

# Mass loss and volume change: from sand-salt analogues to MSW

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**ABSTRACT:** Results from two sets of laboratory test programmes on sand-salt mixtures in which the salt fractions, of different amounts and size, are dissolved are brought together to gather insight into the mechanics of mass loss and its controlling factors. The test results are then used to provide a framework in which to interpret the long term behavior of two landfill reclaimed soils. There is some settlement and in all cases an increase in void ratio. It is shown that settlement and void ratio increases are strongly influenced by the amount of salt but almost insensitive to the particle size, at least over the ranges and size distributions tested. Both settlement and void ratio increases are muted by wider particle size distributions.

## 1 INTRODUCTION

From initial design of a landfill site through to passive aftercare, coupled hydraulic, biodegradation and mechanical phenomena give rise to environmental hazards in the form of liquid and gas emissions. More fundamental approaches to the analysis and design of new landfills and the remediation of old landfills have struggled with the interaction of these complex phenomena. One of the more challenging couplings, both in its conceptualisation and in the practicality of its measurement is the impact of biodegradation (or mass loss) on the mechanical properties of the waste. A number of landfill models (e.g. HBM, LDAT, Moduelo, see McDougall (2011) for a summary) account for the impact of biodegradation on volume change. These models either (i) use a secondary compression coefficient dimensioned according to the degradable content of the waste or (ii) account directly for mass loss. In the former, time is the controlling variable, sometimes in the guise of a gas production model; in the latter, a more fundamental account of mass loss is used but some means of coupling mass loss to volume change is then required.

The impact of mass loss on volume change is complex, although the amount and relative size of material to be lost would seem to be significant controlling factors. With these in mind, a programme of testing on sand-salt mixtures both in the oedometer (McDougall et al, 2013) and in the triaxial machine has been undertaken. A parallel investigation has been done at the University of Saskatchewan. The replicability of MSW by a sand-salt mixture may be

difficult to justify in the case of a typical MSW, i.e. highly compressible matrix with wide particle size distribution, some of which are elongated tensile elements, but it does provide a framework within which to approach the problem.

Recent projects to reclaim soil from old landfills, which offer impressive environmental benefits, process degraded MSW to produce a residual material that is more closely represented by the sand-salt mixtures. The process uses a screening plant with a final screen size of about 50 mm, depending on the waste and the final goals (see Figure 1). If the old waste contains a substantial amount of concrete, especially for construction and demolition debris dumps, a crushing plant may be used in conjunction with the screening plant to reduce the particle size of the concrete and brick material so that it may also be re-used for the controlled backfill. As with any type of recycling process, a small amount of “contamination” is intrinsic to the soil reclamation effort. We define contamination, in this regard, as the carryover of undesirable waste components, such as wood, paper, plastic, metals, glass, etc., into the reclaimed soil. The amount of contamination depends on the original waste composition and the screening process used. However, the small amount of contamination poses the question of the acceptability of the reclaimed soil for purposes of backfill to create a new geotechnical foundation for structures.

While the inclusion of some glass, metal, and other generally non-degradable materials is probably not of concern from a geotechnical point of view (all of these could legitimately be considered a “soil” material by standard geotechnical definitions), it is



Figure 1. Photographs showing the landfill soil reclamation process: material post screening (left) and screening plant (right).

the residual organic fraction that may be of concern, principally because of the potential for long-term settlement.

Considering that residential and commercial developments may have septic leach fields, water lines, sewer lines, stormwater drainage, or other environmental features that may create a net liquid percolation into the underlying soil, it would have to be assumed that any degradable organic fraction in the soil mass would eventually degrade. The question is what will be the impact of the loss of an amount of organic particles on the stability and settlement of foundations built over this soil?

Field studies show that the screened reclaimed soil is very homogeneous, and the distribution of contaminants is likewise so. Laboratory testing, presented in this paper, has shown for one case study that as long as there is good compaction control, and the reclaimed soil is compacted to a high level, potential long-term settlement can be acceptable for foundations of structures.

This paper presents the results of testing of sand-salt mixtures with a range of salt particle amounts and sizes. A total of 158 samples were tested: 118 of which were performed at University of Saskatchewan, and the remaining 40 at Edinburgh Napier University. These results are brought together in order to both reinforce the fundamental behaviours controlling volume change due to particle loss and to provide an *a posteriori* benchmark for the long term performance of reclaimed landfill soils.

## 2 PREVIOUS STUDIES ON DISSOLVING SAND-SALT MIXTURES

Studies by Fam et al. (2002), Shin and Santamarina (2009) and Truong et al. (2010) show that dissolution in coarse-grained soils leads to a change in soil fabric, i.e. structure. These studies focused primarily on the amount of particle loss in mixes with a relatively narrow range of sand to salt particle size diameter ratios ( $D_{50 \text{ sand}}/D_{50 \text{ salt}}$  between 1.44 and 2.34). Consequently, there is little experimental data

and hence understanding of the influence of particle size on fabric changes due to particle loss. This paper presents the findings of experimental investigations undertaken at Edinburgh Napier University and University of Saskatchewan into the volumetric consequences of both the amount and size of particles lost and host particle size distributions and presents those results in the context of the landfill reclaimed soils.

