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APPLICABILITY OF A BENTONITE QUARTZ FLOUR WATER MIXTURE TO UNDERGROUND STRUCTURES

APPLICABILITE D'UN MELANGE DE BENTONITE, DE FARINE DE ROCHE ET D'EAU SUR OUVRAGES SOUTERRAINS

D. König[1] *H.L. Jessberger*[2]

[1]Ruhr-Universität Bochum
Bochum, Germany
[2]Professor, Ruhr-Universität Bochum
Bochum, Germany

SYNOPSIS: The application of a Bentonite quartz flour water mixture to underground construction promise different advantages. Relative movements between soil and structure, e.g. a tunnel or a shaft, can taken place, if the friction between the soil and the structure is reduced by a layer of such a mixture. Structures in water bearing soils have to be sealed. Due to the low permeability of the mixture the installation of other sealings is not necessary, if the structure is embedded in the mixture. Consolidation deformations activate the bearing capacity of the soil around the structure, owing a reduction of the load on the structure. This and other aspects were investigated by a large scale model test and by model tests with a large geotechnical centrifuge. The test results can be used for the practical application of such mixtures.

INTRODUCTION

The behaviour of mixtures based on clay minerals, particularly on Bentonite, with different kinds of additional aggregates is mainly characterized by the water content and the composition. The applications of such mixtures to mineral sealing layers of landfills, to construction of diaphragm walls and to drilling muds are well known. The application of a mixture made from Bentonite, quartz flour and water to underground structures was studied in a research program in cooperation with the Dyckerhoff & Widmann AG supported by the German Federal Ministry of Research and Technology (BMFT).

The target of the application of the mixture in shaft sinking and in tunnelling is the reduction of the friction between the soil and the structure, to activate the bearing capacity of the soil and to reduce the stress and strain of the structure. The reduction of the soil structure friction is necessary, if the structure is placed in an area influenced by soil deformations e.g. due to mining activities. In this case relative movements between soil and structure can taken place without producing stress and strain to the structure causing failure. An additional advance of a Bentonite quartz flour water mixture is the low permeability. A structure built in water-bearing soil have to be sealed e.g. by synthetic flexible membranes. If a structure is embedded in the mixture, other external sealings are not necessary.

Different questions have to be answered transferring the knowledge based on laboratory element tests to the application e.g. to shaft construction or to tunnelling. At first the production of the mixture has to be investigated. The flow properties characterize the pumpability and the propagation behaviour in a cavity or in a hollow space. Consequently the flow properties have to be investigated for placing the mixture e.g. in an annulus gap between tunnel lining and soil. The sealing properties depend on the complete and homogeneous filling of the gap around the structure. Can this be realized by pumping the material? The properties of the material may by influenced by hydrostatic pressure over a long time. The stress and strain of a structure under high overburden stresses and under soil movements depend on the soil-mixture-structure interaction. Is the bearing capacity of the soil activated and the stress and strain of the structure reduced due to consolidation deformations of the mixture?

Some aspects of the questions mentioned above were studied by model tests. Two different kinds of models were used. A section of a sliding shaft was constructed in a large scale model (1:1). The model allowed the simulation of mixture placing in a real dimensioned annulus gap between the inner and the outer lining of the shaft by pumping. Later the sealing properties and the long time behaviour of the mixture under hydrostatic pressure were tested. The soil-mixture-structure interaction of complete systems - shaft and tunnels - was simulated in model tests carried out in a large geotechnical centrifuge under real stress and strain conditions. The influence of embedding a structure in the mixture on the stress and strain of the structure was investigated and the sliding resistance under high overburden stresses was measured.

The application of both kinds of model tests allowed investigations under prototype boundary conditions: real dimensions in the large scale model and real stress and strain conditions in centrifuge model tests as shown by Schofield (1980). Due to this a direct transfer of the test results to the practice is possible.

PROPERTIES OF BENTONITE QUARTZ FLOUR WATER MIXTURES

Schuster (1986) investigated the structure of Bentonite quartz flour water mixtures. The structure is governed by the chemical compound of the different aggregates based on positive and negative electrical charges. The positive surface charge of the platy clay mineral particles and the negative surface charge of the quartz grains lead to a accumulation of clay particles all around each single quartz grain. Due to this effect the properties of mixtures are characterized by the clay mineral even if the clay mineral content is low.

