

**Influence of Cementation on the  
Deformation Properties of  
Bentonite/Quartz Buffer Substance**

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Högskolan i Luleå 77-06-20

Objekt 21.10

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I slutet av rapporten har bifogats en förteckning över av KBS hittills publicerade tekniska rapporter i denna serie.

Report on

## INFLUENCE OF CEMENTATION ON THE DEFORMATION PRO- PERTIES OF BENTONITE/QUARTZ BUFFER SUBSTANCE

Luleå 1977-06-20

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INFLUENCE OF CEMENTATION ON THE DEFORMATION PROPERTIES  
OF BENTONITE/QUARTZ BUFFER SUBSTANCE

GENERAL

Cementation, e.g. precipitation of crystalline or solid amorphous inorganic substance between individual grains, greatly affects the mechanical properties of fine-grained soils. Several processes can cause such precipitation, i.a.:

- "Pressure solution" due to high grain-contact pressure
- Precipitation of  $\text{SiO}_2$  which is dissolved from quartz particles and enriched in the interstitial pore space
- Precipitation of  $\text{SiO}_2$  caused by in situ transformation of montmorillonite to hydrous mica (illite)
- Precipitation of  $\text{SiO}_2$  which is dissolved in supersaturated percolating ground water
- Precipitation of other substances, such as carbonates and iron compounds, by percolation of ground water in which such substances are dissolved.

Such effects are illustrated by Figs. 1-3.

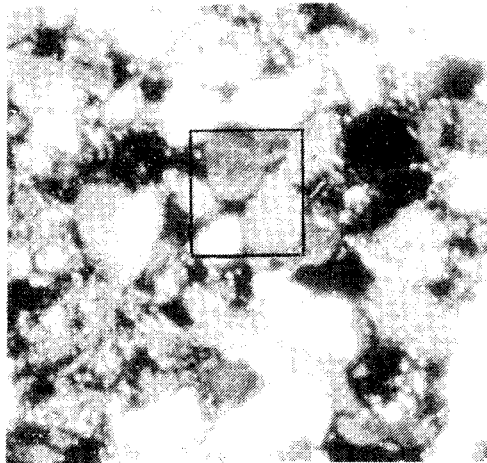


Fig. 1. Thin section of Silurian siltstone from Gotland. A number of interpenetrating grains can be seen which indicates that the overburden pressure has been very high, at least corresponding to 1000 m overlaying sediments. Glacier loads may have caused such pressures. (Magnification about 100 x)



Fig. 2. Clay-sized particles in Cerithium limestone connected and covered by calcium carbonate cement.

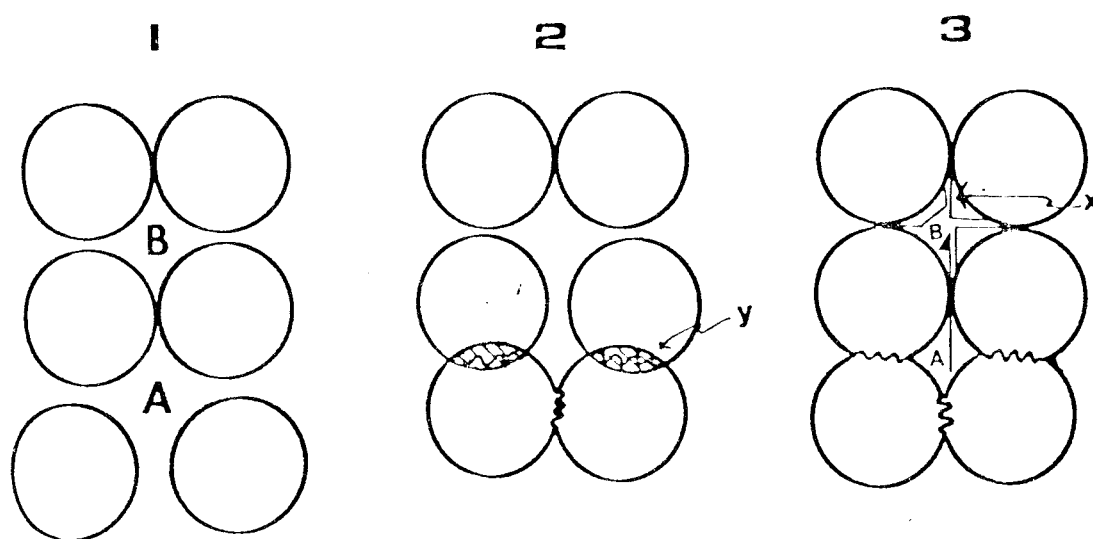


Fig. 3. Sequence of stages in the development of sand grains cemented by pressure solution. In Stage 1 the sand has not yet been compacted. In Stage 2 pressure solution has begun, decreasing the volume of pore space A. In Stage 3 some fluid from A escapes to B, reduces pressure and precipitates quartz. Point X in 3 shows an area which would be identified as authigenic quartz and point Y would be identified as pressure solution in a model analysis. (Modified from Siever, 1962)

As concerns the buffer mass with the composition suggested in the LuH report KBS 1 (10 weight percent bentonite and 90% quartz particles) the intergranular contact pressure between the quartz particles (which form a continuous or almost continuous network, cf Fig. 4) will not be able to cause "pressure solution" (see report KBS 1). Also, the other possible cementation effects will be negligible with the exception of the process which leads to precipitation of  $\text{SiO}_2$  dissolved from quartz particles and enriched in the interstitial pore space. This process and its consequences will be treated in this report.

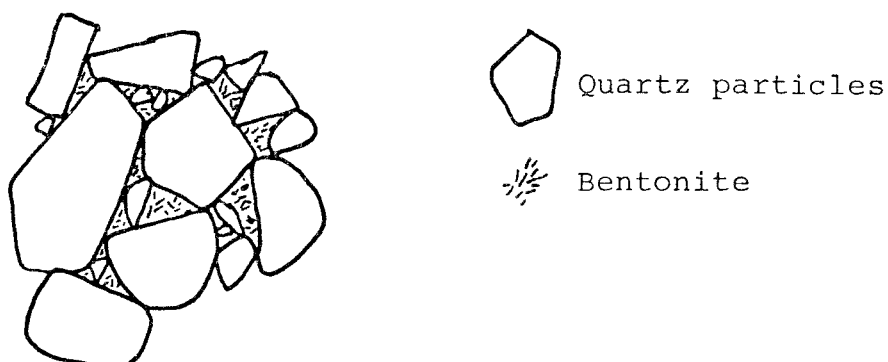


Fig. 4. Schematic microstructural arrangement of the buffer mass.

#### SCOPE OF INVESTIGATION

When the (non-cemented) buffer mass is dry, partially or entirely water saturated, it will behave as a clastic frictional soil with plastic properties, which means that any stress change will produce permanent deformation. The deformation, which is time-dependent, is due to rotation and translation (see Fig. 5) of the majority of the individual particles but the continuity of the quartz grains will be preserved to a large extent. This means that stress changes or forced deformation (for instance in connection with differential movements in the rock in which the buffer-containing tunnel is located) will not cause cracks, fissures or any type of open space.

