Technical Report

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Can the water content of highly compacted bentonite be increased by applying a high water pressure?

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Abstract

Two attempts were made to moisten highly compacted blocks of MX-80 clay with a dry density of 1510 kg/m^3 by injecting water under a pressure of 650 kPa through a perforated injection pipe for 3 and 20 minutes, respectively. The result was that the water content increased from about 9 to about 11–12% within a distance of about 1 centimeter from the injection pipe and to slightly more than 9% at a distance of about 4–5 cm almost independently of the injection time. Complete water saturation corresponds to a water content of about 30% and the wetting effect was hence small from a practical point of view. The moderate effect is concluded to be caused by quick closure of channels through expansion of the hydrating surrounding clay, and by the clogging effect of transported clay particles. It is estimated that a higher injection pressure, i.e. 2–3 MPa, should yield much more effective wetting while an injection time exceeding a few minutes will not improve it. Injection of a very salt solution is expected to be even more effective.

Content

Sammanfattning

Ett stort antal laboratoriebestämningar har visat att vattenupptagningen i högkompakterad lera av typ MX-80 vid låga tryck sker genom diffusion. Det innebär att bevätningen av bufferten i deponeringshålen i ett KBS3-förvar sker mycket långsamt om vattentrycket i berget är lågt och att full vattenmättnad kan ta flera decennier om buffertens ursprungliga vattenmättnadsgrad är låg och bergets förmåga att avge vatten är ringa. Frågan har därför uppkommit om injektering av vatten i de högkompakterade blocken kan bidra till snabbare bevätning och om högt vattentryck i närfältberget kan ge samma verkan.

I denna rapport redovisas försök till bevätning av högkompakterade block av MX-80 med en torrdensitet av 1510 kg/m^3 genom injektering av vatten under ett tryck av 650 kPa via ett perforerat injektionsrör i 3 respektive 20 minuter. Tolkningen skedde genom att bestämma vattenkvoten i ett stort antal prover på olika avstånd från injekteringsröret. Försök att genom användning av SEM-EDX fastställa spridningsmönstret hos injekterad uranacetatlösning visade att de kanaler som lösningen följde självtätade på några få minuter och att dispersion i den homogeniserade leran gav en låg U-koncentration.

Resultatet blev att vattenkvoten förhöjdes från ca 9 till 11–12% inom någon centimeters avstånd från injekteringsröret och till obetydligt mer än 9% på 4–5 cm avstånd oberoende av injekteringstidens längd. Total vattenmättnad motsvarar ca 30% vattenkvot och bevätningsffekten blev alltså ringa från praktisk synpunkt. Med användning av mikrostrukturella modeller kan det visas att det injekterade vattnet följde enbart de vidaste kanaler som kvarstår efter kompakteringen och att dessa kanaler snabbt stängdes genom att omgivande lermaterial tog upp vatten och svällde. En del av de partiklar som härvid frigjordes transporterades med det inströmmande vattnet och åstadkom igensättning av kanalerna, vilket var ytterligare ett skäl till att vatteninträngningen upphörde efter några få minuter.

En bedömning är att högre injektionstryck, 2–3 MPa, bör ge betydligt effektivare bevätning men att längre injekteringstid än några få minuter inte ger bättre verkan. Injektering av en mycket salt lösning bör vara särskilt effektiv.

Summary

A great many laboratory investigations have shown that the water uptake in highly compacted MX-80 clay takes place by diffusion at low external pressure. It means that wetting of the clay buffer in the deposition holes of a KBS3 repository is very slow if the water pressure is low and that complete water saturation can take several tens of years if the intial degree of water saturation of the buffer clay and the ability of the rock to give off water are low. It has therefore been asked whether injection of water can raise the degree of water saturation and if a high water pressure in the nearfield can have the same effect.

The present report describes attempts to moisten highly compacted blocks of MX-80 clay with a dry density of 1510 kg/m^3 by injecting water under a pressure of 650 kPa through a perforated injection pipe for 3 and 20 minutes,respectively. The interpretation was made by determining the water content of a number of samples located at different distances from the pipe. An attempt to interpret the pattern of distribution of injected uranium acetate solution showed that the channels into which the solution went became closed in a few minutes and that dispersion in the homogenized clay gave low U-concentrations.