Bentonite is a clay consisting mostly of the clay mineral montmorillonite. Kenney (1967) measured the angel of internal friction of montmorillonite quartz mixtures in dependence on the clay mineral content (Figure 1). The angel of the internal friction of pore quartz is reduced by adding montmorillonite up to a clay mineral content of 30

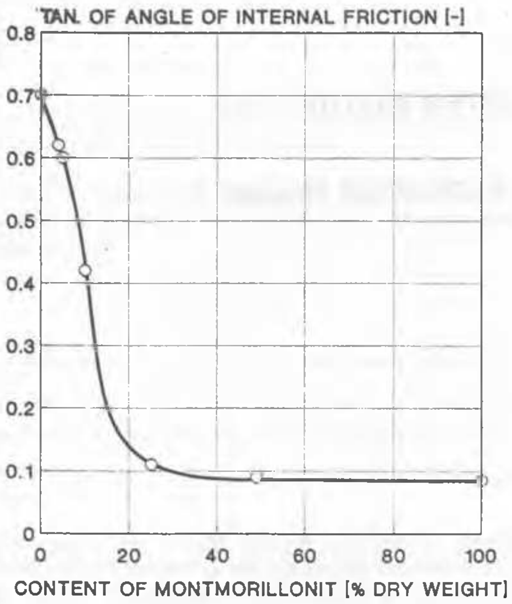

Fig. 1. Angle of internal friction of clay quartz mixtures (Kenney 1967)

mineral content is characterized by the shear properties of the montmorillonite due to the fact, that quartz grains are completely embedded in clay mineral particles. A further friction reduction by adding more montmorillonite is not possible.

The compound of the used mixture (41 % dry weight Bentonite, water content: 88 %) leads to completely embedding of the quartz grains in Bentonite. The angel of internal friction is less than 4° and the shear strength is given by the cohesion, measured in triaxial tests to 22.5 kN/m^2.

In connection with water the Bentonite swells and fills completely the pore space. Due to this the permeability of the mixture is very low. The permeability of the used mixture was measured in laboratory tests to 1.5 10^{-11} m/s.

Further triaxial shear tests were carried out with frozen and thawed material. The freeze thaw cycles cause a slight decrease of the cohesion. Other changes, for example changes in the soil structure by ice lens formation or of the permeability, were not recognised.

The main properties of the used mixture and its components Bentonite and quartz flour are shown in Table 1.

PRODUCING THE MIXTURE

To fill the annulus gap of the large scale shaft model more than 7 m^3 of the mixture were mixed in a compulsory type mixer as used for concrete. The mixing sequence of the components is governed by the water intake of the Bentonite and of the quartz flour. The water intake was determinated by water intake tests according to DIN 18 132. Figure 2 shows the water intake of Bentonite and of quartz flour depending on time. At the beginning quartz flour takes more water than Bentonite. After a few minutes the maximum water intake of quartz flour is reached in contrast to the water intake of Bentonite. Therefore the mixture production starts by mixing quartz flour and water. The Bentonite has to be added some minutes later, when the maximum water intake of the quartz is reached. Other mixing sequences were tested. They led to a lumpy consistence of the mixture and required a long time of mixing.

Table 1. Properties of the used mixture and its components

AKTIVATED CA BENTONITE IBECO S 80	
Content of Montmorillionit (MB Method)	80%
Grain size (dry mechanical grading)	max. 15 % > 0.0063 mm
Density (lose)	700 kg/m^3
Density of solid particles	2650 kg/m^3
Specific surface	250 m^2/g
Liquid limit	450%
Plastic limit	45%
Plasticity	405%
QUARTZ FLOUR SIGRANO SP 8	
Density of solid particles	2650 kg/m^3
Specific surface (Blaine)	0.31 m^2/g
Average grain diameter d 50	0.03 mm
Grain size	max 15 % > 0.06 mm
BENTONITE QUARTZ FLOUR WATER MIXTURE	
Bentonite	22 % by weight
Quartz flour	31 % by weight
Water	47 % by weight
Water content	88%
Liquid limit	150.8 %
Plastic limit	38.6 %
Plasticity	112.2 %
Permeability	1.5 10 EXP -11 m/s
density of solid particles	2720 kg/m^3
Density (porosity: 0.71)	1500 kg/m^3
Angle of internal friction	< 4°
Cohesion	22.5 kPa
Undrained shear strength (vane tester)	4.6 kPa

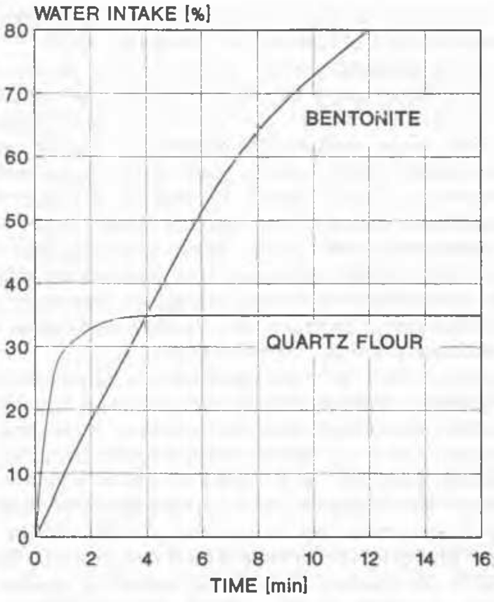

Fig. 2. Water intake of Bentonite and quartz flour

FILLING AN ANNULUS GAP WITH PROTOTYPE DIMENSIONS

Figure 3 shows the large scale shaft model. The model consists of an outer prestressed concrete cylinder and three inner concrete rings. This rings simulate three segments of an inner lining of a sliding shaft. The contact pressure between the rings due to the self weight of the inner lining in a certain depth is simulated by prestressing the rings together in vertical direction. The outer lining was modelled by bricks and wooden plates placed at the inner side of the outer cylinder. The width of the annulus gap between the inner and the outer lining was 30 cm. The average diameter was 3.3 m.

