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RESEARCH AND DEVELOPMENT DEPARTMENT

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PHYSICAL AND MOISTURE RETENTION CHARACTERISTICS OF BIOSOLIDS AND SOIL-BIOSOLIDS MIXTURES

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Metropolitan Water Reclamation District of Greater Chicago
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SUBMITTED TO

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SUBMITTED BY

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INTRODUCTION

The Metropolitan Water Reclamation District of Greater Chicago (District) generates approximately 200,000 dry tons of biosolids annually. Most of this biosolids is generated at the District's Calumet and Stickney water reclamation plants (WRP). Following anaerobic digestion of sewage sludge, biosolids are produced by taking the digested sludge through two main processing trains: by centrifugation (high solids processing train-HSPT) and by gravity thickening (low solids processing train-LSPT). Except for some of the centrifuge cake biosolids (25 percent solids) which are immediately applied to farmland, after generation, most of the biosolids are stored in lagoons for greater than 18 months (aged) or less than 18 months (under aged), then dried to approximately 65 percent solids before final utilization. The biosolids are used in a variety of beneficial reuse projects such as final cover at municipal solid waste landfills, construction of golf courses, parks, and athletic fields, and for reclamation of brownfields. In these projects, biosolids are utilized as a soil substitute or at relatively high application rates (usually greater than 25 percent of soil volume) as a soil amendment. Also, the biosolids are utilized as a fertilizer amendment to farmland.

The primary physical properties of biosolids and biosolids-amended soil that affect plant growth are those that control soil-plant-water relations. The initial distribution of rainfall and irrigation into soil water and runoff is controlled by infiltration rate and in some cases, such as in biosolids and biosolids-amended soil, by hydrophobicity or water repellency. When utilized as a soil amendment, the relatively high organic carbon (OC) content of biosolids affects water retention directly and indirectly (Metzger and Yaron, 1987). The direct effect is due to biosolids particles, which have a high capacity to hold water and thus enhance the water retention capacity of soils. Indirectly, biosolids modify other soil physical properties such as bulk density, porosity, and pore size distribution, which subsequently affects the water retention properties. Once water is in the soil-biosolids medium, the release of water to plant roots is described by the water/tension (water/suction) relations or the soil water characteristic curve. Additions of biosolids to a soil may increase pore space, decrease bulk density, and reduce penetration resistance, which are favorable conditions for root development and plant growth. In biosolids and soils amended with high rates of biosolids that are at low ambient water content, hydrophobicity can potentially limit moisture supply characteristics for plant growth.

The relative impact of biosolids on soil physical and water retention properties depends on the nature of the biosolids as affected by the processes through which they are generated. Information on how the physical properties and the moisture holding and transmission characteristics of the various biosolids produced at the District affect soil physical properties when these biosolids are used as a soil substitute or soil amendment will help in developing management practices for better utilization of the District's biosolids. The purpose of this work was to conduct tests and analyses on six District biosolids and some soil/biosolids mixtures to characterize their physical and their effect on soil moisture relations and suitability of biosolids and biosolids-amended soils as a plant growth medium.

MATERIALS AND METHODS

Samples

The samples used in this study included six District biosolids and one soil sample (Table 1). The biosolids samples were from the Stickney and Calumet WRPs and were generated through the District's low solids (LS) and high solids (HS) processing trains, and were either aged (greater than 18 months) or under-aged. The soil sample was obtained from overburden excavated from Lagoon 8 at the District's Lawndale Avenue solids management area (LASMA). This soil was chosen to represent a poor quality urban soil that is typical of sites where athletic fields, parks, and golf courses are commonly constructed and which require substantial amounts of organic matter and soil nutrients to establish turf successfully. The soil was screened (1-cm mesh) at the site to remove large clods and rocks. Mixtures comprising 85:15, 75:25, and 50:50 soil:SALS biosolids ratios (volume:volume) were prepared using a small portable cement mixer. The biosolids samples added to the mixer in small increments and rotated for 15 minutes to ensure a homogenous blend.

Table 1. Description of biosolids and soil used in the study.

Sample ID	Source	Process
SALS	Stickney WRP	Low Solids, Aged
SAHS	Stickney WRP	High Solids, Aged
SULS	Stickney WRP	Low Solids, Under-aged
SUHS	Stickney WRP	High Solids, Under-aged
CAHS	Calumet WRP	High Solids, Aged
CALS	Calumet WRP	Low Solids Aged
Soil	LASMA Lagoon 8	

Particle Size Analysis

Particle size analysis was conducted on material passing a 2-mm sieve using the pipette method (Gee and Bauder, 1986). The pipette method was used to ascertain particle size on chemically and electronically dispersed samples. The samples were pretreated by hydrogen peroxide digestion to remove organic matter using two methods; a rigorous and a mild treatment. The mild treatment was conducted by adding successive 10-mL aliquots of 30% hydrogen peroxide until foaming ceased. In the rigorous method the peroxide treatment was continued for 96 hrs at 50 °C on a hot sand bed.

