EXTENDED APPLICATION RANGES FOR EPB-SHIELDS IN COARSE-GRAINED SOILS

Dr.-Ing. Christoph Budach[1], Prof. Dr.-Ing. Markus Thewes[2]

[1] *HOCHTIEF Solutions AG, Civil Engineering and Tunneling, Alfredstraße 236, 45133 Essen, Germany*

[2] *Institute for Tunnelling and Construction Management, Ruhr-University Bochum, Universitätsstraße 150, 44801 Bochum, Germany*

KEYWORDS

Mechanized Tunnelling, Earth Pressure Balance (EPB-) Shield, Soil Conditioning especially with Foam

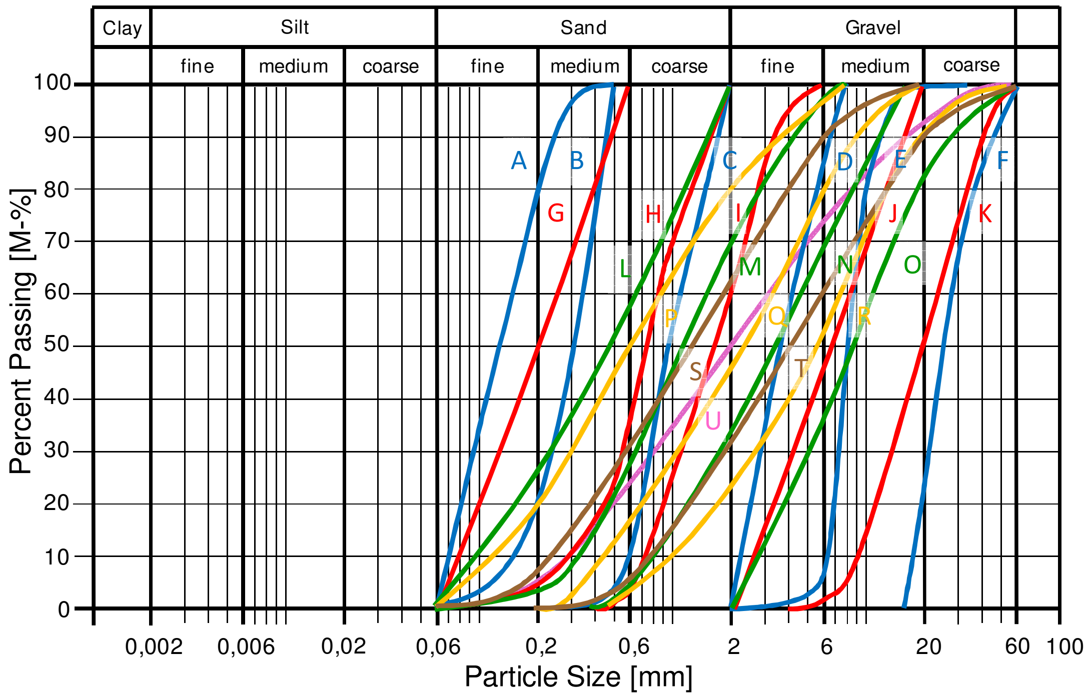
INTRODUCTION

EPB-Shields were originally used in soils with a content of fines (d < 0.06 mm) of at least 30 M-% (Herrenknecht et al., 2011). In coarse-grained soils, conditioning with foams, polymer foams, polymer suspensions or suspensions with a high content of fines has proven to be particularly effective to extend the application ranges of EPB-Shields. The dosage of these conditioning agents is based on practical experiences from previous tunnelling projects. Until now, a verification of these application ranges in coarse-grained soils has not been conducted by systematical research.
Based on methods presented in (Budach, 2012), the main properties of conditioned coarse-grained soil can be determined. These methods were used in laboratory research at the Institute for Tunnelling and Construction Management of the Ruhr-University Bochum (RUB), Germany, to characterize conditioned soils with a systematical variation of properties of soil and conditioning agents.

