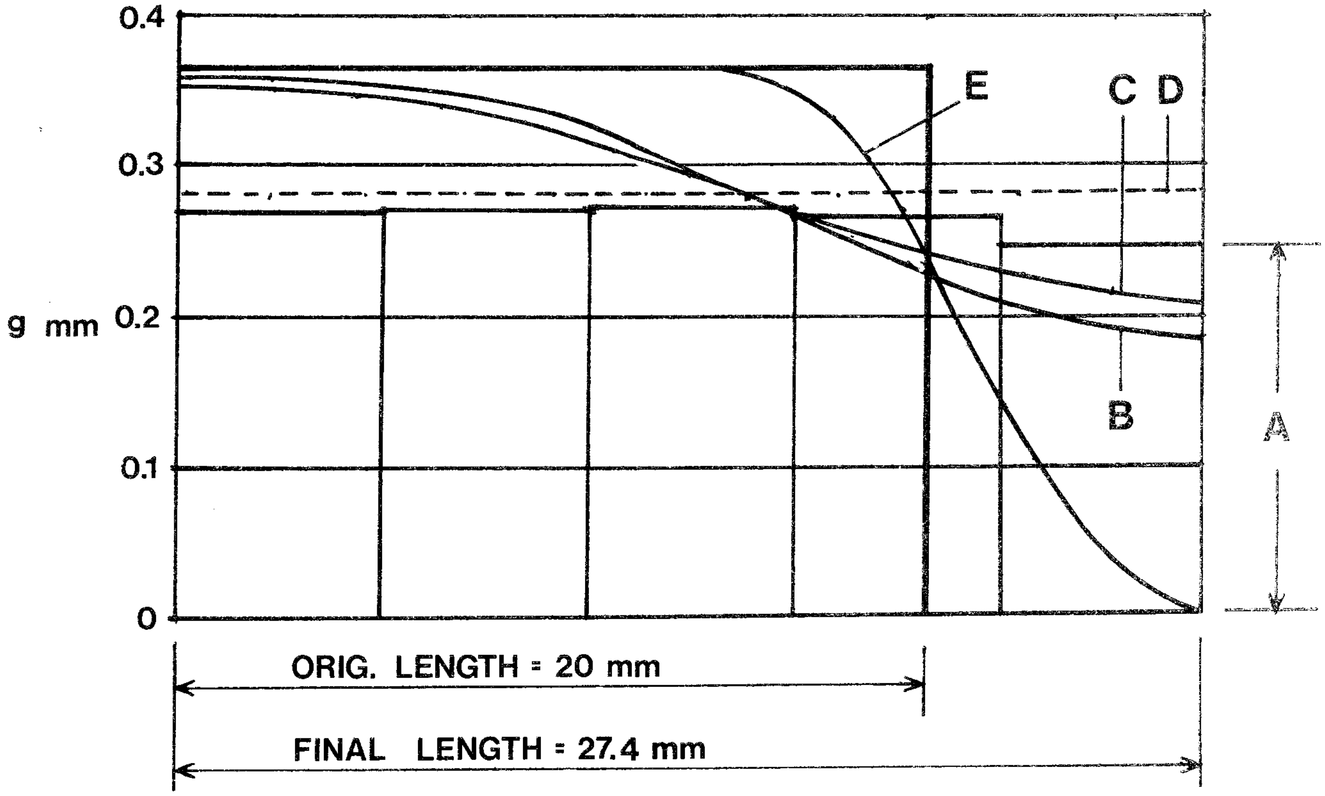


Fig. 22. Example of particle concentration (mass of minerals per millimeter length of core, g/mm) after 7 weeks of diffusion (Test no. 75). A) Experimental,
B) Diff.coeff.=10^{-11} m^2/s, 7 weeks diff.time,
C) Diff.coeff.=10^{-10} m^2/s, 1 week diff.time,
D) Diff.coeff.=10^{-10} m^2/s, 7 weeks diff.time,
E) Diff.coeff.=10^{-12} m^2/s, 7 weeks diff.time.

The fact that a high ground water pressure speeds up the water uptake suggests that access of water is not a limiting factor in deep boreholes. For holes deeper than 50 m it is therefore assumed that the diffusion coefficient $5 \cdot 10^{-11}$ m^2/s is still valid. It yields the average rate of clay redistribution for Stripa-sized holes shown in Fig. 23. The graph can in fact be taken as fairly representative of the swelling process in any deep borehole where there are no limitations with respect to access to water.