If cementation occurs, however, the material may behave as a brittle substance where failure is manifested by cracks, fissures etc (Fig. 6). It is therefore important to investigate how and to what extent  $\text{SiO}_2$  cement affects the mechanical properties of the buffer mass.



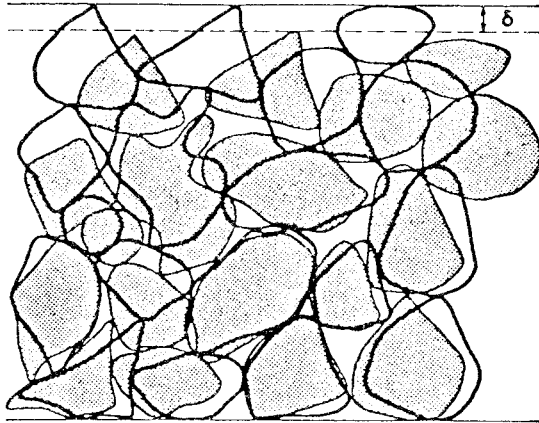


Fig. 5. Grain movements in a compressed granular mass.  
(M Jacobsen).

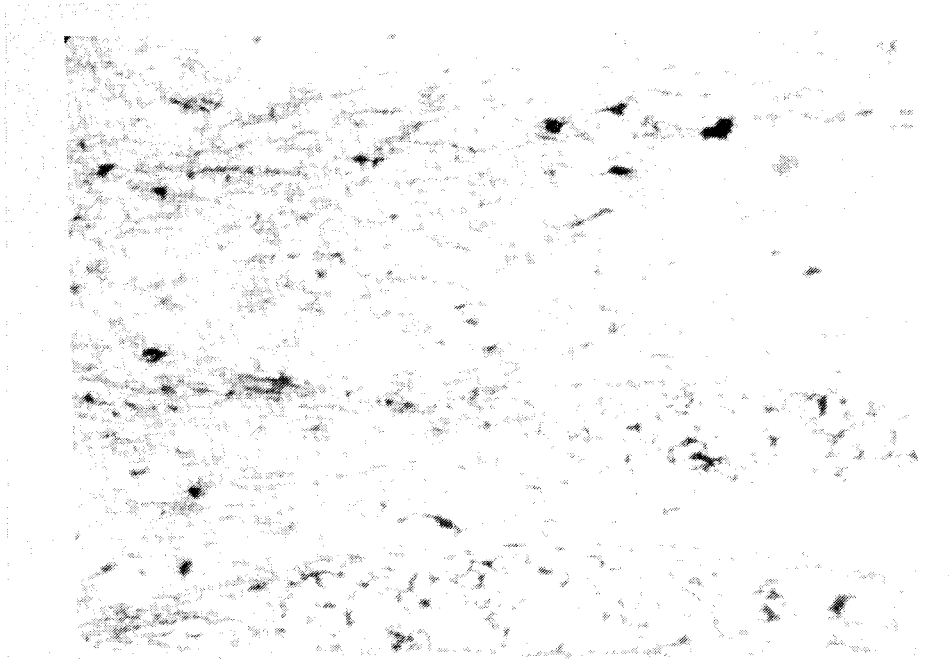


Fig. 6. Microfissures in cemented clay/silt (Tretaspis shale). Magnif 10 x.

The problem will be treated in the following way:

- General discussion of the stress/strain properties
- Theoretical treatment of the influence of the amount of cement on the shear strength
- Formulation of a phenomenologic model
- Survey of relevant cases

#### STRESS/STRAIN RELATIONSHIPS

The main differences between the stress/strain behaviour of non-cemented (sand) and cemented (sandstone) quartz grain masses is shown by Fig. 7.

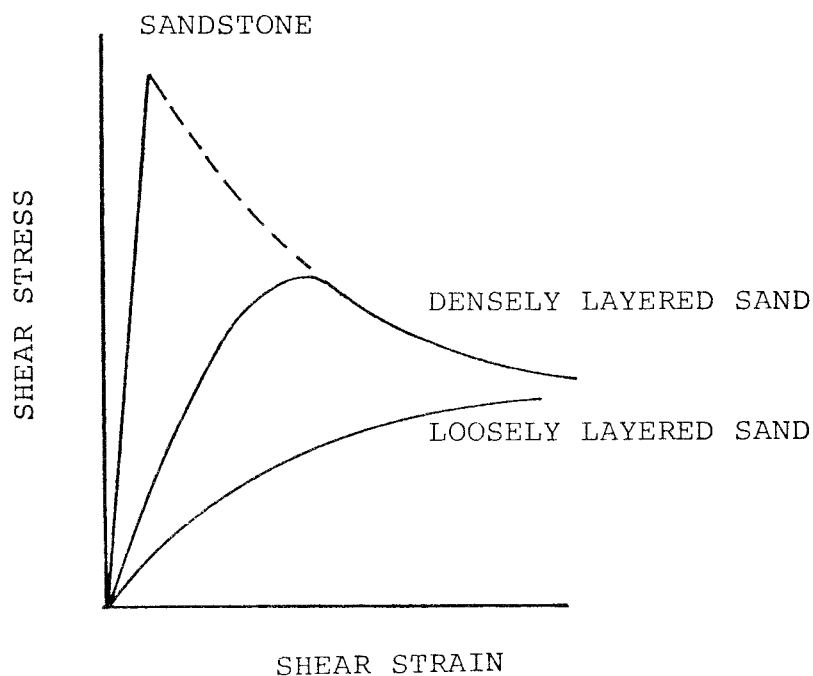


Fig. 7. Stress/strain relationships in simple shear tests for non-cemented and cemented sand ("sand" and "sandstone" respectively).

Cemented sand with a sufficiently high amount of cement behaves elastically until ultimate failure is reached which is accompanied by the formation of continuous and discontinuous cracks and fissures. As illustrated by Fig. 7 failure takes place at a very small angular deformation. Fig. 7 also shows the typical behaviour of non-cemented sand in a loose and denselayering at the beginning of the shearing. Densely layered sand reaches a maximum shear stress value in connection with a volume increase ("dilatancy") but increased shear strain reduces the shear resistance to a limit which corresponds to the so-called critical density. Loosely layered sand shows a successively increased shear resistance and density ("contraction") when the shear strain is increased and the critical density is finally reached. In a sheared element of sand - irrespectively of its density - the particles move individually with a largely preserved continuity. This is in contrast with soft clay-rich soils where large deformations may cause continuous open zones (Fig. 8).

In the present case, a high density of the buffer mass is valuable since it means that shear strain will not cause any decrease in volume (contraction), that the creep properties are favourable, and that the permeability is low. In principle the densely layered buffer mass will behave as illustrated by Fig.9 when sheared. The material is obviously markedly dilatant with the very favourable property of showing dilatancy in a very large strain interval.

