Landmarks in Earth Reinforcement, Ochiai et al (eds),
©2001 Swets & Zeitlinger, ISBN 90 265 1852 8

Clay-cement mix with reinforcing fibres for diaphragm walls

A. Brinkmann, M. Benz, F. Bucher & P. Amann
Swiss Federal Institute of Technology ETH Zurich, Switzerland

ABSTRACT: Diaphragm walls constructed by the slurry trench method are one of the most frequently used and proven possibilities to encapsulate landfills or old industrial sites. Thus, contaminant propagation into ground water may be hindered in cases where insufficient or non-existent bottom sealing capacity exists. In the case of external loading after the execution and hardening of the wall, the diaphragm wall's capacity to withstand these mechanical solicitations without a decrease in performance must be verified. As the most recent research results have shown, in the case of very small deformations, clay-cement mixes for diaphragm walls are only able to withstand low tensile stress levels. In the following article, research results obtained for fibre reinforced samples will be presented. Samples reinforced with polyvinyl alcohol fibres showed increased tensile strength, higher unconfined compressive strength and higher triaxial shear strength. The principal advantage of fibre reinforcing is most probably due to the fact that if tension resistance is exceeded due to bending, the formation of gaping cracks over the entire wall section is hindered.

1 INTRODUCTION

At the Institute for Geotechnical Engineering (IGT) of the Swiss Federal Institute of Technology in Zurich, a clay-cement mixture for two phase diaphragm walls was developed (Hermanns 1993). During the two phase procedure, the trench is supported during excavation by a bentonite suspension (Phase 1). The second phase, in which the diaphragm wall is formed, is carried out immediately after the completion of the trench during the first phase. The above-mentioned mixture is made up of 491 kg/m^3 clay, 368 kg/m^3 Portland cement, 123 kg/m^3 bottom filter ash and 654 kg/m^3 water. This results in a density of $\rho = 1.63$ t/m^3. In order to be able to pump the mixture, the addition of a cement workability agent of approximately 1.5% by weight of the cement mixture was necessary. The feasibility of diaphragm walls using this mixture has been successfully tested on several occasions (Günther et al. 1995, Brinkmann 2000).

During the course of research on the mechanical behaviour of this mixture in a hardened state (Brinkmann & Amann 1999, Brinkmann 2001), it was able to be shown that only small tension stresses could be taken up. Large-scale tests at a 1:1 scale showed that the maximum strain under bending solicitations which may be withstood without damage is only about $\varepsilon = 0.01\%$.

Based on these results, the decision was made to undertake research to determine if fibre reinforcing is capable of improving the mechanical properties of the tested mixture. Tests to investigate the general effect of soil reinforcement have previously been carried out by the Institute (Bucher 1984). The test results presented in this publication were obtained as part of a project for the diploma (Benz 2000).

2 CHOICE OF FIBRES

In the case of fibre reinforcing, attention must be paid so that the barrier effect of the mixture is not compromised. In addition, the workability of the mixture must be guaranteed. In this case, this means that the mixture must be able to be pumped. In addition, the fibres must not lose their mechanical properties in the alkaline medium of the hardened mixture or through contact with the contaminated leachate.

For the tests carried out, polyvinyl alcohol fibres were chosen. These are used in place of asbestos in the production of fibre cement (Akers et al. 1989). Fibres 4 mm, 6 mm and 12 mm in length were available for the tests. The fibres were obtained from two producers: the 4 mm long fibres were provided by Eternit® AG, Niederurnen, Switzerland, and were manufactured in Japan by the Kuraray Co. Ltd. The longer fibres came from the Schwarzwaelder Textil-Werke, Schenkenzell, Germany. The material properties are presented in Table 1. The upper value in each row corresponds to the fibres from the Kuraray Company and the lower value to the fibres from the

Table 1. Material property values for polyvinyl alcohol fibres (PVA), manufacturers' values, upper value Kuraray Company and lower value Schwarzwaelder Textil-Werke.

