The geotechnical testing of municipal solid waste (MSW)

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ABSTRACT
In general, where geotechnical investigations involving MSW are reported, the material is treated as a regular mineral soil. In reality, however, MSW is a highly non-textbook material, being highly fibrous, heterogeneous, erratic, highly compressible, and displaying significant long-term settlement caused by plastic creep and decomposition. In the long term, which could be hundreds or even thousands of years, the total settlement could be more than 80% of the finished thickness of the fill.

RÉSUMÉ
En général, lorsque des investigations géotechniques impliquant MSW sont signalés, le matériel est traité comme un sol minéral. En réalité, toutefois, MSW est un matériel tres unique. Spécifiquement, Il est très fibreux, hétérogène, inégal, très compressible, et démontre des déformations à long terme causé par la décomposition et le fluage plastique. À long terme, qui pourrait être des centaines, voire des milliers d'années, le tassement total pourrait être plus que 80% de l'épaisseur finie de l'enfouissement.

1. INTRODUCTION

The geotechnical characteristics of MSW as observed in a landfill will depend on such variables as (a) the composition of the waste as delivered to the disposal site, (b) the placing method (e.g. lift and layer thicknesses, equipment used, and the thickness and type of daily or interim covers) and (c) the post-placement stress-time history of the constituent layers.

On delivery to the landfill, MSW comprises varying proportions of paper, organics and plastics in addition to inert debris, metals, glass etc. MSW may also contain relatively large particles such as construction debris. Many of the constituents are flat in shape (e.g. paper, glass, timber products, and textiles) or are readily flattened on compaction, resulting in a highly anisotropic material. The degree of anisotropy will be increased further if mineral cover materials have sufficient cohesion to remain as distinct layers within the landfill. Granular soils used as cover material are more likely to infiltrate the waste under the action of water or vibrations, resulting in increased waste density.

2. SOME GEOTECHNICAL PECULIARITIES OF MSW

2.1 Fibrosity

Most of the waste constituents have a high to extremely high aspect ratio (greatest dimension ÷ least dimension), i.e. the "degree of fibrosity" is generally high. The MSW therefore behaves like a reinforced material, having discontinuous "fibre" reinforcement generally in a direction parallel to the bedding of the material as placed. This fibrosity is one reason that MSW should not be treated as a conventional soil.

The K_0-values measured in the split ring shear tests reported in this paper were as high as 0.25-0.40, despite the reinforcing action of the elongated constituents ("fibres"). The reason for these relatively high values is that under conditions of zero lateral strain the fibre reinforcement is only partly mobilized. If the fibre reinforcement were fully mobilized (i.e. the active pressure condition) K_a would be equal to zero, whereas for no mobilization K_0 would be close to 0.5 ($K_0 \approx 1\text{-}\sin\varphi$).

In general, the value of K_0 would decrease with an increasing amount of fibrous (elongated) constituents. The total fibre content of MSW decreases with time, as many organic fibres will decompose over a long period.

2.2 Decomposition

Another peculiarity of MSW, as compared with mineral soils, is that the material is subject to decomposition, i.e. its geotechnical properties will change with time. The amount of time will vary considerably, depending on the nature of the MSW constituent, from a few years to several hundred or even thousand years. The contribution to the settlement of a landfill caused by decomposition cannot generally be included in laboratory analyses and can only be partly accounted for in the field, even if settlement measurements are made over several years.

2.3 Compression, consolidation and creep

Bjerrum's (1967) concept of instant and delayed compression applies particularly well to MSW material because of its generally high permeability, high compressibility and, in general, low degree of saturation. This concept describes instant compression as being equal to primary consolidation without viscous (water) delay, and delayed compression as being equal to plastic creep plus compression due to decomposition. Preceding the instant compression is elastic compression.

2.4 Strength consideration

The strength of MSW is a combination of (i) frictional resistance along planes parallel to the prevailing direction of the elongated constituents (“fibres”), (ii) fibre resistance in tension and sliding, and (iii) bending and tearing resistance along planes across the fibres. The fibre resistance accounts for the frequently observed phenomenon of high vertical or near vertical cuts in landfills.

The stability of landfills depends, however, not only on the strength of the MSW material itself, but in many cases on the strength of the underlying soil.

3. SAMPLING OF MSW

Conventional sampling, such as SPT and Becker sampling, is generally not feasible. Test pits are generally limited to about 3 m depth. Daily covers (and any other mineral layers) can be directly observed and measured from the surface, and the volume can be measured reasonably accurately with a sliding stick arrangement. If relatively accurate weights can be obtained, unit weights may be determined for the MSW material and the cover soil separately as well as for the combined landfill. Test pits deeper than three metres can be excavated in relatively dry landfills, but it does not seem practical to determine unit weights below about three metres depth.

While hollow-stem augering is generally not possible, both 150 mm and 280 mm diameter solid-stem continuous augers have been used successfully in MSW. The augers have to be withdrawn to the surface every 1.5 to 3 m depth intervals to unload the sample between the auger flights. The 150 mm auger has been used to depths of approximately 30 metres.

Bucket augers, typically with diameters in the range 300 to 750 mm, may also be used in MSW. The bucket auger can be expected to create a cylindrical hole of diameter approximately the same as the diameter of the auger, both above and below the ground water level. This is possible because of the reinforcing fibre action of the MSW material. However, the material sampled is extensively chopped into small pieces by the auger cutting bits, so that the material sampled is not strictly representative of the MSW in situ.