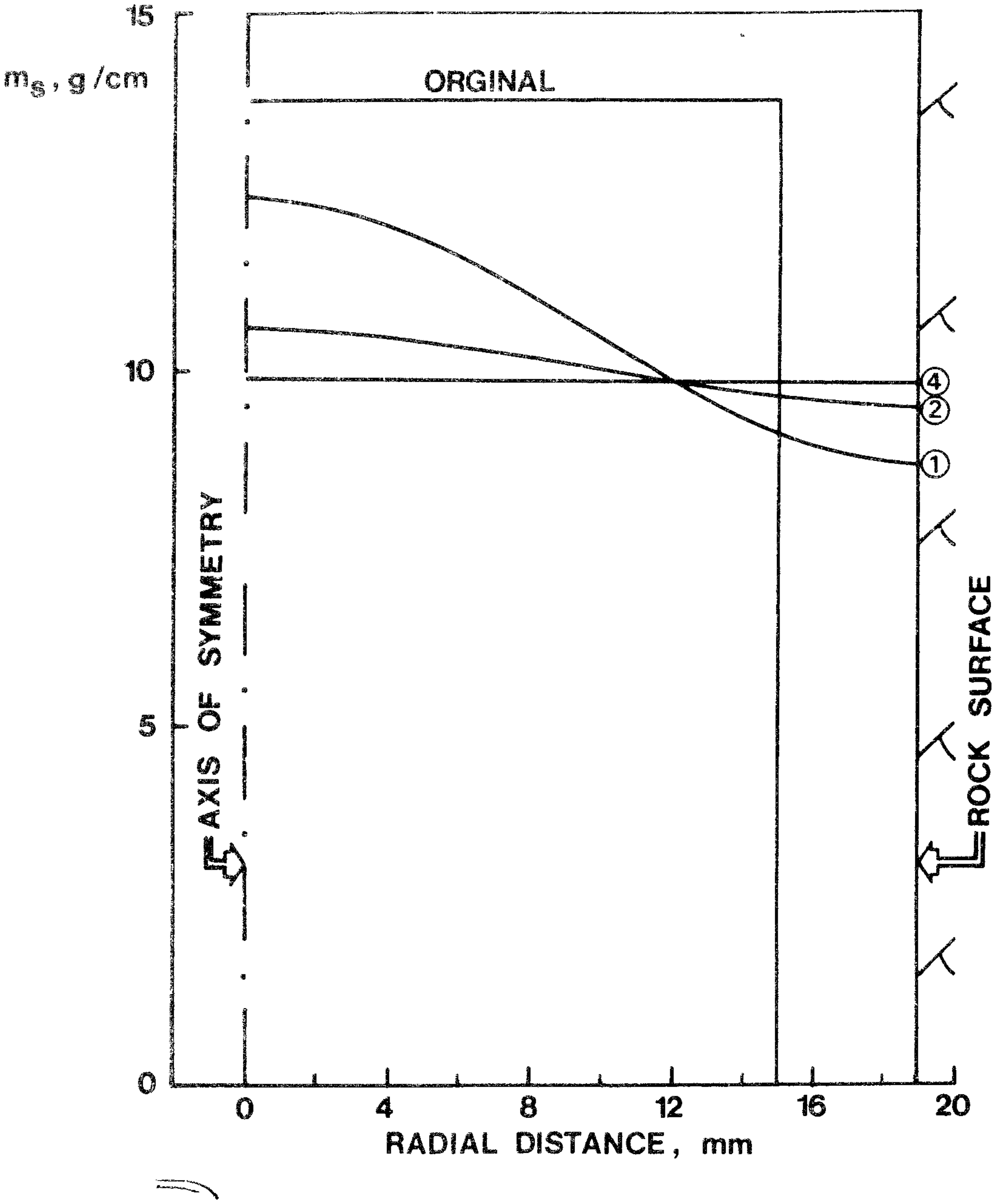


Fig. 23. Redistribution of mineral mass in Stripa-sized, deep boreholes for the diffusion coefficient $5 \cdot 10^{-11}$ m^2/s. The figures refer to the number of weeks after plugging.