COARSE-GRAINED SOILS USED IN LABORATORY RESEARCH

Different grain fractions were used to produce soils with a variation of grain size distribution curves. With six different grain fractions (fine sand, medium sand, coarse sand, fine gravel, medium gravel, coarse gravel; all standardized laboratory quality) a total of 21 coarse-grained soils were created. Their grain size distribution curves are shown in figure 1. Their colors are representing the number of required fractions (see legend of figure 1). Usually, the soils were moistened to a water content w of 10 M-% before any conditioning took place.

These soils were mixed with different conditioning agents for 30 seconds in a free fall concrete mixer. The mixing time was chosen based on preliminary tests regarding the influences of stirring foam with soil. The recommended time is suitable for a homogenous mixing while minimizing the influences of other influences during mixing (Budach, 2012).



Colour of grain size distribution curve	Number of required grain fractions
Blue	1
Red	2
Green	3
Yellow	4
Brown	5
Violet	6

Figure 1: Grain size distribution curve of tested soils (Budach, 2012)

LABORATORY RESEARCH TO DETERMINE PROPERTIES OF CONDITIONED COARSE-GRAINED SOIL

The main properties of the support medium are its workability, compressibility and water permeability (Thewes et al., 2011). Also, the density and vane shear strength of the conditioned soils were measured. These properties are explained in the following paragraphs.

Workability

The workability of the conditioned soil can be estimated using the slump test after (DIN EN 12350-2, 2008). According to (Vinai, 2006) the slump values of between 10 and 20 cm could allow an adequate workability, if the conditioned material is homogenous. In a first step of the laboratory testing at RUB, the aim was to determinate a slump value of soils with different Foam Injection Ratios (FIR) between 10 and 20 cm. It is also possible to measure the diameter of the deformed conditioned soil (Thewes et al., 2012). This value is called “flow diameter*” according to (DIN EN 12350-8, 2009).

In figure 2 (above) examples of homogeneous conditioned soils (fine and middle sand, soil G, grain size distribution curve see figure 1) are shown. This material is homogeneous, because no loss of water or foam was identifiable and the top of the original soil cone was visible. At the bottom in figure 2 inhomogeneous soils (coarse sand and fine gravel, soil I, grain size distribution curve see figure 1) are presented. These soil-foam-mixtures are not suitable as support medium, because water or foam was lost and the soil samples fell apart, so that no adequate workability could be shown. The properties of the foam (foam agent, Foam Expansion Ratio (FER), concentration of foam agent c_f) were not varied.

The soils listed in table 1 reached the required slump values by adding foam at varying FIR. Soils with grain size distribution curves shown in figure 1 but not listed in table 1, e. g. soil I, could not guarantee an adequate workability.

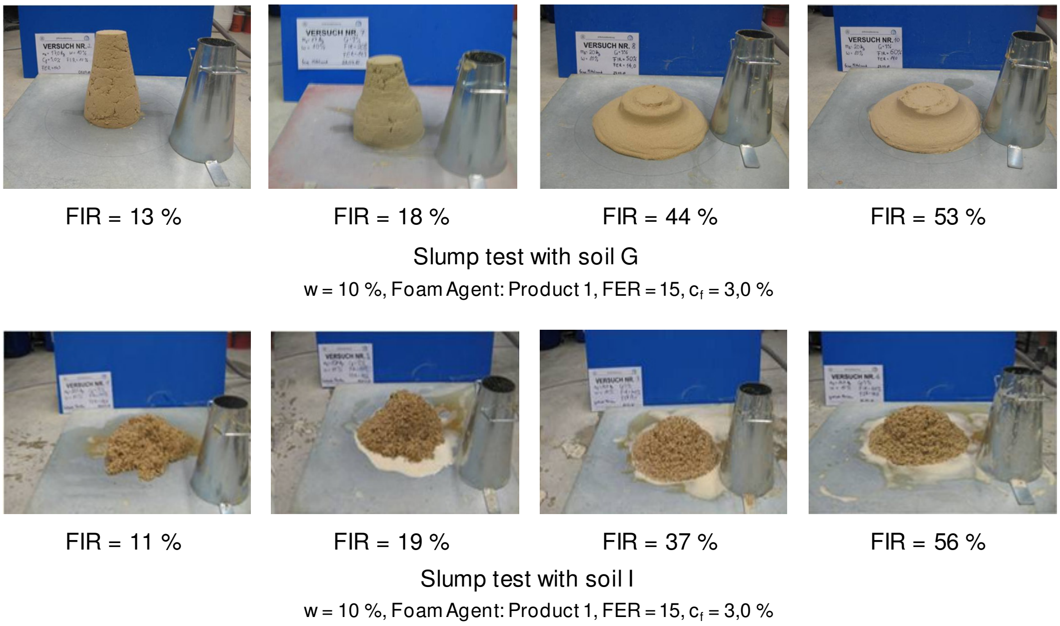


Figure 2: Tests to determine the slump value of different soil-foam-mixtures (Budach, 2012)