Property	Value	Property	Value
Length	4 mm 6, 12 mm	Elastic modulus	36'000 MN/m^2 40'000 MN/m^2
Diameter	14 µm 13 µm	Limit strain (tension)	7.4% 6-7%
Density	no data 1.3 g/cm^3	Cost	about 5 CHF/kg no data
Tensile strength	1'530 MN/m^2 1'830 MN/m^2		

Schwarzwaelder Textil-Werke. Longer fibres than those described here were not available from the above companies.

An OH group is bound in the molecule of the polyvinyl alcohol fibres which synthesises with the available calcium bond in the cement. This results in a good bond between the matrix and the fibres.

3 TEST PROGRAM AND RESULTS

3.1 *Mixing tests, workability, sample preparation*

Before carrying out tests on the hardened samples, it was necessary to investigate at which point in time during the mixing procedure the fibres should be introduced in order to guarantee the most even distribution. In addition, it remained to be seen how the consistency of the mixture was modified through the addition of the fibres. Mixing tests were carried out in accordance with the fibre quantities presented in Table 2. After the mixing tests, the samples for the laboratory tests were prepared with the given fibre contents. Sample heights were 100 or 120 mm, diameters 56 or 100 mm.

Table 2. Fibre quantities used.

	Fibre content (% cement weight)				
Fibre length	0.3%	0.7%	1.3%	2.6%	3.9%
4 mm	x	x	x		
6 mm			x	x	
12 mm				x	x

For the non-reinforced mixture, the components were introduced in the following order: water, clay, bottom filter ash and cement. A blade mixer with a speed of 1200 rpm was used for the mixing. The mixing tests showed that the distribution of the fibres was most favourable when they were introduced at the end of the mixing process with a reduced mixer speed of 300 rpm. The suspension became stiffer as the fibres were introduced. Through the addition of approximately 3-4% cement workability agent, the same consistency as that of the non-reinforced mixture may be obtained visually. Tests using the mixing and pumping equipment used on site should be carried out to test the pumpability under site conditions. The density of the fibre reinforced mixture remained virtually unchanged with respect to that of the non-reinforced mixture.

3.2 *Unconfined compression tests*

Unconfined compression tests were carried out on 14 and 28 day old samples. Non-reinforced samples of the same age were tested to obtain reference values. It was seen that the unconfined compressive strength remained unchanged with the addition of 4 mm long fibres.

The test results on samples containing 6 mm and 12 mm long fibres are presented in Figure 1. Each value shown represents the average of three individual tests. The values of the reinforced samples are presented with respect to those of non-reinforced samples, 100% being the strength of the non-reinforced samples.

It may be observed that the unconfined compressive strength q_u of the reinforced samples was higher than that of the non-reinforced samples. For identical fibre content, the samples prepared with 12 mm long fibres showed the greatest increase. The results showed that fibre content greater than 2.6% of cement weight would probably not result in further strength increases.

The largest increase occurred for fibre contents between 1.3% and 2.6% of cement weight. The increase in strength seemed to decrease with increasing sample age. The 14 day samples reached an increase in strength between 10% and 23%, while for the 28 day samples an increase of only 7% to 17% was observed. The coefficients of variation ν (ν =

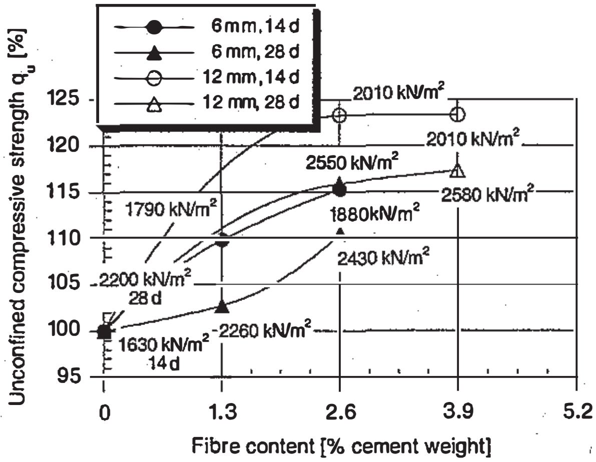

Figure 1. Normalized unconfined compressive strength q_u for various fibre contents.

average value/standard deviation) lay between ν = 0.8% and ν = 4.6% for the test series.