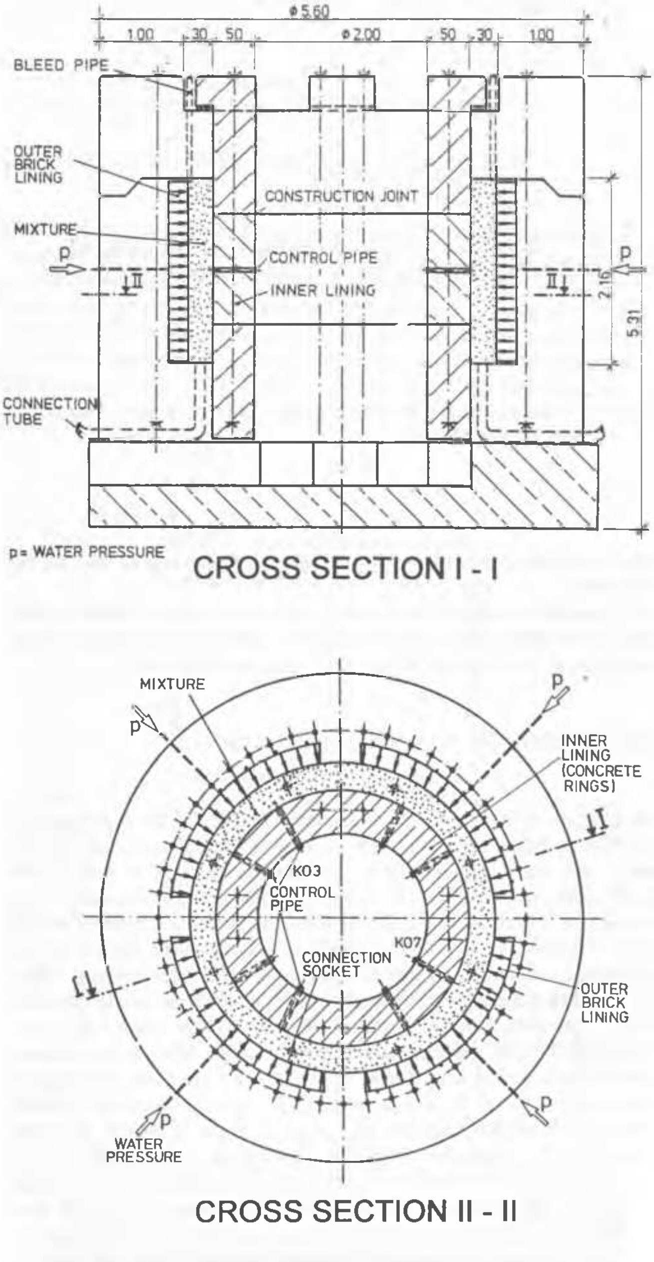

Fig. 3. Cross sections of the large scale shaft model

The filling of the annulus gap was the first test step. The mixture was pumped into the annulus gap by a solids-handling pump through flexible pipes and one of the eight connection tubes. This tubes reached in the bottom of the annulus gap. The diameter of the flexible pipes and of the tubes was 10 cm. The total length of both parts was 8.5 m. Before filling the annulus gap two mixtures were pumped through the flexible pipes, one with a water content of 88 % (mixture 1) and one with 59 % (mixture 2). In both cases the material moved through the pipes as a plug sliding at the inside of the pipes. The pressure loss inside the pipes were measured to 220 kPa/m (mixture 1). According to the pressure loss the sliding resistance can be calculated to 5.4 kPa. This value corresponds to the shear strength of the mixture measured by vane tester to 4.6 kPa. If the water content of the mixture was reduced, the sliding resistance increased. The sliding resistance was determinated for the mixture 2 to 8.1 kPa. This value is slight lower than the undrained shear strength of 10.6 kPa. Reiner (1968) pointed out, that the inner sliding resistance, here described by the undrained shear strength, may be different from the sliding resistance at contact surfaces due to smearing and obstructive contact surfaces. Smearing contact surfaces cause a movement of the material as a plug sliding at the contact surfaces equivalent to the observed movement.

