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MATERIAL VALUES FOR SOME MECHANICAL PROPERTIES OF DOMESTIC WASTE

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SUMMARY: Results of tension test on different waste samples show, that the presented bearing model describe the bearing behaviour of waste correctly. We call the tensile forces, which waste can incorporate, "fibres cohesion". In correspondence to the found linear correlation between normal stress and fibres cohesion we define an angle of internal tensile forces ζ. The size of this material value are determined and used in slope failure calculations. In calculations we found high stabilty for steep slopes. That confirms to previous observations.

1 INTRODUCTION

There are many problems with stability calculations for domestic waste landfills based on usual methods of soil mechanics, because of the big differences between the properties of soil and domestic waste. The reasons for that are the heterogeneity of the composition of waste, the anisotropy, which is due to the deposition in layers, and the changing of composition and properties of waste by biological, chemical and physical processes during the time of deposition. From that the use of proof methods of soil mechanics like triaxial compression and shear test is not suitable to record the bearing characteristics and the real strength of waste, at least it is very critical. Nevertheless the exact geotechnical design of waste landfills is required. Within a research project supported by German Research Organisation (Deutsche Forschungsgemeinschaft, DFG) our institute started to investigate the bearing behaviour of domestic waste in 1991. At Sardinia 93 we presented first results of some model tests.

2 THE BEARING MODEL FOR DOMESTIC WASTE

Based on the knowledge about the bearing behaviour of fibrous waste and other fibres containing material, we get from shear and triaxial compression tests (Kölsch, 1993) the bearing model shown in figure 1 and 2 was developed.

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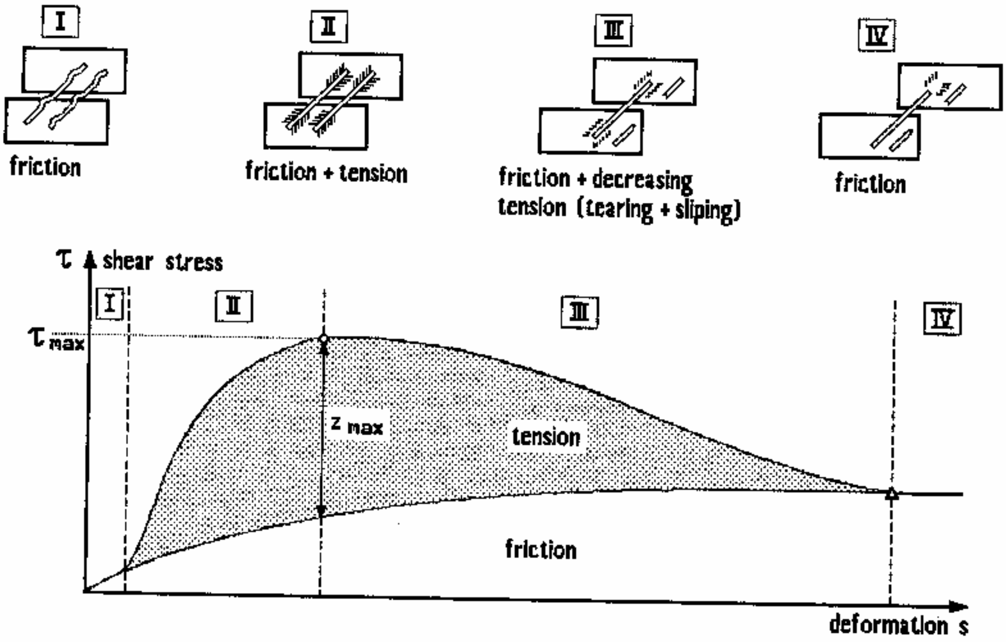

Figure 1: bearing behaviour of waste
model of interaction of frictional and tensile forces

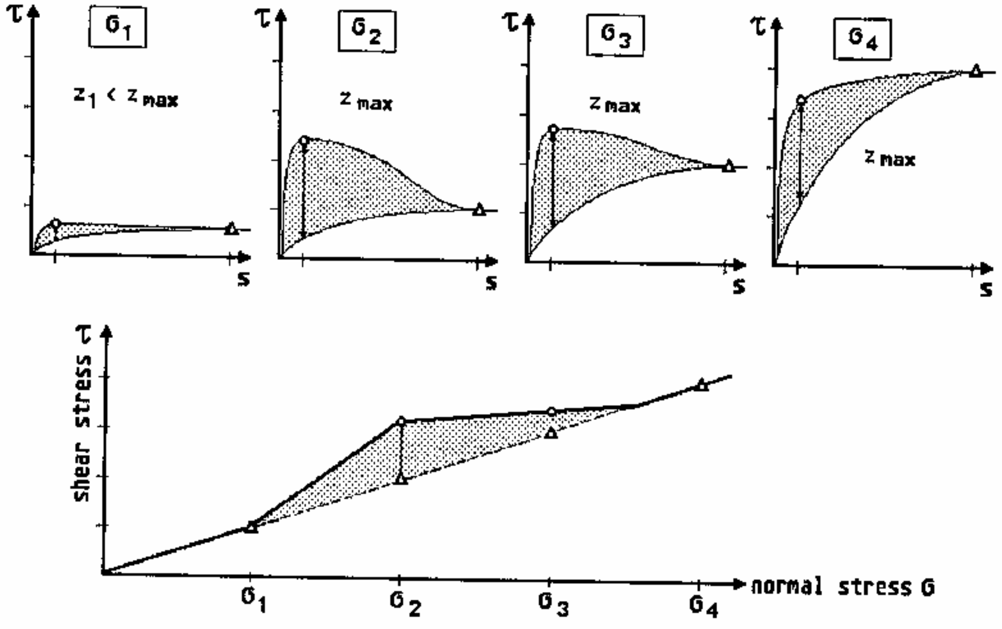

Figure 2: bearing behaviour of waste
model of increasing of total shearing resistance by tensile forces

The bearing model considers that fibrous materials are able to incorporate tensile forces and transmit the tensile forces out of the deformation zone. Furthermore the model considers that the developement of tensile forces in the fibres, having the same effect than a reinforcement, depends on the bonding of the fibres i.e. that means depending on normal stress. The total shearing resistance is composed of the friction in the shear plane and the tensile force in the fibres. Depending on the transmission of force into the fibres which increases with the normal stress and depending on the tensile strength of the fibres the total shearing resistance in a determined normal stress range is higher than the frictional resistance. Because there is a linear correlation between frictional resistance and normal stress described by the angle of internal friction φ a nonlinear, discontinuous correlation between total shearing resistance and normal stress results at the tensile force of the fibres.