ASPECTS OF THE PRACTICAL APPLICABILITY

Handling and storage of bentonite plugs

The highly compacted bentonite elements should be stored in an atmosphere with a relative humidity of less than 60%, since they otherwise absorb moisture and tend to get fissured. This is most easily achieved by keeping the temperature fairly high; ordinary room temperature is preferred. Plugs prepared for a particular sealing project should have the form of rather long segments, 3-10 m, which are filled with bentonite elements, and wrapped in plastic. They can then be stored, transported and handled at the deposition site without any risk of unforeseen changes of the physical status of the bentonite elements.

Application, time aspects

The tremendous swelling ability of the Na bentonite is illustrated by the series of pictures showed in Fig. 23. The stiffness of the protruding clay columns is very low in the first few days since only the originally present water in the slot is absorbed by the clay. This means that also very long plugs can be installed in boreholes with no risk that the pipe gets stuck, provided that the insertion is completed in a few days.

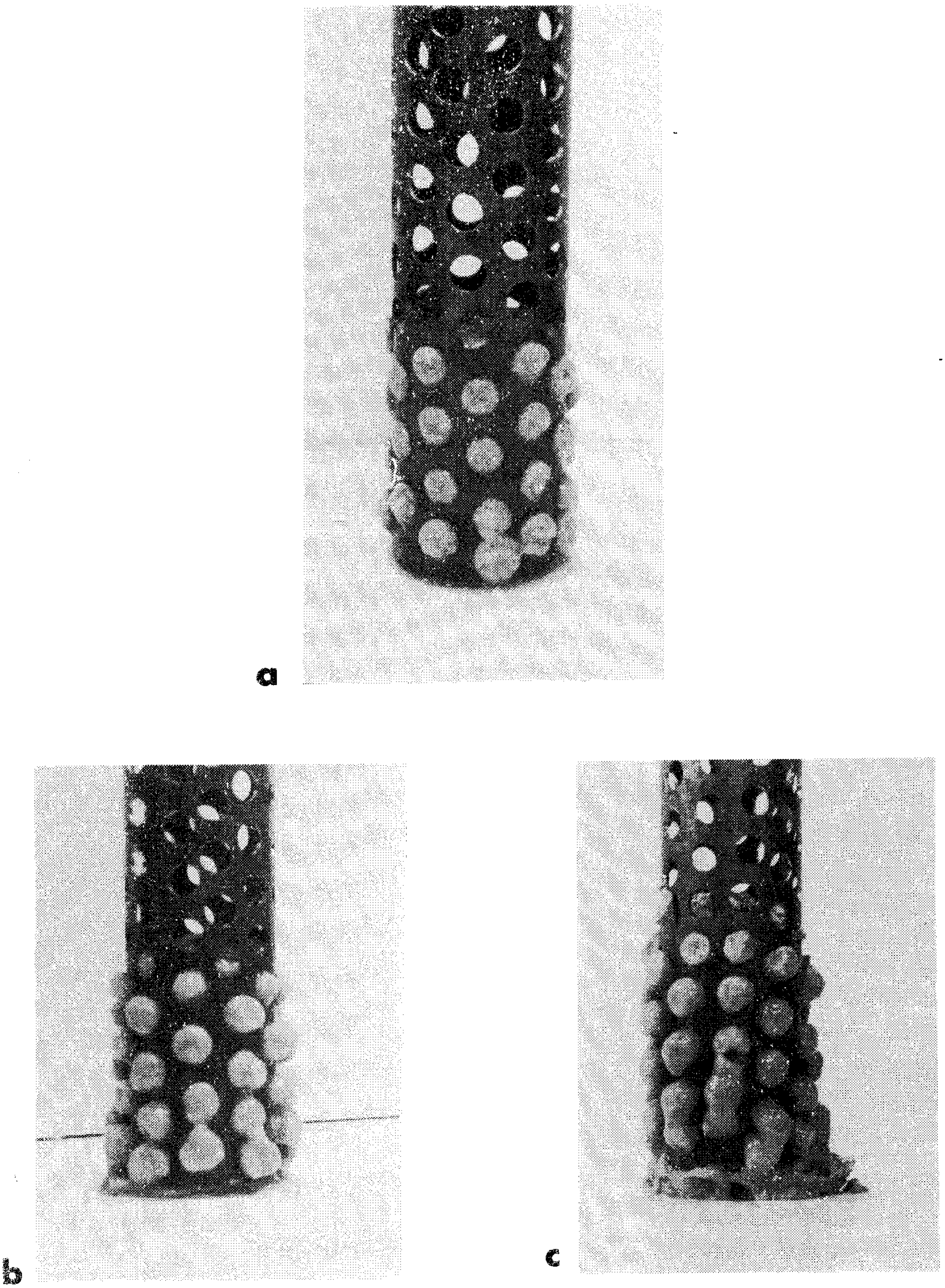


Fig. 24. Stages of swelling in laboratory tests. A copper pipe with highly compacted bentonite elements was submerged in water and lifted out of the bath after a) 1 hour, b) 8 hours, and c) 24 hours, respectively.

