Shear strength of waste

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SUMMARY: In this paper the results of large scale shear tests on various samples of fresh and biologically treated waste are presented. The large shear box provides a shear plane area of 1 x 1,80 m, the waste samples amount to 2 m^3. Untreated waste shows non linear shear planes, because a portion of the shear resistance recorded in the direct shear test is due to reinforcement effects. Pure friction angles amount to about 30°. Biologically treated, screened waste shows friction angles from 33° to 38° degrees. Unscreened, decomposed material reached even higher shear strength, but does also incorporate reinforcement effects. Material values for stability analysis derived from these tests are summarized as recommended by German Geotechnical Society. Useful links are provided how to implement the material values to advanced stability calculations.

1. INTRODUCTION

In terms of mechanical properties, untreated municipal solid waste (MSW) is a composite material. The shear strength of MSW consists of two major resistance components, friction and tension (reinforcement). Frictional forces arise between all waste particles, particularly between granulars. Tensile forces on the other hand are incorporated in fibrous elements (foils, fibers), only. The shear resistance generated by tensile forces is called fiber cohesion.

In many regards the granular part of the matrix is different from the fibrous part. Among others, isotropy, stress-strain behaviour and sensitivity against biological and chemical decay processes vary significantly. Those different properties result in several consequences. It is a matter of fact, that it is impossible to exactly determine the shear strength in one single laboratory test. Using comprehensive mechanical models help to come over those constraints. These models base on more than the conventional shear parameters (φ, c) to describe the mechanical properties of MSW, but introduce advanced mechanical parameters for the tension properties (fiber cohesion). However, more parameters mean more laboratory testing, which raises the problem not to record the same resistance effects twice.

The following presentation is dealing with the simple direct shear test on MSW in a big shear box. It provides information on how to interpret shear testing results in the context of combined shear strength of MSW.

2. SHEAR TESTS

2.1 Waste Materials

Owed to the huge efforts for extracting and placing a sample of about 2 tons into the shear box, only a limited number of 7 tests could be carried out. Figure 1 illustrates the enormous efforts to exploit a sample out of the landfill by means of large scale drilling. The selection of sample variations aimed on covering a range of different size distributions (screened, non screened) and different stage of decomposition.

Figure 1. Sample drilling at Ihlenberg landfill

Table 1. Shear test samples

name	condition	max particle size	source
GERM	fresh	500 mm	MSW mixed with shredded bulky waste
KOLEN	fresh	120 mm	MSW mixed with shredded bulky waste
IRII	stabilized	500 mm	MSW after MBT (active aeration)
SIEB	stabilized	40 mm	MSW after MBT (active aeration)
WHV	stabilized	120 mm	MSW after MBT (passively aerated)
BORN	stabilized	15 mm	MSW after MBT (passively aerated)
GÖ-PO1	decomposed	500 mm	MSW, 10-15 years in landfill

Table 1 provides an overview on the variation of samples. All waste samples were analysed and classified according to the recommendation E 1-7 of the German Geotechnical Society (DGGT, 1997). The main part of the identification is carried out by means of hand assorting analysis regarding the kind of materials. Since the assorting procedure needs to be useful to handle, kinds of materials are grouped corresponding to their geotechnical effect and behaviour (different from waste analysis for waste management purposes).

The groups are:

- paper/cardboard
- synthetics – soft (rubber, foils, tetra, leather, textiles)
- synthetics – rigid (plastics)
- metals
- minerals (glass, ceramics, ashes, soil)
- wood
- organics (vegetables, food, fruits, green)
- small particles I: 8-40 mm
- small particles II: < 8 mm

For geotechnical purposes, size, shape and condition of all material groups need to be determined. The size of particles was screened at 40, 120, 500 and 1000 mm. After splitting the material groups into different sizes, the shape of all groups was examined and classified into four types of shape:

- Dim 1 (one side long, two short): wires, cables, ropes
- Dim 2 (two sides long, one short): foils, sheets
- Dim 3 (all sides long): cubes, boxes, rocks
- Dim 0 (all sides short i.e. < 40 mm)

Beside the kind, size and shape of particles, the biochemical condition influences the geotechnical properties. In order to identify and classify the sample a number of biochemical tests have been carried out. Table 2 provides an overview on the material properties of the samples.

