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# Modified Bentonite Slurries for Slurry Shields in Highly Permeable Soils

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ABSTRACT: The slurry shield method is a widely-used tunneling method in soft soils. Bentonite suspensions are used to stabilize the working face by building up support pressure. In coarse, highly permeable soils, the suspension penetrates the ground and the required support pressure cannot be reached. Improvements of the commonly used bentonite suspensions can be achieved by modifying the bentonite slurries. In the laboratory, the effects of the additives polymer, sand and vermiculite were studied. A suspension containing these three additives in well defined proportions enables the formation of a tight membrane and filter cake even in highly permeable soils. Proof of the concept was obtained by the successful application of the modified bentonite suspension in a project in Switzerland.

## 1 INTRODUCTION

For tunneling projects in saturated soils tunnel boring machines (TBMs) with so called slurry or hydro shields are widely used. Recent projects show the successful applications, e.g. the 4$^{th}$ pipe of the Elbe Tunnel in Hamburg, where a cutting wheel of 14.2 m diameter was used, and the tunneling works in Zurich Thalwil, part of the "Bahn 2000" ("Railway 2000") project.

The mode of action of a slurry shield consists of a continuous support of the face and its vicinity by a suspension under pressure. The effectiveness of the support depends on the actual suspension pressure, the formation of a sealing membrane or filter cake at the excavation surface and the penetration of the suspension into the ground. For coarse, highly permeable soils (c.f. Fig. 1), the commonly used bentonite suspensions penetrate the ground without building up the required support pressure. For such situations

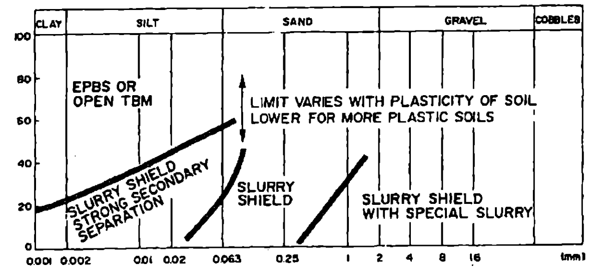


Fig. 1 Applicability of Earth Pressure Balance (EPB) and Slurry Shields (Steiner, 1996)

special conditioning of the suspension may be necessary. The admixture of different components influences the geometrical and rheological properties of the suspension in a way that even under adverse conditions the formation of a membrane and thereby of a sufficient support pressure may be reached.

During the advance of a sewage gallery of 2.80m diameter in Zurich (Fritz and Tandler, 1999), with bentonite slurry only a limited pressure could be achieved, giving rise to various surface failures (Fig. 2).

Fig. 2 Surface Failure in an Allotment

The current report describes the process of conditioning the suspension for this construction site with various components, until a mixture which was promising in the laboratory tests and proved to be successful during the advance of the second section of the gallery was found.

## 2 SLURRY SHIELD METHOD

### 2.1 *Excavation Procedure*

Tunnels in unstable ground below the groundwater table are often excavated by the closed-type shield method. If the stand-up time of the face is short or even vanishing, the face must be supported, in the case of a slurry shield by a suspension under pressure.

The suspension is pumped into the so called working chamber (Fig. 3), where it is put under pressure by compressed air. The effective support pressure depends on the pressure of the compressed air, the density of the suspension, the ability to form a membrane or cake of low permeability, and the penetration distance of the suspension in the ground. The support pressure must be high enough to withstand the earth and water pressure at the face.