More recently, sonic drilling methods have been used to successfully recover samples in landfill waste up to 34 m thick (Burlingame et al. 2007).

3.1 MSW unit weight

A comprehensive review of MSW unit weights is given by Zekkos et al. (2006). They state, in agreement with our own observations, that the value of the unit weight of MSW continues to be a major source of uncertainty. Various observed ranges and values of unit weight are given in Fig. 3.1-1. The indicated shaded range may be used as a guide in the geotechnical analysis of MSW landfills. The upper bound could thus be used (conservatively) for the active case, i.e. for driving moments or forces, and the lower for the passive case, i.e. for stabilizing moments or forces.

4. FIELD TESTING

Conventional equipment is not applicable in MSW (vane test, undisturbed sampling, pressuremeter test, SPT), and it is necessary to resort to larger-scale equipment.

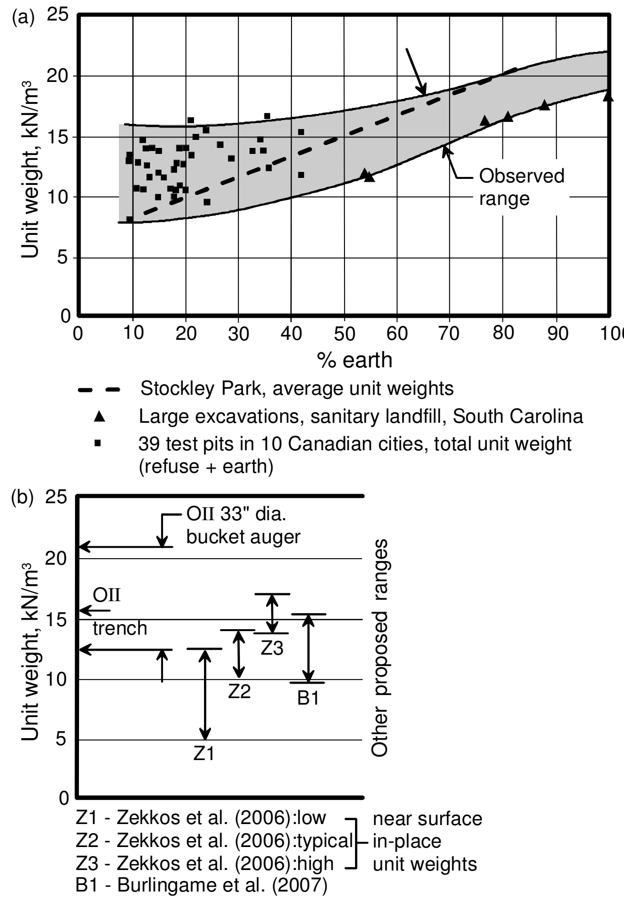


Figure 3.1-1. Observed range of unit weights of MSW materials.

4.1 Plate load test

The diameter of the load plate should be as large as possible and preferably not less than one metre. Since the construction equipment used for counterweight generally cannot be tied up for extended periods, the measured settlement will only correspond to the instant compression referred to above.

A test pit should be excavated at the exact location of the load test for the purpose of determining the nature of the material tested.

4.2 Stockpiles of cover materials

The main advantage of test fills on MSW is their large size relative to the size of the MSW constituents and the thickness of the daily covers. Combined with drilling and sampling, test fills will furnish valuable information on the compressibility of the landfill, both short-term and long-term. A short-term test fill will yield the elastic plus the instant compression (provided that the settlement plates are installed before the stockpile is placed); a long-term fill will also yield the beginning of the plastic creep.

The cost of the material used for the test fill may be kept to a minimum by making use of cover material, i.e. by stockpiling it on the top of the landfill for as long a period as possible.

Schmertmann (1993) has devised a field load testing method that can approach full scale by constructing a conically shaped mound of soil dumped or otherwise heaped at its angle of repose into an approximately conical form.

5. LABORATORY TESTING

Again, conventional equipment is not suitable for MSW material (consolidation tests, shear strength tests, permeability tests, grain size analyses, index and routine tests), and it is necessary therefore to resort to larger-scale equipment and special testing procedures.

As it is not possible to obtain undisturbed samples of MSW, it is necessary to work with samples prepared in the laboratory. Two alternative preparation methods have been used: (i) sampling by auger borings or through grab sampling in test pits, reconstituting samples by compacting the sampled material to a density corresponding to that measured in the field (e.g. in test pits), and (ii) fabricating samples by using constituents similar to those sampled in situ and combining these constituents in the same proportions as those existing in situ.

5.1 Consolidation tests

The consolidation tests reported in this paper were carried out in steel rings of diameters 457 mm and 600 mm. For both diameters, flat particles larger than about 100 mm in length and width and 60 mm in thickness were either removed or reduced in size. The long axis of large flat particles with high aspect ratios (greatest dimension ÷ least dimension) was oriented along the horizontal plane for the purpose of replicating the MSW structure in situ. Large particles with low aspect ratios (e.g. cobble size) were removed.

Because of the relatively high compressibility of MSW samples, the total height of the samples before loading should typically not be less than about 75% of the diameter. The samples were compacted in approximately 100 mm thick horizontal lifts to the in-situ density.