The increased unconfined strength can be attributed to the reinforcing effect of the fibres. In compression testing, traction stresses occur above all perpendicular to the loading direction, which could then be taken up by the fibres. It was clear that the anchoring length began to be sufficient at 6 mm; samples with 4 mm long fibres and fibre content of 1.3% cement weight showed no increase in strength. The absolute highest strength of all of the samples with 12 mm long fibres confirms this consideration. For a fibre content of 3.9% cement weight, the number of fibres was apparently so high that the matrix strength could no longer be developed in the same amount, as in the non-reinforced samples, and the positive effect of the reinforcing was no longer felt.

3.3 *Indirect tension tests (Brazilian tests)*

It was also observed during the indirect tension tests that the addition of 4 mm long fibres did not result in any increase in tensile strength.

In Figure 2, results from indirect tension tests on samples with 6 mm and 12 mm long fibres are presented. The behaviour was similar to that observed during unconfined compression testing. The tensile strength of the reinforced samples was higher than that of the non-reinforced samples for all fibre contents and lengths. It may be seen in these tests that for fibre contents greater than 2.6% cement weight no further improvement in strength properties occurred. 14 day old samples with a fibre content of 3.9% cement weight are an exception.

A further trend may be observed where the strength increase for 28 day samples was lower than the increase for 14 day samples. Thus, 14 day samples with a fibre content of 2.6% cement weight (6 mm long) showed a 15% strength increase while similar 28 day samples showed only 7%. The test series on 14 day samples with a fibre content of 3.9% cement weight also proved to be an exception here. Samples with 12 mm long fibres showed generally higher strength increases. For a fibre content of 2.6% cement weight, the samples with 6 mm long fibres and an age of 28 days reached an increase in tensile strength of 7%. The corresponding samples with 12 mm long fibres showed an increase of 14%. The coefficients of variation lay between ν = 0.3% and ν = 6.6% for this test series.

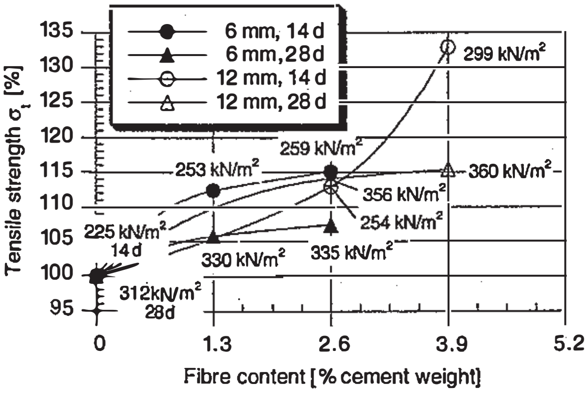

Figure 2. Normalized tensile strength σ_t for various fibre contents.

In Figure 3, the stress development for individual samples as a function of piston displacement is shown. This figure clearly shows the sample behaviour after the exceeding of the tensile strength. The curve for a 28 day non-reinforced sample is included for comparison. This sample broke after failure in two halves, such that the sample offered no more resistance under the press.

This was not the case for the reinforced samples. Even after exceeding the failure stress, the reinforcing held the samples together. No cracks were able to be observed with the naked eye after exceeding the tensile strength. The higher the fibre content and the longer the fibres, the less the stress decrease after reaching the maximum stress value.

In addition, this decrease was less for 28 day samples than for 14 day samples. Therefore, if may be concluded that an improved anchoring of the fibres in the matrix occurred with increasing fibre length and sample age.

3.4 *Triaxial shear tests*

Based on the test results up to this point, it was decided to carry out drained triaxial shear tests on samples with a fibre content of 2.6% cement weight and 12 mm long fibres. The greatest improvement in behaviour appeared to occur for this fibre length and content. The test program for the triaxial shear tests is presented in Table 3.

The triaxial shear tests were carried out under consolidated drained conditions. Isotropic consolidation was carried out over a time period of two days.