The annulus gap was filled from one tube with mixture 1 (w = 88 %). The filling process was observed by an endoscope. The head of the endoscope was placed inside the gap using the bleed pipes installed at the top of the gap. Figure 4 shows the propagation behaviour of the mixture over the circumference of the annulus gap. First the material propagated in the same way up to the top of the gap and to the right and left side. When the mixture front reached the top of the gap the material expanded in a symmetrical way to the sides. At the end the two mixture fronts met at the opposite portion of the annulus gap. This propagation behaviour led to a complete, homogeneous filling of the gap without air inclusions.

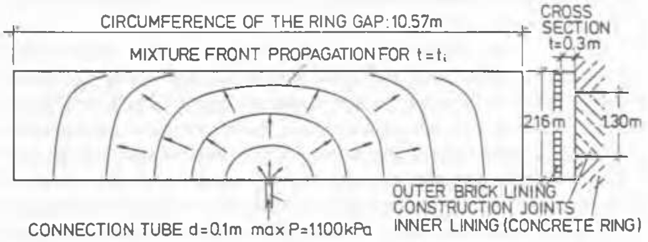

Fig. 4. Propagation behaviour of the mixture over the circumference of the annulus gap

The maximum pump pressure at the end of the connection tube at the bottom of the annulus gap was measured to 1100 kPa in the final filling situation. The mass flow was about 2 m^3/ h, so the gap was filled within 4 hours.

The shape of the mixture front over the width of the gap is shown in Figure 5a. The mixture front was flat in the centre part of the gap. Near the boundaries the mixture left behind the material in the centre. It seems, that the propagation speed of the mixture was lower at the boundaries than in the centre of the gap. Due to the general low propagation speed it may be allowed to identify the shape of the mixture front with the velocity profile of the flowing mixture and to compare it with general velocity profiles of liquids flowing in a gap. It is obvious, that the observed profile correspond to the general velocity profile of a visco-plastic liquid in a gap (Fig. 5b) shown by Reiner (1968).

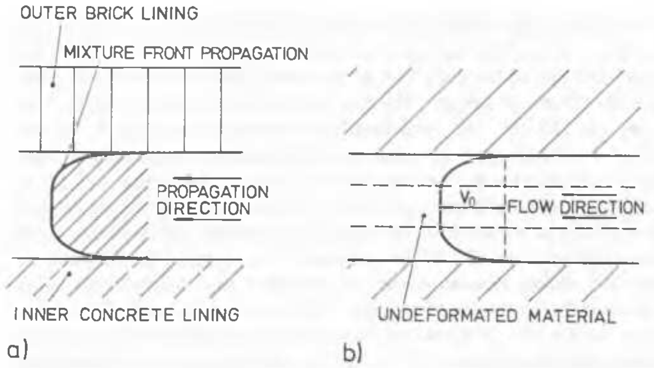

Fig. 5. Shape of the mixture front over the width of the annulus gap (a) and velocity profile of a visco-plastic liquid flowing in a gap (b)

BEHAVIOUR UNDER HYDROSTATIC PRESSURE

The permeability of the Bentonite quartz flour water mixture is well investigated by laboratory permeability tests as mentioned before. Due to the low permeability good sealing properties were expected. One target of the large scale test was the demonstration of the sealing properties of the mixture under prototype boundary conditions. The concrete rings of the inner lining were produced one after the other. The construction joints were not worked or sealed. Such construction joints are typical points of leaks.

After filling the annulus gap with the mixture the water was pressurized up to a pressure p between 300 and 1000 kPa outside of the mixture layer for a period of more than a half year (Figure 3). Passages of water were not observed at the construction joints or at any other point inside the shaft during the whole time.

Control pipes were installed in the inner lining to get samples from the mixture and to place transducers inside the mixture. During the filling of the gap the control pipes were closed at the gap side and mixture couldn't penetrate into the pipes. When the pipes were opened after filling the gap and raising up the water pressure there was no leakage.

The results show, that the unsealed lining, consisting of the concrete rings, become in combination with the Bentonite quartz flour water mixture an impermeable lining. Pumping the mixture in the annulus gap around the lining a homogeneous flexible sealing layer is produced.

Before the water pressure was applied samples from the mixture were taken out of the gap by using the control pipes. The water content was determined. The procedure was repeated half a year later. The results are shown in figure 6. The initial water content determinated to 90.3 % can be calculated by the compound of the mixture with respect to the natural water content of the Bentonite. This result corroborated the homogeneous filling of the annulus gap. After a half year under hydrostatic pressure an irregular decrease of the water content was observed. The change of the water content can be explained by the effect of hydraulic consolidation. Due to the hydraulic gradient between the outside of the mixture layer (100 % water pressure) and the inner part of the shaft (0 % water pressure) water flow through the mixture layer and the inner concrete lining took place. The quantity of seepage water was very small due to the low permeability of the mixture. Owing to the water flow traction forces acted on the particles of the mixture. The particles moved in direction of the water flow to the inner lining. Due to this effect the density of the mixture increased at the inside of the mixture layer and the water content decreased. Different distributions of water content over the thickness of the mixture layer can be calculated in dependence on the flow duration. Before a final state is reached distributions corresponding to the measured one can be calculated.