Compressibility

By adding foam into soil, the resulting soil-foam-mixtures become compressible. The determined height of the soil sample at atmospheric pressure and at support pressure in a pressure container was necessary to calculate the relative compressibility of the soil-foam-mixtures (Thewes et al., 2012). The percentage compressibility for different conditioned soils was between 1.4 and 17.3 % (see table 1). Obviously, soil-foam-mixtures with high FIR lead to a large compressibility, because of the high content of air inside. According to the geometric and process technology of EPB-Shields a minimum compressibility of the support medium of about 2 % should be required (Budach, 2012).

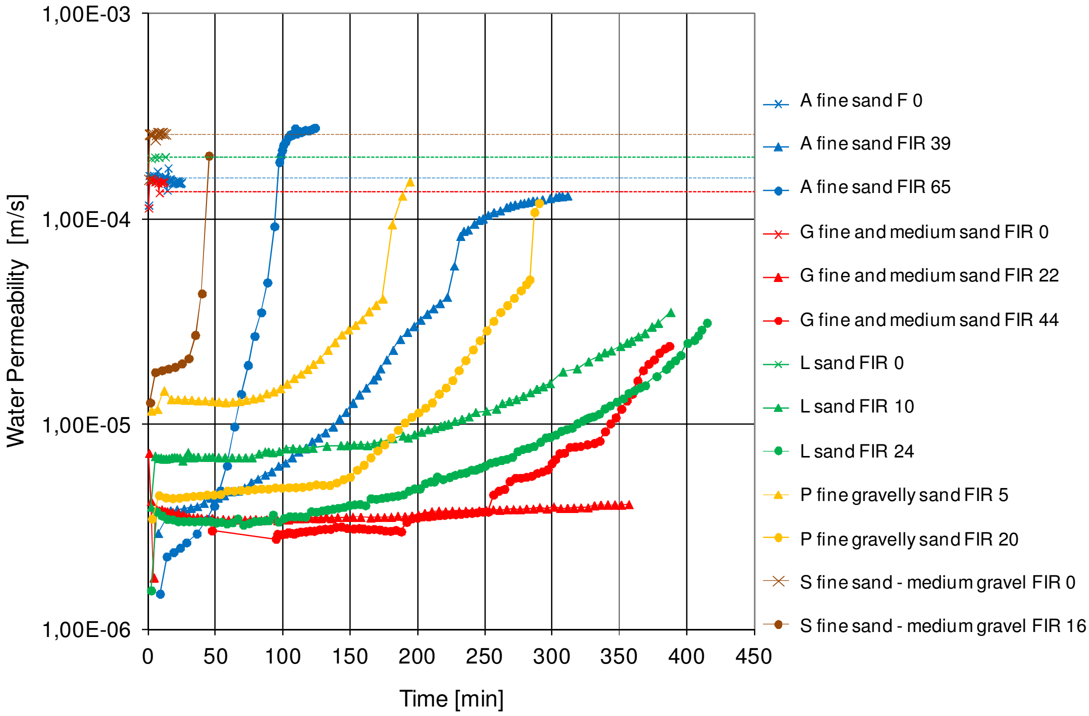
Water Permeability

Some time-dependent curves of water permeability of soil-foam-mixtures are presented in figure 3. Here, soils were used, which had a certain percentage of fine sand. The water permeability increased with testing time, due to the drainage of foam.

The curves of the water permeability of the unconditioned soils are also presented in figure 3 (dashed lines). These permeability values were determined within a time period of 30 minutes. Water permeability of the conditioned soils usually is lower than for unconditioned soil, so that the influence of foam within the support medium is noticeable. The comparatively high water permeability of fine sand (soil A) could be influenced by high FIR.