The result was that the water content increased from about 9 to about 11–12% within a distance of about 1 centimeter from the injection pipe and to slightly more than 9% at a distance of about 4–5 cm almost independently of the injection time. Complete water saturation corresponds to a water content of about 30% and the wetting effect was hence small from a practical point of view. By use of microstructural models it can be shown that injected water enters only the widest channels that remain after the compaction and that these channels are quickly closed by expansion of the hydrating surrounding clay. Part of the particles that are thereby released become transported by the flowing water and cause clogging of the channels, which is another reason why the inflow ceases after a few minutes.

It is estimated that a higher injection pressure, i.e. 2–3 MPa, should yield more effective wetting but that an injection time exceeding a few minutes will not improve it. Injection of a very salt solution is expected to be particularly effective.

1 Scope

Several series of laboratory investigations have been made earlier in order to determine how water is taken up by highly compacted MX-80 clay and the present view is that the wetting of dense buffer clay takes place by diffusion at low external water pressure. It means that wetting of the clay buffer in many deposition holes of a KBS3 repository is very slow and it has been concluded that it may take several decades to reach a high degree of saturation. Since the heat-generation caused by the canisters results in temporary drying of a considerable part of the buffer, which raises the temperature, a technique has been worked out in SKB's R&D work to give the compacted blocks a high degree of water saturation by moistening the clay powder to be compacted. The present study aimed at investigating whether another techniqe, injection of water in freshly prepared buffer blocks, can raise the degree of water saturation and if a high water pressure in the nearfield of KBS3 deposition holes can have the same effect.

2 Test plan

Cylindrical samples with 10 cm diameter and 6 cm height were prepared by compacting air-dry powder of MX-80 clay in a steel form. A hole was drilled for a central perforated pipe with 5 mm diameter that was pushed in before closing the cell. Two tests were made, one with uranium acetate solution and the other with ordinary tap water. The injection pressure was 650 kPa and the injection time 3 minutes in the test with uranium solution and 20 minutes in the tap water injection test.

Evaluation of the water injection tests was made by determining the water content of samples extracted at different distances from the injection pipe. The test with uranium acetate was made in order to try to identify the pathways of water injected in highly compacted MX-80 clay. Interpretation was made by use of SEM-EDX, i.e. element analysis technique in conjunction with scanning electron microscopy.

The clay powder had a water content of 8.90% in the uranium solution test and 8.70% in the water injection test. The clay dry density in both tests was 1510 kg/m^3.

The uranium acetate solution had a concentration of 0.1%. The tap water had an electrolyte content of less than 0.05% with sodium as major cation.

3 Equipment

The cell used for the tests is shown in Figure 3-1. The compaction pressure 30 MPa was maintained for about 10 seconds and yielded a dry density of 1510 kg/m^3.

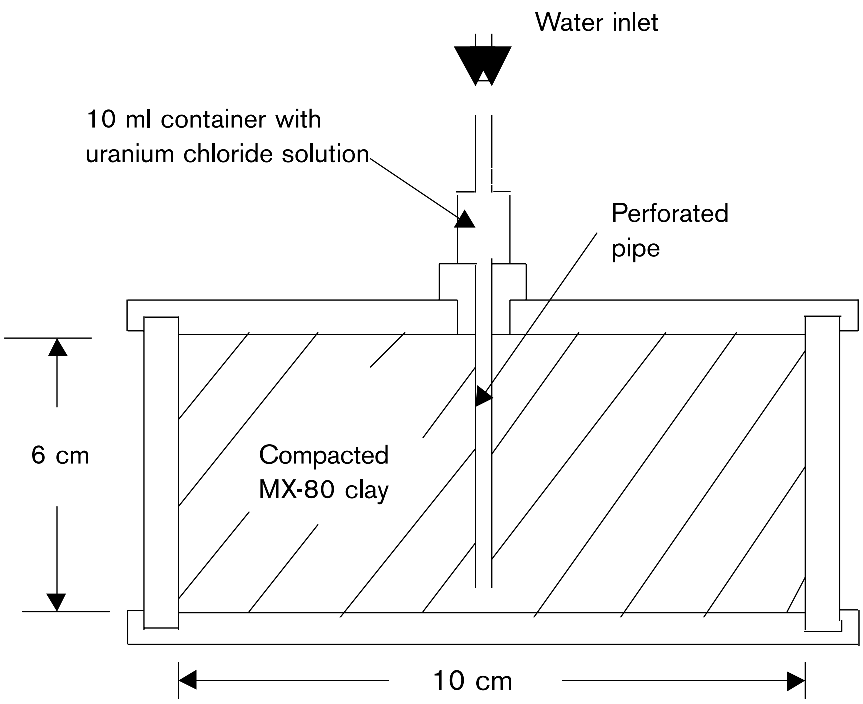

Figure 3-1. Cell in which clay powder was compacted. The lower picture shows the cell with lid and bottom plate removed and samples being extracted for determination of the water content distribution and for microstructural analyses after the water injection.