Table 2. Properties of shear test samples

name	size	shape	kind	chemical (8-40 mm)		biological (< 8mm)
	<40 mm [mass%]	**dim 1/2 [mass%]**	**plastics [mass%]**	**TOC [mass%]**	**loss of ign. [mass%]**	**respiration 4 d [gO_2/kg dry mass]**
GERM	45,5	37,3	23,7		30,7	15
KOLEN	73,4	21,4	18,6			
IRII	65,3	30,8	21,6	7,3	24,3	0,2
SIEB	100,0	0,0			16,0	0,5
WHV	79,2	18,3	12,4	18,4	38,7	1,5
BORN	100,0	0,0		7,9	22,0	0,4
GÖ-PO1	53,4	35,5	18,1	8,3	27,0	1,3

The biologically stabilized samples show a respiration activity of lower than 5 gO_2/kg, the fresh waste has significantly higher values (15 gO_2/kg). It should be noted that the respiration tests have been carried out before the test was standardized. Therefore, small deviations to present testing results may be possible. All samples contain large fractions of synthetics in quite similar portions (around 20 %). The portion of smaller particles is influenced by the screening and grounding methods as well as the state of decomposition ranging from 45 % (fresh, unscreened) over 79 % (screened at 120 mm, biotreated) to 100 % (fully screened). From this point of view, the size distribution is restrictedly meaningful unless backed by additional information.

2.2 Testing equipment

The testing arrangement of simple, direct shear test is well known from soil mechanics. It has been up scaled making it useful for unmodified MSW. A sufficient size is required to facilitate the large particles sizing up to 500 mm. Figure 2 shows the large shear box with a shear plane area of 1 m x 1,80 m. The shear box contains a waste sample of approximately 2 m^3. The box is movable, since the placement of the waste sample needs to be done at the landfill site. Figure 3 shows the equipment during pick up at the laboratory facility.

After sampling the equipment is transported back to the laboratory and connected to the loading appliances. Normal load is applied by hydraulic pressure pads, shear load by means of a hydraulic jack (figure 4). The testing procedure of large shear test is similar to conventional small scale direct shear test. Normal load is applied on the sample. After the consolidation of the sample is finalized, one frame is moved against the other. Shear deformation is increased till the shear strength is exceeded.

After the failure, either normal load is increased up to the next loading step or a new sample is placed. Three stages of normal load are usually conducted with the highest normal load corresponding to the stress situation on site.