## 3 EXPERIMENTS – EDINBURGH NAPIER UNIVERSITY

Salt particle sizes ranging from 0.063 mm to 1 mm, added to sand with a  $D_{50}$  of 0.85 mm, in amounts from 2% to 15%, were tested. In such an investigation, the initial packing of the mixes assumes greater importance.

The inert fraction is a coarse rounded to sub-rounded quartz sand from Leighton Buzzard in the UK ( $D_{50} = 0.85\text{mm}$ ;  $C_U = 1.4$ ;  $G_S = 2.65$ ). The salt is sodium chloride ( $G_S = 2.165$ ), chosen for its high solubility in water, which after crushing to the required dimension, has a more angular form.

Particle size distributions are defined by a sieve stack having a sequence of aperture dimensions that double in size, i.e. 0.063, 0.125, 0.25, 0.5, 1.0 and 2.0 mm. Hence, in this paper, 0.063 mm particle fraction refers to particles between 0.063-0.125 mm. Figure 2 shows the relative sizes of the sand and salt particles for two of the gradings used: 1mm salt particles in Figure 2(a) and 0.063 mm particles in Figure 2(b).

### 3.1 Equipment

The dissolution tests were performed in an oedometer that was modified to allow for (gravity-driven) permeation of water, see Figure 3. The oedometer is 100 mm in diameter. It has an extended confining ring to accommodate a sample height of up to 30 mm and to retain a reservoir of water above the loading cap and sample. The Perspex loading cap

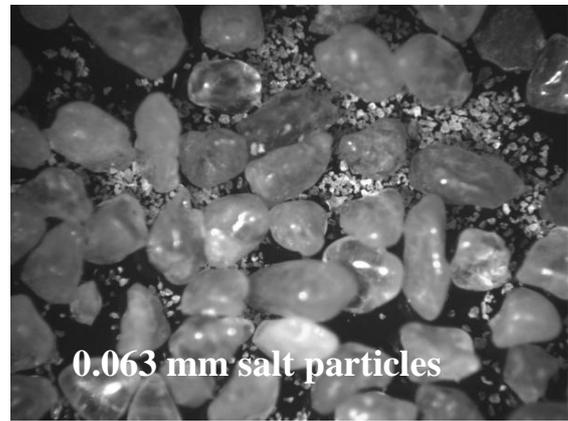
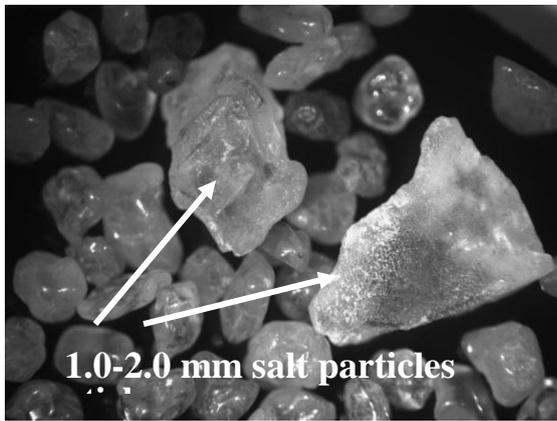


Figure 2. Photographs of sand-salt (Leighton Buzzard) mixes showing relative sizes and shapes: (left) 1.0 mm salt particles; (right) 0.063 mm salt particles

has a number of small (1 mm) holes to improve the flow of water from the overlying reservoir to the sample. Permeation avoids the accumulation of ion-saturated solution in the pores and encourages a more even distribution of particle dissolution within the sample. Complete dissolution is usually obtained in less than an hour, which is confirmed by electrical conductivity measurements and final sample masses. Pore fluid exits through two ports in the oedometer base into an external 4 litre reservoir, which is continuously stirred. A peristaltic pump transfers solution from the external reservoir back to the oedometer. Both reservoirs are open to atmosphere so pump flow rate is used to control the level in the oedometer reservoir.

### 3.2 Test programme

The programme comprised 40 dissolution tests in 2 groups of 20. In each group of 20 tests, 5 different single salt particle size fractions (0.063, 0.125, 0.25, 0.50 and 1.00 mm) were added to Leighton Buzzard sand in 4 different proportions (2%, 5%, 10% and 15%). These percentages are calculated as a fraction of the total dry *mass*. In one group, dissolution occurred under a vertical stress of 62 kPa; in the other

group, vertical stress was 250 kPa

## 4 EXPERIMENTS – UNIVERSITY OF SASKATCHEWAN

A sealed cylindrical load cell is used which allows liquid flow from the bottom of the cell. Its diameter is 159 mm and the sample is loaded to a height of approximately 82 mm. Permeable filter paper on the bottom and a porous stone at the top allow the flow of water and brine in/out of the sample without the loss of solid material. A known load is applied to the sample by a calibrated pneumatic consolidation system (PCS) that loads the sealed piston on top of the sample (Figure 4). Displacement is measured by a linear variable differential transformer (LVDT) interfacing with computer software. A pump circulates water to an inlet on the piston or on the bottom of the cell.