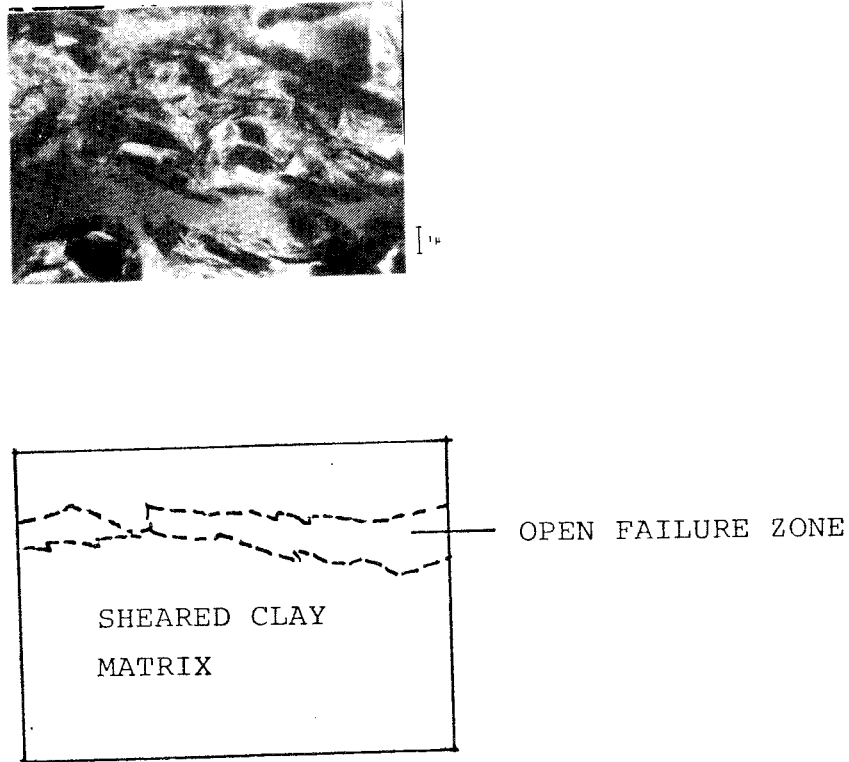


Fig. 8. Creation of open zones in soft illite clay due to large shear strain produced in the laboratory. Upper picture shows electron micrograph of an ultra-thin section of acrylate-treated clay. Lower picture shows schematic interpretation.

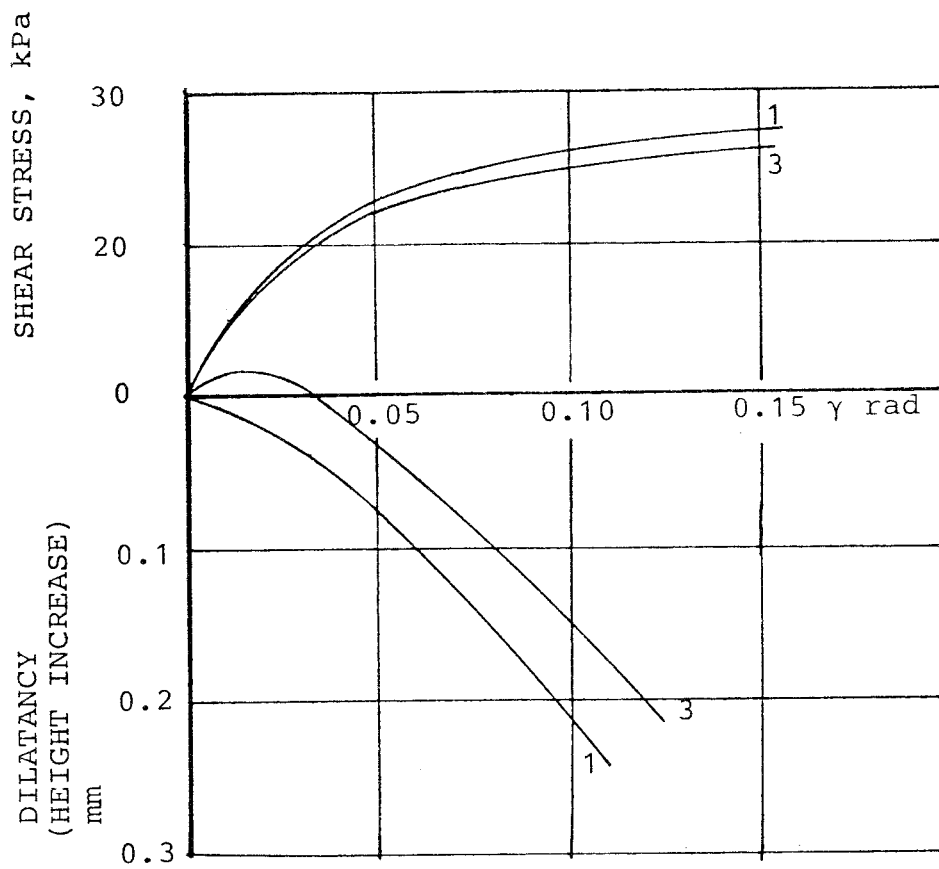


Fig. 9. Stress/strain behaviour of 10% bentonite/90% Pite silt obtained in consolidated drained direct shear tests at a normal effective stress of 53 kPa. The test is relevant with reference to the stress situation of the buffer substance in the tunnel.

An illustration of the behaviour of a cemented clayey siltstone with the microstructural pattern shown in Fig. 1 is given by Fig. 10. The previously stated characteristic property of cemented substances to show an almost linear stress/strain relationship to the state where brittle failure with cracking and fissuring occurs is valid also for this siltstone. No analysis of the degree of pressure solution or of the amount of precipitated cementing agents has been performed but the high bulk density (about  $2.5 \text{ g/cm}^3$ ) indicates that the void ratio is small and, thus, that the amount of cementing substances is considerable.

We can conclude from what has been said that the deformation properties are completely changed when a clastic silt/sand material is cemented and turns into siltstone or sandstone. The main question is of course if this change is abrupt due to the development of a certain critical amount of cementing substances or if there is a successive change. In the latter case there must, however, be some limit of cementation below which the mass behaves as a clastic system with individually movable grains.

#### INFLUENCE OF THE AMOUNT OF CEMENT ON THE SHEAR STRENGTH

The case of  $\text{SiO}_2$  precipitation will be considered here. The most unfavourable assumption is that this substance forms solid crystalline quartz with the same strength properties as the primary quartz particles.

For the sake of simplicity we will assume that all the particles are equally sized and regularly distributed as shown in Fig. 11. Three grain diameters, 0.01 mm, 0.05 and 0.1 mm, will be considered. The average grain diameter ( $d_{50}$ ) of the quartz fraction of the buffer mass will probably be about 0.05 mm and is thus well within the investigated particle size interval.