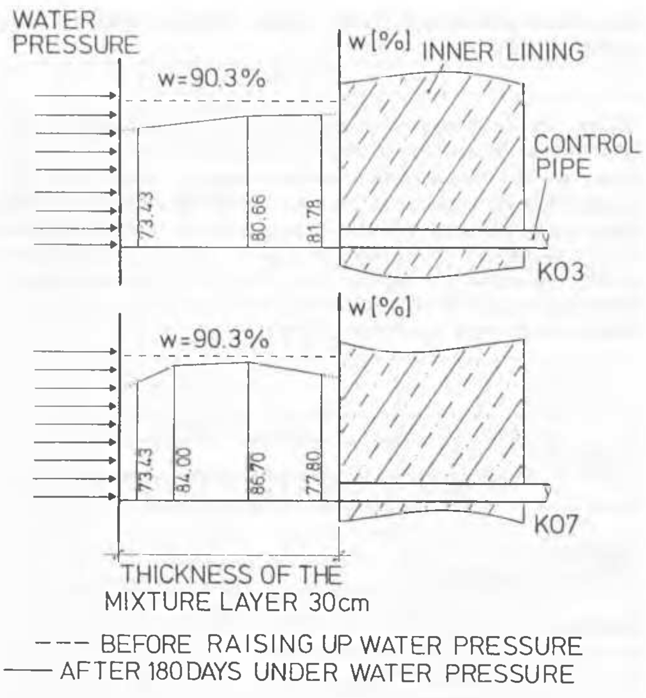

Fig. 6. Water content of the mixture before and after half a year under hydrostatic pressure

The hydraulic consolidation caused settlements of the mixture, that means the thickness of the layer became smaller and a small water filled gap between the mixture and the outer lining was produced.

APPLICATION TO SHAFT CONSTRUCTION

The principle of a sliding shaft is shown in Figure 7. The upper part of the shaft is influenced by subsidence due to mining activities. In this part of the shaft a double lining construction is used to reduce the friction between soil and shaft. The outer lining is in direct contact with the soil and is horizontally loaded by the earth pressure, the inner lining, which is based on a foundation structure, is horizontally loaded by the hydrostatic pressure. The gap between outer and inner lining is filled with a sliding material, e.g. by the Bentonite quartz flour water mixture. Due to this system movements between soil and the inner lining can take place. Vertical settlements of the soil and the outer lining activate shear stresses at the inner lining determined by the shear strength or sliding resistance of the sliding material. Due to the results of triaxial tests the Bentonite quartz flour water mixture is suited for this application. The behaviour of the complete system - inner lining, sliding layer made of the mixture and soil - was simulated in model tests carried out in the Bochum Geotechnical Centrifuge Centre in the centrifuge ZI. The design of the centrifuge was shown by Jessberger et al. (1988). A vertical movement between the inner lining and the soil was modelled and the vertical stress and strain in the shaft lining due to the activated sliding resistance was measured.

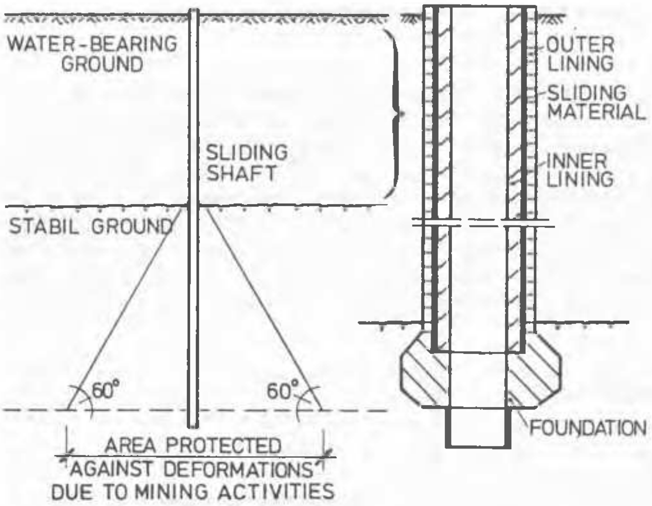

Fig. 7. Principle of a sliding shaft

Figure 8 shows the cross section of the model. The shaft was modelled by an aluminium tube with 60 mm diameter and 1.5 mm wall thickness. The shaft was embedded in water saturated fine sand (Table 2) inside of a circular strong box. Between the shaft and the sand a sliding layer was placed made of the Bentonite quartz flour water mixture 5 mm thick. Two pressure cushions were placed under the shaft. Due to increase the water pressure within the cushions the shaft model moved up. A movement between the shaft and the soil took place. The vertical strains of the shaft lining - parallel to the axis of the shaft - were measured in four cross sections by eight strain gauges each cross section. The scaling factors are shown in Table 3.