Figure 1 shows the model of one potential interaction of frictional and tensile forces during a shear deformation of a fibrous material at constant normal stress. During the deformation only frictional forces arise in the beginning (I), caused by the increase of deformation (II) the fibres are getting stressed and the tensile force is growing (effect like reinforcement). Exceeding the tensile strength or the bonding, the fibres are tearing or sliping out of bonding (III). In this case the maximum of shear stress is reached. With further deformation the shear stress drops down to the size of friction (IV).

The size of friction is considerably determined by the normal load, it is increasing linear to the normal stress increase (angle of internal friction φ). The tensile strength is increasing as well with the normal stress, because the transmission of tensile forces is improved by a firmer bonding of the fibres. The incorporation of tensile forces into the fibres is restricted to the tensile strength of the fibres, so there is a determined normal stress, where the value of tensile force reaches a maximum level. Various interactions of frictional and tensile forces depending on different normal stress conditions result from this.

Figure 2 shows the interaction of tensile and frictional forces for various normal stresses. In this figure the circles indicate the spots of maximal tensile force, the triangles mark the spots of maximal friction at one determined normal stress. At the lowest normal stress σ_1 only low tensile forces are arising (loose bonding), at higher normal stress the tensile forces in the fibres are increasing (firmer bonding), before the tensile forces exceed the maximum at the normal stress σ_2. At higher normal stresses ($\sigma \geq \sigma_2$) only the frictional component of total shearing resistance increases. Depending on the proportions between frictional and tensile forces the total shearing resistance is dominated by the tensile forces ($\sigma_1 \leq \sigma \leq \sigma_4$) or by the frictional forces (σ_4). In that range of normal stress, where the total shearing resistance is dominated by tensile forces, the shear straigth line shows the break, which is characteristic for fibrous materials. In figure 3 (**Al-Refeal, 1991**) this break is shown for reinforced sand. Size and range of the break depend on the properties of material (share and strength of fibres, property of friction).

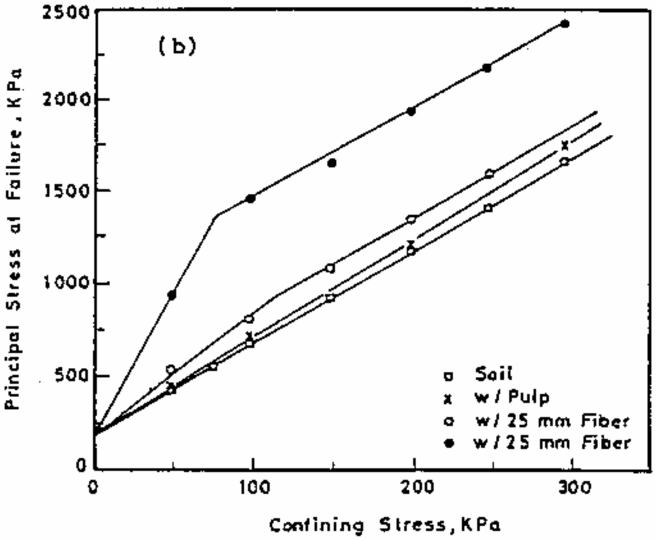

Figure 3: Behaviour of reinforced granular soils
principle stress at failure versus confining stress (**Al-Refeal, 1991**)

3 TEST METHODS

3.1 Idea

There are many problems to investigate the bearing behaviour of domestic, fibrous waste. The main problems being:

- The results of the triaxial compression test and the direct shear test of waste do not describe the bearing behaviour, because in these test arrangements the anisotropy of waste is not sufficently recorded.

- The bearing characteristics of the different material components will be influenced by biological, chemical, and physical processes in a landfill. So the proportion between frictional and tensile forces is constantly changing.

As a consequence of this we decided to distinguish our investigations between the friction and the tension component. We are able to investigate the friction component in the direct shear test. This test will bring good results when reducing the waste to smaller pieces. Even though the shear strength can also be tested on non-treated samples, because in direct shear test only a small part of reinforcement forces are recorded. That could be considered in calculations. For the investigation of the tensile forces we had to develop a new tension test.

3.2 testing arrangements

Due to the results of model tests, we conducted before (**Kölsch, 1993**), we developed the tension test equipment, which is presented in figure 4. The sample box has a size of 3 x 1 x 1.5 m (l x w x h). It contains a waste sample of about 4 m^3. The box is movable, so it can be transported by truck to the landfill and can be filled on site. The waste is mounted in layers with a thickness of 20-30 cm and compacted by a dredger. The filled box is installed in the test apparatus and there connected with a hydraulic ram. The waste in the box is compressed by a normal load plant, which is composed by load plates and load girders with high pressure pads between. For the tension test the sample box is opened at a vertical surface in the middle of the box. The front part of the box is connected to the ram, the back part to an anchoring. Now the front part is pulled, so the waste sample fall under tension load. This load is raised path-controlled to the break of the sample. The procedure of the tension test is shown in figure 5. The test is conducted in stages with various normal loads. We raise the normal load after obtaining the break. The maximum of normal load is 50 t/m^2.

The investigation of the frictional component we conduct in a big shear box with sizes of 2 x 1 x 1.5 m (l x w x h) and a volume of about 3 m^3. The shear surface is 2 m^2. The shear box can be installed in the same test apparatus like the tension box. The shear test equipment and the principle of the test procedure is presented in figure 6 and 7. The test procedure does not differ from tests in smaller shear boxes. We exspect the first results in june 1995.