Figure 2: Large shear box

Figure 3: Hauling

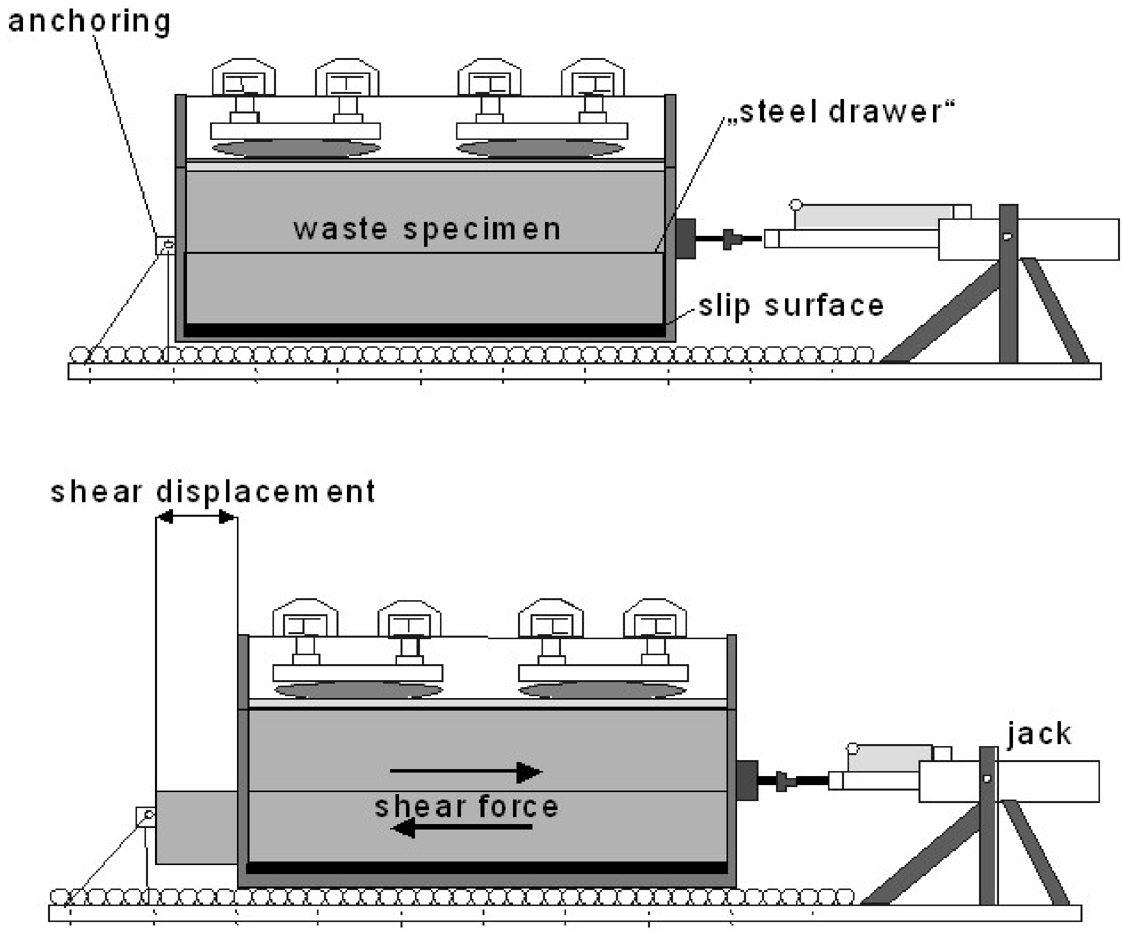


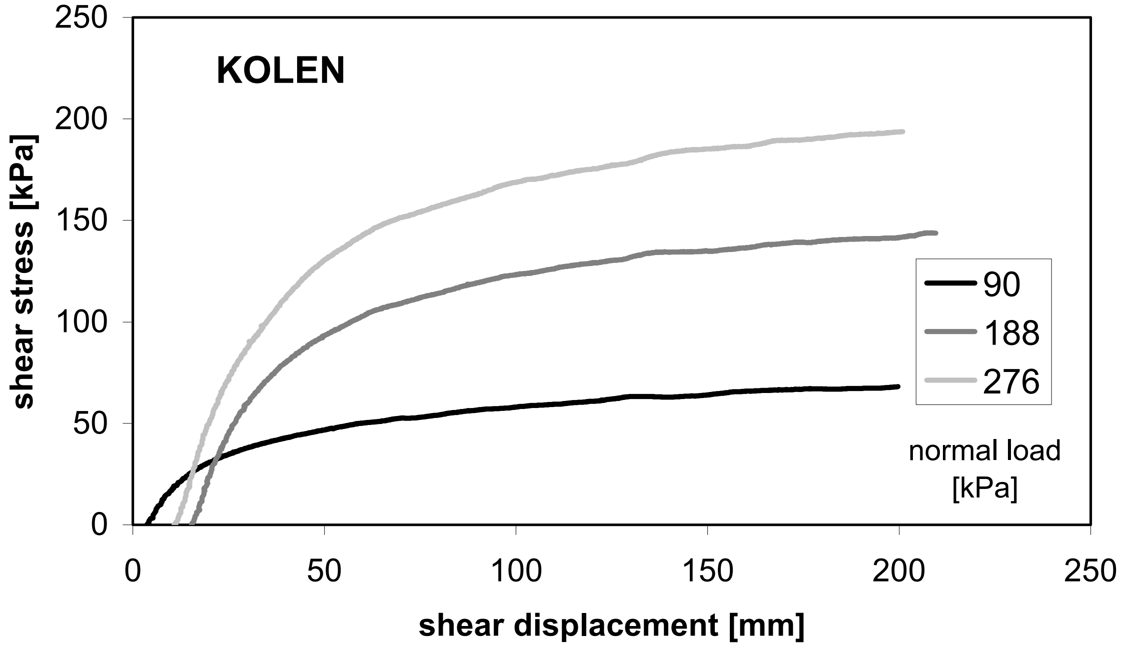
Figure 4: Large direct shear test – testing procedure

2.3 Evaluation

In general, two material parameters can be obtained from direct shear tests, the internal angle of friction φ and the cohesion c. Results of direct shear tests on MSW need to be evaluated thoroughly. Shear tests on unmodified MSW regularly show higher shear strength than one could expect from friction properties. This is due to the fact that in direct shear tests fiber-cohesion may be activated, although the shear plane is approximately parallel to the main fiber direction.

Since the testing concept aims on determining the shear resistance components separately for executing advanced stability calculations, it has to be secured, that material values obtained from tension and from shear tests do not overlap. Non-linear shear planes (curves) result from those overlappings.