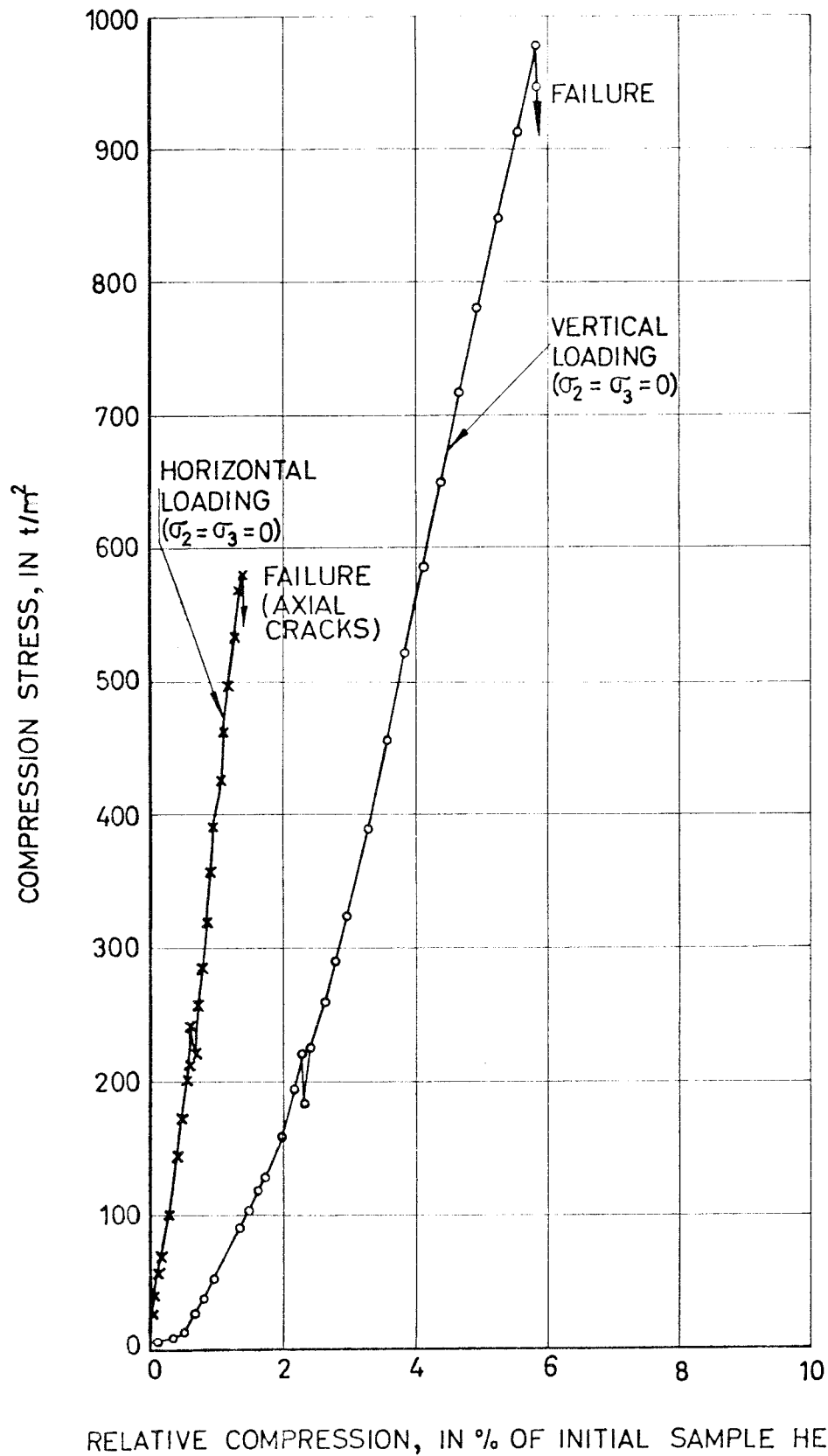


Fig. 10. Uniaxial compression tests of clayey siltstone showing brittle failure. Horizontal loading means load application parallel to the stratification.

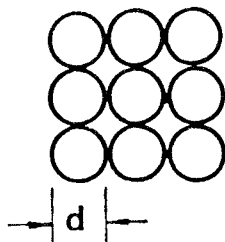


Fig. 11. Generalized arrangement of primary quartz grains in the buffer mass.

The most important factor in the analysis is the solubility of quartz. It is assumed here that it is 50 ppm. It is also assumed that 50% of the dissolved  $\text{SiO}_2$  is precipitated and that the deposition occurs on quartz particle surfaces. Experience shows that quartz growth preferentially takes place on certain crystal planes or topographical features and that only part of the precipitation occurs in the particle contact areas. In the analysis it is assumed that 30% is deposited in the last-mentioned positions. This is a conservative estimation.

At each particle contact of the idealized type shown in Fig. 12 the cementing  $\text{SiO}_2$  is assumed to form an axi-symmetric body geometrically described by the parameters  $h$  and  $x$ .

We find that the total amount of  $\text{SiO}_2$  precipitated at the quartz particle contacts is  $4 \cdot 10^{-7} \text{ m}^3$  per  $\text{m}^3$  total volume and that the quartz bodies thus formed are characterized by the values given in Table 1.



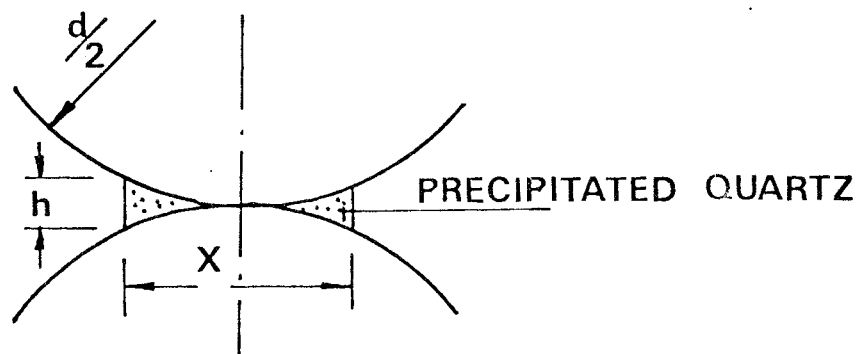


Fig. 12. Geometrical parameters of the idealized quartz cement body in the contact between two primary quartz grains.

Table 1.  $x$ - and  $h$  values of cement bodies.

Grain diameter m	Volume of indiv. grain $m^3$	Number of par- ticles per $m^3$ total volume	$h$ m	$x$ m	$\Sigma \pi x^2/4$ $m^2/m^2$ section
$10^{-5}$ (0.01 mm)	$5.2 \cdot 10^{-16}$	$1.2 \cdot 10^{15}$	$4 \cdot 10^{-9}$	$2.8 \cdot 10^{-7}$	$6.3 \cdot 10^{-4}$
$5 \cdot 10^{-5}$ (0.05 mm)	$6.5 \cdot 10^{-14}$	$9.2 \cdot 10^{12}$	$2 \cdot 10^{-8}$	$1.4 \cdot 10^{-6}$	$6.2 \cdot 10^{-4}$
$10^{-4}$ (0.10 mm)	$5.2 \cdot 10^{-13}$	$1.2 \cdot 10^{12}$	$3.5 \cdot 10^{-8}$	$2.7 \cdot 10^{-6}$	$5.5 \cdot 10^{-4}$

It follows from Table 1 that the size of the quartz body formed at each contact corresponds to that of a single clay particle in the coarser part of the clay fraction. It can therefore be concluded that even if the quartz forms crystals without imperfections they will only contribute moderately to the bulk shear strength of the mass. Thus, the strength would be similar to that of a fairly stiff clay but only a very small fraction of that of an ordinary sandstone. In practice the cementing bodies will have a varying size and strength which largely affects

the stress/strain properties in bulk. This fact and the negligible influence of the bodies on the geometry of the system form the basis of a phenomenological model which may be useful for the understanding of the mechanical behaviour of the weakly cemented buffer mass.