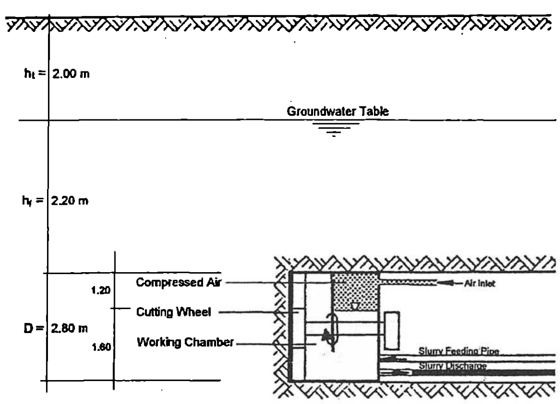


Fig. 3 Slurry Shield at Hermetschloo Site

Besides the stabilizing effect of the suspension, it serves also as a means for transporting the excavated soil, which is mixed with the slurry.

The two chamber design of a suspension shield is very flexible for inspection and repair works. By simply varying the pressure of the compressed air the level of the suspension in the working chamber may gradually be varied without having to undertake any other measures. At the same time the working chamber may be set under compressed air, which maintains the necessary support pressure. Under these conditions access to the working chamber is possible.

### 2.2 *Mode of Action of the Suspension*

Depending on the porosity of the soil, the excavation surface may act as a filtration area for the suspension, and a thin nearly impermeable membrane may be formed. If there is enough time available, a secondary filtration on the membrane may take place, which leads to the formation of a so called filter cake. Taking into account that during excavation the cutting wheel may rotate several times per minute, the existence of a filter cake is not likely. However, before accessing the working chamber under unfavorable compressed air conditions, usually it is aimed to let a filter cake be built up. In both cases, i.e. with an impermeable membrane or a filter cake, the pressure of the suspension takes effect immediately at the excavation surface, where it may be taken into account for stability investigations.

If the suspension penetrates the ground, the difference between the pressure of the suspension and the groundwater is gradually transferred to the ground, either from grain to grain or by adhesion. The body forces beyond a potential sliding face do not contribute any more to the stability, i.e. the effective pressure of the suspension depends on the actual penetration distance, which again depends on the pressure conditions, the properties of the soil and the suspension, and the advance rate. Observations during physical access to the face at the Hermetschloo site showed that a small filter cake had been formed, and that the suspension only penetrated some centimeters into the ground.

Further exposition of the subject may be found in Fritz and Tandler (1999).

## 3 BENTONITE SLURRIES

### 3.1 *Composition of Bentonite*

Much experience is available for bentonite slurries, not only from slurry shields, but even more so for diaphragm walls and the drilling industry. Bentonite is a type of clay that is formed by weathering of volcanic ash. It consists mainly of the clay mineral montmorillonite. Montmorillonite is assigned to the smectites and is a 3 layer clay mineral, consisting of two silicon tetrahedron layers and one aluminium octahedron layer. In the octahedron layer, trivalent aluminium ions are partly substituted by divalent magnesium ions, leading to a negative charge on the surface of the layers. This negative surplus charge is responsible for the capability of cation exchange (adsorption of Na- or Ca-cations). Depending on the type of the adsorbed ions, the bentonite is designated as Na- or Ca-bentonite.

When water is available, the cations can hydrate and the distance between the layer packs will widen; this is called inner crystalline swelling, a typical property of montmorillonite or bentonite. The absorption of water and thus the swelling is higher for Na-bentonites than for Ca-bentonites, as the Na-ions hydrate more easily when adsorbed.

### 3.2 *Properties and Limitations of Bentonite Slurries*

Bentonite slurries are viscous substances with special properties, such as:
- thixotropic flow behavior,
- formation of a yield point,
- high viscosity (depending on concentration),
- capability of water retention,
- inner crystalline swelling,
- ability to stagnate, i.e. mainly in sandy soils, the bentonite suspension will stagnate after a certain penetration depth and a filter cake will be built up.