Soil-foam-mixtures with low FIR and with soil G, soil L and soil P the values of the water permeability were mostly above the values of conditioned soils with high FIR. For soil A and soil G, that were conditioned with high FIR (65 % and 44 %), it was determined, that the water permeability of the soils with high FIR was greater than the water permeability of soils with lower FIR. It is assumed that very high FIR could lead to a faster drainage of the foam out of the mixture and to faster increase of the water permeability.

For projects with EPB-Shields below the groundwater level it is necessary, that water permeability of soil-foam-mixtures should be lower than $1*10^{-5}$ m/s (Wilms, 1995). This value should be guaranteed for a sufficient time period. According to (Maidl et al., 2009) the required time period for this value is 90 minutes (Budach, 2012).

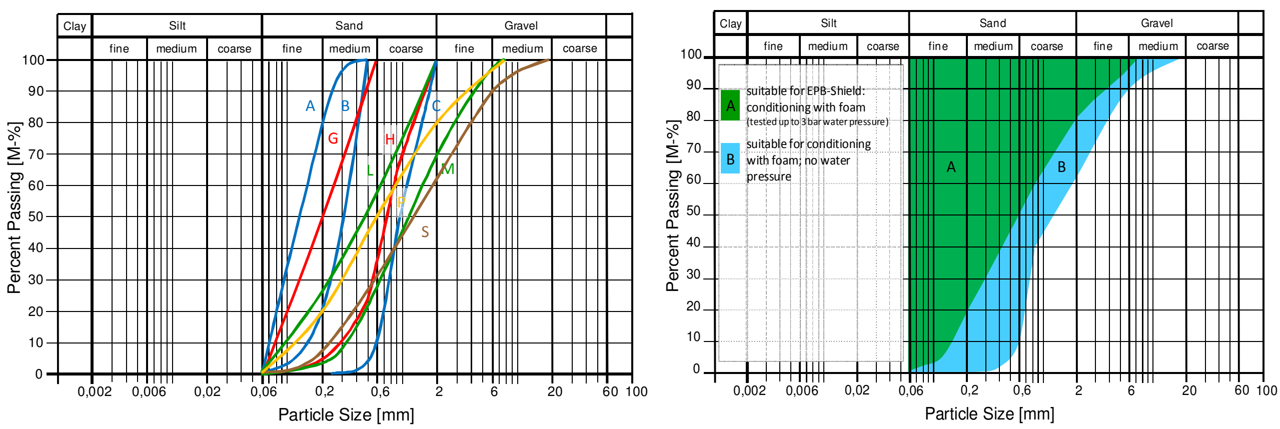


FG3, Q_F = 70 l/min, Product 1, FER = 15, c_f = 3,0 %, length of foam gun = 29 cm, filling material = glass balls 5 mm, supply pressure 5 bar , c_p = 0 %, water content w = 10 %

Figure 3: Water permeability of different soil-foam-mixtures with grain fraction of fine sand depending on time (Budach, 2012)

Also tests to determine the density and vane shear strength of the different foam-soil-mixtures were done. The results of these tests are shown in table 1.

It was possible to condition soils with grain size distribution curves successfully, that are shown in figure 4 (left). These soils allow an adequate workability by using different FIR. Application ranges of EPB-Shields in coarse-grained soils by using foam as conditioning agent could be developed based on the test results (see figure 4 right).



FG3, Q_F = 70 l/min, product 1, FER = 15, c_f = 3,0 %, length of foam gun = 29 cm, filling material = glass balls 5 mm, supply pressure 5 bar , c_p = 0 %, water content w = 10 %

Figure 4: Grain size distribution curves of soils, that were conditioned successfully with foam (left) and application ranges of EPB-Shields with foam conditioning (right) (Budach, 2012)

The results of the tests to determine the properties of the soil-foam-mixtures are shown in table 1. In the first two columns the letter and the description of the soils are listed in the same color of the grain fraction (see figure 1). The FIR, that are presented in column 3, were necessary to reach the slump values of approximately 10 and 20 cm. For some soils it was not possible to reach both values, in these cases only one value is listed. The results of determination the flow diameter*, compressibility, water permeability, density and vane shear strength are listed in the following columns.