#### PHENOMENOLOGICAL MODEL

Let us first consider the general stress/strain relationship. Even if the precipitated  $\text{SiO}_2$  forms a crystalline solid substance we have to consider the effects of the strength and stress distribution among the cementing bodies. Strength variation is due to a varying amount of crystal imperfections and to the strength anisotropy of the crystals. Stress variation is due to the microstructural arrangement (geometry) and to the grain size distribution. It is well known from soil and rock mechanics that these effects produce a natural variation in strength and strain properties in soil and rock masses. In order to explain the effects of this we can apply the following reasoning (cf. PUSCH, 1973).

The general distribution of the strength of the cementing bodies is given by Fig. 13.

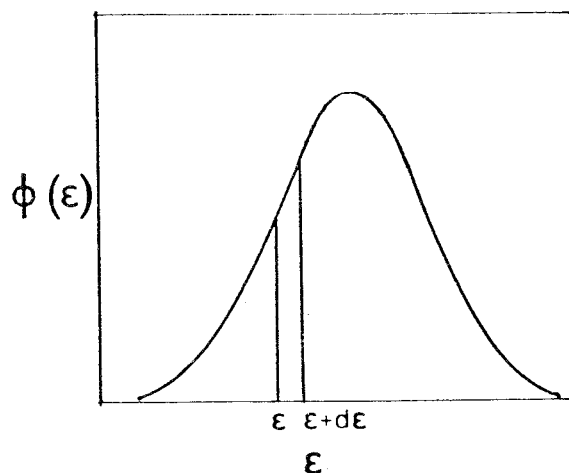


Fig. 13. Distribution of strength of cementing bodies.

When the strain is  $\epsilon$ , the fraction  $\psi$  of intact bodies will be

$$\psi = \int_{\epsilon}^{\infty} \phi(\epsilon) \epsilon \quad (1)$$

If we assume a modulus of deformation  $E$ , the stress in a specimen is:

$$\sigma = \epsilon E \int_{\epsilon}^{\infty} \phi(\epsilon) \epsilon \quad (2)$$

The load is maximum when  $d\sigma/d\epsilon = 0$ , that is when:

$$E \int_{\epsilon}^{\infty} \phi(\epsilon) d\epsilon - \epsilon E \phi(\epsilon) = 0 \quad (3)$$

which yields:

$$\int_{\epsilon}^{\infty} \phi(\epsilon) d\epsilon = \epsilon \phi(\epsilon) \quad (4)$$

If the corresponding  $\epsilon$ -value is termed  $\epsilon_0$ , we obtain maximum stress:

$$\sigma_{\max} = E \epsilon_0^2 \phi(\epsilon_0) \quad (5)$$

Assuming a linear stress/strain curve and a normal frequency distribution we obtain the schematic relationship in Fig. 14 which clearly shows the reduction in strength resulting from the early breakdown of certain bodies.

In the case of constant rate of stress application, the relation below the maximum load will be the same as in the case of constant strain. When this load is exceeded the failure process is cumulative and the whole specimen ruptures. The important conclusion of this is that an increasing shear stress or an increased deformation produces a successively increased number of bond failures which involves individual

grain movement. Here the geometry of the system comes in as a very important factor. If the cementing bodies had been so big that the total quartz mineral substance had turned into a continuous system of column-like members, the interlocking effect would prevent free rotation and translation of individual particles. A rough estimation indicates that the amount of precipitated quartz in the contact areas must be at least 100 times the calculated value  $4 \cdot 10^{-7} \text{ m}^3$  per  $\text{m}^3$  total mass before it will tend to show brittle properties. The buffer mass will therefore behave as a clastic frictional soil material. It may be added that this property will be even more obvious if the precipitated  $\text{SiO}_2$  will be partly or entirely amorphous (silica gel). This will probably be the case.

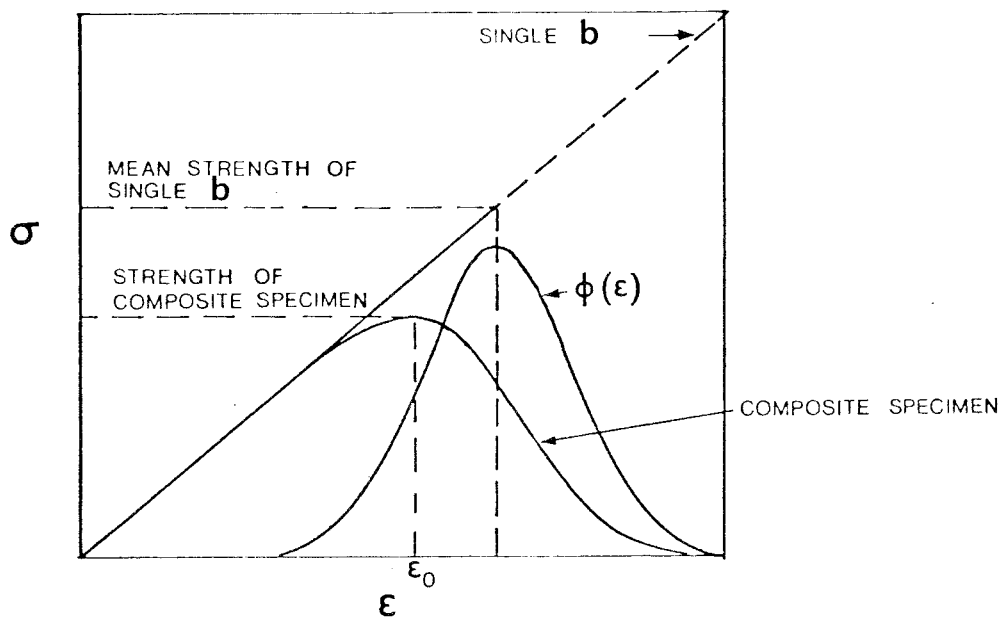


Fig. 14. Composite-specimen stress/strain curve.  
b means  $\text{SiO}_2$  body.

It is relevant here to refer to some known physical/chemical conditions for quartz precipitation in the presence of clay minerals. Thus, according to MARZOLF (1976) the presence of clay minerals might increase quartz solution rates but tends to retard precipitation. In fact clay minerals have an ability to inhibit silica precipitation according to a number of investigators (cf. HEALD 1956, PITTMAN & LUMSDEN 1968 and PITTMAN 1972). We also have to consider the geometry in the pore space with special reference to the space and arrangement of the montmorillonite particles. In the first stage of deposition when the buffer mass is in an airdry condition the Na-montmorillonite particles in the pore space between coarser particles (cf. Fig. 4) seem to be non-uniformly distributed in a "cornflake"- or star-like arrangement (Fig. 15). Each particle consists of a fairly small number of elementary sheets with a repeat distance of about 15 Å. The arrangement is in fact similar to that observed by ALMON, FULLERTON & DAVIES (1976) in porous sandstones from the Upper Cretaceous Horsethief Formation. The flaky clay minerals (montmorillonite and mixed-layer minerals) in these sandstones which seem to be of authigenic origin are attached approximately perpendicularly to the surfaces of host-grains (mainly quartz and feldspars).