Various standardized tests are available which lead to index values characterizing the bentonite slurries:
- shear strength: called yield limit if determined with the "Kugelharfe", Kasumeter or Pendulum, and called gel strength if determined with the Shearometer or Viscosimeter. A greater shear strength reduces the penetration of the suspension.
- run out time of the Marsh Funnel: shows the combined effect of viscosity, shear strength and density.
- stability against segregation of the liquid and solid phase, determined with the Filter Press: the smaller the volume of the liquid pressed through the filter, the more stable the suspension is.
- density, determined by a mud balance test.
- distribution of grains, which gives a clue to the permeability.
- size and geometry of grains, for the application of filter criteria.

For highly permeable soils pure bentonite suspensions cannot be used any more, because they penetrate the ground and the required suspension pressure may not be reached. As rough pointers for the applicability of bentonite suspensions the grain distribution, the permeability and the heterogeneity of the ground may serve. A generally accepted rule of thumb states that the limit may be reached for gravel with a permeability greater than about $10^{-3}$ m/s (c.f. Fig. 1 and Krause, 1987).

## 4 MODIFICATION OF BENTONITE SLURRIES

### 4.1 *Basic Additives*

If the permeability of the soil is too high for the applicability of a pure bentonite suspension, additives may be used which change both the physical and the geometrical properties of the suspension. The following questions may be used to find effective additives:

- which components should be added, and in what proportion?
- what is the effect of these component with regard to the formation of a membrane or filter cake, penetration, and overall quality?
- how can these effects be tested and controlled?

Additives other than bentonites have seldom be used for slurry shields. The first comprehensive investigation was made by Krause (1987), who tested the influence of the additives sand, polymer, cement and mica flakes. One of the first applications of additives in a slurry shield was in the Grauholz Tunnel (Jancsez and Steiner, 1994), where sand, polymer and sawdust have been added. However this suspension was only used in one place to build up a filter cake before accessing the working chamber under compressed air conditions, but not during normal advance works.

Cement is not investigated here due to the requirement that its concentration and processing time must remain within narrow limits to avoid negative effects.

Similarly, mica flakes are not considered because of the insufficient bonding at the ground. Peeled off parts at the face would endanger safety unacceptably.

If sand penetrating the ground fulfills the filter criteria of Terzaghi and Peck (1956) it may plug the pores, and lead to a welcome progressive filtration process. However, for the coarse gravel considered here the sand would also require a large grain size, so that further additives may be necessary.

Sawdust with its long fibers is bound to clog the soil pores directly at the surface. However, if they are too long the problem will arise that they also clog the sieves at the separation plant.

### 4.2 *Preliminary Laboratory Tests*

All tests listed in 3.2 for pure bentonite suspensions are indirect tests, as they just give values for the physical properties. From these values the ability to support the face must be deduced, a rather difficult and uncertain undertaking. Therefore a more direct test was used by directly measuring the suspension pressure and the corresponding penetration depth (Fig. 4). With increasing pressure the depth increases. At a critical value, the so called maximum support pressure, suddenly the whole suspension is expelled.

The grain distribution of the gravel (③ in Fig. 4) has been determined in such a way, that the maximum reachable support pressure for a pure bentonite suspension coincided with the conditions encountered in situ.

Additionally, the indirect tests of 3.2 have been executed mainly for the sake of completeness. Sometimes the Marsh Funnel could not be employed as due to its high viscosity the suspension did not run out.

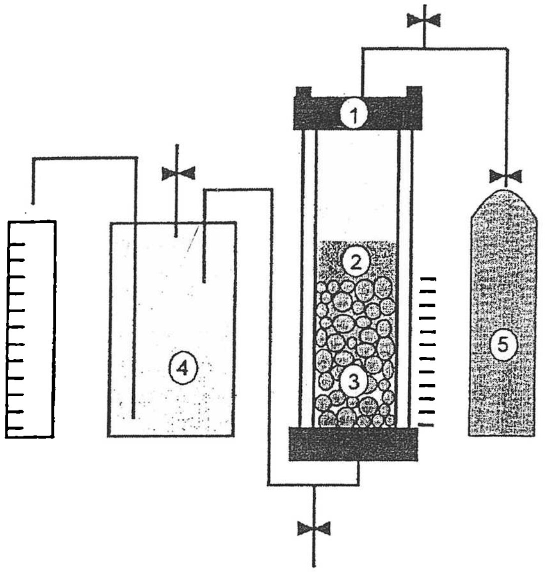


Fig. 4 Apparatus for measuring the Suspension Pressure
① Perspex Tube (15 cm diameter)
② Suspension
③ Gravel (4/8 mm)
④ Water
⑤ Air Pressure Supply