Table 1: Overview of properties of soil-foam-mixtures with vary the properties of the soil (Budach, 2012)

Soil		FIR	Slump Test	Flow Diameter*	Compressibility			Time to achieve water permeability of				Density	Shear strength
					0,5 bar	1,0 bar	2,0 bar	$5*10^{-6}$ m/s	$1*10^{-5}$ m/s	$5*10^{-5}$ m/s	$1*10^{-4}$ m/s		
Letter	Description	[%]	[cm]	[cm]	[%]	[%]	[%]	[min]	[min]	[min]	[min]	[kg/l]	[kN/m²]
A	fine sand	39	10,0	25,5	5,8	5,8	5,8	72	137	222	245	1,23	0,9
		65	20,0	38,0	16,3	17,4	17,4	55	64	90	96	1,04	0,3
B	medium sand	9	12,0	24,5	2,7	2,7	2,7	27	280	412	431	1,38	1,0
		17	21,0	36,5	5,6	5,6	5,6	48	224	315	> 315	1,29	0,4
C	coarse sand	5	19,5	34,5	6,8	6,8	6,8	0	0	7	8	1,48	1,2
G	fine and medium sand	22	10,5	23,5	2,9	2,9	2,9	> 356	> 356	> 356	> 356	1,32	0,8
		44	19,5	39,5	12,5	12,5	12,5	265	342	> 387	> 387	1,21	0,3
H	medium and coarse sand	5	15,0	29,0	2,6	2,6	2,6	0	0	24	25	1,43	0,5
		9	20,0	38,0	7,0	7,0	7,0	0	0	20	26	1,39	0,3
L	sand	10	10,0	22,5	4,1	4,1	4,1	0	170	> 290	> 290	1,45	0,8
		24	19,0	30,5	10,2	11,1	11,1	123	250	> 300	> 300	1,41	0,5
M	gravelly sand	5	20,0	35,0	2,3	2,3	2,3	0	0	9	10	1,58	0,8
P	fine gravelly sand	5	10,0	23,0	1,4	1,4	1,4	0	0	174	180	1,59	1,5
		20	19,0	31,0	9,8	10,2	10,2	120	190	280	286	1,49	0,5
S	fine sand - medium gravel	16	20,0	32,5	5,5	5,5	5,7	0	0	40	42	1,71	1,0

FG 3; Q_F = 70 l/min, product 1, FER 15, c_f = 3,0 %, length of foam gun = 29 cm, filling material = glass balls 5 mm, supply pressure = 5 bar, c_p = 0 %
water content w = 10 %

Further tests using soils and different conditioning agents (polymers, polymer suspensions, suspension of fines and combinations of these including foam) with varied injection ratios were done to determine the main properties (Budach, 2012). Based on these results, the application range of EPB-Shields can be estimated.

APPLICATION RANGE OF EPB-SHIELDS

Based on different application ranges depending on each tested conditioning agent an overview for the use of EPB-Shields was developed (figure 5).