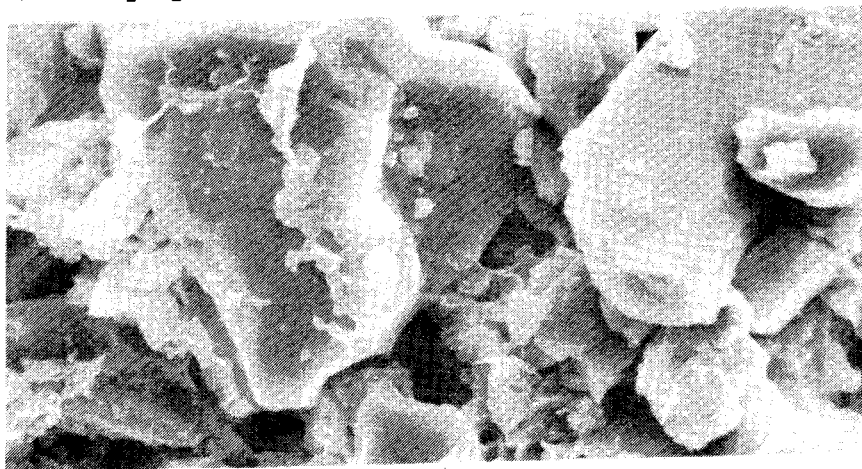


Fig.15. Cornflake-type montmorillonite particle groups attached to host grains in the buffer mass.

When water is introduced in the buffer mass water molecules migrate into the space between the elementary sheets and produce a swelling in the crystallographic c-direction. This brings up the very important question of the physical state of the water adsorbed in montmorillonite.

NORRISH (1954) in a classical study investigated Na-montmorillonite and found the relationship between lattice expansion and water content given in Fig. 16.

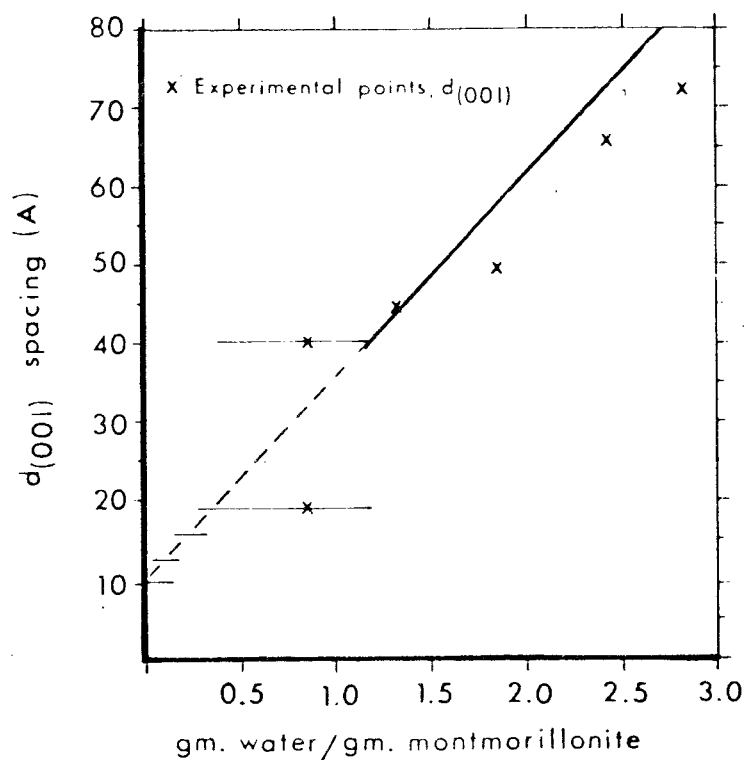


Fig. 16. Montmorillonite  $d_{001}$  spacing as a function of observed water content (NORRISH, 1954)

Later studies by FORSLIND & JACOBSSON (1973) based on the Edelman-Favajee montmorillonite structure confirmed NORRISH's value as can be seen from Table 2.

Table 2. Water content and (001) spacing in Na-montmorillonite (Forslind & Jacobsson, 1973).

Number of layers	Theoretical water content g H <sub>2</sub> O/g clay	Calculated spacing Angstrom units	Observed spacing in Angstrom units according to Norrish
3	0.179	18.73	18.7
14	0.833	39.89	40
16	0.952	43.57	43.8
20	1.190	50.93	49.2
28	1.665	65.65	65.2
32	1.903	73.01	72

FORSLIND & JACOBSSON suggested that only certain stationary or stable hydration states exist (Fig. 17). In the author's opinion only a restricted number of water layers, probably 3, can exist with a preserved stability of each montmorillonite sheet aggregate ("particle"). Higher numbers of layers (cf Table 2) probably indicate the average distance between the montmorillonite sheets including intra-montmorillonite sheet distances and aggregate distances (cf. Fig. 18). However, NORRISH's results and evidence given by OAKES definitely show that Na-montmorillonite takes up large amounts of water. OAKES stated that the maximum amount of adsorbed water averages 2.78 g H<sub>2</sub>O per gram of Wyoming bentonite with a maximum deviation of about 1%. This means that the ordering influence of montmorillonite on water molecules is effective within an average distance of at least 70 Å from the mineral surfaces.

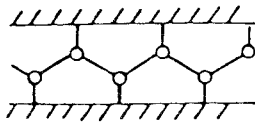
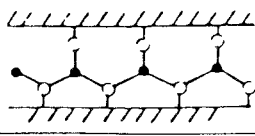
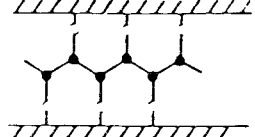
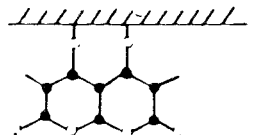
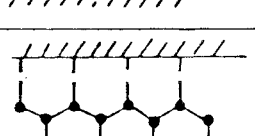
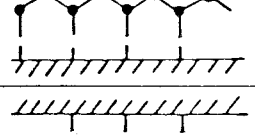
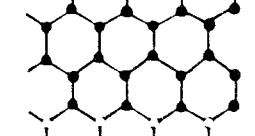
	SCHEMATIC INTER-LAYER STRUCTURE	H <sub>2</sub> O MOLECULES PER UNIT CELL	BASAL SPACING Å	g H <sub>2</sub> O/g CLAY	mM H <sub>2</sub> O PER g CLAY	REMARKS
0		0	12.30	0 0.084 AT COMPLETE DEHYDROXYLATION	0 4.667 AT COMPLETE DEHYDROXYLATION	UNSTABLE NO HYDRATION : 4 OH GROUPS PER UNIT CELL
1		2.66	15.05	0.059	3.278	UNSTABLE
2		5.33	17.81	0.119	6.661	STABLE MONOLAYER
3		8.0	18.73	0.179	9.944	UNSTABLE
4		10.67	21.49	0.238	13.222	STABLE 2 LAYERS
5		13.32	22.41	0.297	16.5	UNSTABLE
6		16.0	25.17	0.357	19.833	STABLE 3 LAYERS

Fig. 17. Schematical arrangement of water molecules at the interface of hydrophilic clay surfaces with silica layer in trans-coordination (Forslind & Jacobsson, 1973).