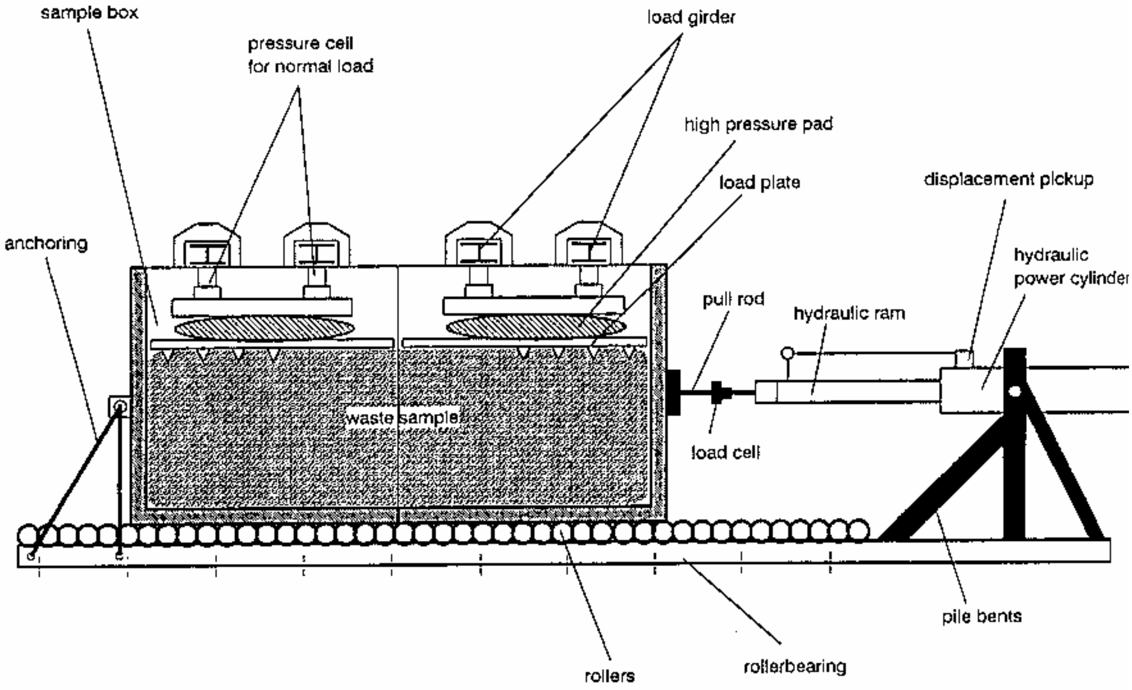

Figure 4: tension test - test equipment

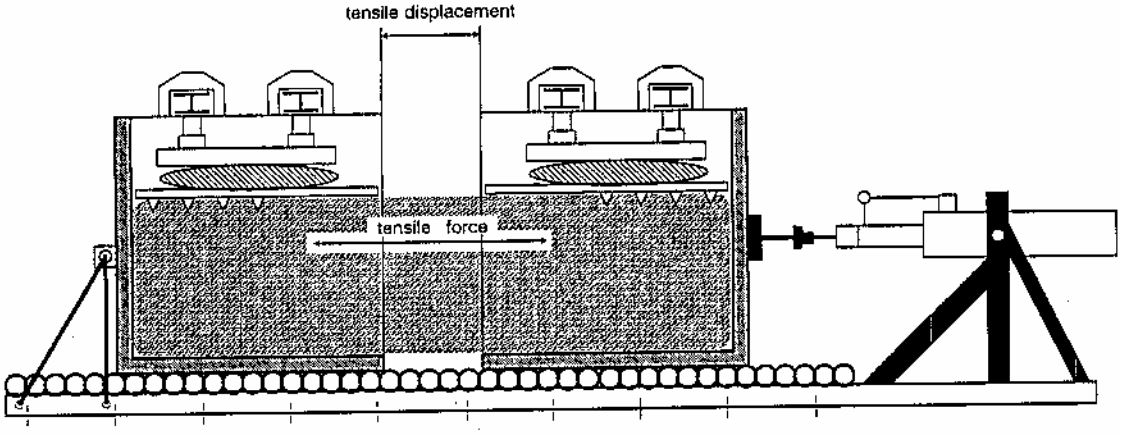

Figure 5: tension test - test procedure

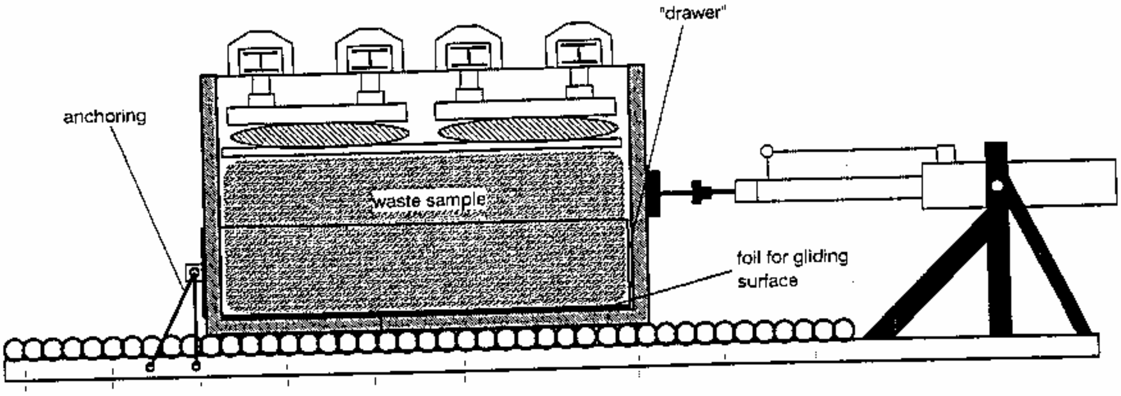

Figure 6: shear test - test equipment

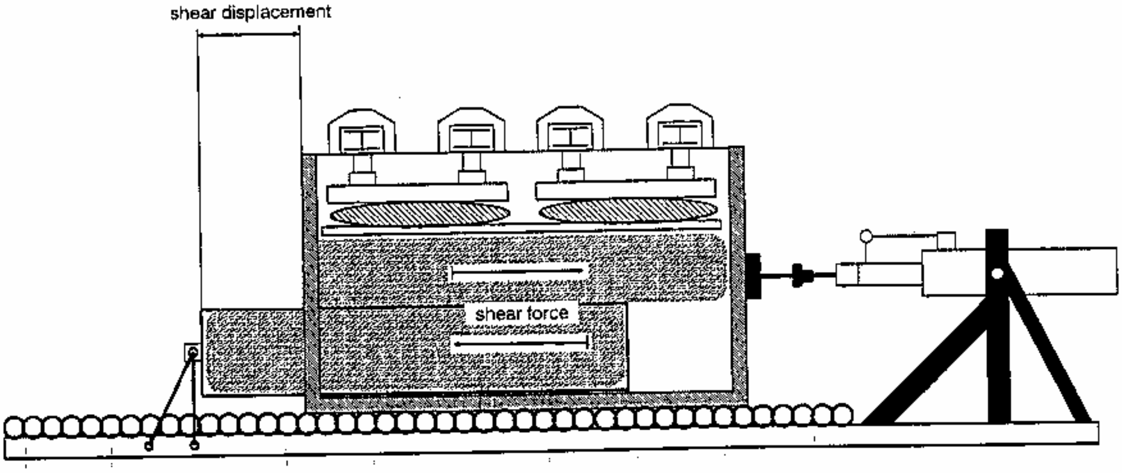

Figure 7: shear test - test procedure

The classification of the four waste samples in material groups (figure 8) shows, that REST contains considerably more smooth synthetics and paper than the other samples. The range of sizes (figure 9) shows, that all samples contain almost the same part of sizes ≥ 120 mm. This part ranges between 15 and 25 %. At the sizes ≤ 40 mm one can see a clear difference between the fresh samples and the other samples. FRESH and RESIDUAL contain 25-35 % of this sizes, ROTTED 18 and SITE nearly 65 %. The range of dimensions is shown in table 1.