4 Results

4.1 Test with uranium acetate solution

4.1.1 Water content

The determination of the water content gave the results in Figure 4-1, from which one concludes that the water content rose from about 8.90 to an average content of 12% within a distance of about 1 centimeter from the injection pipe, and to an average content 11% at 1–2 cm distance, and to 10% at 2–3 cm distance. At about 4 cm distance the water content was increased insignificantly and at 5 cm distance no change could be found. Complete water saturation would correspond to a water content of about 30% and the wetting effect was hence small from a practical point of view.

4.1.2 Flow distribution

The distribution of water in the injected sample is shown in Table 4-1. The volume fraction of the total amount of water, 3.92 g, that went into the clay was smallest for the innermost 0–1 cm annulus since it had the smallest volume, and largest for the 2–3 cm annulus, which had the largest volume. However, the water uptake in percent of the respective clay volumes was highest for the 0–1 cm annulus (4.7%), intermediate for the 1–2 cm annulus (3.1%), and lowest for the 2–3 cm annulus (1.5%).

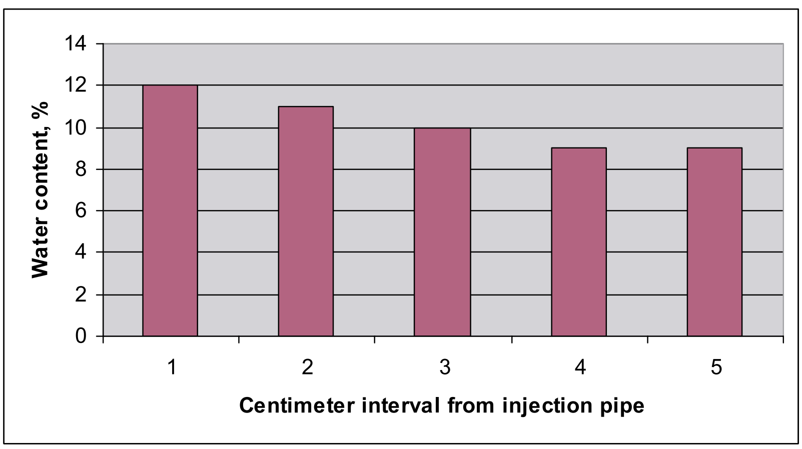

Figure 4-1. *Water content distribution in the uranium acetate solution experiment. The initial water content was 8.90%.*

Table 4-1. Distribution of water in the sample

Volumes	Clay annulus within 1 cm from the pipe	Clay annulus within 1 to 2 cm from the pipe	Clay annulus within 2 to 3 cm from the pipe
Clay volume, cm^3	18.6	54.0	90.0
Injected water volume, cm^3	0.87	1.70	1.35
Fraction of total amount of injected water (3.92 cm^3)	23%	43%	34%

Samples were cut from the clay for determination of the flow paths using SEM-EDX technique and local uranium patches could be found, indicating that this element had migrated in channels and from there into the surrounding clay matrix yielding a very low U-concentration. Figure 4-2 shows such matrix near the injection pipe and element spectra. The matter is further discussed in Chapter 5.