Our first tests aimed to better understand the mechanism of filtration. For this purpose the influences of Polymer (Carboxymethylcellulose), NaCl, $CaCl_2$, Cetylpyridinium (CPC) and Hydrotalkit (HT) were examined. The basic suspension was always an activated bentonite (product Ibeco HT-X), sand < 1mm and sawdust < 2mm.

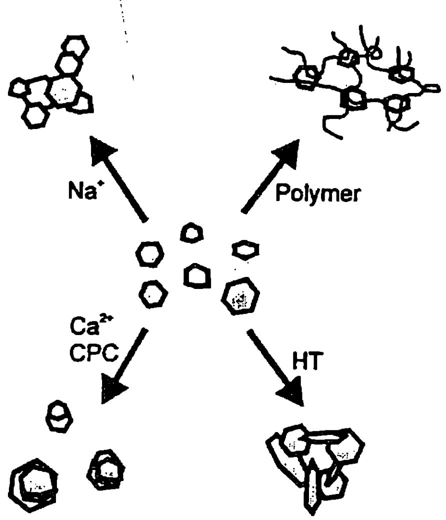


Fig. 5 Models of the aggregate structure for some additives (Penner and Hermanns, 1998)

It was seen (Penner and Hermanns, 1998), that adding polymers and NaCl, to a lesser extent also HT, improved the maximum support pressure of the suspension. This is attributed to the effect, by which these additives form network-like, favorable strutures (Fig. 5). Combined addition of polymers and NaCl further improved the supporting ability. $CaCl_2$ and CPC have a much stronger flocculation tendency than NaCl, which favors the formation of a filter cake, but prevents penetration. Higher concentrations of $CaCl_2$ cancel the positive effect of polymer.

In the sense of a standardized procedure, the suspensions were always mixed in the following way:

1. polymer was dissolved in water,
2. sand was mixed with the dry bentonite, and
3. other additives were stirred into the previously mixed suspension.

When mixing the polymer it was noted that it was not completely dissolved. However, if before adding the polymer the water was heated to $40^0$C (Fig. 6), the solubility was much better. This procedure was also adopted at the construction site.

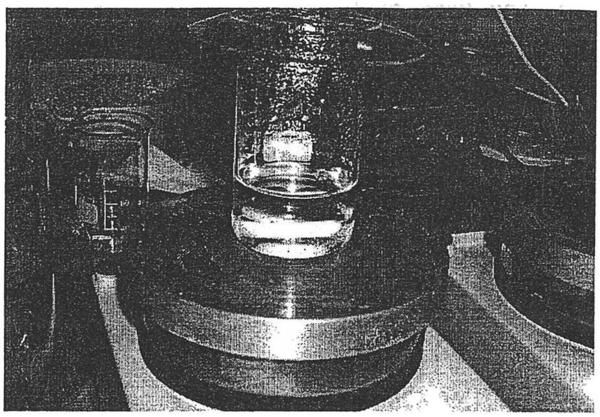

Fig. 6 Heating and stirring the Polymer for better Solubility

The next test series of experiments aimed at finding from all potentially possible mixtures at least one which allowed to provide the required support pressure in Situ of 0.5 bar.. The first success was reached with a mixture consisting (per $m^3$ water) of

- 40 kg bentonite,
- 0.5 kg polymer, and
- 40 kg sawdust.