Fig. 18. Electron micrograph of Tertiary London clay. A system of interwoven laminae of large flakes of montmorillonite is seen. Definition of aggregate distance is given by  $d_a$ . Intra-montmorillonite sheet distance refers to the spacing within each particle (aggregate).

It has been shown (cf. PUSCH 1970 a) that an ordered state of the water molecules increases the viscosity of the system. Thus, the author's NMR studies gave spin-spin coherence time ( $T_2$ ) values for illite which show that the average molecular mobility of the water is much smaller than that of free water even at water contents in the range of 20-40%. As shown by Fig. 19 WU's value for Na-montmorillonite with a water content of 100% (corresponding to about 30-50% of the amount of adsorbed water in the case of the buffer substance) also indicates a largely reduced water molecule mobility.

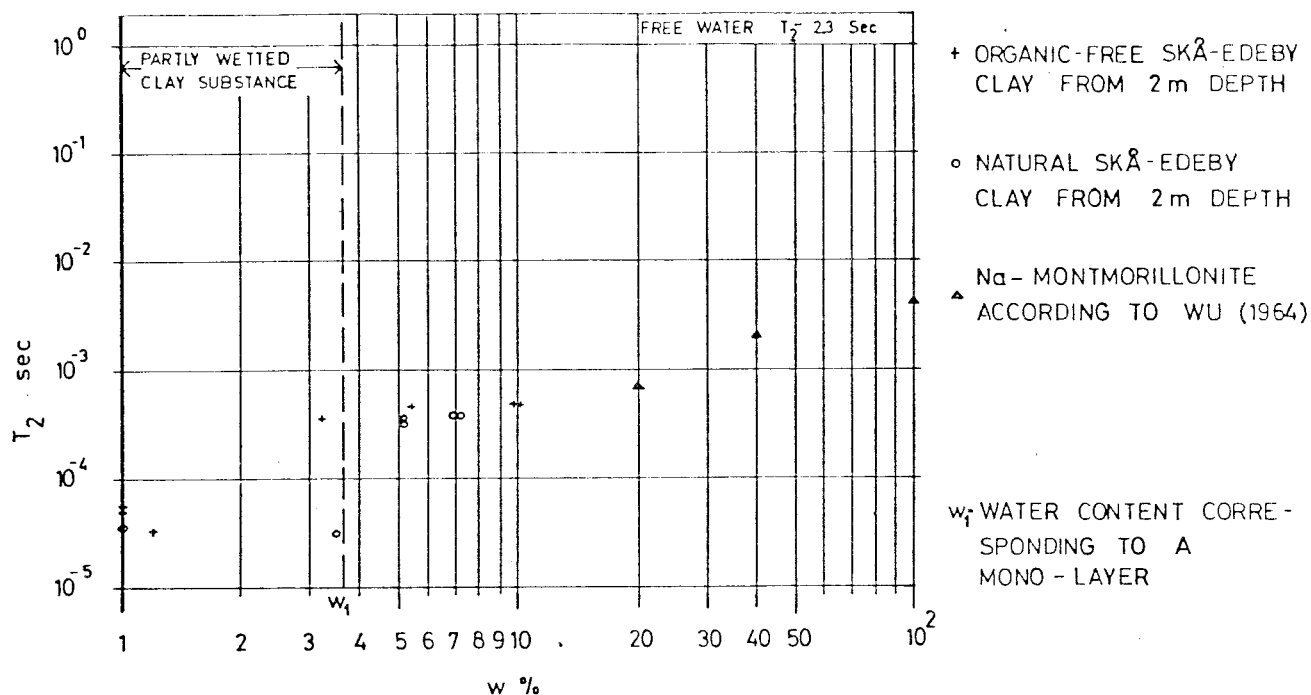


Fig. 19. Spin-spin coherence time  $T_2$  as a function of the water content. Skå-Edeby clay from 2 m depth.

Hence, a considerable part of the pore water in the montmorillonite has a much higher viscosity than that of free water even at maximum water uptake. Considering Fig. 18 we can also conclude that the least ordered water, that is the water situated in the central parts of the larger voids between the aggregates, hardly forms a continuous medium but is more or less locked in these voids. This condition may explain an observed deviation from Darcy's law in very fine-grained illitic clays (cf. Fig. 20). This diagram shows that water flow is smaller than expected at low hydraulic gradients in such clays. This effect should be even more pronounced in montmorillonitic clays.

Let us now see what the consequence of this will be for the buffer mass.

The bulk dry density of the buffer mass will be of the order of  $1.6 \text{ t/m}^3$ . If we assume a specific density

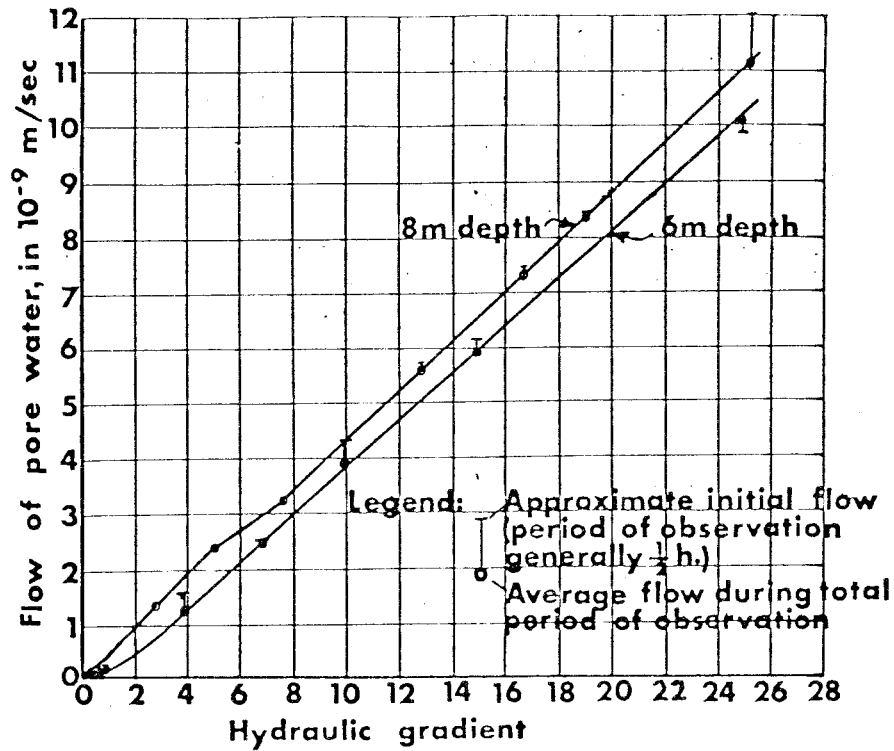


Fig. 20. Flow of pore water versus hydraulic gradient for Skå-Edeby clay taken at depths of 6 and 8 m. Tests performed at an ambient temperature of  $+7^{\circ}\text{C}$  in the first case (6 m depth) and  $+24^{\circ}\text{C}$  in the second case (8 m depth). (HANSBO, 1973).