sample:	RESIDUAL	ROTTED 18	SITE	FRESH
		---- [%] of total amount ---		
Dim 0	68.3	26.7	62.5	not assorted
Dim 1	2.8	3.5	3.7	not assorted
Dim 2	20.3	39.9	18.8	not assorted
Dim 3	8.6	31.8	15.0	not assorted

table 1: identification of waste samples - range of dimensions

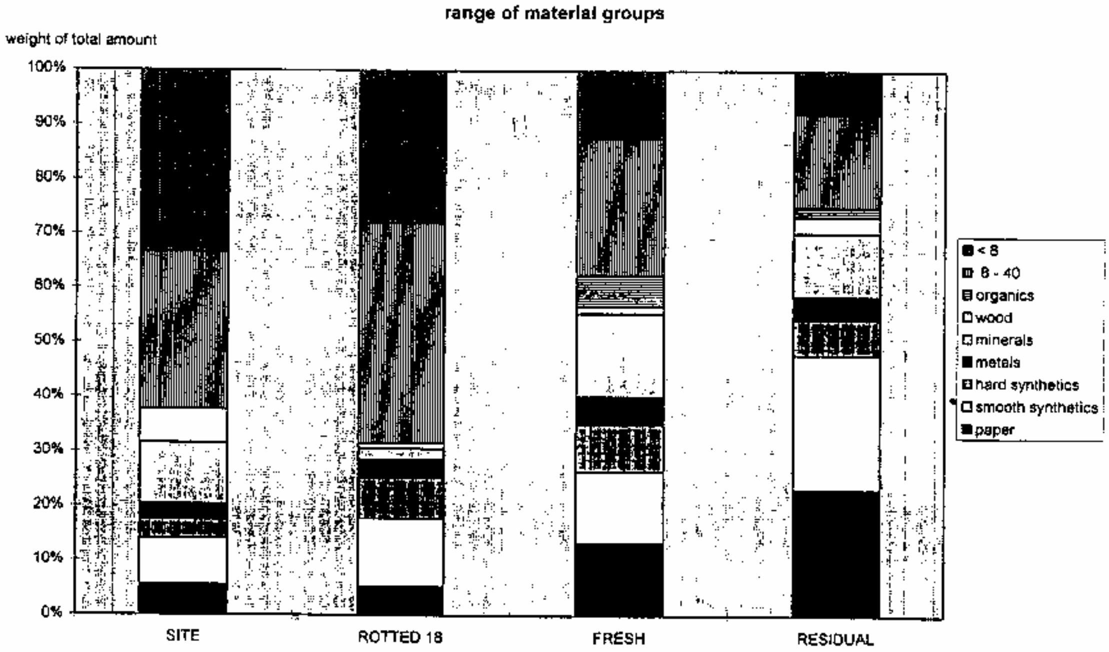

Figure 8: identification of waste samples - range of material groups

4 RESULTS OF TENSION TESTS

4.1 test materials

For example we want to present the results of the tests on four different samples of urban waste:

- FRESH
  complete waste without separation of organic components, fresh (not pretreated), directly gathered from dust cart
- RESIDUAL
  residual waste (separation of organic components), same property like "fresh"
- ROTTED 18
  complete urban waste, after 18 months aerobic pretreatment at rotting heaps
- SITE
  urban waste, excavated from a landfill 5 years after compacted placing

For the investigation of the mechanical properties of waste an identification of each waste by a special waste analysis is requiered. The detalis of analysis procedure are recommended by (**DGGT, 1994**). The complete identfication is conducted in three assorting steps:

- **material groups** (only pieces ≥ 40 mm)
  7 kinds of groups are assorted: paper (incl. cardboard), smooth synthetics (incl. foils, rubber, leather, textiles), hard synthetics (incl. plastics, hard leather), metals, minerals (incl. glass, ceramics, soil), wood, organics (incl. biowaste, grass, leaves). The rest of assorting is classified in groups according to sizes (8-40 mm, ≤ 8 mm)
- **size of pieces**
  size of pieces are classified according to sieve sizes 8, 40 and 120 mm. Parts above 120 mm are distinguished opticly at 500 and 1000 mm.
- **dimension of pieces**
  The examination of dimensions is requiered to describe the form of the waste pieces. Four dimensions are distinguished:
  Dim 0: grain (each side of piece short, i.e. ≤ 8 mm)
  Dim 1: fibres (one side long, two sides short)
  Dim 2: foils (two sides long, one short)
  Dim 3: box (three sides long)