Figure 5.1-1 shows the results of consolidation tests on the MSW samples listed in Table 5.1-1. The width of the stress-strain band does not seem excessive for a material as variable as MSW.

The results of the consolidation test on sample AR1 (Fig. 5.1-2, Landva et al. 2000) show a behaviour close to the model suggested by Bjerrum (1967) with respect to developing a “reserve resistance” against compression during delayed consolidation. For example, the application of another load step at the end of load step 1 causes very little compression initially (point *b* to point *c*) because of the resistance developed during creep point *a* to point *b*. The longer the material is left to creep under the same load, the greater is the plastic resistance developed.

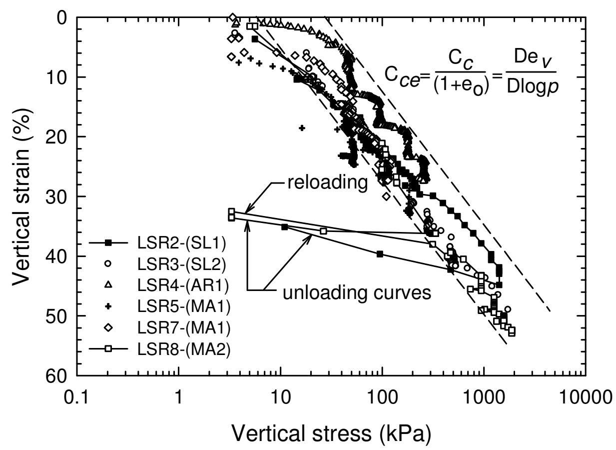


Figure 5.1-1. Primary compression index for refuse, composite plot (Landva et al. 2000).

Table 5.1-1. Weight percent of refuse sample constituents and K_o values measured in split ring

	Spruce Lake		Artificial	Mixed	
Constituent	SL1	SL2	AR1	MA1	MA2
Paper	46.3	22.8	8	12.5	8.1
Fines	24.7[a]	46.8[b]	66[b]	59.0[b]	43.5[a]
Stones	10.3	-	4	4.4	-
Plastic	6.3	12.8	2	8	9.5
Wood	3.7	2.8	7	5.1	1.4
Glass	3.5	0.9	-	0.8	-
Metal	2.8	3.6	5	5.6	2.8
Textiles	2.2	3.1	-	1.1	2.5
Rubber	-	0.6	8	3.5	3.9
Food and garden waste	0.26	5.8	-	-	-
Miscellaneous	-	0.8	-	-	28.3
K_o	0.23	0.29	0.40	0.34	0.26

[a] Fines were based on weight percent passing the 4.75 mm sieve size.
[b] Fines were based on weight percent passing the 12.5 mm sieve size.

If no unloading takes place, the final destination in a stress-strain-time plot would be independent of the stress-strain path. Considering, for example point *d* in Fig. 5.1-2 to be the final destination, possible stress-strain paths are (i) rapid loading *a-c* (no plastic resistance developed at *a*), followed by creep *c-d*, (ii) rapid loading *b-c* (plastic resistance developed at point *b* during creep *a-b*, followed by creep *c-d* or (iii) slow loading (no creep) *b-d*.

5.2 Large direct-shear (LDS) and large simple-shear (LSS) tests

The dimensions of the direct shear and simple shear equipment reported in this paper are 430 mm length by 280 mm width by up to 600 mm deep (upper and lower boxes are 300 mm deep each). Flat particles larger than

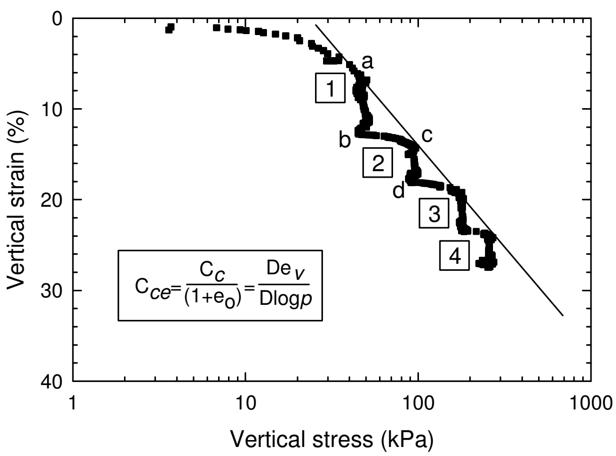


Figure 5.1-2. Consolidation test of sample AR1, 600 mm diameter (Landva et al. 2000).

about 60 mm in length and width and 40 mm in thickness are either removed or reduced in size. The long axis of large flat particles with high aspect ratios is oriented along the horizontal plane for the purpose of replicating the MSW structure in situ. Large particles with low aspect ratios (e.g. cobble size) are removed.

The results of direct shear tests on various MSW materials have been reported previously by, *inter alios*, Landva and Clark (1990) and Pelkey (1997). These results – and the mode of deformation in direct shear of fibrous materials such as MSW – have recently been reviewed and scrutinized carefully in light of the mode of deformation and the results of simple shear tests on MSW, examples of which are reported in this paper. In direct shear, particularly at large displacements, the sample is significantly distorted, and it is clear that both the shear stress distribution and the shear strain are really indeterminate. Under these circumstances we have concluded that direct shear tests on MSW materials cannot be recommended. In connection with Pelkey's (1997) thesis work the direct shear equipment was modified to accept the simple shear testing mode. Figure 5.2-1 shows a photograph of an LSS test on an MSW sample at a shear strain of 0.26 (or 26%). The slanted, originally vertical, paint stripes on the sample show that the mode of deformation is close to one of simple shear strain.