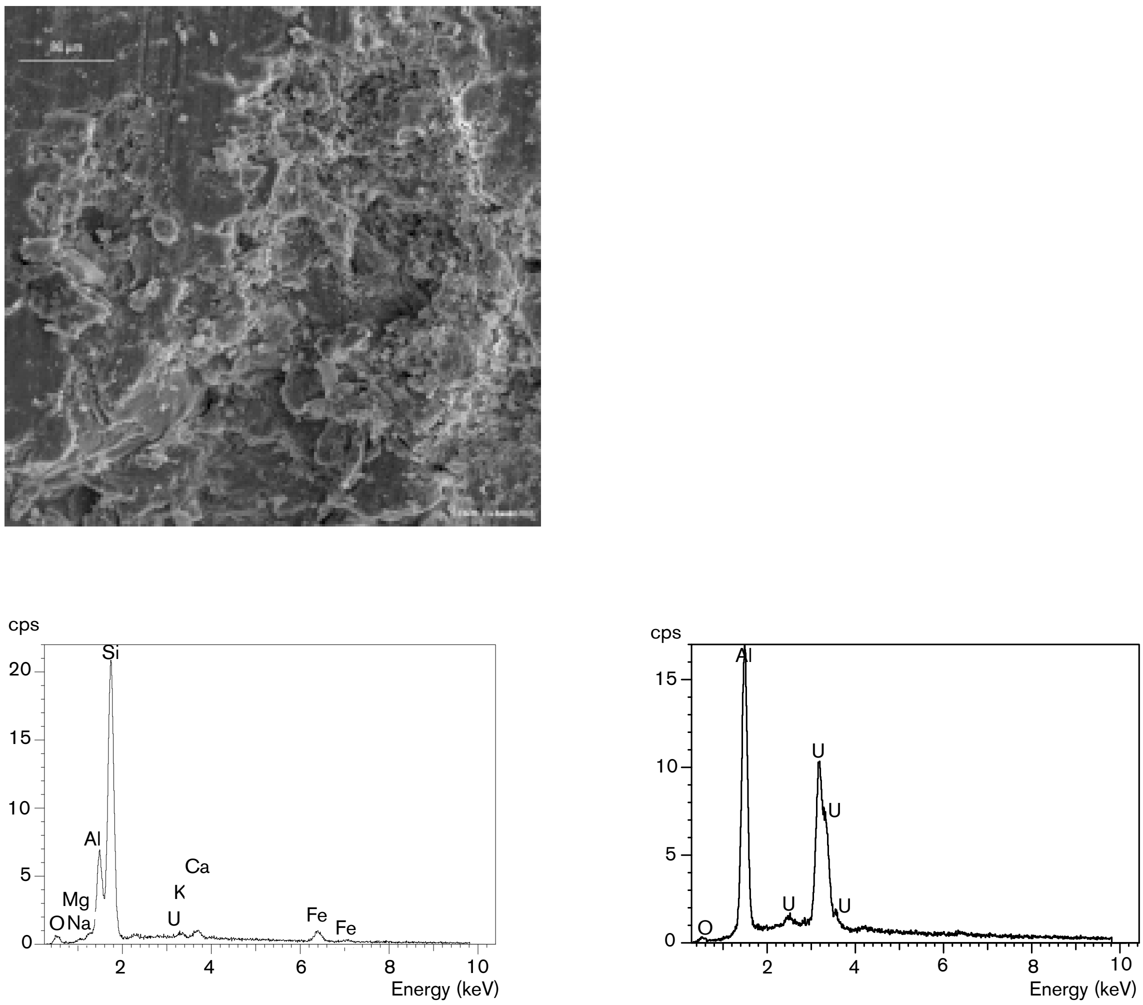

Figure 4-2. *SEM-EDX examination of MX-80 samples with a dry density of 1510 kg/m3 into which uranium acecate solution was injected. Upper : SEM picture (250x magnification). Lower left: U-traces in the analyzed area. Lower right: Calibration test with uranium solution on an aluminum sample holder.*

4.2 Test with tap water

4.2.1 Water content

The determination of the water content gave the results in Figure 4-3, which shows that the water content rose from about 8.70% to an average content of 13% within a distance of about 1 centimeter from the injection pipe, and to an average content 12% in the interval 1–2 cm distance, and to 10% at 2–3 cm distance. For the interval 3–4 cm the water content was increased insignificantly, i.e. to the average value 9%, and for the 4–5 cm distance the same very slight increase was recorded. As for the uranium solution test the wetting effect was hence small from a practical point of view.

4.2.2 Flow distribution

The distribution of water in the injected sample is shown in Table 4-2. The volume fraction of the total amount of water, 4.81 g, that went into the clay was lowest for the innermost annulus of which it made up 4.7%, than for the 1–2 cm annulus of which it made up 3.1%. The 2–3 cm annulus took up 1.5% of its volume.

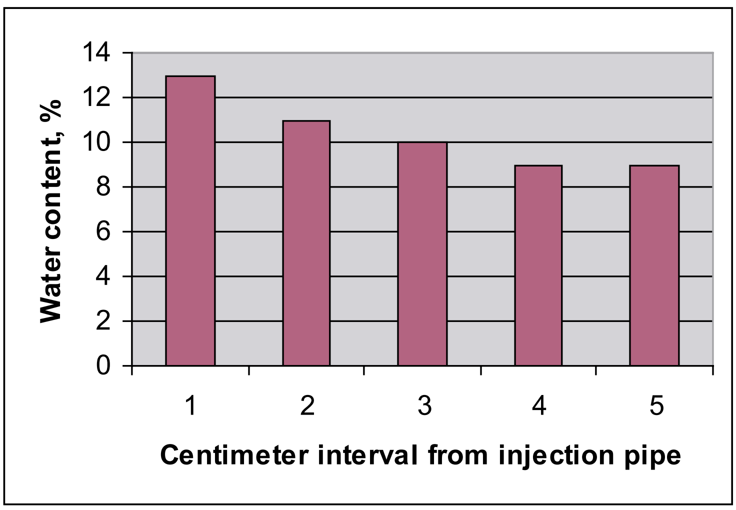

Figure 4-3. *Water content distribution in the tap water experiment. The initial water content was 8.70%.*