However, use of this suspension in situ revealed, that the sawdust could not pass through the sieves in the separation plant. Replacing all sawdust after each cycle would have meant adding about 16 tons per hour, which was not realistic. Therefore, it was tried to determine the minimum amount of sawdust required. This was found to be 10 kg, but as compensation 100 kg of sand had to be added.

Thus the recommended mixture was

- 40 kg bentonite,
- 0.5 kg polymer,
- 100 kg sand, and
- 10 kg sawdust.

It was interesting to see that all components of this mixture have been necessary. When one was left out the required support pressure could no longer be reached.

### 4.3 *First in situ Tests*

The mixture found above was employed in a test run for the slurry shield at Hermetschloo (Fritz and Tandler, 1999). As a first measure the hydrocyclones and the sieves were adjusted until reaching a nearly complete recycling of the sawdust. Then the slurry shield worked successfully for two weeks. The required suspension pressure could always be reached.

All problems seemed to have been solved until in the reserve tank and in the pipes the development of a strong foam was observed. Therefore, in the whole system the required pumped volume could not be achieved and the circulation could not be maintained. The development of foam could also be reproduced in the laboratory. Some substances were set free from the sawdust which caused a more or less strong foam development.

As a consequence we had to go back to the laboratory to find a replacement component for the sawdust.

### 4.4 *Enhanced Additives*

The problem was to find a component with a similar positive effect as the sawdust, but without its shortcomings. It should also have relatively large fibers or grains to enable sealing with a membrane, and a small density to allow pumping.

As mentioned above, Krause's (1987) mica flakes could not be employed due to insufficient bonding and easy peeling off. Nevertheless the idea was to investigate components which also belong to the mica group. One was expanded vermiculite, gained from the 3 layer clay mineral vermiculite, an aluminium-ferrous-magnesium silicate, which belongs to the mica group. When subjected to heat of 300 $^0$C vermiculite has the property of exfoliating or expanding into small balls, similarly to the expanded clay used in flowerpots. The increase in bulk volume is up to 25 times, and the resultant density is 900 kg/m$^3$.

Another basic material investigated was siliperl, a granular perlite with a grain size of 2 to 4 mm. Perlite is a vitreous volcanic rock, whose pearl–structure stems from shrinking during cooling. Siliperl is expanded at temperatures of 1'000 $^0$C to about 20 times its volume. The grain size varies from 2 to 4 mm, the density is again about 900 kg/m$^3$. Brand names of the expanded siliperl are Isoself, and Nivoperl. The latter is coated with a natural resin.

A further path investigated was not only to replace the sawdust but also the polymer. A component considered was Bentonite CB ("Catsan Bianco") of the firm Süd-Chemie, which is also used as pet litter. It contains about 40% bentonite and has a strong tendency to clumping.

### 4.5 *Second Set of Laboratory Tests*

The preliminary tests aimed to investigate the influence of vermiculite on the standard index values. Fig. 7 shows the improvement of the yield limit determined with the "Kugelharfe" due to the addition of vermiculite with a grain size of 0.7 to 4 mm. Interesting is the great influence of the bentonite used.

However, also the volume of the liquid passed through the Filter Press increases with increasing vermiculite concentration, which points to an increased tendency of segregation.

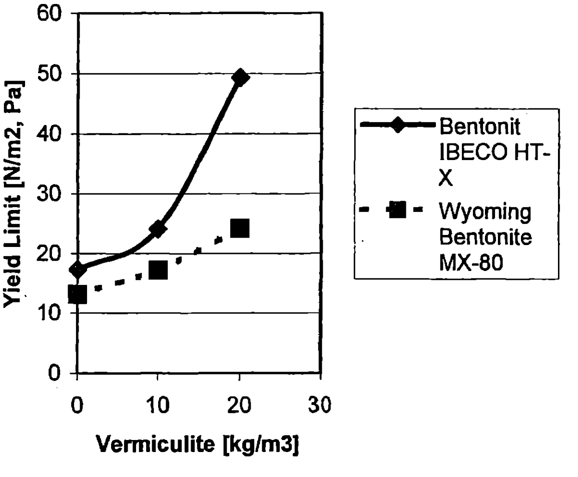


Fig. 7 Influence of Vermiculite Concentration on Yield Limit (Suspension with 40 kg Bentonite, 0.5 kg Polymer and 100 kg Sand)