Behavior in fractured rock zones

Experience shows that drilling through crushed zones or very fracture-rich rock may displace or set loose rock fragments. This can produce obstacles so that the insertion of the perforated pipe is hindered or that it gets stuck and cannot be either pushed down or pulled up again. To prevent this, pregrouting with cement is required to stabilize the rock. Drilling is then repeated after which the plug is inserted. Ordinary cement may have an unsufficient longevity, however, which suggests the use of other substances, such as magnesium oxide1). This material swells through hydration by which brucite, i.e. one of the elementary crystal lattice components of smectites, is formed. This makes the practically impermeable and mechanically very strong $Mg(OH)_2$ substance chemically stable in any environment in which smectites survive. After the hydration process, the borehole can be opened again to the original width by repeated drilling, and the bentonite plug device can then be introduced. If ordinary cement is used for the same purpose, it may be dissolved after a long period of time, and leave openings between rock elements through which bentonite from the plug can expand and be lost. This suggests the use of coarser plug segments when passing cement-stabilized zones. If these plugs have a till-like granulometry (mainly silt and sand) and only a small content of smectite, they will be fairly low-permeable and resistant to erosion.

Very good rock which does not require stabilization still contains open joints and fissures. Widths of the order of tenths of a millimeter are very common and even about 1 mm wide joints are occasionally observed, while larger openings are usually associated with such a permeable or structurally

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1) Pers.comm. Prof W.S. Fyfe, Univ. of Western Ontario, Can.

unstable rock zone that it calls for grouting. Bentonite will expand and migrate from the plug core into all open joints extending from a borehole by which the beneficial self-sealing property of highly compacted bentonite will be manifested. Since the migration will lead to a reduced density of the bentonite plug, it is essential, however, to predict the rate and extension of the migration and this has been done in preliminary analyses which are presently pursued through a comprehensive study.

The present opinion is that in narrow joints less than 1 mm wide, the rate of bentonite extrusion is very slow except for the first few centimeters of movement that may take place over a few months. The extrusion of dense bentonite will probably not exceed 10 or 20 cm even after thousands of years. Considering here the very small dimensions of boreholes, it is clear that such bentonite losses will lead to a local density drop, it is recommended that grouting be performed where hydraulic conductivity tests, television inspection or other means of borehole logging indicate larger widths of joints and fissures than 0.5 mm.

CONCLUSIONS AND COMMENTS

The valuable isolating properties of highly compacted Na bentonite, which makes it a key substance in the KBS 2 concept, are equally beneficial when the same substance is used to plug boreholes. The technique for production and insertion of bentonite plugs is sufficiently known to allow for full scale application.

The present study offers a basis for the prediction of the sealing processes which will take place when the bentonite interacts with water in the hole. Also, there is sufficient understanding to estimate, roughly, the required time to obtain a relatively homogeneous state of the bentonite; for rock with an average joint frequency of one per meter or higher, very good homogeneity and sealing ability of the clay are expected within a few months after the application of the plug. The observation that a high water pressure speeds up the water uptake of the clay in the peripheral slot, indicates that the state of very good homogeneity will be reached sooner in deep boreholes than under the testing conditions.

Possible influence of altered groundwater chemistry on the plug functions requires attention, finally. It brings up the question whether the microstructure of highly compacted Na bentonite can be altered due to changed groundwater chemistry conditions. While this will hardly happen in the very dense bentonite of the deposition holes in a repository for high level wastes, it is more plausible in the less dense bentonite in boreholes. Thus, at a bulk density of 1.7-1.8 t/m^3 and less, a largely increased salinity of the ground water and especially a higher Ca and Mg content, will most probably yield increased permeability and a drop in swelling pressure and self-sealing ability. No dramatic changes will take place, however, and the plug will still be operative although the efficiency is somewhat reduced.

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