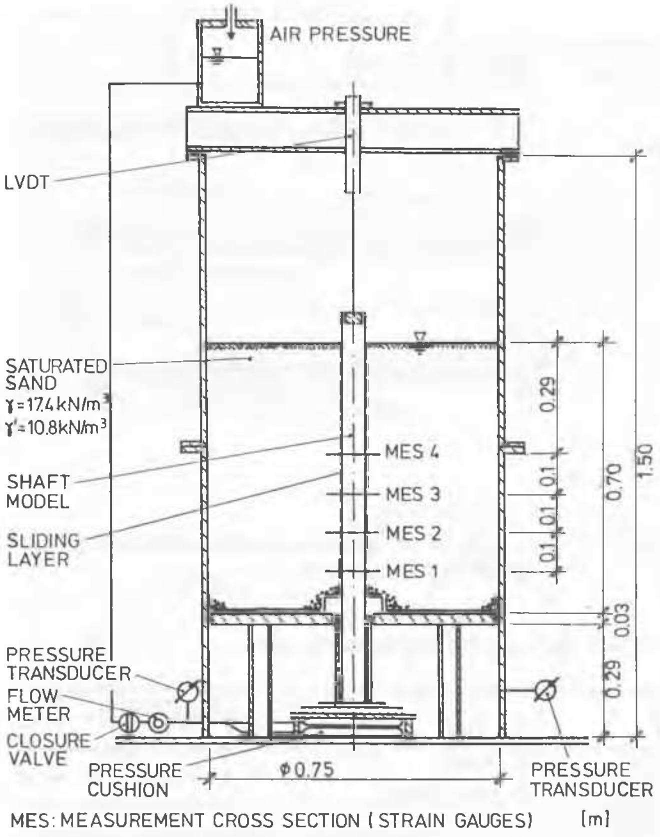

Fig. 8. Cross section of the strong box with shaft model

Table 2. Soil properties of the model sand

Density of solid particles	2630 kg/m³
Minimum index density	1470 kg/m³
Maximum index density	1770 kg/m³
Average grain diameter d 50	0.37 mm
Uniformity coefficient	1.82
Angle of internal friction	34.5°

The model preparation was carried out by pluvial deposition of the sand to a relative density of more than 90 %. The sliding layer was kept frozen during this procedure. The complete model fixed in the centrifuge bucket was accelerated to the selected g - level of 150 g (150 times of earth gravitation). An initial stress condition in the soil built up. After two hours consolidation of the Bentonite quartz flour water mixture the cushions were pressurized. The filling was controlled by a flow meter. The shaft moved up slowly.

Figure 9 shows the vertical compressive stress distribution in the shaft lining caused by the sliding resistance of the sliding layer versus the prototype depth measured in state of rest and in state of movement. In comparison results of a system without sliding layer were presented, that means there was a friction contact between the shaft lining and the sand. The friction contact was provided by gluing sand on the outside of the shaft model, simulating a rough concrete surface. This results are shown in dependence on the dimensionless movement s/r (s: relative displacement between soil and shaft; r: radius of the shaft). The maximum stress before failure occurs was reached at s/r = 5.4 %.

It is obvious, that the stress was strictly reduced by the sliding layer. In all cases the vertical compressive stress in the shaft lining increased proportional to depth. For the system with sliding layer the stress was slightly higher in state of movement than in state of rest.

The vertical compressive stress in the shaft lining was caused by a integration of shear stresses on the outside of the shaft lining over the depth. On the other hand the shear stresses can be calculated by differentiation of the vertical stress distribution. The results are shown in figure 10. Constant shear stresses were effective in distinct depth zone in both cases with and without sliding layer. The installation of the sliding layer caused a reduction of the shear stress to 5 % of the shear stress without sliding layer. In this case the shear stresses were defined by the cohesion of the mixture of 22.5 kPa. A further reduction seems to be possible due to the effect of hydraulic consolidation causing a water gap between the outer lining and the sliding layer as mentioned before.

Table 3. Scaling relations of the shaft model

	Model	Prototype (n = 150)
	cm	m
Diameter of the shaft	6	9
Thickness of the shaft lining	0.15	0.23
Depth of MCS 1	28.5	38.1
Depth of MCS 2	38.5	52.3
Depth of MCS 3	48.5	66.9
Depth of MCS 4	58.5	81.9
Maximum depth	60	104.3
Thickness of the mixture layer	0.5	0.75

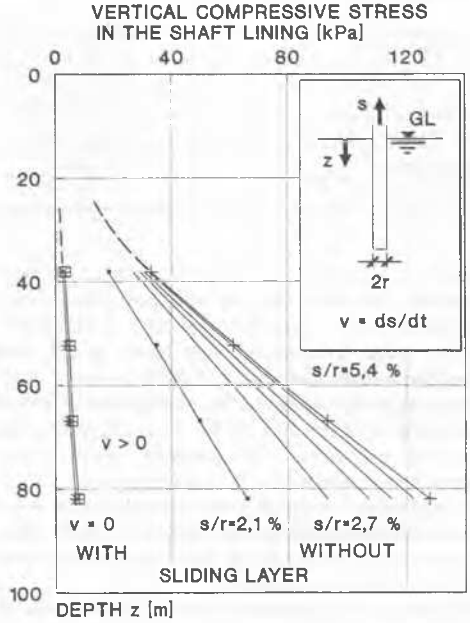

Fig. 9. Vertical comprehensive stress distribution in the shaft lining

However, in case of movement between the shaft lining and surrounding soil the shear stress due to cohesion of the mixture produces additional force to the shaft. Comparison calculations on existing shafts show that this additional force can be sustained by concrete linings in addition to their self weight.