Figure 5 shows the results of the three stage shear test on the sample KOLEN, a fresh unmodified MSW. The sample contains large particles up to a size of 500 mm, which can act as reinforcement. The normal stress/shear stress diagram illustrates, that the shear resistance over proportionally increases with the normal load, theoretically resulting in a negative cohesion value if evaluated in a conventional way. That indicates that additional shear resistance is activated with increasing normal load. Since friction forces have in most cases a linear relation to normal stress, the "stiffing" of the waste sample must be due to reinforcement effects.



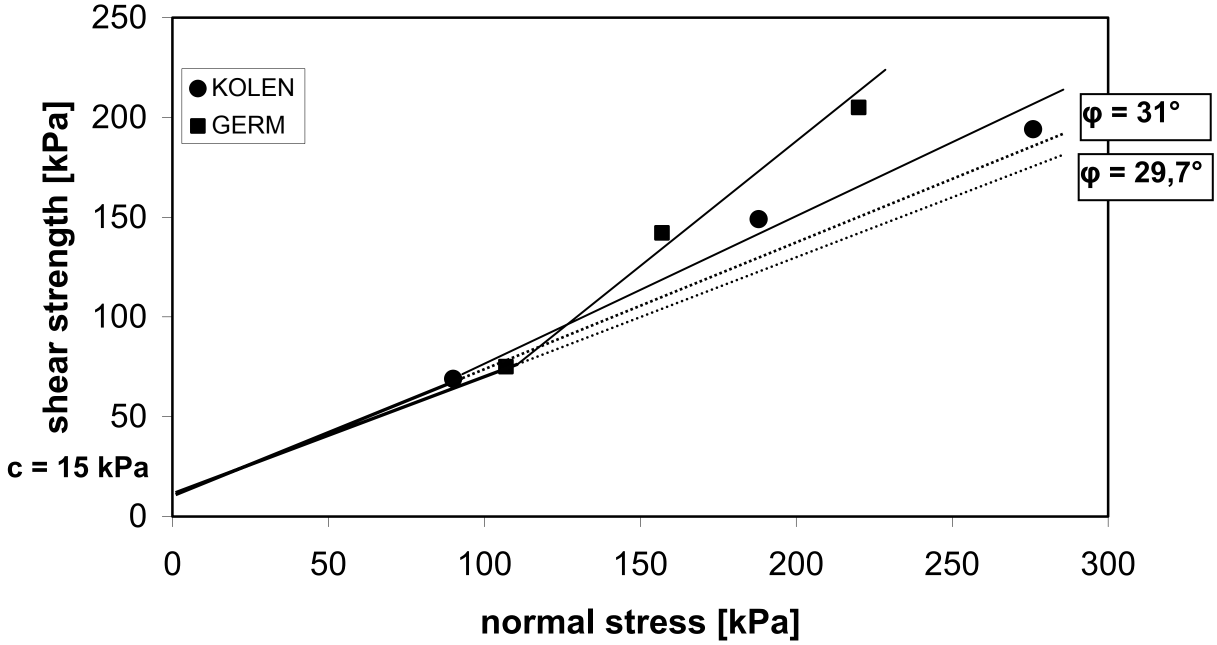


Figure 5: Direct shear test on MSW – results: stress-strain (above), non linear shear planes (below) for untreated waste

In order not to consider those effects twice, the shear testing results were cleared from reinforcement effects. It was assumed, that the cohesion of the material amounts to 15 kPa and that no reinforcement effects have been activated in the first loading stage. The friction angle was then obtained forming a linear relation between both values as shown in figure 5 for the samples of untreated MSW (GERM, KOLEN). The assumptions of this data evaluation procedure could be confirmed by conducting unloaded shear tests on several samples.

For example, the friction angle for the sample GERM amounts to φ = 48,5°, the cohesion c = -41,6 kPa, if evaluated conventionally. If assuming a cohesion of 15 kPa and activated reinforcement as described above, the friction angle amounts to φ= 29,7°. In order to validate this calculation, the contribution of fiber cohesion to the shear strength can be recalculated as shown below for loading stage 2 (σ = 157 kPa) of the sample GERM.