### 4.1 Method

Each test begins by choosing, weighing, and mixing the appropriate sand-salt combination (e.g. 90% SP-10% HM) and then loading the dry mixture into the

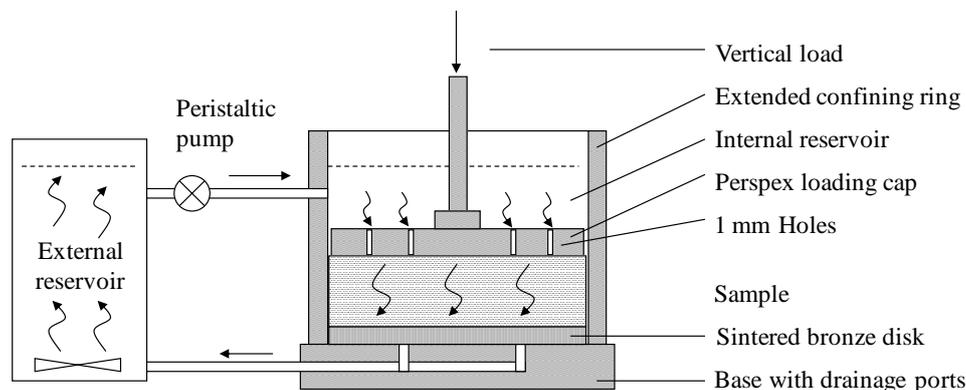


Figure 3. Schematic diagram of modified oedometer allowing for circulation of pore fluid through sample and large (4 litre) external reservoir (not shown to scale)



Figure 4. Sample cell seated in pneumatic consolidation cell.

load cell in 3-4 layers, tamping each layer as it is added. The cell is positioned in the PCS and subjected to a 5 kPa seating load. Once settled, LVDTs are positioned and the height of the piston above or below the top rim of the cell is measured manually. Data acquisition begins and, after a few minutes of sampling to acquire a base line, the load is increased to 60 kPa. The sample is then left for 300 minutes during which time settlement is measured. Hoses are attached and the sample is inundated with water entering from the bottom of the cell. Filling is from the bottom to help purge air from the sample.

Water is initially pumped intermittently at a rate of ~ 30 mL/min in intervals of 3 minutes pumping with 3 minutes rest until the cell was saturated. Once saturated, the hoses are reversed so that fresh water enters from the top of the cell. Pumping continues in 3-minute intervals. Each pumping cycle produces a mass of solution, which is collected and the mass of solute determined based on the volume of effluent collected and the known relationship between total dissolved solids and electrical conductivity.

This control of the dissolution process used in Saskatchewan differs from that in the Edinburgh Napier tests, in which a single (much larger) volume

of water is continually circulated between the sample cell and an external reservoir into which the solute gradually accumulates. However, in both cases, the dissolution process is allowed to run until settlement has ceased and effluent conductivity measurements show either (i) zero in the case of the Saskatchewan tests or (ii) have stabilized at some non-zero value in the case of the Edinburgh Napier tests.

Final, i.e. post-dissolution masses, of both sand and salt, are checked by drying and weighing of the remaining sand samples. In the Saskatchewan tests, dissolved salt masses are estimated from batch conductivity measurements and corresponding salt solubility relations (NIST, 2007). In the Edinburgh Napier tests, the salt solutions were evaporated to enable solute masses to be checked.

## 5 CHARACTERISING THE TWO TEST PROGRAMMES

Key characteristics of the two test programmes are described below and summarised jointly in Table 1.

### 5.1 Particle size: relative sand and salt particle sizes – diameter ratio

The relative size of the sand and salt particles is shown to be one of the main factors controlling the mechanical response to particle loss. It is here defined by the diameter ratio,  $D_r$ , which is the ratio of  $D_{50}$  of sand particle to  $D_{50}$  salt particles. The two test programmes cover diameter ratios ranging between 9 and 0.25. The larger diameter ratio corresponds to a Leighton Buzzard sand ( $D_{50} = 0.85$  mm) and salt particles retained on a 0.063 mm sieve (median  $D_{50}$  for the 0.063 – 0.125 mm sieves = 0.094 mm). The smaller diameter ratio corresponds to a poorly-graded Ottawa sand ( $D_{50} = 2.36$  mm) and coarse salt particles ( $D_{50} = 9.42$  mm). Both Leighton Buzzard and the Ottawa sand are poorly-graded with  $C_U$  values of 1.4 and 1.18 respectively. Table 1 shows the combinations of diameter ratio and amount of salt by percentage of total mass.