The tightness of existing sliding shafts is provided by welded steel linings commonly installed at the outside of the inner lining. Due to the sealing effect of the mixture mentioned above it seemed to be possible to design the shaft without steel lining.

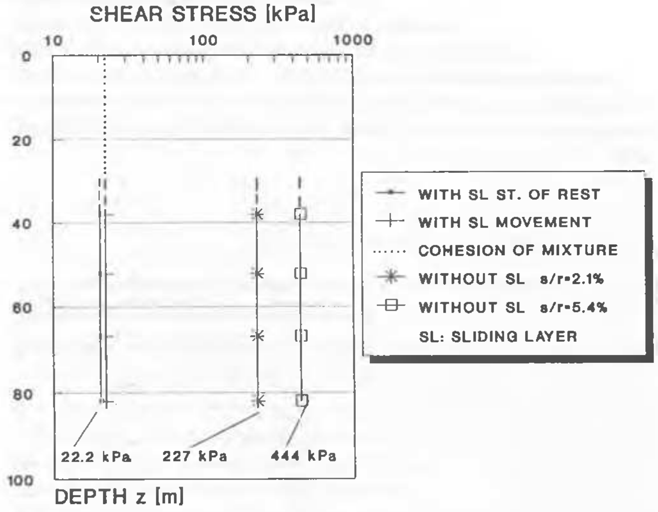

Fig. 10. Shear stresses effective outside of the shaft lining

APPLICATION TO TUNNELLING

Stress and strain in a tunnel lining embedded in a layer of the Bentonite quartz flour water mixture depend on the soil-mixture-structure interaction. Consolidation of the Bentonite quartz flour water mixture is caused by overburden pressure and leads to a thickness reduction of the mixture. This deformation produces a load transfer from the tunnel lining to the soil. This effect is shown by model tests with the large geotechnical centrifuge. A cross section of the model and details of the tunnel model are shown in figure 11. The tunnel model is made of an aluminium tube. The scaling factors of the model are shown in Table 4.

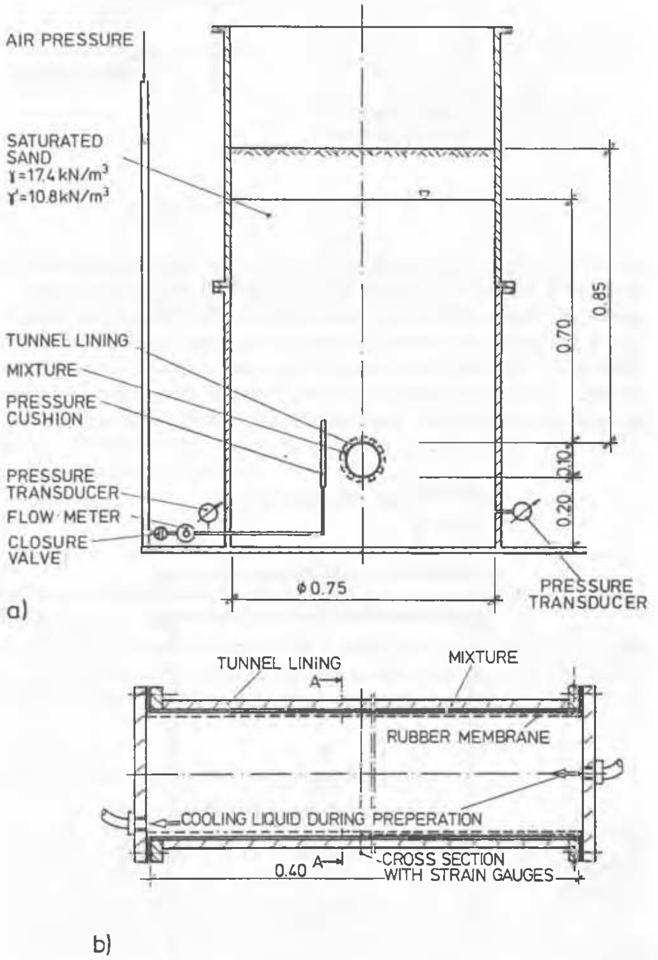

Fig. 11. Cross section of the strong box with tunnel model (a) and cross section of the tunnel model (b)