Table 4-2. Distribution of water in the sample

Volumes	Clay annulus within 1 cm from the pipe	Clay annulus within 1 to 2 cm from the pipe	Clay annulus within 2 to 3 cm from the pipe
Clay volume, cm^3	18,6	54.0	90.0
Injected water volume, cm^3	1.20	1.86	1.75
Fraction of total amount of injected water (4.81 cm^3)	24.9%	38.7%	36.3%

The difference between the tests with uranium solution and tap water was rather small, meaning that the prolonged injection did not bring in much more water. Still, about 50% more water went into the 0–1 cm annulus in the 20 minutes long test with tap water, while the difference in injected amounts of water into the 1–2 and 2–3 cm annuli as compared to the 3 minutes long injection of uranium acetate solution was smaller. The fact that practically no increase in water content was recorded beyond the 2–3 cm annulus in the longer test demonstrates that the pressure at the wetting front was not sufficient to cause deeper penetration. This can be explained by a strong reduction in void size in the already penetrated clay caused by hydration and by particle transport yielding clogging of the voids at the wetting front.

5 Microstructural aspects

5.1 General

The study has a considerable scientific value by giving insight in how water penetrates into the more or less continuous void system of compacted clay powder. This is obvious by considering microstructural models and comparing the void space available for filling with water calculated by use of such models with the measured water uptake.

5.2 Microstructural modelling

5.2.1 Space that can be filled with water

The strain produced by compressing air-dry MX-80 clay powder can be calculated in 3D by considering the grain size distribution and physical properties of the bentonite grains /1/. Taking the initial powder grains to be spherical and form unit cells consisting of one eighth of a big grain (0.35 mm diameter) and 1 small grain (0.10 mm diameter), which roughly matches the granular distribution of MX-80 powder, one finds that the initial ”effective” porosity (i.e. excepting the small voids in the granules) is 47%. A unit cell is shown in Figure 5-1.

The resulting uniaxial deformation of the unit cell with 0.175 mm edge length under 100 MPa pressure is about 0.05 mm, yielding a total uniaxial compressive strain of the system of 28%. The final ”external” porosity is illustrated in Figure 5-2 as a function of the dry bulk density. For the dry density 1510 kg/m^3 obtained in the present tests it was about 26%, which hence represents the volume of water in percent of the total volume that would be required to completely saturate the clay sample.

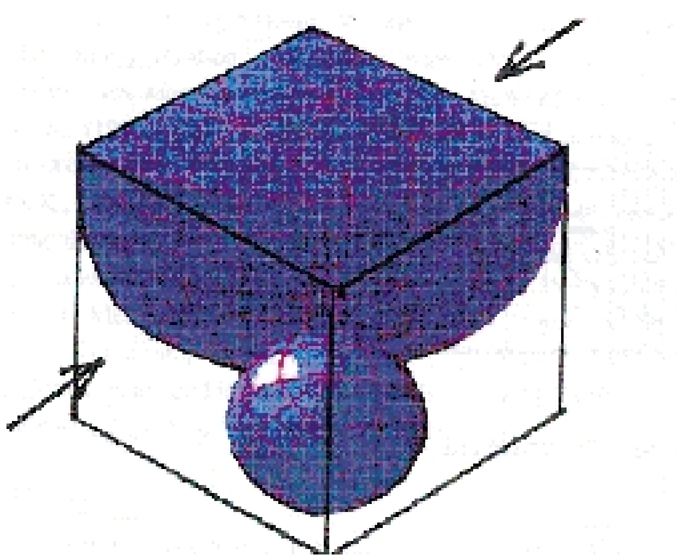

Figure 5-1. *Unit cell with 1/8 of big grain (0.35 mm) contacting one small grain (0.10 mm). The edge length of the cubical cell is 0.175 mm. Arrows show assumed compression direction.*