Table 1. Summary of number of tests performed at Edinburgh Napier (ENU) and University of Saskatchewan (UoS) by diameter ratio and amount of salt in each of tests – poorly-graded sand fraction.

|                           | Amount | Diameter ratio = $D_{50 \text{ sand}}/D_{50 \text{ salt}}$ |       |       |       |       |        |       |       |
|---------------------------|--------|--|-------|-------|-------|-------|--------|-------|-------|
|                           |        | 9  | 6.6   | 4.5   | 2.3   | 1.1   | 1      | 0.6   | 0.25  |
| Percentage salt (by mass) | 0      |  | 1 UoS |       |       |       |        |       |       |
|                           | 2      | 2 ENU  | 2 UoS | 2 ENU | 2 ENU | 2 ENU | 2 UoS  | 2 ENU | 2 UoS |
|                           | 5      | 2 ENU  | 2 UoS | 2 ENU | 2 ENU | 2 ENU | 2 UoS  | 2 ENU | 2 UoS |
|                           | 10     | 2 ENU  | 2 UoS | 2 ENU | 2 ENU | 2 ENU | 4 UoS  | 2 ENU | 2 UoS |
|                           | 13     |  | 8 UoS |       |       |       | 10 UoS |       | 4 UoS |
|                           | 15     | 2 ENU  |       | 2 ENU | 2 ENU | 2 ENU |        | 2 ENU |       |
|                           | 21     |  | 4 UoS |       |       |       | 4 UoS  |       | 4 UoS |

There are other influences on the mechanical behavior that are not explicitly recognized in Table 1. These are:

### 5.1.1 Vertical load

The Saskatchewan tests were performed under a vertical stress of 60 kPa. The Edinburgh Napier tests were duplicates at two different vertical stresses: 62.5 kPa and 250 kPa. In these tests no distinguishable difference between the test results, either in terms of initial void ratio, settlement, or change in void ratio due to dissolution, was found.

### 5.1.2 Particle size distribution

A second suite of tests was performed at the University of Saskatchewan using a well-graded Ottawa sand fraction. Its  $D_{50}$  was also 2.36 mm but its  $C_u$  was 6.98. Table 2 summarises the percentage and size characteristics. There is then a combined total of 158 tests, 95 of which were performed using poorly-graded sand and 63 tests using a well-graded sand.

## 6 RESULTS - SETTLEMENT

Previous studies have reported relatively little settlement due to particle loss by dissolution. Fam et al.(2002) conducted tests on salt-sand particle mixtures with diameter ratios of 2.30 noted virtually no settlement whilst Shin and Santamarina (2009) measured settlement between 1.2% and 8.2% for their range of salt contents (5% - 15%) with diameter ratios of 2.33. Truong et al. (2010) testing mixes with diameter ratios of 1.44 showed settlements of 2% and less for mixes containing up to 10% of salt particles.

### 6.1 Poorly- graded soils

Vertical settlements induced by dissolution for each of the poorly-graded sand-salt mixes are shown in Figure. 5. Also shown are (i) the settlement at constant void ratio line, i.e. the settlement that would

occur if solid volume loss and corresponding void volume change maintain a constant void ratio, and (ii) the Shin and Santamarina data presented as mass fractions.

The settlement data show two principal features: the first relates to the influence of the amount of soluble particles, the second to the size of the soluble particles. Clearly settlement is directly related to the amount of soluble material but not uniformly related. Compared to low salt contents, the rate of settlement is greater where the amount of soluble material exceeds 10% or 15%. The second principal feature is less well defined but discernable. Small particles, i.e. particles with diameter ratios of 2 or greater, at percentage amounts of 5% or greater, tend to occupy the upper part of the settlement bandwidth. Larger particles, i.e. diameter ratios of 1 or less, occupy the lower part of the bandwidth. Hence, it might be deduced that small particles, which can nestle within the inter-sand void spaces, are dissolved with little corresponding settlement. For example, less than 2% vertical strain was observed during dissolution in samples containing 10% of 0.063 mm salt particles.

The Shin and Santamarina (2009) data, obtained from glass bead-salt mixtures with a diameter ratio of 2.33, all settle more than the poorly-graded sand-salt mixtures shown here. This may be due to the lower frictional resistance and shape of the glass beads (Proctor & Barton, 1974) facilitating particle rearrangement. It is well recognised from experimental and numerical DEM studies that both inter-particle friction and particle shape have a significant effect on the behaviour of granular materials (e.g. Cavaretta et al, 2010). All settlements are, however, significantly less than the settlement occurring under a constant void ratio condition. Hence particle dissolution, for the amounts and sizes of the soluble particles in the poorly-graded sands, leads to an increase in void ratio.