Two types of simple shear test may be run: (i) consolidated drained and (ii) consolidated constant volume. For either type the upper load plate is kept parallel to the horizontal base by adjusting the loads applied by two hydraulic cylinders (jacks). For test type (i), the sum of the two jack loads is kept constant. For test type (ii) the jack loads are adjusted so as to keep the upper load plate horizontal and at the same time keep the height of the sample constant.

Figure 5.2-1. Large simple shear test equipment.

Figure 5.2-2 shows the results of some typical simple shear tests on 430 x 280 mm samples of the same (AR 1) material (Pelkey 1997), plotted as normalized shear stress versus shear strain. The shear strain for this type of test is the horizontal displacement divided by the original height of the specimen after consolidation. It is seen that a relatively high shear strain is required for the maximum shear stress (i.e. the shear strength) to be reached. There was no indication of lower (residual) strength behaviour after the peak.

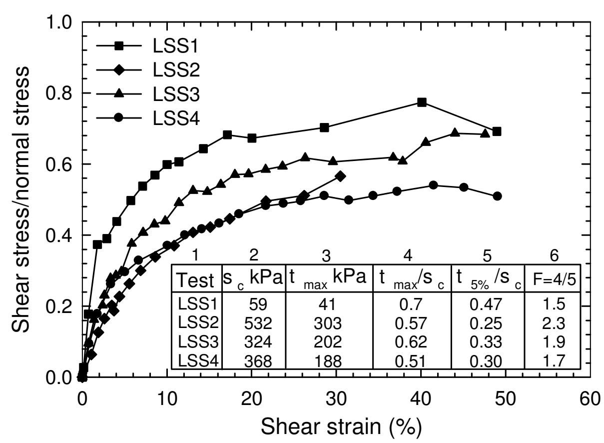


Figure 5.2-2. Large consolidated drained simple shear test results.

The results of the large simple-shear tests are plotted also in the Mohr diagram in Fig. 5.2-3. The test results represent the shear strength of the MSW material along planes parallel to the direction of fibres, since in the case of simple shear tests, the direction of the fibres is largely horizontal. The failure envelopes fall within a range of c = 0, φ = 27º to c = 50 kPa, φ = 29º. This range does not seem excessive for a material as erratic and variable as MSW.

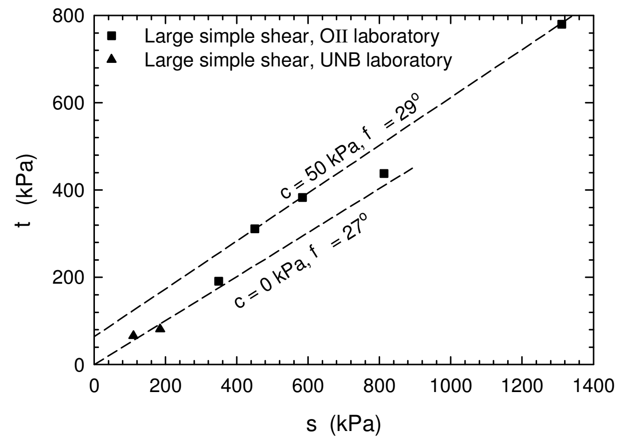


Figure 5.2-3. Mohr stress diagram for large direct and simple shear tests on MSW material.

The results of another type of test will also be reported here, mainly for the purpose of demonstrating that some caution is required when testing highly compressible materials and when interpreting the test results. Bouazza and Van Impe (1998) carried out a large-scale test intended to replicate vertical expansion ("piggy-backing") of MSW landfills. Two bales of MSW 1.3 m long x 1.0 m wide x 0.8 m high were placed on top of each other as shown in Fig. 5.2-4a. The shear load was applied through a steel beam of approximate width 180 mm placed near the base of the upper bale. The reaction to this load was taken partly by friction along the base of the lower bale and partly by another 180 mm bar placed near the top of the lower bale. This arrangement would have been satisfactory for two blocks of a rigid material such as concrete. However, in the case of a highly compressible material such as MSW the mode of deformation would be more like that shown in Fig. 5.2-4b, and this type of mode would be highly indeterminate with respect to both strains and stresses. The reported test results shown in Fig. 5.2-4c in fact suggest that the MSW was stressed laterally in compression, therefore displaying no peak stress. Caution is thus required when testing highly compressible materials and when interpreting the test results.

5.3 Large split-ring tests

The split-ring test equipment (Fig. 5.3-1) was introduced for the purpose of determining the effects of the fibrosity of MSW material on the geotechnical properties of this material. The equipment consists of a 600 mm diameter split ring with a height of 460 mm. The ring is held together at the back by hinges and at the front by three load cells. Two sets of split plates and rollers are provided, one at the top and one at the bottom. The split plates and rollers permit the sample to expand laterally as it is compressed under the vertical load. If lateral expansion is prevented, the front load cells will record the corresponding lateral force (pressure) at rest.

The split ring samples are compacted in approximately 100 mm thick horizontal lifts to the in-situ density, if this is known.