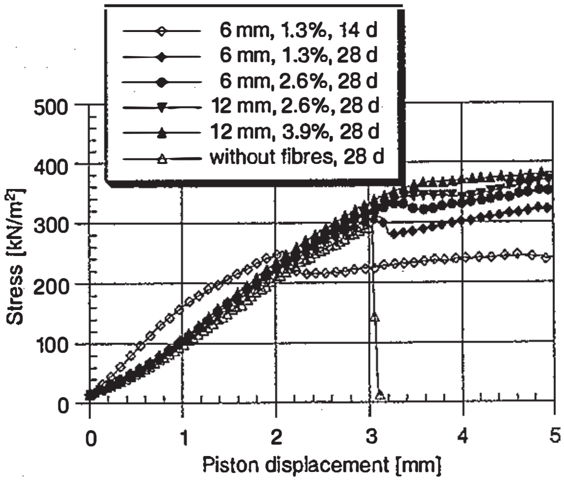

Figure 3. Results from indirect tension tests for various fibre lengths and contents.

Table 3. Test program: triaxial shear tests.

Lateral Pressure σ_3 [kN/m^2]	50	100	200	400	200 (without fibres)	400 (without fibres)
Sample age [d]	36	38	41	43	30	45

The volume change of the sample during this time was less than $\Delta\varepsilon_{vol} = 1\%$. The shearing process was deformation controlled. The stress σ_1 was applied with a constant deformation speed of v = 0.002 mm/min. Drainage was permitted on both the upper and lower faces of the sample.

The test results of the two reinforced samples with lateral pressures of σ_3 = 200 kN/m^2 and σ_3 = 400 kN/m^2 and the non-reinforced samples with identical lateral pressures are presented in Figure 4. The deviator $\sigma_1 - \sigma_3$ is presented as a function of sample deformation ε.

It may be stated as a result of this comparison that the results for reinforced samples reached higher deviators than those of the non-reinforced samples. However, it should be noted that the reinforced sample with a lateral pressure of σ_3 = 200 kN/m^2 was 11 days older than the non-reinforced sample and thus part of the increased strength was attained through further hydration of the cement. For the samples with a lateral pressure of σ_3 = 400 kN/m^2, the reinforced sample reached a 14% higher deviator than the non-reinforced sample. It may also be observed that for the reinforced samples the maximum deviator was reached for a larger deformation than for the non-reinforced samples. For the samples with a lateral pressure of σ_3 = 200 kN/m^2, an increase from ε = 1.4% to ε = 1.9% occurred, while for σ_3 = 400 kN/m^2 the increase is between ε = 2.7% and ε = 4.2%. The stress-deformation curves were practically identical for both reinforced and non-reinforced samples up to a deformation of ε = 0.7%. This means that the elastic modulus is identical in this section.

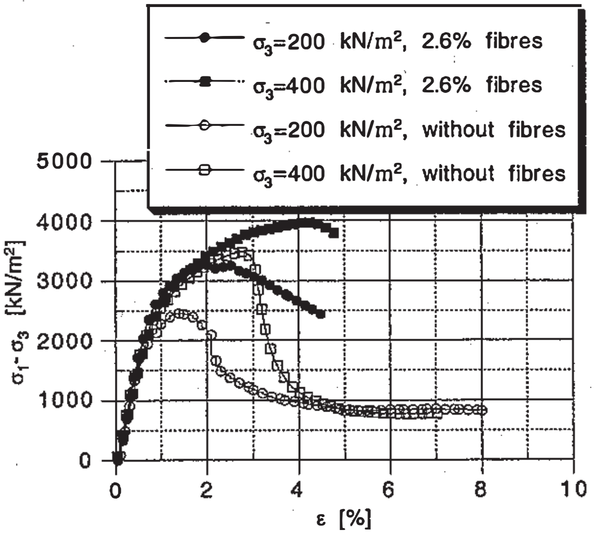

Figure 4. Results of triaxial shear tests under consolidated drained conditions for reinforced and non-reinforced samples.