Direct pressure tests with vermiculite exhibited equally good results as with sawdust. With 10 kg vermiculite per m$^3$ water the required pressure for equilibrium of 0.5 bar could be reached, and with 20 kg as much as 1.5 bar.

With Nivoperl it was not possible to reach even the equilibrium pressure. On the other hand Isoself led to similar results as vermiculite. However, Isoself did not really penetrate the ground, just a kind of a cover was formed, but not a real membrane or filter cake. Such a cover is unlikely to be built up in real conditions under the constant erosion by the turning cutting wheel.

The suspension with Bentonite CB (without any other bentonite) was not as smooth as the others. It contained sandy grains or agglomerations of grains of variable size, which helped clogging of the pores in the ground. The rheological behavior and standardized index values are comparable to Bentonite HT-X. For a concentration of 200 kg per $m^3$ water the required pressure could be reached even without polymer, i.e. with just 100 kg sand. However, due to delivery problems for the great volumes needed and the expected high price Bentonite CB was not further considered.

Based on the tests described above for the rest of the driving work of the Hermetschloo gallery a mixture of

- 40 kg bentonite (IBECO HT-X),
- 0.5 kg polymer (Carbocel C190),
- 100 kg sand (grain size < 1mm), and
- 20 kg vermiculite (0.7 to 4 mm)

per $m^3$ water was chosen (Fig. 8).

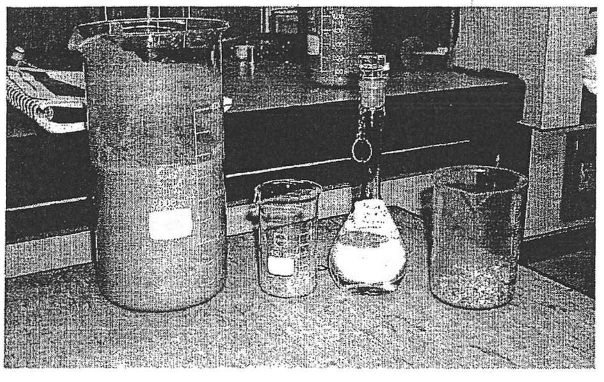

Fig. 8 The four components of the Suspension Bentonite, Sand, Polymer and Vermiculite

## 5 EXPERIENCE DURING ADVANCE

The practical experience gained during the advance has been described elsewhere (Fritz and Tandler, 1999). Here it suffices to say that, in contrast to the first section, the face could always be successfully supported without any incidences. Even a test under compressed air with access to the working chamber presented no problems.

## 6 GENERAL CONSIDERATIONS AND CONCLUSIONS

Because the excavation process at the Hermetschloo site had to be stopped to wait for the results of our laboratory investigations, the work had to be carried out under enormous time pressure. Therefore, several questions could not be completely answered. E.g. all the tests with the different additives had just been carried out to prove that the required suspension pressure could be reached. But it was not checked how big the remaining safety margin was.

When advancing the gallery it was noticed, that the vermiculite grains were crushed during the circulation of the suspension. For compensation simply new vermiculite was added. However, for major construction sites this could become uneconomic.

In a current study, the rheological properties of bentonite suspensions are further investigated by means of a modern rheometer. Among others, the flow behavior, the yield point and the thixotropic behavior are determined.


## ACKNOWLEDGEMENTS

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They would also like to express to the valuable contribution of Dr. G. Kahr, who first introduced vermiculite as a possible additive.


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