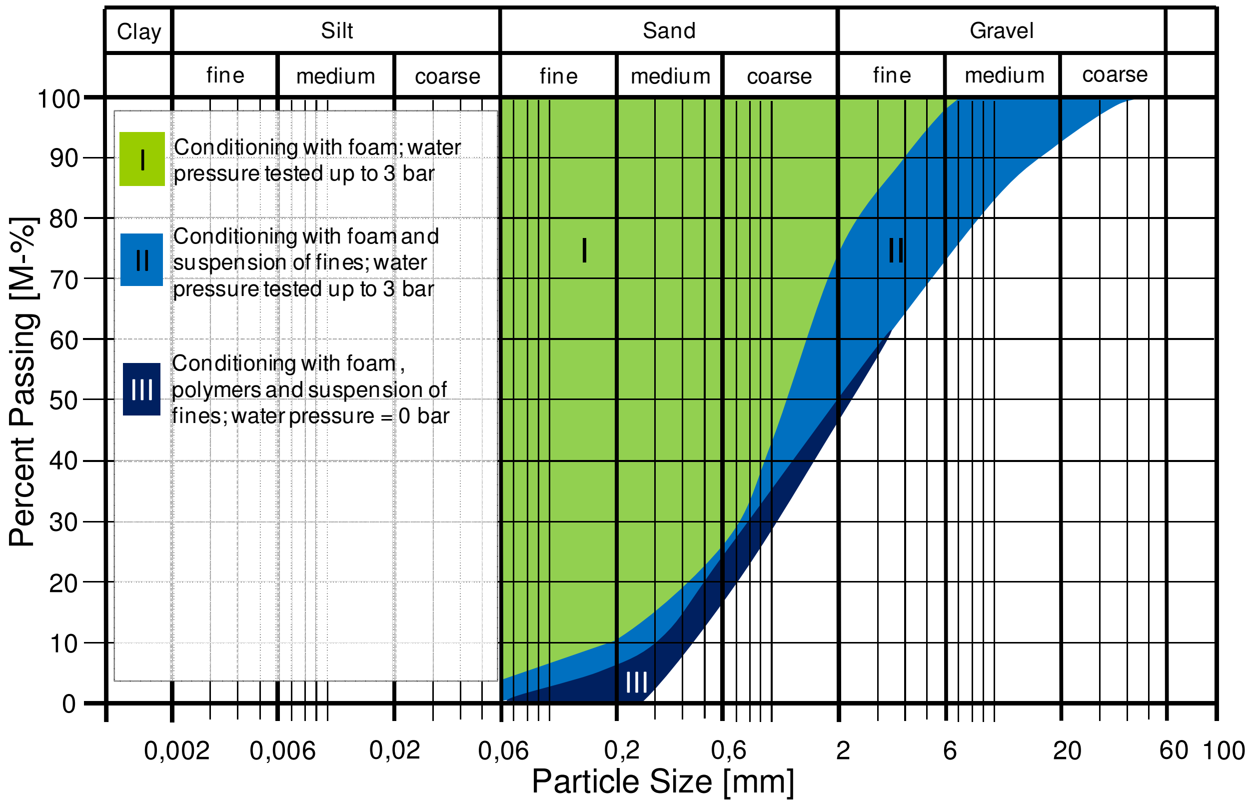


Figure 5: Overview of application ranges for EPB-Shields in coarse soil based on laboratory research (Budach, 2012)

An EPB-Shield with foam as conditioning agent is normally applicable to realize a tunnel drive beneath the water table, if the grain size distribution curve of the soil is within range I (colored green in figure 5). The content on fines in the soil should be higher than 5 M-%. Range II (colored light blue in figure 5) defines the grain size distribution curves of soils, which allow a tunnel drive, if additional conditioning agents, like polymers and suspensions, are used. These agents could change the properties of the support medium, so that adequate workability, fair compressibility and low water permeability is possible. These requirements will be reached, if the grain size distribution curve of the soil is in range II and also perhaps in range I.

In range III (in figure 5 colored dark blue) combination of tested conditioning agents could lead to an adequate workability and compressibility but not to a sufficiently low water permeability lower than $1*10^{-5}$ m/s. If the grain size distribution curve is within the range III, II and also perhaps I, it should be possible to condition the soil, that an EPB-Shield could be used for tunnel drives above the water table.

If grain size distribution curves of coarse-grained soils are in part or completely out of the ranges I, II and III, it is likely, that full face EPB-face-support during a tunnel drive above or beneath the water table will be very difficult, because no adequate workability can be achieved.

For the use of EPB-Shield in coarse-grained soils and for conditioning the soil with different agents the required injection system have to be installed on the shield machine. Therefore, it could be necessary that three independent injection systems (foam injection respectively foam injection with a content of polymers, polymer injection and injection of suspensions of fines) should be on the shield machine. An example for these three injection systems could be a soil, that grain size distribution curve is within the ranges II and III.

Figure 6 shows the developed three application ranges of coarse-grained soils and also the borders of the application ranges based on jobsite experience (Thewes, 2007) - shown as lines - normally for mixed-grained soils depending on conditioning agents.