- Friction
  φ = 29,7°, σ = 157 kPa, friction (including cohesion) τ_f = 104 kPa
- Fiber cohesion (reinforcement)
  ζ = 22,4° (obtained from tension test), σ = 157 kPa, max fiber cohesion τ_z = 65 kPa
- Shear strength at σ = 157 kPa (measured in direct shear test)
  τ = 142 kPa, activated fiber cohesion: 38 kPa equal to 58 % of max fiber cohesion (65 kPa)

2.4 Test results

Table 3 summarizes the testing results of the seven shear tests. The fresh samples show friction angles around 30°. Friction is higher in the decomposed waste samples showing friction angles between 33° and 40° and a peak value of 45° in the decomposed old waste sample. The cohesion mostly ranges between 10 and 17 kPa. The samples IR2 and GÖ-PO1 are unscreened and it seems, that especially the large particles (wood pieces, rocks) contribute to the friction, probably due to "nailing" effects.

Table 3: Results of direct shear test

sample	**unloaded**		**1st loading stage**		**friction**	**cohesion**
	σ [kPa]	τ [kPa]	σ [kPa}	τ [kPa]	φ [°]	c [kPa]
GERM	not tested	15	107	76	29,7	15
KOLEN	not tested	15	90	69	31	15
SIEB	5,5	21,3	121	110	37,5	17,1
WHV	7,5	22,4	103	92	36,1	16,9
BORN	8,5	15,9	77	62	33,9	10,2
IR2	not tested	15	103	101	39,8	15
GÖ-PO1	5,9	16,6	90	101	45,1	10,7

Figure 6 and 7 display the shear straight lines for the decomposed materials (fresh waste has already been shown in figure 5).

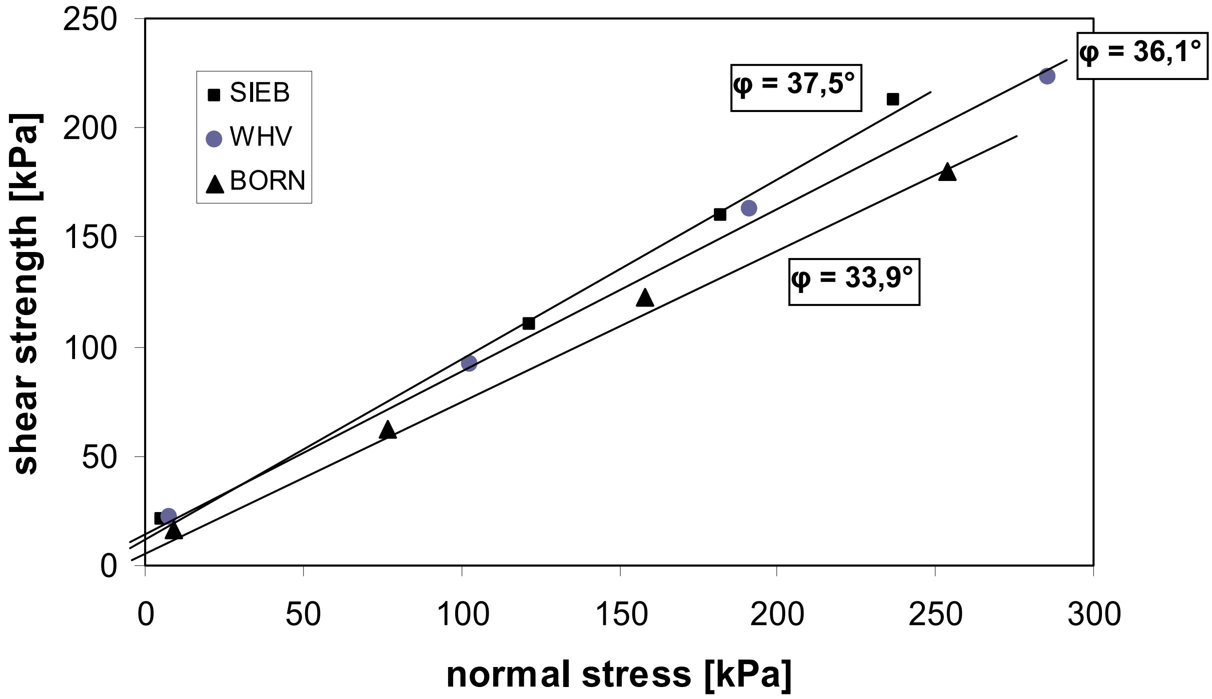


Figure 6: Direct shear test on MSW – shear planes for decomposed waste (screened)