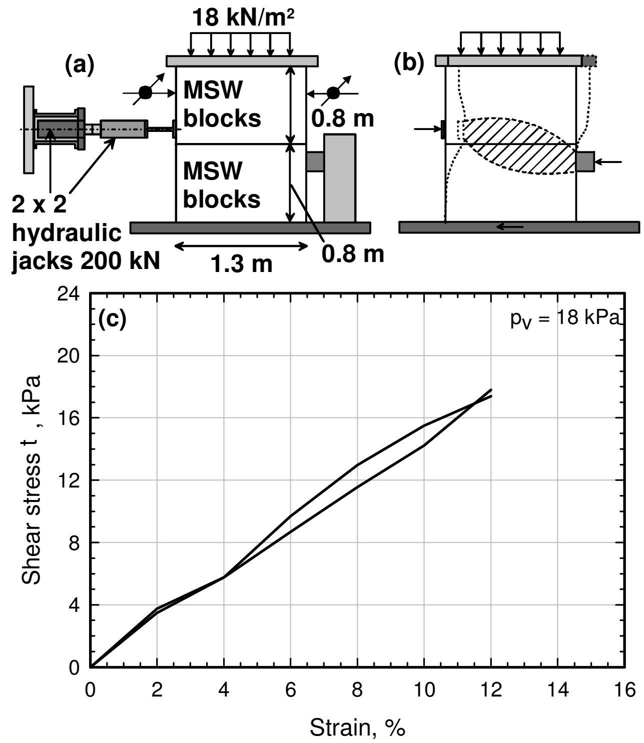


Figure 5.2-4. Large shear (Bouazza and Van Impe, 1998).

Flat particles larger than about 200 mm in length and width and 60 mm in thickness are either removed or reduced in size. The long axis of large flat particles with high aspect ratios is oriented along the horizontal plane for the purpose of replicating the MSW structure in situ. Large particles with low aspect ratios (e.g. cobble size) are removed. This apparatus can be used as a regular consolidometer, but it is designed specifically to yield information about behaviour under controlled-strain lateral expansion as well as behaviour under unconfined conditions, depending on the mode of testing. Typically, the vertical load would be applied in several stages up to some predetermined level. This alone constitutes a regular consolidation test, but since lateral movements are prevented (by adjusting the loads in the lateral load cells), the magnitude of the coefficient of lateral pressure at rest is then automatically determined for each vertical pressure increment.

Having reached the chosen level of vertical pressure, the lateral stress-strain behaviour of the sample can subsequently be checked by allowing a small lateral expansion and recording the corresponding reduction in lateral pressure. Because of the fibre reinforcement of the MSW material, the lateral pressure can actually be reduced all the way to zero and the corresponding lateral strain recorded for this state.

The results of a split ring test carried out on the artificial material AR 1 described above are shown in Fig. 5.3-2 (Pelkey 1997, his figure 4.8). The coefficient of lateral pressure under conditions of zero lateral strain for this particular test was determined to be K_0 = 0.40. (Other split ring shear tests carried out by Pelkey (ibid.) on various other compositions of MSW had given K_0 values in the range 0.29 to 0.36.) In the case of the test shown in Fig. 5.3-2, the sample was allowed to expand laterally in several steps, the purpose being to investigate the relationship between lateral stress and strain in this type of material. One interesting finding during this type of test was that only a very small lateral expansion was required to reduce the lateral pressure to zero (the lateral strain being defined as the average increase in diameter divided by the original diameter).

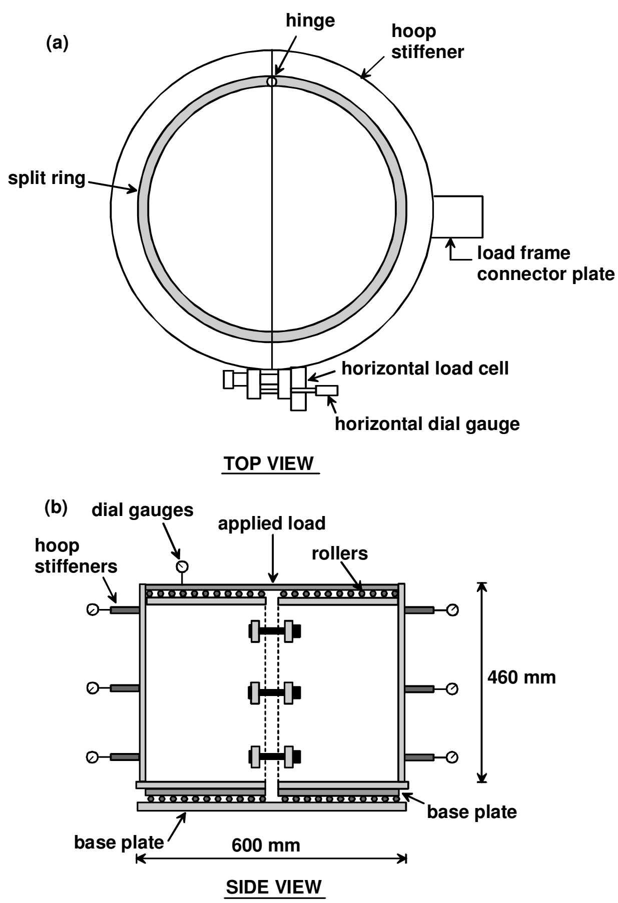


Figure 5.3-1. Split ring apparatus (Landva et al. 2000)