Table 4. Scaling relations of the tunnel model

	Model	Prototype (n = 150)
	cm	m
Diameter of the tunnel	10	15
Thickness of the tunnel lining	0.2	0.3
Depth of the tunnel axis	95	82
Length of the tunnel	40	60
Thickness of the mixture layer	0.8	1.2

16 strain gauges were installed in the centre of the tube simulating the tunnel lining. The strain gauges detected the tangential strains of the tunnel lining inside and outside. The model is embedded in saturated fine sand (Table 2) inside a strong box. Between the tunnel lining and the soil a sliding layer is placed made of the mixture. A pressure cushion was installed at one side of the tunnel to simulate increasing horizontal earth pressure by filling the cushion with water and increase the water pressure. The model preparation was corresponding to the shaft tests. The complete model was fixed in the swinging bucket of the centrifuge and was accelerated to the selected g level of 150 g. The high acceleration field produced initial stress conditions in the system and consolidation took place in the mixture (sliding layer).

Figure 12 shows the development of the bending moments measured in the crown and the side wall in the tunnel lining versus time. When the selected g - level was reached (Time A) and the initial stress condition was produced positive bending moments in the crown and negative bending moments in the side wall were measured. The overburden load leads to consolidation and decrease in thickness of the mixture and further to stress transfer from the stiff lining to the surrounding soil. Caused by this effect the bending moments in the lining decreased with consolidation time and reached after 3.5 hours model time (9 years prototype time) about 30 % of the initial values.

When the horizontal earth pressure was increased by pressurizing the cushion (Time B) the bending moments in the lining changed. Negative bending moments were measured in the crown, positive in the side wall. After closing the valve to the cushions, that means the water mass inside the cushion stay constant, the bending moments decreased again. Further consolidation of the mixture leads to a load transfer from the lining to the soil and to the reduction of the stress and strain in the lining.

The influence of the mixture consolidation on the normal stress development in the tunnel lining is topic of further research. Corresponding test results to the bending moments are expected.

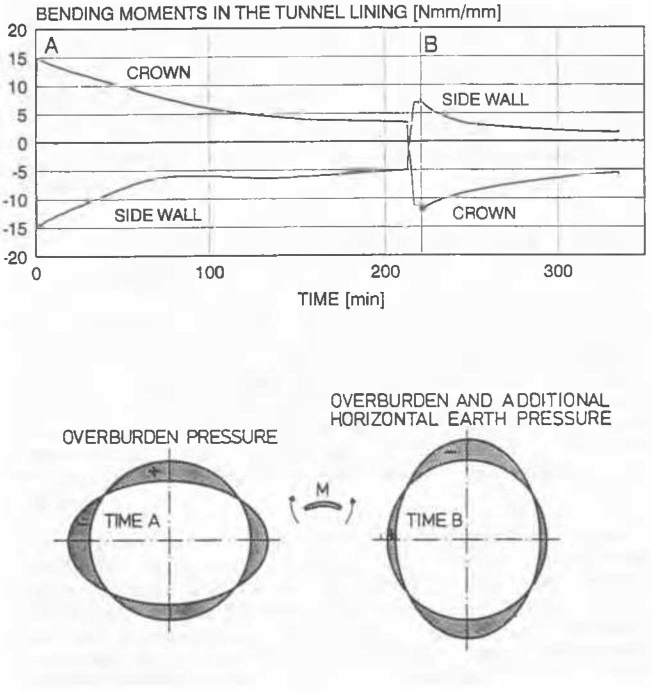

Fig. 12. Development of the bending moments in the tunnel lining versus time

SUMMARY AND CONCLUSIONS

The application of a mixture made from Bentonite quartz flour and water to underground structures was studied by model tests. Different aspects were investigated:

- production of the mixture
- pumpability
- propagation behaviour in an annuls gap
- sealing properties and behaviour under hydrostatic pressure
- reduction of the soil structure friction
- soil - mixture - structure interaction

Two different kinds of models were used. A section of a sliding shaft was constructed in a large scale model (1:1). The model allowed e.g. the simulation of mixture placing in a real dimensioned annulus gap between the inner and the outer lining of the shaft by pumping. The soil-mixture-structure interaction of complete systems - shaft and tunnels - was simulated in model tests carried out in a large geotechnical centrifuge under real stress and strain conditions.

The test results show, that the friction between soil and structure (tunnel lining or shaft lining) can be reduced by embedding the structure in the mixture. Due to this fact movements between the soil and the structure can take place without overloading the structure. Consolidation deformations of the mixture activate the bearing capacity of the soil and cause a reduction of the stress and strain of the structure. Filling a annulus gap between the structure and the soil by pumping the mixture, a sealing layer is produced and other sealings are not necessary. Placing the mixture by pumping, an economical operation method is available.

Supplementary investigations concerning the long time soil-mixture-structure interaction under definite and changing loads should be done.

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