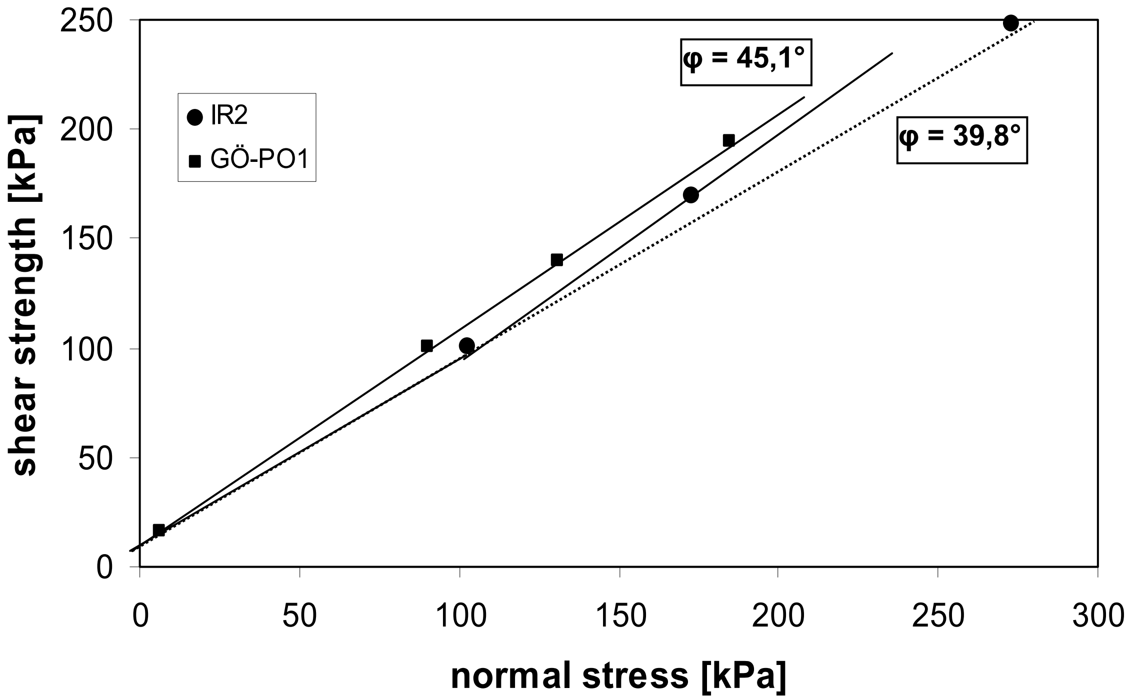


Figure 7: Direct shear test on MSW – shear planes for decomposed waste (unscreened)

3 CONSEQUENCES

The evaluation of the shear tests, particularly of those on unscreened waste samples (figures 5 and 7), indicates that the interpretation of shear test data and the determination of friction properties is tricky. It became clear, that fiber cohesion in unscreened materials occurs not only in the tension test, but in direct shear test, too. Therefore, reinforcement effects may be recorded twice, since they are (partly) described in both material values. It should be noted that a simple merging or adding of material values obtained from the different tests can lead to an overestimation of shear strength. On the other hand, just neglecting significant portions of shear resistance will result in incorrect stability assessments, because the most unfavourable sliding figures will not be identified.

Table 4 summarizes the recommendations for material values as published in GDA recommendation E 2-35 by German Geotechnical Society (Gartung, Neff, 2000), which reflect the research results described in this publication, but have been adjusted by conservative safety considerations.

Table: 4: Material values for municipal solid waste

Parameter	unit	untreated MSW	MBT-waste	comments
respiration activitiy AT_4 (4 days)	mg O_2/g ds	> 5	< 5	
dry density ρ_d	t/m^3	0,2-0,5	0,2-0,7	loose dropped
		0,5-1,0	0,8-1,5	compacted
Shear strength (anisotropic)				
tensile angle ζ	°	25-35 dim 1+2 > 30%	10-14 dim 1+2 < 20%	
friction angle φ_{GM}	°	25-30	30-35	
cohesion c_{GM}	kPa	<10		
modulus of stiffness E_S	kN/m^2	$E_S = -a + b*\sigma$ a: -100 bis -300, b: 10-13		

MSW: Municipal solid waste   MBT: Mechanical biological treatment

Advanced stability calculations can be carried out using the presented material values (Kölsch, Ziehmann, 2004). Suitable software is available on the market like the program GGU Stability 9, free test calculations can be carried out at:

http:\\testdrive.civilserve.com

If experienced in programming, software can be generated by oneself. Information on technical details how to transform the shear law can be found at Kölsch (2007)

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