In Figure 5 the results of the triaxial tests in a p'-q diagram are presented and interpreted. The interpretation is based on the hypothesis that during the shear process no pore water pressure developed. This hypothesis remains to be verified by further tests. The points lie on a line verified by the correlation coefficient R. This correlation yields the following shear parameters:

$$\varphi' = 39° \text{ and } c' = 610 \text{ kN/m}^2$$

3.5 *Permeability tests*

Figure 4. Results of triaxial shear tests under consolidated drained conditions for reinforced and non-reinforced samples.

The permeability behaviour of the fibre reinforced mixture was investigated in the triaxial cell at room temperature (20° C). The test equipment described by Hermanns (1993) was used. The gradient i with which the samples were percolated was 30 and was increased to 50 for 28 day samples. The samples were percolated from the bottom to the top. The tests were carried out with samples with fibres 6 mm and 12 mm long, for fibre contents between 1.3% and 3.9% cement weight (see Table 1).

One sample was mounted for each fibre content. A non-reinforced sample served as a reference.

In Figure 6, the results of permeability tests are presented. The tests were begun at a sample age of three weeks and ran approximately seven weeks. In four out of the five tests, clogging of the filter stone occurred, thus impeding further flow through it. Thus, the samples were remounted with new, smoother filter stones on the surface and the tests were restarted. The results of these samples are presented from the day of the new mounting. The reason for the clogging was attributed to the incomplete hydration of the cement, which in conjunction with the fine fibres led to the described situation.

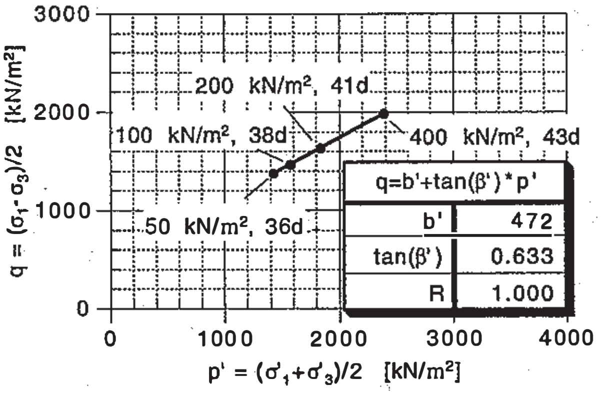

Figure 5. p'-q diagram with test results for reinforced samples.

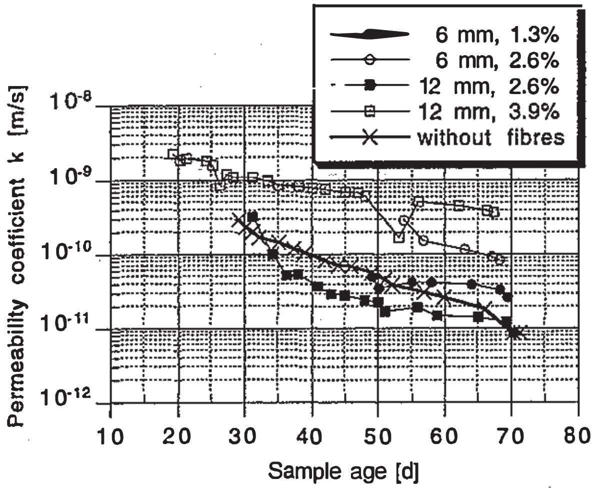

Figure 6. Results of the permeability tests for various fibre lengths and contents.

For all of the samples, a decrease in the permeability coefficient k was observed for an increase in test duration, as was already observed by Hermanns (1993). The decrease in permeability over time was similar for all of the samples.

All of the samples reached the usually required permeability value of $k = 1 \times 10^{-9}$ m/s. For the sample with a fibre content of 3.9% cement weight (12 mm), this was first reached at a sample age between 35 and 55 days.

Higher permeability values were observed for samples with higher fibre content for identical fibre lengths. For samples that were prepared with 12 mm long fibres, the difference was greater than an order of magnitude. It was clearly seen that, on the average, the addition of fibres in comparison with the non-reinforced mixture led to an increase in permeability.