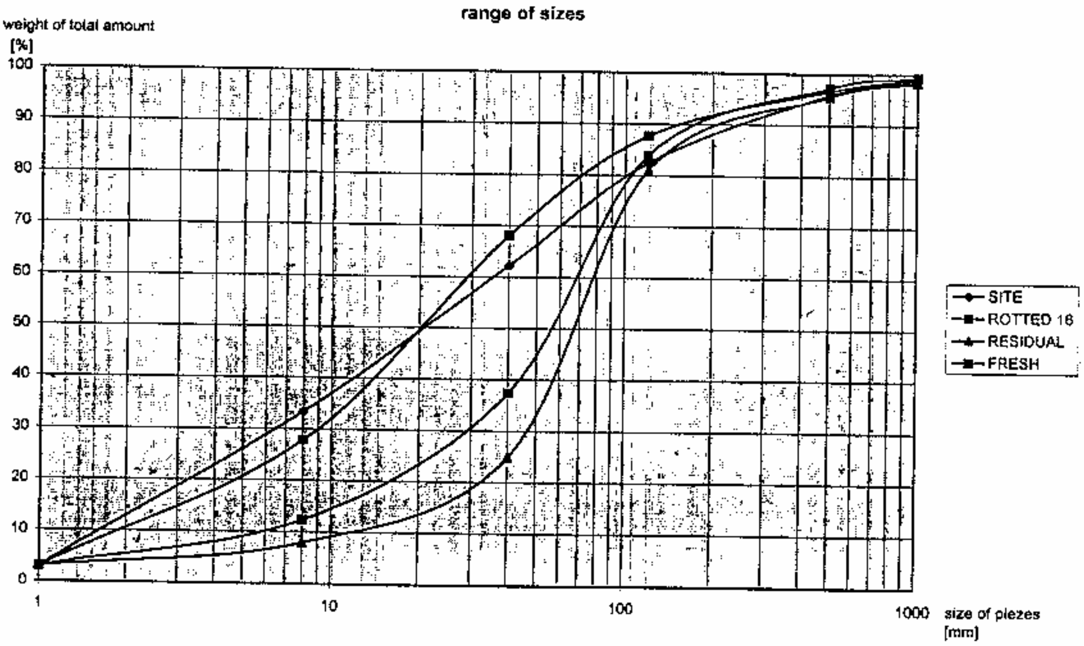

Figure 9: identification of waste samples - range of sizes

Because the dimension 0 is composed by the sizes ≤ 40 mm exclusively, it shows the same proportion like the range of size: ROTTED 18 and SITE contain a considerably higher number of this pieces. Otherwise RESIDUAL contain twice the share of dimension 2 (foils) than the older materials.

4.2 test results

Figure 10 shows a typical relation between tensile stress and deformation. The deformation behaviour is considerable elastic-plastic. The maximum of tensile stress amounts to 230 kN/m^2 under a normal stress of 284 kN/m^2. That confirms the results of the model tests partly (**Kölsch, 1993**). Figure 11 shows the relation between tensile stress and normal load for all samples. The fresh waste samples (FRESH, RESIDUAL) are obtaining considerably higher tensile strengthes than the other samples. We presume, that the higher number of bigger sized pieces of accounts for that. The difference of the results between FRESH and RESIDUAL can be attributed to the higher water content of FRESH. FRESH hold a water content of near 44 %, REST only 32 %. As an result of the high water content either a pore-water pressure, which reduces the normal stress on the fibres, or an simple sliding effect between the fibres can arise.

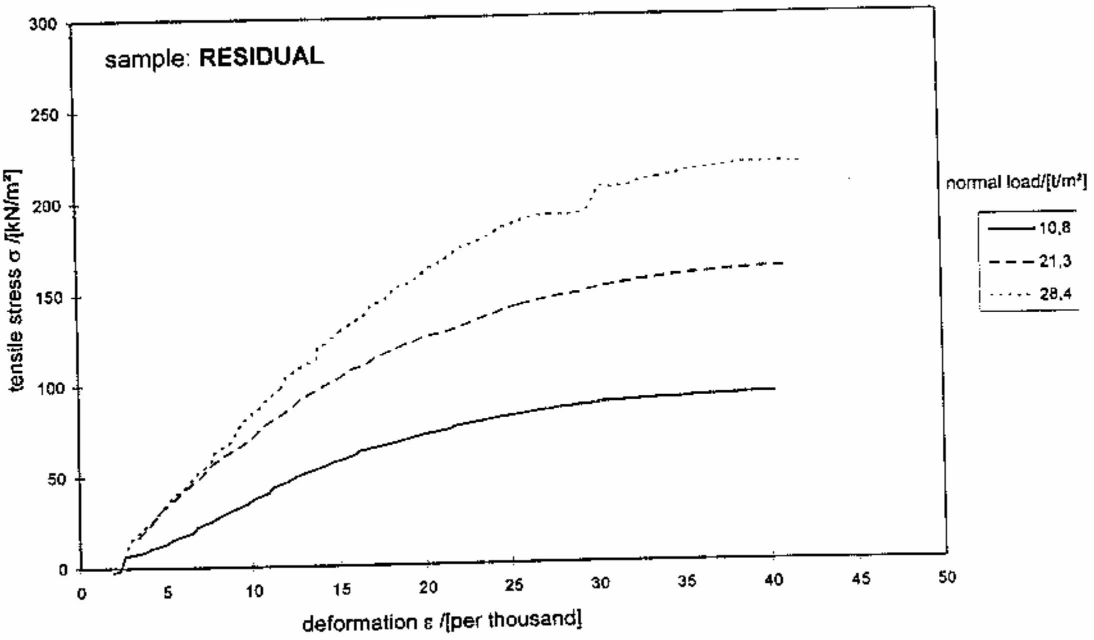

Figure 10: results of tension test - tensile stress-deformation realtion

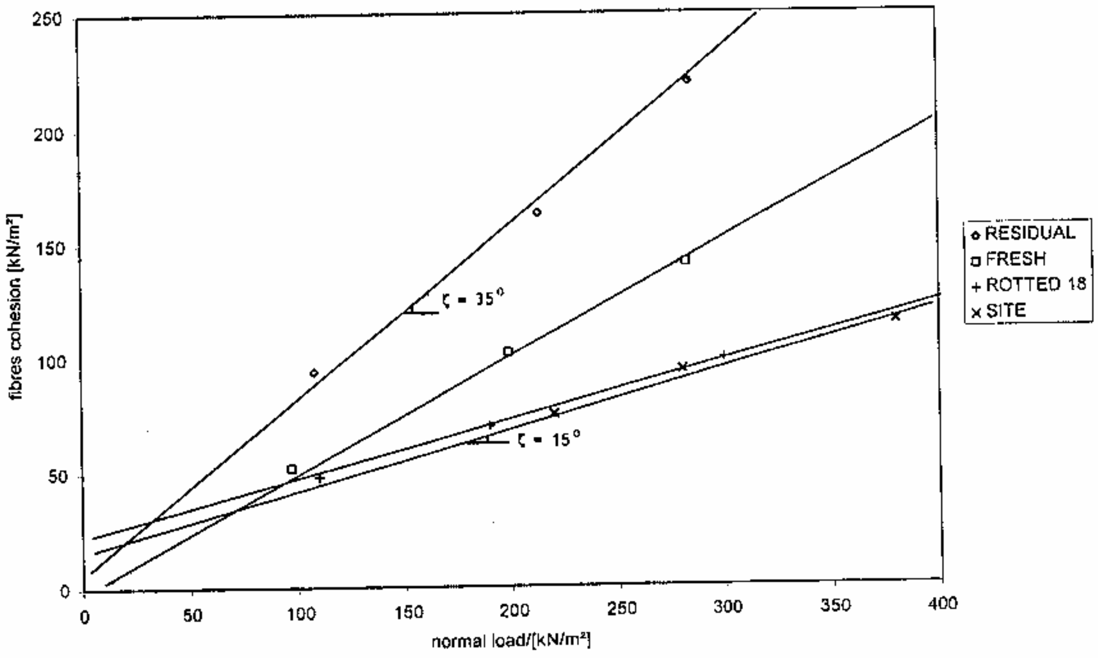

Figure 11: results of tension tests - realtion between fibres cohesion and normal load