Notice that the relationship for the clay at 6 m depth does not represent a straight line according to Darcy's law:  $v=k \cdot i$ . The tests were made with great precision using capillaries for a very careful measurement of flow velocities.

of 2.65 t/m<sup>3</sup> we find that 1 m<sup>3</sup> of the "dry" mass has a void volume of 0.4 m<sup>3</sup> and a mineral volume of 0.6 m<sup>3</sup>. The bentonite fraction equals ten percent of the weight of the total mineral substance, that is 0.16 t/m<sup>3</sup>. According to the previous reasoning this amount of bentonite will take up about 0.45 t of water which corresponds to somewhat more than 0.45 m<sup>3</sup>. This volume is a little bigger than the void volume, which means that swelling will take place or that a swelling pressure will appear if the volume is kept constant. This is also verified in experimental studies (cf. report KBS 1). The interesting thing is that a considerable part of the pore water will obviously be in intra-montmorillonite positions and therefore not readily available for chemical reactions such as those involved in the dissolution and precipitation of SiO<sub>2</sub>. Also, diffusion in the buffer substance will probably be very slow due to special physical state of the pore water. We can therefore assume that the amount of precipitated SiO<sub>2</sub> which was calculated in the previous text is over-estimated.

#### SURVEY OF RELEVANT CASES

Geological evidence should be valuable in the discussion of the extent and rheological consequences of cementation.

The most convincing evidence of the very minute effect or occurrence of SiO<sub>2</sub> cement in quartz-rich clayey soils is:

- Moraine clays (more than 100 000 years old) are not SiO<sub>2</sub>-cemented. Furthermore there is no report on cemented Danish moraine clays at all despite their high content of carbonate minerals (pers. comm. of Prof Moust Jacobsen who has worked with these soils for a long time).

- Scandinavian Quaternary clayey sand/silt deposits (except for shallow layers affected by vegetation or percolation of surface water) are not  $\text{SiO}_2$ -cemented. Several of these have been intensely percolated by ground water for very long periods of time. The author knows of no such deposit (age in Sweden less than about 10 000 years) which is cemented to an extent which makes the soil brittle. Where cementation has occurred other agents than  $\text{SiO}_2$  have been active (carbonates and iron compounds).

It should be stressed, however, that the temperature of all these deposits have not exceeded 10-20°C.

A few cases of cemented (non-brittle) young soils have been reported in literature and a few representative examples will be commented on here.

In a detailed study of a marine (mainly illitic) clay from the Swedish west-coast KARLSSON & PUSCH (1967) observed that the compression curves in ordinary oedometer tests showed a pronounced influence of broken cementation bonds when the preconsolidation pressure was exceeded. Similar results have been reported by Norwegian investigators from studies on silty clays. However, all these soils show a perfect post-failure plastic behaviour as indicated by a complete microstructural distortion (cf. PUSCH, 1970 b) and by the fact that the liquid limit determined without any pre-treatment is of the order of 50-70%. This indicates a complete disintegration at the very moderate energy input produced by remoulding.

Certain Canadian clays are known to be fairly strongly cemented as reported by many investigators. QUIGLEY (1969) stated that most of eastern Canada's extra-sensitive, "quick" clays are characterized by inter-

particle cementation or bonding. The Toulnoustouc clay has a tensile strength of up to about 100 kPa probably caused by cementation by adsorbed aluminum and iron hydroxide complexes. Although cementation was not caused by  $\text{SiO}_2$  in this case it is still of great interest since the tensile strength corresponds to a shear strength of about 50 kPa which is of the same order as the calculated strength of the buffer mass in the theoretical example (cemented state) previously given in this report. The interesting thing is that the cemented Canadian clay behaves as a plastic soil when failure is reached. Thus, the liquid limit determined without any pre-treatment is of the order of 40-50% which indicates a complete disintegration.

A very interesting study of sandstone cementation has been reported by SIBLEY & BLATT (1976). A large number of samples from the Silurian Tuscarora ortho-quartzite were investigated in order to determine the amount of pressure solution and authigenic silica.  $\text{SiO}_2$  cement was found to fill up to 40% of the rock volume. The authors estimated that prior to lithification the well sorted, slightly compacted medium sand size sediment had a porosity of about 40%. The analysis showed that 21% of the quartz was authigenic and that one third of this was due to pressure solution. Thus, the other two-thirds of the silica must have been derived from other sources. The authors considered various possible sources and concluded that ground water-transported  $\text{H}_4\text{SiO}_4$  was the most likely one. Their reasoning is very interesting and is therefore presented here in some detail.

The main problem is to calculate the amount of water which must flow through a sand mass in order to cement it. This was solved by the authors by assuming (on the basis of various references) an initial concentration of 32.5 ppm  $\text{SiO}_2$  in solution from which 26.5 ppm

is precipitated. They found that the porosity will decrease by one  $10^{-5}$ th for each pore volume of water which passes through the mass. The number of pore volumes necessary to bring about the cement was found to be  $2 \times 10^5$  which demonstrates the vast quantities of fluid that must circulate through a sand body in order to cement it. An increase in the amount of silica precipitated to 265 ppm would only reduce the number of pore volumes to  $2 \times 10^4$ . Assuming the average flow rate of ground water to be 10 m per year  $2 \times 10^5$  pore volumes would pass through in two hundred million years. Thus, if cementation started soon after deposition it could have been completed by the end of the Paleozoic. The author considers this case study to be very instructive. Thus, since ground water percolation in the buffer mass will be much less than in SIBLEY & BLATT's case it is concluded that cementation through solution and precipitation of  $\text{SiO}_2$  will be very limited in the buffer mass and that, even after thousands of years, it will not be able to change the plastic properties into brittle behaviour.

#### CONCLUSIONS AND COMMENTS

The nature of silica solution and precipitation is not known in detail. The chemical environment, temperature, pH and ion strength are known to be controlling factors which combine to make possible alternating solution and precipitation of silica. Simultaneous solution and precipitation, that is the case considered to be a possible process in the buffer substance, can produce cementation as indicated by MARZOLF's (1976) surface texture studies of Navajo sandstone. This may be the cementing process when ground water percolation is negligible. However, as shown by the case survey and the presented theoretical treatment the amount of precipitated  $\text{SiO}_2$  will not be able to produce a brittle behaviour of the buffer mass even

after thousands of years.

Luleå 77-06-20

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A handwritten signature in black ink, appearing to read 'Roland Pusch', with a long, wavy horizontal line extending to the right.

Roland Pusch



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