### 6.2 Well-graded soils

Consider now the settlement data for the well-graded

Table 2. Summary of number of tests performed at University of Saskatchewan (UoS) by diameter ratio and amount of salt in each of tests – well-graded sand fraction.

| Percentage salt (by mass) | Amount | Diameter ratio = $D_{50 \text{ sand}}/D_{50 \text{ salt}}$ |       |     |       |     |        |       |       |
|---------------------------|--------|--|-------|-----|-------|-----|--------|-------|-------|
|                           |        | 9  | 6.6   | 4.5 | 2.0   | 1.1 | 1      | 0.6   | 0.21  |
| 0                         |        |  | 1 UoS |     |       |     | 1 UoS  |       | 1 UoS |
| 2                         |        |  | 2 UoS |     |       |     | 2 UoS  |       | 2 UoS |
| 5                         |        |  | 2 UoS |     | 1 UoS |     | 2 UoS  | 1 UoS | 2 UoS |
| 10                        |        |  | 2 UoS |     | 1 UoS |     | 2 UoS  | 1 UoS | 3 UoS |
| 13                        |        |  | 8 UoS |     |       |     | 12 UoS |       | 7 UoS |
| 15                        |        |  |       |     | 1 UoS |     |        |       | 1 UoS |
| 21                        |        |  |       |     |       |     | 4 UoS  |       | 4 UoS |

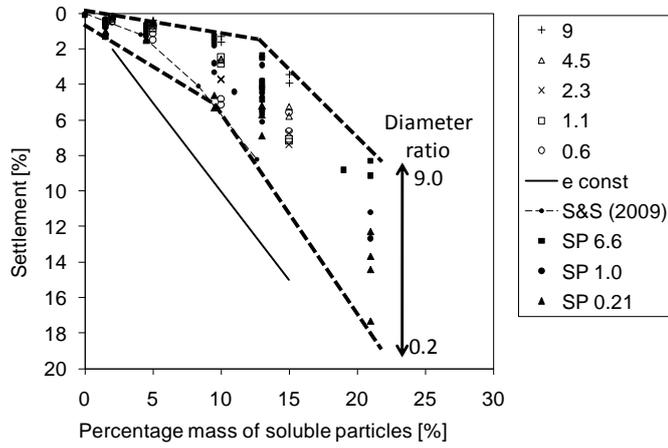


Figure 5. Settlement of sand-salt (poorly-graded sand) mixtures by particle size and percentage (by mass) of salt.

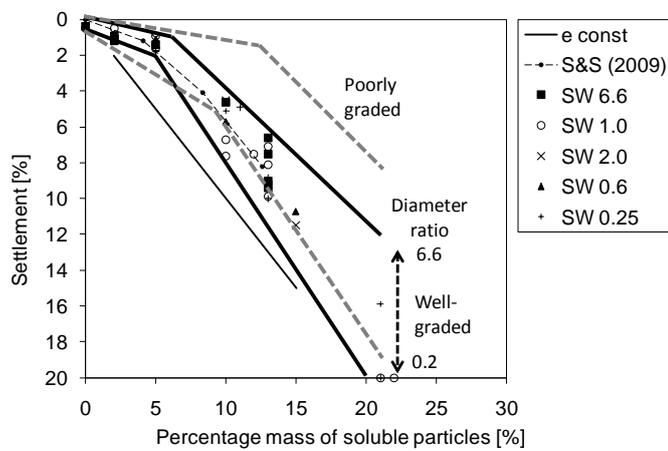


Figure 6. Settlement of sand-salt (well-graded sand) mixtures by particle size and percentage (by mass) of salt.

soils shown in Figure 6. All poorly-graded sand-salt mix data shown in Figure 5 has been removed although the bandwidth for these data is shown by the broken lines. The bandwidth for the well-graded sand data is shown by the solid lines. The muted response to small amounts of salt particle loss is still evident. There is also a change in the rate of settlement with amount of particle additions but the change appears to occur at a lower percentage of salt particles, i.e. about 5% to 10%. Furthermore, the bandwidth in this part of the settlement curve appears to be narrower and the distribution of particle sizes lack the separation of the poorly-graded samples. As with the poorly-graded sand, the position of the experimental data in relation to the constant void ratio line indicates, at least at percentage additions up to 20%, that particle loss leads to an increase in void ratio.

## 7 RESULTS - VOID RATIOS, PRE- AND POST-DISSOLUTION

### 7.1 Initial void ratio

The initial or pre-dissolution sand-salt void ratios are shown in Figure 7, from which the influence of the added salt particles is revealed. In the case of poorly-graded sands, increasing amounts of fine salt particles lead to gradually reducing initial void ratios as the fine particles fill up the voids surrounding the coarser sand particles. The addition of coarser salt grains serves only to displace sand particles with a range of initial void ratios that is relatively insensitive to the amount of added salt. In the case of the well-graded sand samples there is little opportunity for ‘nestling’ so the addition of salt particles, either fine or coarse has little impact on the initial void ratios, all of which are significantly lower than the poorly-graded sand with coarse particle mixes.

### 7.2 Poorly-graded salt samples

Changes in void ratio due to dissolution in the poorly-graded samples with diameter ratio for all percentage salt amounts are shown in Figure 8. The most striking feature revealed is the difference in the void ratio response to these two controlling factors. There is an increase in void ratio that is almost independent of diameter ratio but clearly related to the amount of added salt. Moreover, there appears to be no sensitivity to the wide range of initial void ratios evident in Figure 7.