The linear relation between tensile and normal stress can be described by an angle of internal tensile forces ζ. It is shown in figure **11** for the samples RESIDUAL and ROTTED 18. For RESIDUAL it amounts to 35^0 and for ROTTED 18 to 15^0. That part of tensile forces, which is not depending on normal stress, is comparable to cohesion. We defined ζ, to adapt the results of the tension test to the methods of slope failure calculation. In the same way you could use the tensile forces like an cohesion, which is increasing with depth.

At first the tensile strength is not depending on the density of waste. The older waste samples (ROTTED 18, SITE) get considerably higher dry densities (0.9-1.1 t/m^3) than the fresh ones (0.5-0.7 t/m^3), but lower tensile forces. On the other hand we exspect a higher shear strength based on friction for the older materials as a result of the higher density. In addition the lower part of flat pieces ($\geq$ 40 mm), which are able to produce sliding surfaces easily, will improve the friction properties. The relation between normal stress and dry densities is shown in table 2.

	RESIDUAL	FRESH	ROTTED 18	SITE
normal stress [kN/m^2]	----	dry density [t/m^3]		----
100	0.58	0.54	0.89	
200	0.65	0.64	0.95	1.04
300	0.72	0.72	1.01	1.06
400				1.10

table 2: results of tension test - dry densities

5 SLOPE FAILURE CALCULATION

5.1 material values

5.1.1 frictional forces

That part of shear strength, which is based on frictional forces, can be described by the internal angle of friction φ. There is a big range of values presented in literature. A reason for that is, that the investigation of mechanical properties of waste by using the methods of soil mechanics (triaxial compression test, direct shear test, vane test) are not suitable for the investigation of waste. The results of these tests are neither describing the real shear strength nor the friction properties. Always tensile forces are recorded, more in triaxial compression test, less in direct shear test. It is impossible to distinguish both effects and as a consequence of this it is also impossible to consider the anisotropy.

We found two values for the angle of internal friction φ in the literature, which seem to discribe the friction properties almost correctly. **Spillmann (1980)** conducted according to DIN 4017 an on site penetration test on fresh waste. Before the test, he reduced the waste to smaller pieces, so we can suppose, that the reinforcement effect of the fibres was destroyed almost completly. He determined an internal angle of friction of $\varphi = 15^0$. **Jessberger, Kockel (1991)** presented results of triaxial compression test on older waste. The measured results of triaxial test were analyzed by the method of path of stress. Jessberger found, that the internal angle of friction φ grows up to an maximum of $18-19^0$ at a deformation of $\varepsilon = 15\,\%$. With increasing deformation φ is staying constant, only the cohesion is still growing. A break could not be reached. So we can presume, that the internal angle of friction of $\varphi = 18-19^0$ describes the friction properties sufficently. Own direct shear tests on model waste **(Kölsch, 1990)** brought comparable results, so an internal angle of friction of $\varphi = 15^0$ seems to be realistic for fresh waste. As own test results for older waste are missing we calculate with an internal angle of friction $\varphi = 22^0$.

5.1.2 tensile forces

The tensile forces improve the shear strength of waste. They are distinguished between cohesion, which is independent on normal stress, and tensile stress, which is depending on normal stress. It is plausible to call this part of tensile forces "fibres cohesion". The fibres cohesion is due to the reinforcement effect of the fibres and foils. The fibres cohesion can be described by the internal angle of tensile forces ζ. For the investigated fresh waste it amounts to $\zeta = 35^0$.

Using the fibres cohesion in stabilty calculations, it has to be considered, that the size of active fibres cohesion is depending on the angle between the fibres direction and the sliding surface. This connection is investigated on materials of Reinforced Earth extensively. Based on the results of **Jewell, Wroth (1987)** it seems to be correct to calculate with completly active fibres cohesion, if the angle is bigger than 45^0. For lower angles the fibres cohesion is reduced to $0.5 \cdot \zeta$.

5.2 calculation methods

The slope failure calculations are conducted on sliding figures with two plane sliding surfaces. For the calculation the slice method was used, which is recommended by DIN 4084. These sliding figures were varied:

- The inclination of the deep sliding surface between 0° and 20°
- The inclination of the upper sliding surface between 90° and 20°
- The distance from the crossover of the sliding surfaces to the bottom of the slope between 10 m and 50 m

For all these figures the stability of a slope with an altitude of 30 m was calculated. The angle of the slope was varied from 30° to 90°. The usage of the material values, found in the tensile test (density γ, internal angle of cohesion ζ, cohesion c) and the literature (internal angle of friction φ) is shown in figure 12. In calculation φ and ζ were added to an sum of internal angels φ_{sum}. Two different slope materials (fresh and rotted waste) were examined in calculation.

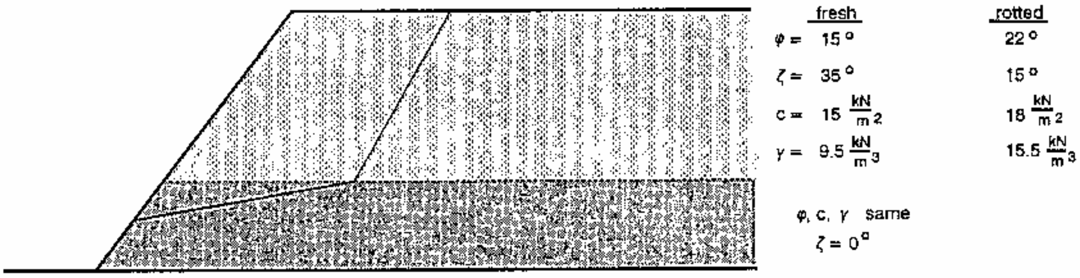

Figure 12: slope failure calculations - usage of material values

5.3 results of calculation

The results of the calculation are demonstrated on three silding figures describing the typical and critical conditions of the slope. table 3 shows the proportions of the sliding figures.