Thus the Fig. 5.3-2 results would indicate that an expansion of less than 0.5% would be required if the lateral pressure was reduced to zero in one step and about 1.5% if the lateral pressure was reduced in several steps, allowing periods of rest at each level of reduced lateral pressure. Clearly, this low strain must have been a result of the MSW fibres resisting lateral expansion. Another result – unexpected and somewhat surprising - was that the lateral pressure, which had been reduced by letting the sample expand gradually, actually increased with time when the lateral expansion was stopped and the diameter held constant. Figure 5.3-2 shows that the lateral pressure was on its way back up to the pressure at rest. It seems clear that the relatively rapid reduction in the lateral stress with lateral strain first caused part of the lateral stress to be taken by the mostly horizontal fibres, and that with time the fibres would stretch (creep) so that the lateral load taken by them would slowly be transferred back to the unyielding ring wall.

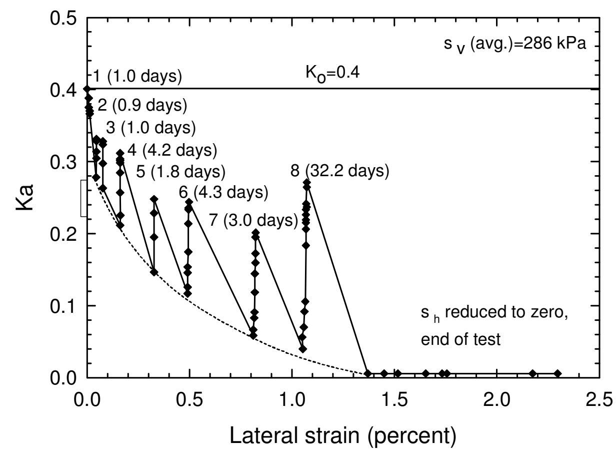


Figure 5.3-2. Measurement of Ka in the split ring apparatus, sample AR1 (Table 5.1-1).

After having reduced the lateral pressure to zero, it was maintained at zero by just maintaining light contact between the steel rings and the sample. The vertical pressure was then increased while recording the lateral expansion of the sample. This mode corresponds to an unconfined compression test (UCT) and it will also yield a value for Poisson's ratio. Figure 5.3-3a shows the results of two such tests on MSW material. The unconfined part of the compression tests started at stresses of 500 kPa (MA1) and 230 kPa (AR1) after being compressed under confined conditions. There was no sign of failure of the unconfined samples. Figure 5.3-3b shows that the vertical strain at the termination of the MA1 test was 18% and the lateral strain less than one tenth of this, again as a result of the MSW fibres resisting lateral expansion. The value of Poisson's ratio remained practically constant at about 0.10.

Further evidence of fibre action (tensile strength) in MSW material is seen in Fig. 5.3-4a, which shows the results of large-scale triaxial tests on fabricated (artificial) samples consisting of 6% cloth and wood, 32% paper, 8% plastic, 32% rubble and 22% organic matter (Grisolia et al. 1992). The tests had been carried out on compacted samples of diameter 250 mm and height 600 mm. Superimposed on the triaxial test results is a range of consolidation test results on compacted fabricated MSW samples confined in a steel ring of diameter 600 mm and height 460 mm (Pelkey 1997). The similarity between the triaxial and the consolidation stress-strain plots leaves little doubt that the highly unusual shape of the triaxial plots is due solely to the confining action of the MSW fibres. Because of this reinforcing action, the real lateral (minor principal) stress keeps increasing with increasing vertical (major principal) stress, in much the same way as it does when confined in a consolidation ring.

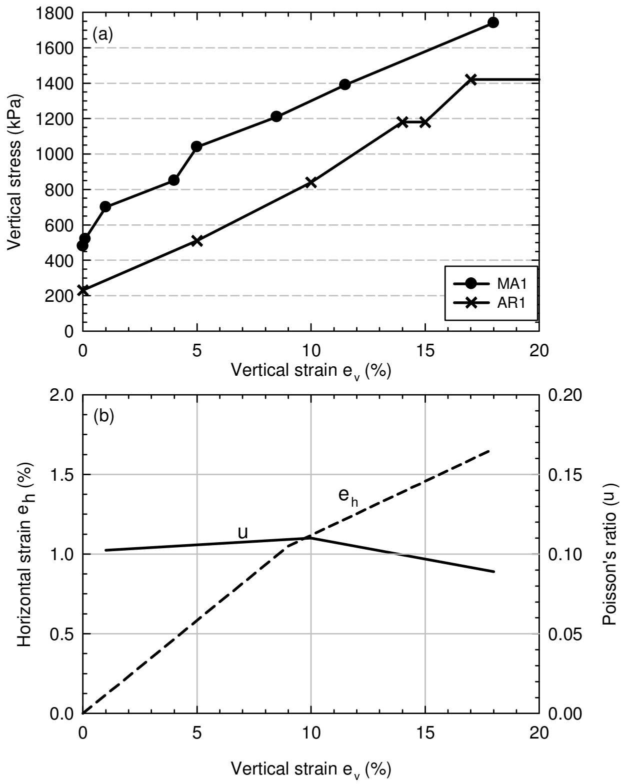
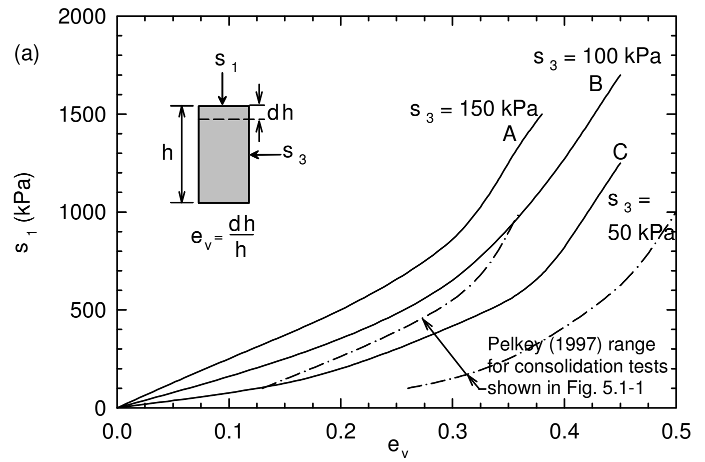