### 7.3 Well-graded salt samples

Compare now the changes in void ratio due to dissolution observed in the well-graded sands (Figure 9). Where added salt amounts are in the range 2% to

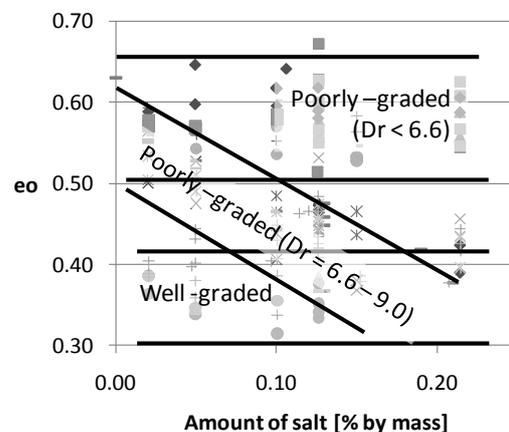


Figure 7. Initial void ratio for both poorly-graded and well-graded sand salt mixtures.

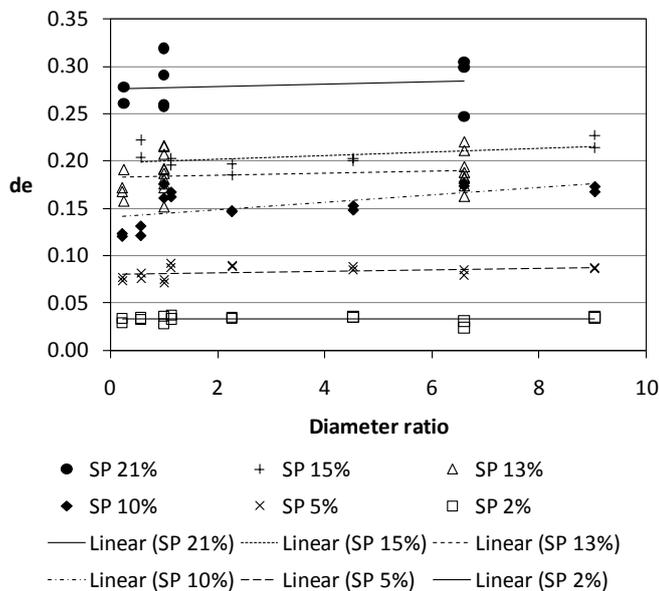


Figure 8. Change in void ratio due to dissolution in (poorly-graded) sand-salt mixtures by particle size and percentage (by mass) of salt.

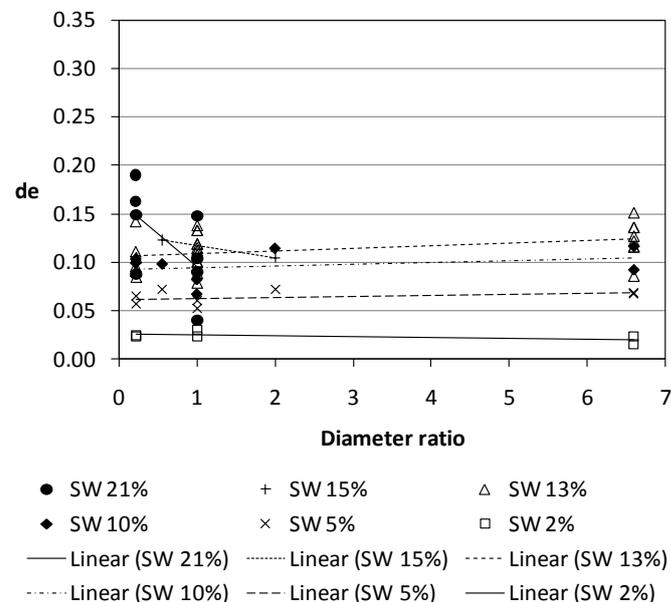


Figure 9. Change in void ratio due to dissolution in (well-graded) sand-salt mixtures by particle size and percentage (by mass) of salt.

5%, regardless of diameter ratio, void ratio increases are similar to those observed in the poorly-graded sand mixes. However at 10% added salt and above, the increase in void ratio is markedly less than is the case in the poorly-graded sands. At 15% and 21% the insensitivity to diameter ratio appears to be lost, although in the case of these tests the data are few and are obtained for large salt particles only (Diameter ratio = 0.25 – 1.0 to 2.0).

#### 7.4 Void ratio changes with amount of salt

Figure 10 shows increases in void ratio for the combined Edinburgh Napier / Saskatchewan data for both the poorly- and well-graded sample tests, where the void ratio change is read from the midpoint of the fitted lines in Figures 8 & 9. In the poorly-graded samples, the relationship is almost linear over the range in question, whereas in the well-graded samples, the rate of increase is indeed seen to lessen beyond 5 % salt content.