5.2.2 Void geometry

The system of interconnected voids in the compacted clay has a varying cross section area as indicated in Figure 5-3. Taking the voids to form channels and assuming that they have a circular cross section with a diameter that is normally distributed, one can use the categorization scheme in Table 5-1 for more detailed description of the void network. It is based on microscopic examination of compacted block surfaces and on computer-derived evaluation of parallel, consecutive sections of a uniaxially compressed unit cell, which showed that there are open voids in all sections consisting of two to three channels with 10–20 mm diameter in the tightest ones, while in the most open sections there are three channels with up to 80 mm width. Following earlier worked out microstructural theorems /2/ the volumetric n_3 and two-dimensional n_2 porosities are taken to be related as n_2/n_3 =1.3 for a dry density of 1510 kg/m³.

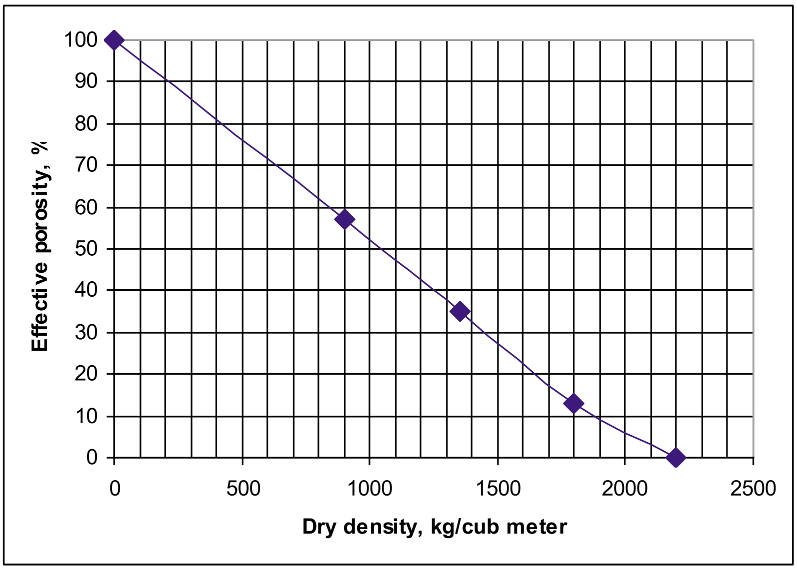

Figure 5-2. *Effective porosity versus dry bulk density of MX-80 clay consisting of grains with a water content of about 10%.*

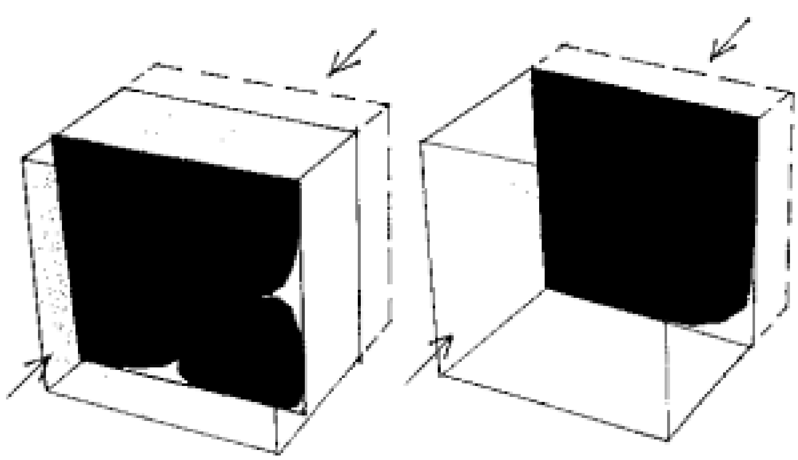

Figure 5-3. *Compression of MX-80 powder showing the axial shortening of the unit cell and resulting permeable "external" voids forming channels in two sections (0.175 mm edge length) normal to the compression.*

Table 5-1. Cross section area of channels representing the effective porosity of clay prepared by compaction of air-dry powder. Area in percent of total cross section area

Bulk dry density, kg/m³	Effective porosity,% (3D)	Effective porosity,% (2D)	Channel diameter 50–100 µm	Channel diameter 10–50 µm	Channel diameter 1–10 µm
1800	13	17	12	4	1
1510	26	34	24	7	3
1350	35	46	32	10	4
900	57	74	53	15	6

Using the data in Table 5-1 one can calculate the volume represented by the different channel categories in the respective annuli, the results being compiled in Table 5-2.