4 CONCLUSIONS AND NEED FOR FURTHER RESEARCH

It was seen that with the addition of polyvinyl alcohol fibres, quite homogeneous mixtures were able to be produced. An increased amount of workability agent was however necessary in order to render the mixture texture optically identical to that of the non-reinforced mixture. The pumpability of the reinforced mixture remains to be tested under site conditions.

The permeability values of the reinforced mixture were on the average less than an order of magnitude higher than those of the non-reinforced mixture. It is to be expected that the required limit values be reached for the tested mixture. Higher fibre contents than those tested probably would lead to an distinct worsening of the permeability behaviour.

Concerning the unconfined compression and tensile strength values, for 28 day samples, an increase of approximately 15% was reached. It is important that the samples did not break after reaching failure but held together with a high resistance. For unconfined compression tests, this also occurred for deformations greater than 5%.

Higher shear strengths and higher failure deformations were seen in drained traixial shear tests. The stiffness of the reinforced samples remained the same compared to that of non-reinforced samples.

In order to confirm the results obtained, investigations on a larger number of samples are necessary. Tests on older samples are especially necessary in order to see if for aged material, improved mechanical properties can also be counted on.Further variant possibilities, in addition to fibre amount, are fibre length and diameter. During tests on longer fibres, attention should be paid that the samples are large enough in order to exclude any scale effects. In addition, it remains to be tested if longer fibres can lead to problems with the mixing machinery. The bond with the cement matrix should be checked for fibres with larger diameters in comparison to that with the finer fibres used here. It is possible that the use of thicker fibres could enable an even better distribution of the fibres in the mixture, and less fibres would be needed for identical fibre content.

If fibre reinforcement is used, the principal advantage seems to be that after failure no breaking of the material occurs. This means for bending solicitations greater than the tensile strength of the material, no continuous, gaping cracks occur. Part of the wall cross section would be under pressure. It can be assumed that in this pressure zone the barrier effect of the material remains the same. For further investigations, small and large-scale tension bending tests are being planned.

REFERENCES

Akers, S.; Studinka, J.; Meier, P.; Dobb, M.; Johnson, D.; Hikasa, J. (1989). Long term durability of PVA reinforcing fibres in a cement matrix. *International Journal of Cement Composites and Lightweight Concrete,* 11(2): 73-78 Longman Scientific & Technical, Harlow.

Benz, M. (2000). Verbesserung der mechanischen Eigenschaften einer tonzementgebundenen Dichtwandmischung durch eine Faserbewehrung. Diploma project at the Institute for Geotechnical Engineering, ETH Zurich (unpublished).

Brinkmann, A. (2000). Ton- zementgebundene Dichtwandmasse für das Zweiphasenverfahren, Ergebnisse aus Forschung und Praxis. *Mitteilung des Instituts für Grundbau und Bodenmechanik, Technische Universität Braunschweig.* No. 63.

Brinkmann, A. (2001). Untersuchungen zum mechanischen Verhalten von ton-zement-gebundenem Dichtwandmaterial für das Zweiphasen-Verfahren. *Publication of the Institute* *for Geotechnical Engineering, ETH Zurich* Verlag der Fachvereine Zürich.

Brinkmann, A.; Amann, P. (1999). Klein- und grossmassstäbliche Versuche zur Ermittlung des mechanischen Verhaltens einer ton- zementgebundenen Dichtwand. *Bauingenieur 74:* 390-396. Springer VDI Verlag.

Bucher, F. (1984). Verfestigung von Böden durch Fasern. *Publication of the Swiss Society for Soil and Rock Mechanics.* No. 108, 65-68

Günther, K.; Kucera, P.; Kudla, W.; Lächler, W.; Mergelsberg, W. (1995). Die Sanierung der Sonderabfalldeponie Malsch. *Bautechnik 72.* 622-630, Ernst & Sohn.

Hermanns, R. (1993). Sicherung von Altlasten mit vertikalen mineralischen Barrieresystemen im Zweiphasen- Schlitzwandverfahren. *Publication of the Institute for Geotechnical Engineering, ETH Zurich,* No. 204, Verlag der Fachvereine Zürich.