Figure 5.3-3. (a) Unconfined compression tests on samples AR1 and MA1 (b) Unconfined compression test on sample MA1.

The Fig. 5.3-4a triaxial results are plotted in a Mohr stress diagram in Fig. 5.3-4b. Circles A, B and C correspond to the test results shown in Fig. 5.3-4a, the major principal stresses being the maximum values shown in that figure for σ_1. Superimposed on the Mohr diagram is the lower MSW failure envelope c = 0 and φ = 27° from Fig. 5.2-3. Circles A', B' and C' also correspond to the Fig. 5.3-4a test results, but for these circles the minor principal stress has been increased to such a value that the MSW failure envelope is tangent to the circles. The differences $\Delta\sigma_3$ between the minor principal stresses for the two sets of circles represent the lateral resistance provided by the fibrous MSW constituents.

5.4 Tension tests

According to research carried out by Kölsch (1995) and Pelkey (1997), MSW material may possess considerable tensile strength as a result of its fibrous nature. In the laboratory, under controlled-strain conditions, the split-ring tests at the University of New Brunswick had shown that only a very small lateral strain was required to reduce the lateral pressure to zero. These tests also showed that, in the split-ring mode of unconfined compression, the MSW displayed a very significant tensile strength, as evidenced by a lateral strain of less than 2% at a vertical strain of almost 20%. A similar mode of deformation occurs in triaxial testing, and it is seen from Fig. 5.3-4 that the tensile strength can be quite significant.



Triaxial test results (Grisolia et al. 1992)

(b)

Test	s 3c kPa	s 3' kPa	s 1max kPa	Ds 3=s t kPa	d °	A f/A
A	150	532	1400	382	15.3	0.54
B	100	652	1720	552	17.8	0.63
C	50	513	1350	463	18.9	0.67

A f=area covered by fibres
A=total area
A f / A = Ds 3 / (s 1max tanf)

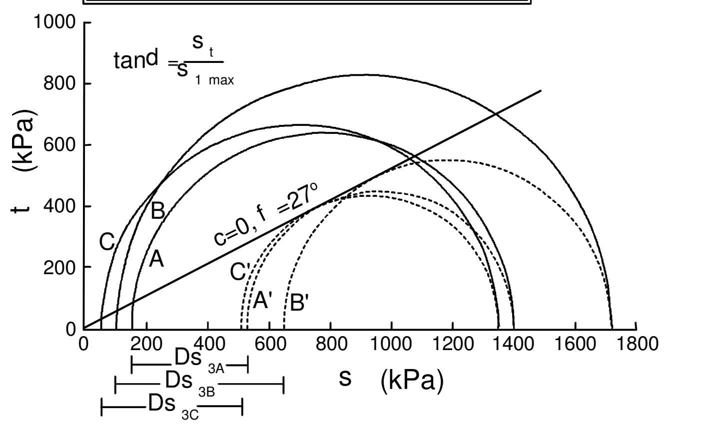


Figure 5.3-4. (a) Consolidated triaxial tests (A, B and C, Grisolia et al. 1992) and consolidation tests on fabricated samples, Pelkey 1997. (b) Triaxial test results plotted in a Mohr diagram.

It is important to specify which mode of deformation is considered when assessing the tensile strength of the MSW. In the cases of unconfined compression and triaxial compression tests, the sample attempts to expand laterally but is hindered from doing so by the mobilization of friction between the mostly horizontal elongated constituents, leading to the development of a tensile resistance (Vidal 1969, Landva and La Rochelle 1983). In the case of tension tests such a those described by Kölsch (1995; shown in principle in Fig. 5.4-1), the sample is stressed in tension within or close to a narrow strip between the two load plates. The tensile resistance recorded is a function of the strength and the width and length of the fibres.

Figure 5.4-2a shows the Mohr stress circles for the two materials referred to by Kölsch (ibid) as *site* ("complete urban waste after 18 months aerobic pre-treatment at rotting heaps") and *rotted* ("urban waste excavated from a landfill 5 years after compacted placing").

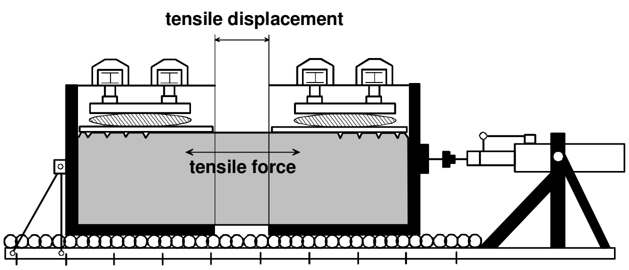


Figure 5.4-1. Tension test of MSW (after Kölsch 1995).