Table 5-2. Volume of channel categories in clay annuli of the investigated clay (26.0% effective porosity)

Volumes	"External" void space, cm³	Volume of 50–100 µm channels, cm³	Volume of 10-50 µm channels, cm³	Volume of 1–10 µm channels, cm³
0–1 cm from the pipe	4.83	1.13	3.39	0.38
1–2 cm from the pipe	14.04	3.39	10.17	1.14
2–3 cm from the pipe	23.40	5.66	16.77	1.90

3.3.3 Void filling

Flow paths

The increase in water content recorded in the tests is given in Table 5-3, from which one concludes that the "effective" void space was filled to 18–25% in the 1 cm annulus surrounding the injection pipe, and that the corresponding degree of saturation was 12–13% in the annulus extending from 1 to 2 cm distance from the pipe. The figure was about 6% for the annulus extending from 2 to 3 cm distance.

Table 5-3. Water uptake in cm³ and % of the "effective" void space of the respective annulus surrounding the injection pipe

Annulus	Volume of annulus, cm³	Effect. void space, cm³	Uranium solution		Tap water	
			Volume, cm³	Degree of filling of void space, %	Volume, cm³	Degree of filling of void space, %
0 to 1 cm from injection pipe	18.6	4.83	0.87	18.0	1.20	24.8
1 to 2 cm from injection pipe	54.0	14.04	1.70	12.1	1.86	13.2
2 to 3 cm from injection pipe	90.0	23.40	1.35	5.8	1.75	5.8

If it is assumed that water entered only the widest channels it would mean that the degree of filling of these voids in the 0–1 cm annulus was about 75–100%. For the 1–2 cm annulus the corresponding degree of filling would have been about 50%, while it would be about 25% for the 2–3 cm annulus. The attenuation suggests that very little water could have entered the clay beyond the latter annulus, which is hence in perfect agreement with the observations.

Flow rate

The reason why only very little additional water went into the clay after 3 minutes is believed to be the expansion of the clay grains by which the aperture of the penetrated channels started to decrease. Depending on the orientation and hence expandability of the grains some ”external” voids became closed while a few may maintained their cross section, the net result being a stronger tortuosity of the channels and increased flow resistance.

It is known that grain expansion by hydration is associated with exfoliation of stacks of smectite lamellae from the grains and that these stacks rearrange to form more or less dense clay gels in the contracting external voids /3/, cf. Figure 5-4. This process, which must have been significant in the present experiments already in the first few minutes after exposing the grains to liquid water, further reduced the permeable space and retarded water penetration. It is also known that flowing water erodes particles and aggregates from soft gels (Figure 5-5) and this is believed to have caused migration of released aggregates towards the tips of the permeated channels, where they accumulated and made further water penetration difficult.

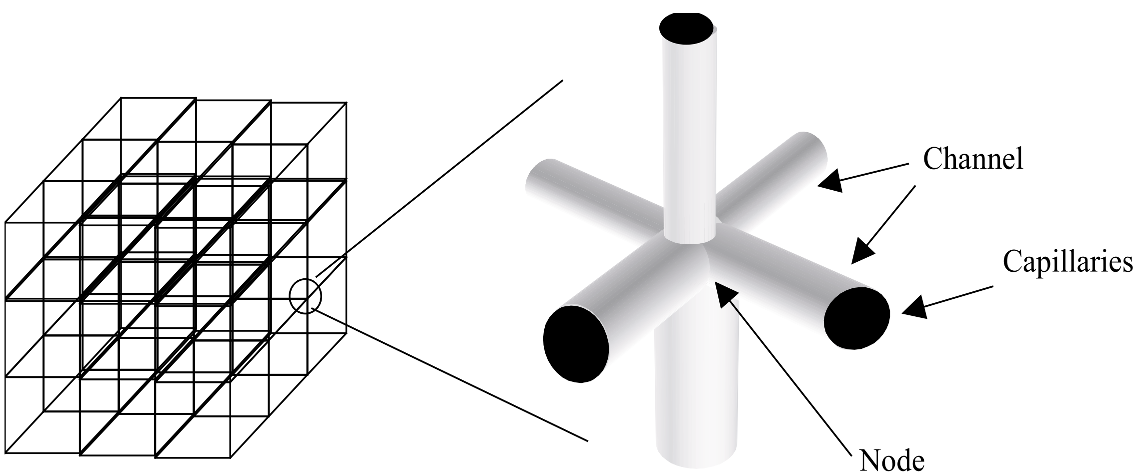

Figure 5-4. *Channel network mapped as a cubic grid with channels intersecting at a node in the grid /3/.*