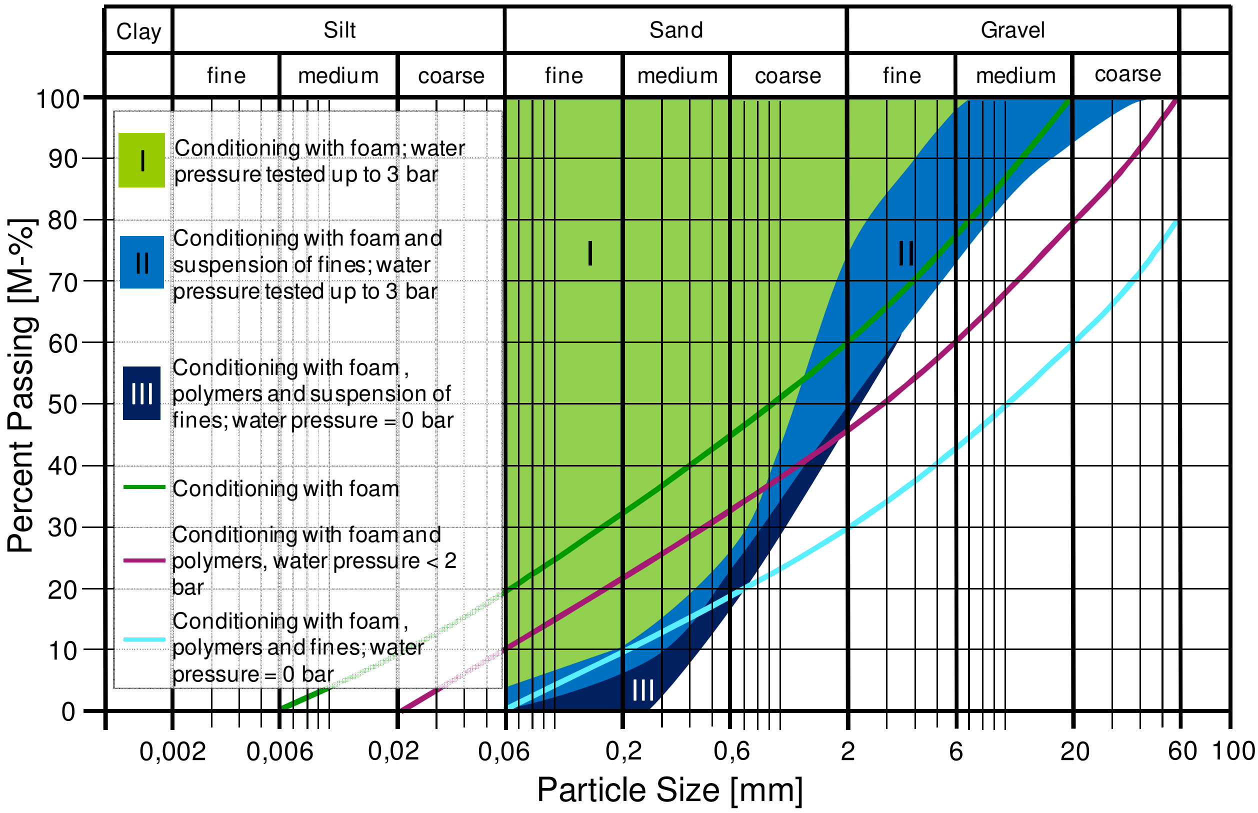


Figure 6: Application ranges of EPB-Shield based on laboratory research (Budach, 2012) in comparison with empirical recommendations from (Thewes, 2007)

The green line in figure 6 is approximately the border for the application range of EPB-Shield with foam as conditioning agent (Thewes, 2007). The soils should posses a content of fines of more than 20 M-%. Based on test results of the laboratory research, this application range could be extended into soils with lower content of fines, if the grain size distribution curve is within the green colored range. With the new application range, the conditioning of soils is also possible, if the soils have a lower coefficient of uniformity.

According to (Thewes, 2007) an EPB-Shield with foam and polymers as conditioning agent can be used, if the water pressure is lower than 2.0 bar (see violet line). The results of the laboratory research using foam with different content of polymers lead to an application range similar to the application range only with foam as conditioning agent, because the tested polymer did not show any influence on the main properties (Budach, 2012). Due to this, the violet line could be compared with the green colored range. An extension of the application range is possible, if the grain size distribution curve of the soil is within the green colored range and has a lower content of fine and middle sands than the violet line.