The writers have interpreted the test results according to Vidal (1969) and Landva and La Rochelle (1983). Thus for each test, i.e. for each pair of circles, the larger circle represents the applied major principal stress and the applied minor principal stress at failure, interpreted to occur at the maximum lateral tensile (i.e. negative) stress. The smaller circle for each pair represents the applied major principal stress and the minor principal stress corresponding to the strength of the MSW without fibre reinforcement (c=0, φ=27°). The fibre reinforcement thus corresponds to the difference between the minor principal stresses for each test, i.e. for each pair of circles. The resulting tensile strengths σ_t are plotted in Fig. 5.4-2b as a function of the applied major principal stresses σ_1, giving a σ_t intercept *i* of 22 kPa and a gradient ξ of 32°. This compares with a σ_t intercept *i* of 20 kPa and a gradient ξ of about 15° as interpreted by Kölsch (1995), apparently on the basis of the large-scale tension tests on '*site*' and '*rotted*' MSW materials, as referred to above.

In the field, tensile failure will occur along the path of least resistance, which could be expected to follow a tortuous path dictated by low friction (e.g. plastic constituents), low tensile strength of individual constituents (e.g. wet paper), voids created by ravelling or by physico-chemical and bio-chemical decay, and possibly voids created by spontaneous ignition (Sowers 1973). The real tensile strength of MSW can therefore be expected to be indeterminate and almost certainly lower than that measured in the laboratory.

6. SUMMARY

Several characteristics set MSW materials apart from conventional inorganic soils: fibre reinforcement, high aspect ratio, high compressibility, long-term plastic creep, long-term decomposition, and ravelling. These materials should not therefore be treated as conventional soils, as usually seems to be the case. The lateral pressure at rest in a landfill is generally quite low in young fills, but will increase with time as the MSW decomposes, a process that could take anywhere between a few years and perhaps as much as several thousand years.

Bjerrum's (1967) concept of instant and delayed compression applies particularly well to MSW material because of its generally high permeability, high compressibility and, in general, low degree of saturation.

(a)

	s_t	s_{1c}	s_3 applied	$s_3 = s_1 \frac{1-\sin 27°}{1+\sin 27°}$
S1	257	380	-114	143
S2	199	280	-94	105
S3	157	221	-74	83
R1	210	299	-98	112
R2	141	190	-70	71
R3	90	110	-49	41

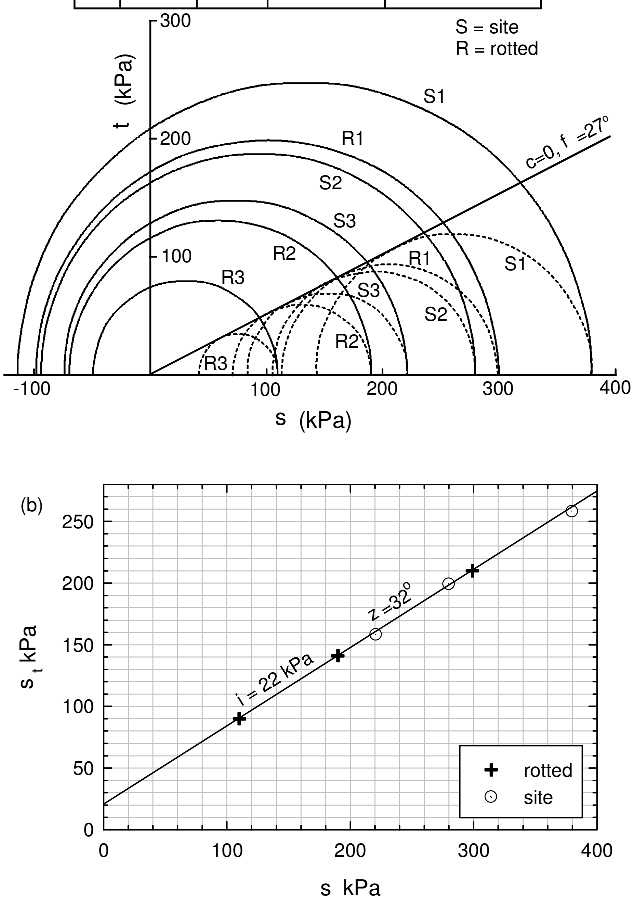


Figure 5.4-2. (a) Mohr stress circles and (b) resulting tensile strengths for materials referred to by Kölsch (1995).

Conventional sampling of MSW material is generally not possible. Samples can be obtained with solid-stem augers and in test pits. The unit weight of MSW material varies within a wide range, depending on the type of fill, the method of placing and the cover materials used. A range of unit weights is suggested, the higher applicable to the active case and the lower to the passive.

The contribution to the settlement of a landfill caused by decomposition cannot in practice be included in laboratory analyses and can only be partly accounted for in the field, even if settlement measurements are made over several years.

The interpretation of shear tests such as the simple shear, the split-ring shear and the tension tests is significantly affected by the fibre content and the mode of deformation. It is very important to test MSW material in a mode comparable to that obtaining in the field.

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