## 8 RECLAIMED LANDFILL SOIL SAMPLES

Samples of fines produced from excavation and screening at two different disposal sites, one in Canada and one in the United States, were tested at the University of Saskatchewan. The samples were characterized in terms of waste composition, potential for degradation and settlement, the main characteristics and findings are presented in Table 3. In the remaining part of this paper, the behaviour of these two samples is considered within the context of the

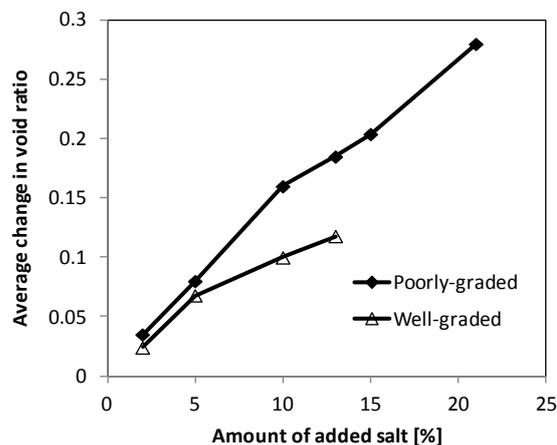


Figure 10. Average change in void ratio due to dissolution in sand-salt mixtures by particle size and percentage (mass) of salt.

aforegoing sand salt tests. However, it should be noted that at the time of writing, the test on the sample from site 1 is still in progress and so the insights drawn are necessarily tentative.

From the data presented in Table 3, it can be seen that the two soils represent two quite different materials: the soil from site 1 has the narrower particle size range ( $C_U=10$ ), high degradable content (nearly 20%) and a diameter ratio of degradable to inert material that is less than one. In contrast, Site 2 soils have a much wider particle size range ( $C_U = 200$ ), less than half the degradable content of Site 1 (based on LOI data) and a diameter ratio that is similarly difficult to estimate but probably much greater than one. In other words, Site 1 soils have a degradable fraction of predominantly large particles, whereas at Site 2 they are predominantly small particles.

Table 3. Comparison of key characteristics and measured behavior of two landfill reclaimed soil samples

| Property                          | Site 1         | Site 2      |
|-----------------------------------|----------------|-------------|
| D <sub>50</sub>                   | 2.0 mm         | 1.0 mm      |
| Cu                                | 10             | 200         |
| Inert fraction (by dry mass)      | 81.1%          | 95%         |
| Degradable fraction (by dry mass) | 18.9%          | 5%          |
| Loss on ignition                  | 8.2% - 12.4%   | 4.2%        |
| Size range of degradable fraction | 90% >0.85 mm   | 78% <1.2 mm |
| Diameter ratio*                   | 0.2–0.8        | 0.8–12      |
| Biochemical methane potential     | 4.7 – 9.3 ml/g | -           |
| Initial compression               | 1.0 mm         | 2.6 mm      |
| Compression (after 65 days)       | 2.8 mm         | 3.5 mm      |
| Biogas production (L/kg dry mass) | 1.6            | 0.02        |
| Compression (after 244 days)      | 6.7 mm         | -           |
| Long term settlement              | 1.1%           | 0.16%       |

\* Degradable fraction size range spans several sieves complicating determination of diameter ratio.

Figure 11 shows the observed settlement of the Site 1 and 2 soils superimposed on the settlement data from the well-graded soil samples (Fig. 6).

While definitive conclusions cannot yet be reached regarding the long term performance of the post-screening fines from the landfill mining project at Site 1 (at the time of writing, this test is still in progress), measured gas production compared with gas potential indicates that the substantial organic content of this material will be associated with greater long term degradation-induced settlement. Site 1 settlements are as shown in Figure 11 and predicted to move as shown by the accompanying arrow. Settlement of the Site 2 test is located where it might be expected – lying in the upper part of the settlement bandwidth for a 4-5% settlement with large diameter ratio. This material exhibited little measurable deformation.

However, it is interesting to speculate on the change in void ratio accompanying mass loss, and

the impact on compaction characteristics and use of the materials as engineered fill. The two sites fit into the overall scheme established by the Saskatchewan data and are jointly presented in Figure 12. Of note is the implication that even though settlement is significantly different in the two scenarios, the difference in the change in void ratio is less marked.

While it seems unsurprising that the volume fraction of degradable material represents an important control on the amount of settlement that may be expected under load, the mechanisms are less easily explained. The relative size of the degradable fraction plays a less significant role in determining the amount of overall volume change, and the particle size characteristics of the inert fraction (i.e. uniform

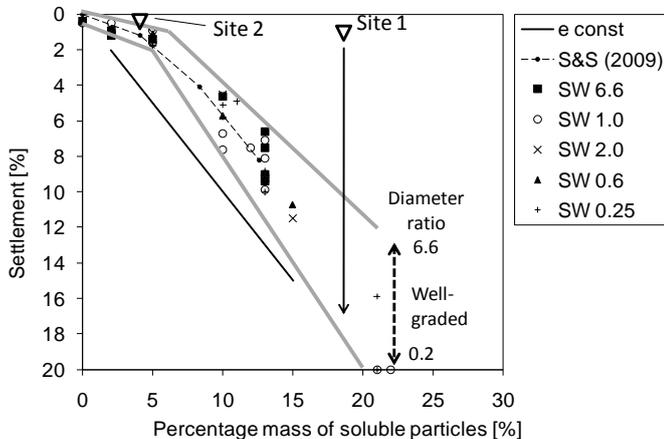


Figure 11. Comparison of current and predicted settlement of landfill reclaimed soil samples with (well-graded) sand salt mixtures.