Figure	distance between bottom and crossover [m]	inclination of sliding surface	
		deep [^{0}]	upper [^{0}]
1	20	10	43
2	40	9	64
3	50	21	61

table 3: slope failure calculations - proportions of sliding figures

Figure 13 shows the results of the slope failure calculation on the three sliding surfaces with the material values of fresh waste. The slopes are showing stability for almost all sliding figures and slope angels. There is no considerable influence of the slope angle recognizable. In every way the figure 3 was the most unfavourable case, because the upper sliding surface, where the high tensile forces are effective, becomes extremly short. Corresponding to this considerably high stabilities were found for sliding figures with proportions like figure 1 (short deep surface - long, steep upper surface). The part of fibres cohesion of the holding back forces often amounts to more than 75 %.

In the calculation we made some simplifications, e.g. we ignore the influence of the angle between fibres direction and sliding surface on the activity of tensile forces. On the other hand we do not consider any tensile forces in the deep sliding surface. Proving this simplification we found, that this proceeding is permissable. Moreover we suppose in all calculations an equal occurance of the maximal sizes of frictional and tensile forces. The worst case can be evaluated, by using either frictional or tensile forces in the calculation exclusivly. If the holding back forces of a sliding figure are dominated by one bearing effect (e.g. sliding figure 1 by the tensile forces), the other bearing effect can be ignored without losing stability in calculation. In most cases the material contans sufficient bearing reserves. It seems to be correct, to consider the non equal occurance of the different bearing effects by an reducing factor of 50 % on the frictional forces. The exact calculation with a reducing factor leads to higher stability than the simplified calculation. From that we can discern, that the chosen estimation is sufficently unfavourable.

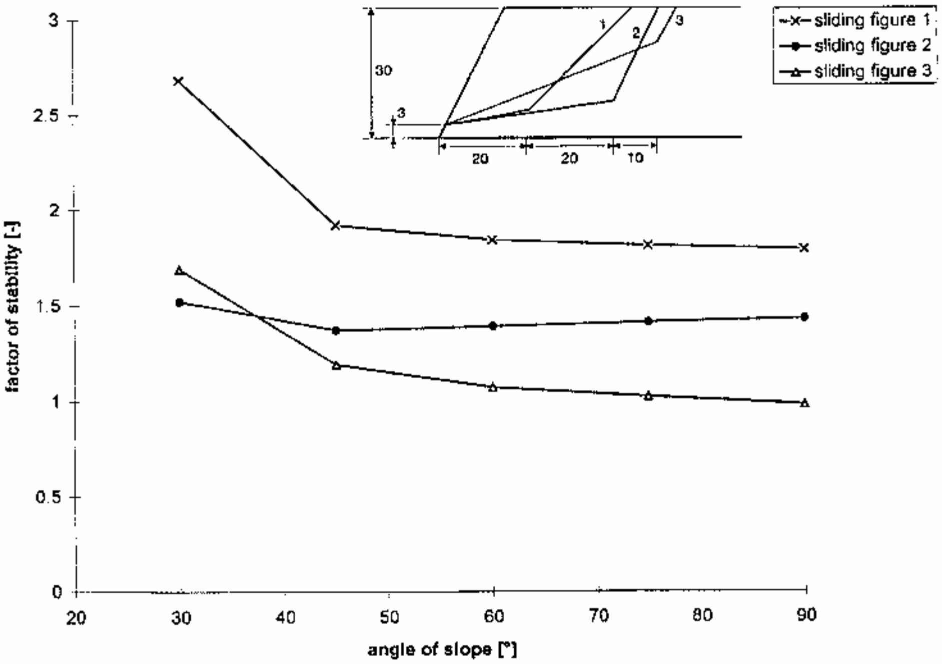

Figure 13: results of slope failure calculations

While fresh waste is sited on a landfill the mechanical properties gradually change to those of rotted waste. From that we exspect, that the internal angel of tensile forces ζ decreases and the internal angle of friction φ increases. The comparison of the calculation for fresh and rotted waste is suitable to show the consequences of this change of properties. For those sliding figures dominated by tensile forces this change brings a lower stability (figure 14a). In contrary to this, the stability of friction dominated sliding figures is improved (figure 14b).

Because of the restriction of tensile forces by a tensile strength as described in the bearing model, it is not allowed to exterpolate the mechanical values for higher normal loads. On the other hand we don't suppose to exceed the tensile strength of fresh waste in normal load ranges up to 700 kN/m^2, because the share of fibres is to big and the tensile forces, which can incorporate theoreticaly, are essentialy higher.