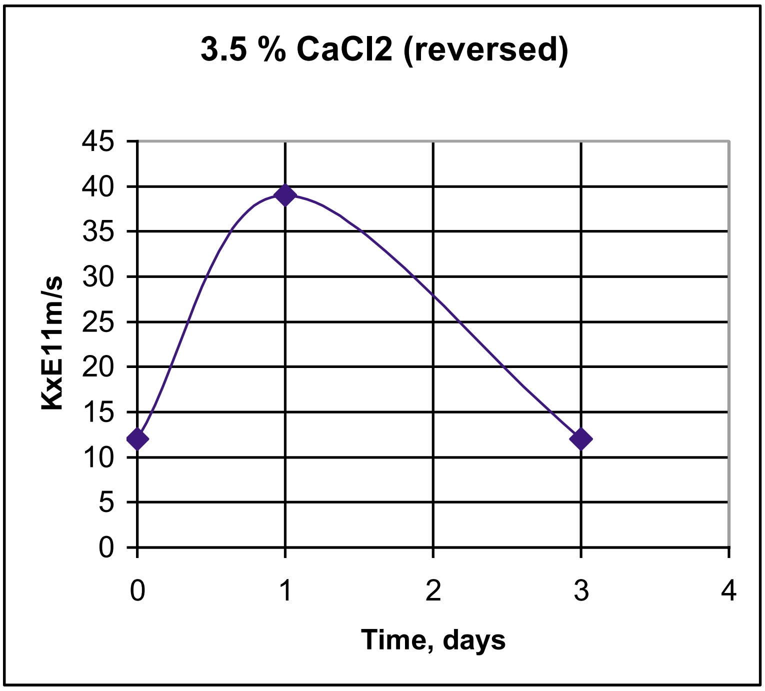

***Figure 5-5**. Example of successive clogging of channels in smectitic clay by transported particles. Change in hydraulic conductivity by reversing the flow direction /4/.*

Uranium tracer experiment

The hydration associated with the injection of water explains why concentrated channel-type uranium patches were not detected despite the extensive SEM-EDX work that was made on extracted samples. Thus, the channels into which the solution went became closed in a few minutes by the expanding clay grains, which caused dispersion of the uranium into the surrounding clay to an extent that gave rather low U-concentrations where this element could at all be detected.

6 Discussions and conclusions

6.1 Main findings

A very important conclusion from the two tests is that very little water entered the compacted clay after 3 minutes under the applied pressure. The main reason for this is believed to be:

- Drop in water penetrability by quick reduction in size of the large water-filled channels through expansion of the clay grains that became wetted by uptake of water from the channels.
- The flow paths became more tortuous through the grain expansion, which increased the flow resistance.
- Exfoliation of stacks of lamellae formed clay gels in the contracting external voids, which further reduced the permeable space and retarded and practically stopped water penetration.
- Clay gels formed from particles released from hydrating grains were sensitive to erosion and disintegrated. In the experiments this caused migration of released aggregates towards the tips of the permeated channels, where they accumulated and made further water penetration difficult.

6.2 Means of increasing water penetration

A major conclusion from the study was that injection of water under 650 kPa pressure into compacted MX-80 clay with about 9% water content and a dry density of 1,510 kg/m^3 does not increase the average water content significantly. Within 1 cm distance from the injection pipe the water content was raised to 11–12% but beyond this distance wetting was not significant.

It seems probable that an increase in water pressure to 2–3 MPa would greatly increase the penetration depth and degree of saturation. This is because both major and less wide channels will be filled with water that is forced in at the injection even at larger distance from the injection point. Still, even at these pressures water penetration would probably be effective only in the first few minutes.

Preliminary tests have shown that the wetting of dense bentonite blocks increases if the water is very salt. This means that injection of a strongly saline solution with electrolytes that do not compromise the corrosion resistance of the canisters, preferably NaCl and $CaCl_2$, will speed up the wetting process. Similarly, saline groundwater under high pressure is expected to increase the saturation rate. The reason for this effect is that the reduction in channel size is less than when the water is poor in electrolytes because the expansion of the grains is smaller, and also that the clay gels formed by exfoliated clay are much more permeable due to coagulation in salt water.

6.3 Aspects on the rate of buffer saturation in KBS3-holes

It appears that if the water pressure in lower parts of KBS3 deposition holes is high, which is assumed to be a normal case, the penetration of water into the buffer blocks may speed up the saturation rate beyond what ordinary diffusion would cause /5/. Salt water will contribute to this effect.

References

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