EPB-Shields using foam, polymers and suspension of fillers could be used in soils with a maximum grain size distribution curve like the light blue line. Therefore, only no water pressure is recommended. Using these conditioning agents in laboratory research, the application range for EPB-Shields beneath (light blue range II) and above the water level (dark blue range III) is divided.

In soils with a lower content of fines than 20 M-% it could be possible to use an EPB-Shield (compared light blue range II and violet line), if the grain size distribution curve is within the light blue range.

Furthermore, the use of conditioning agents allow an extension of the application range of EPB-Shields into soils, which do not inhibit a content of fine sand (see dark blue range III and light blue line). In these soils it is necessary that no water pressure appears, because the conditioned soil could not guarantee an adequately low water permeability.

Based on the laboratory research, the following results can be summarized:

- The use of different conditioning agents allows an extension of the application ranges of EPB-Shields into coarse-grained soils.
- By using different conditioning agents (like polymers and suspension of fines) and combination of these, tunnel drives with EPB-Shield are also possible in cohesionless soils beneath the water table, where EPB-Shields only with foam conditioning could not guarantee the required properties of the support medium.
- Improved recommendations for the application ranges of EPB-Shields based on a wide parameter variation in laboratory research were developed.

CONCLUSIONS

Different methods were used for laboratory research to determine the main properties of conditioned cohesionless soils with adequate conditioning agents. Tests with soils with widely varied grain size distribution curves and different conditioning agent were carried out. Mainly, the workability, compressibility and water permeability of the support medium are important to define the application range of EPB-Shields in coarse-grained soils. A large number of tests were done with different soils using foam, polymers, polymer suspensions and suspension of fines as conditioning agent. The analysis of the test results lead to an extension of the application ranges of EPB-Shields. Modified application ranges for EPB-Shields in coarse-grained soils based on laboratory research were developed.

REFERENCES

Budach, C. (2012): *Untersuchungen zum erweiterten Einsatz von Erddruckschilden in grobkörnigem Lockergestein (Transl.: Extended application ranges of EPB-Shields in coarse-grained soils)*, Dissertation, Ruhr-University Bochum, Germany, 2012

DIN EN 12350-2, (2008): *Prüfung von Frischbeton – Teil 2*: *Setzmaß*, Berlin

DIN EN 12350-8, (2009): *Prüfung von Frischbeton – Teil 8: Selbstverdichtender Beton – Setzfließmaß-Prüfung*, Berlin

Herrenknecht, M.; Thewes, M.; Budach, C. (2011)*: The development of earth pressure shields: from the beginning to the present*, Geomechanics and Tunnelling, No. 1, pp. 11 - 35

Maidl, U.; Wingmann, J. (2009): *Predicting the performance of earth pressure shields in loose rock*, No. 2, 2009, pp. 189 – 197

Thewes, M. (2007): *TBM Tunnelling Challenges - Redefining the State-of-the-Art.* Keynote lecture at the 2007 ITA World Tunnel Congress, Prague, Tunel, Vol. 16, pp. 13 - 21

Thewes, M.; Budach, C. (2011): *Soil Conditioning for EPB Shields: New Results from Research on Foams and Soil-Foam-Mixtures*, Proceedings of World Tunnel Congress 2011, Helsinki

Thewes, M.; Budach, C.; Galli, M. (2012): *Vortrieb mit Erddruckschilden: Empfehlungen für Laboruntersuchungen zur Bestimmung wesentlicher Eigenschaften von Konditionierungsmitteln und konditionierten Lockergesteinen*, 8. Kolloquium Bauen in Boden und Fels, Ostfildern

Vinai, R. (2006): *A contribution to the study of soil conditioning techniques for EPB TBM applications in cohesionless soils*, PhD thesis, Politecnico di Torino, Turin

Wilms, J. (1995): *Zum Einfluss der Eigenschaften des Stützmediums auf das Verschleißverhalten eines Erddruckschildes*, Mitteilungen aus dem Fachgebiet Baubetrieb und Bauwirtschaft, Essen