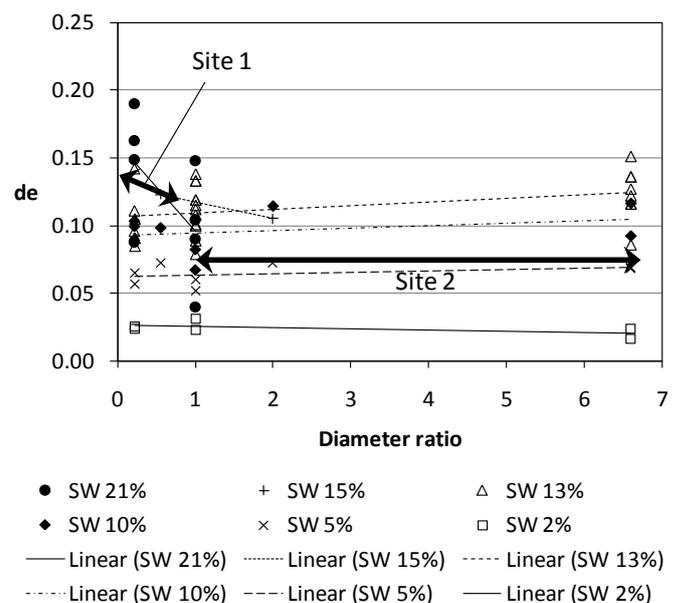


Figure 12. Comparison of current and predicted void ratio increases of landfill reclaimed soil samples with (well-graded) sand salt mixtures.

vs. well-graded) exerts some control on the degree of particle redistribution into growing voids and thus on the relationship between mass loss of degradable solids and change in void ratio. The interaction of relative particle size and amount of degradable material for the simpler mono-disperse mixtures is explored in more detail in McDougall et al (2013). In addition, the effects of initial relative compaction of the soil matrix with the degradable materials will likely influence the ultimate settlement characteristics.

## 9 CONCLUSIONS

Given that rigorous, well-documented tests of this type require many months for each test, rapid tests using analogues have been undertaken and report here and elsewhere. Such analogues include sand/salt mixtures which can be “degraded” under load in a few hours or days has the potential to relatively quickly shed light on the underlying mechanisms and the relative importance of the various parameters that may control the amount of volume change. These are hypothesized to include the following: the fraction of degradable material; the relative size of the degradable and inert particles; the applied load and the particle size characteristics of the inert soil. In the case of the landfill reclaimed soils, the degree of initial compaction, relative to minimum and maximum potentials under standard energy inputs, is also a factor deserving of future evaluation.

The ultimate goal is to provide a rigorous, evidence-based standard for geotechnical engineers to follow when using these sorts of “non-ideal” soil fills. As “green” construction practices increasingly become a societal goal and indeed an economic benefit, the author suggests that geotechnical engineers may wish to reconsider the age-old (safe and cautious) practice of bulldozing away poor-quality soil to be replaced only with high quality imported granular fill. The research programme of which some first steps are described in this paper represents an effort to provide industry with such evidence and guidance.

## 10 REFERENCES

- Cavarreta I, Coop M, O’Sullivan C (2010) The influence of particle characteristics on the behaviour of coarse grained soils. *Géotechnique* 60(6):413-423
- Fam MA, Cascante G, Dusseault MB (2002) Large and small strain properties of sands subjected to local void increase. *J. of Geotechnical and Geoenvironmental Eng.* 128(12):1018-1025

- McDougall, J.R. (2011) Settlement: the Long and the Short of it. *Geotechnical Special Publication 209*, ASCE, Virginia, ed. Zekkos, 76-111.
- McDougall J, Barreto D, Kelly D (2013) Particle loss and volume change on dissolution: experimental results and analysis of particle size and amount effects. *Acta Geotechnica* (Online First) doi: 10.1007/s11440-013-0212-0
- NIST. (2007, 12 6). *IUPAC-NIST Solubility Database*. Retrieved 8 21, 2012, from <http://srdata.nist.gov/solubility/index.aspx>
- Procter DC, Barton RR (1974) Measurements of the angle of interparticle friction. *Géotechnique* 24(4):581-604
- Shin H, Santamarina JC (2009) Mineral dissolution and the evolution of  $k_0$ . *J. Geotechnical and Geoenvironmental Eng.* 135(9):1141-1147
- Truong QH, Eom YH, Lee JS (2010) Stiffness characteristics of soluble mixtures. *Géotechnique* 60(4):293-298