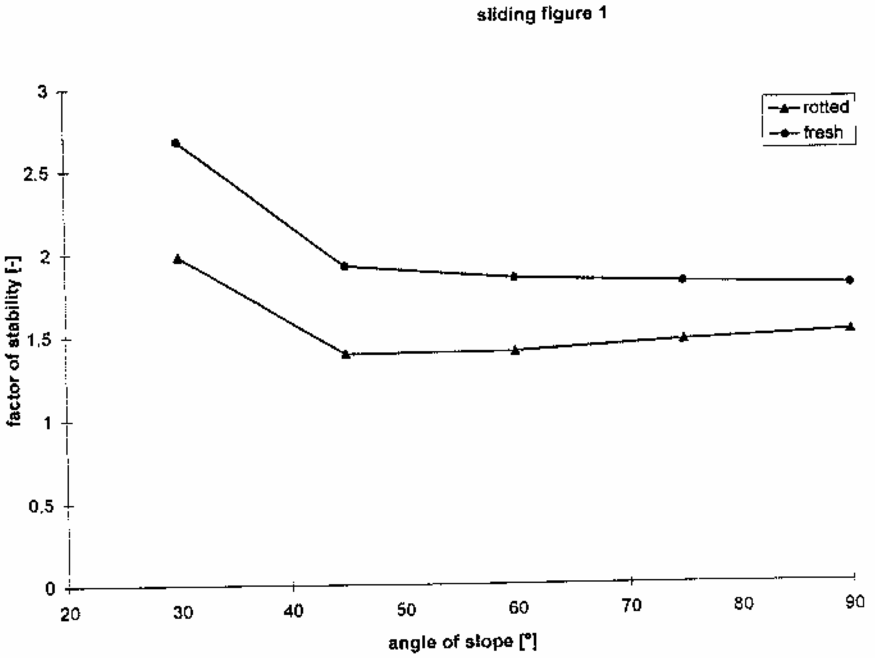

Figure 14 a: slope failure calculations - comparison of rotted and fresh waste

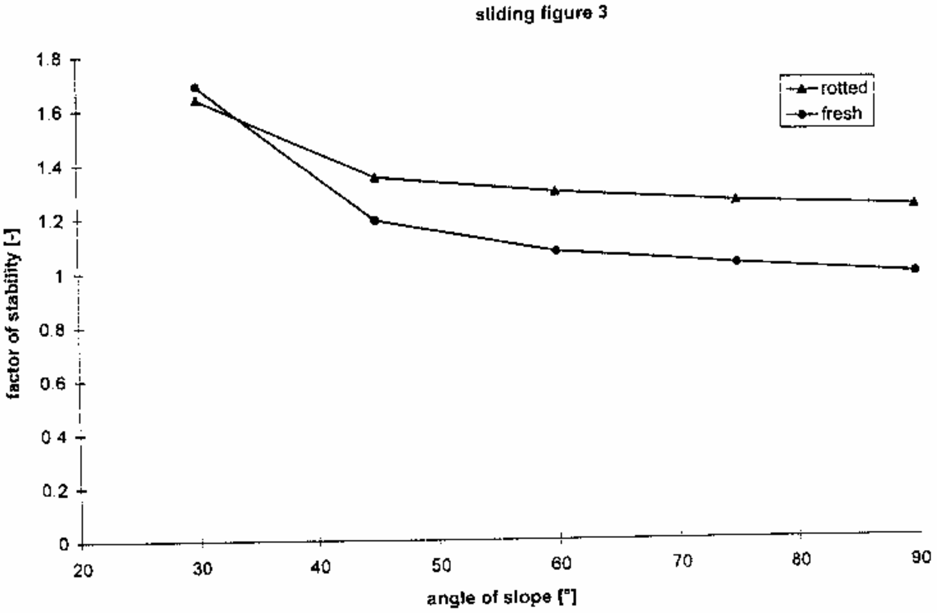

Figure 14 b: slope failure calculations - comparison of rotted and fresh waste

4 CONCLUSION

The results of the current stability calculations coincide with previous observations. While carefully estimating the results from the laboratory for tension or friction properties of waste and model waste there was stability found for up to 90^0 of slope inclination. Stable 15 metre high vertical slopes have often been seen on landfills.

Especially sliding figures with short deep and steep upper sliding surfaces show high stability. This explains why it was impossible to bring slopes to failure during previous on-site tests. The geometry of such trial slopes aims at sliding figures with steep upper sliding surfaces. Due to a high portion of active fibres cohesion these slopes are particulary stable. **Cowland et al. (1993)** reports about such an unsucessful test to break the slope.

Model scaled breaking tests for slopes carried out by **Jessberger, Kockel (1993)** by means of the geotechnical centrifuge show the same problems. The vertical trial slopes show no failure unless the portion of fibres inside the waste is reduced and the reinforcement effect cut down. The breaking characteristics of such model tests still show a interaction between tension and friction forces. Especially from the ocurrance of gaping cracks in the upper part of the slopes we infer, that a reinforcement failure in regions with low normal load accounts for the break of the slope. In the calculation this breaking mechanism is considered by usage of the angle of internal tensile forces.

The founded correspondences between the calculation and observations show that the bearing model is suitable to describe the bearing behaviour of waste and comparable fibres containing materials. Considering this the conventional material values i.e the usage of an angle of internal fricton exclusively, should be used carefully. The usage of specific test methods has to be reconsidered too. Especially the triaxial test, which is wide-spread in soil mechanics, seems to be less suited for the investigation of waste, because of anisotropic and the requiered deformations for the reinforcement effects. Seperate tests distinguishing the friction and tension part of shear strength seem to work better.

5 CONSEQUENCES

The prognosis for the bearing behaviour of landfills based on the presented bearing model leads to different results than common calculations. The stability ensured by fibres cohesion mainly, is endangered by two factors:

- the development of unfavorable sliding figures with only a minor part of fibres cohasion coming into effect
- the weakening of fibre cohesion by changing the share and the properties of fibres, by means of reducing the waste to smaller pieces, sorting out of plastics, changing the water content etc.

As a change of the mechanical properties resulting from intended operational and ecological activities (recycling of synthetics, biological pretreatment) is not avoidable, the stability calculations have to consider this. A reducing of the reinforcement effects requires smaller slope inclinations and leads to bigger deformations. The weakness of the reinforcement can partially be compensated by better friction properties. In this case the stress-deformation behaviour of the waste is changing too. In deep sliding surfaces friction forces increase, leading to higher spreading stress at the landfill base.

REFERENCES

AL-REFEAI, T. O. (1991): Behaviour of Granular Soils Reinforced with Discrete Randomly Oriented Inclusions. Geotextiles and Geomembranes 10, 319-333

DGGT, Deutsche Gesellschaft f_r Geotechnik (1994): Empfehlungen des Arbeitskreises "Geotechnik der Deponien und Altlasten". E 1-7: Identifizierung und Beschreibung von Abfällen (Entwurf). Bautechnik 71, Heft 9, Berlin: Wilhelm Ernst_& Sohn.

COWLAND, TANG, GABAY (1993): Density and strength properties of Hong Kong refuse. CISA (Hrsg.): Proceedings of the Fourth International Landfill Symposium, Vol 2, 1433-1446, Cagliari (Italy).

JESSBERGER, KOCKEL (1991): Mechanical properties of waste materials. XV Cicolo di Conferenze die Geotecnica di Torino

JESSBERGER, KOCKEL (1993): Determination and assessment of the mechanical properties of waste materials. CISA (Hrsg.): Proceedings of the Fourth International Landfill Symposium, Vol 2, 1383-1392, Cagliari (Italy).

JEWELL, WROTH (1987): Direct shear tests on reinforced sand. Geotechnique 37, 53-68

KÖLSCH, F. (1990): Materialkennwerte von Abfall in Hinblick auf die Standsicherheit von Mülldeponien. Diplomarbeit am Leichtweiß-Institut für Wasserbau, TU Braunschweig (unpublished)

KÖLSCH, F. (1993): The bearing behaviour of domestic waste and related consequences for stability. CISA (Hrsg.): Proceedings of the Fourth International Landfill Symposium, Vol 2, 1393-1410, Cagliari (Italy).

SPILLMANN, P. (1980): Beitrag zur langzeitig standsicheren Konstruktion hoher Abfalldeponien, Teil 1 und 2, M_ll und Abfall 12, 311-317, 337-339