Volatile Solids

Volatile Solids were determined by weight loss on ignition of oven dry 10-g samples oxidized in a muffle furnace at 430°C for 24 hrs. Organic carbon was estimated from the volatile solids results using the formula:

$$OC\ (\%) = \text{volatile solids}\ (\%)/1.71$$

Particle Density

Particle density was determined by a modified pychnometer method (Blake and Hartge, 1986.). Fifty grams of sample was added to a 100-ml volumetric flask, then the flask was filled to volume with de-aired water at 25°C. The volume of the sample (displaced volume) was calculated by difference. Particle density was determined on the untreated samples and on samples that were treated by oxidation in a muffle furnace (430°C). The untreated particle density values were used to calculate porosity of whole samples.

Bulk density

Preliminary investigations were conducted to estimate the ultimate densities attained in the long term when biosolids are applied in the field. In one instance, bulk density was determined on soil cores collected in fall 2001 from Waters Edge Golf Course located in Worth, Illinois. The golf course was established in 1998 on a three- to nine-inch thick layer of District biosolids. Also, samples of the soil:biosolids mixtures described above were placed in the field for five months to undergo a series of wetting and drying cycles, then cores were obtained to determine bulk density.

Bulk density was done on loose, packed, and repacked sample cores placed in metal rings of known volume. Cores were initially filled under water tension (loose) and settled in water then allowed to dry. The packed samples were prepared by adding in 1-cm increments and packing with a pestle. Repacked cores were wet, dried then additional soil was packed into crevices formed by drying. The samples were oven-dried at 105°C, then weighed to calculate the bulk density. Bulk density was calculated using the formula:

$$\text{Bulk density} = \text{oven dry weight}/\ \text{volume}$$

Porosity

Porosity was not determined directly but was calculated using the formula:

$$\text{Porosity} = (1 - \text{bulk density}/\text{particle density}) \times 100,$$

where particle density = particle density of the unoxidized samples.

The particle density of the unoxidized sample was used because it represents an averaged density for the proportional contribution of both the mineral and the organic matter fractions of the samples.

Moisture/Suction Relationship

The soil moisture/suction relationship (moisture retention curve) was determined on disturbed biosolids samples in high-pressure ceramic extractors using nitrogen gas over a suction range of 0.10 to 15 bars. The moisture content at each of the suctions was performed in triplicate. Gravimetric water contents and plant available water contents were calculated from this data.

Water Repellency (Hydrophobicity)

Water repellency was measured using the molarity of ethanol drop (MED) test (King, 1981). This is the most reliable and repeatable method for assessing hydrophobicity in soils. In this procedure, the molarity of drops of ethanol that infiltrate the soil or biosolids within 10 seconds is measured. The ethanol facilitates the entry of the droplet into soil particles by lowering the surface tension of the liquid, which in turn lowers the liquid-soil contact angle. The more water repellent the soil or biosolids, the higher the molarity of ethanol needed to penetrate the soil. Hydrophobicity indices are largely subjective but provide a rank order for the biosolids samples and for the various soil:biosolids mixtures.

This test was done on disturbed samples at a range of water contents from 0.33 bar suction [referred to as field capacity (FC), the maximum water content of the soil after the moisture saturated field is drained by gravity] to oven dry. Based on preliminary work, 1*M* increments of ethanol solutions ranging from 0 to 5*M* were used.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity analysis was conducted according to the procedure described by (Klute and Dirksen, 1986.). Samples were packed in metal cylinders wrapped in cheesecloth on the lower end then placed in water overnight to achieve saturation. The samples were put in a constant head conductivity apparatus. A second empty cylinder was placed above the sample and the two cylinders were sealed with a rubber strip. This device provided a constant head of 7.5 cm, which is sufficient to provide measurable flow in most samples. Water output at the bottom of the core was collected and measured over a known period of time. This procedure was repeated three times and saturated conductivity (Ks) was calculated using the formula:

$$Ks = \text{Output Volume x Core Height/Cross Sectional Area of Core x Time x Hydraulic Gradient}$$

RESULTS

Particle Size Analysis

Soil textural analysis performed on samples that were pretreated with a rigorous digestion method are presented in Table 2. Silt sized particles ranged 63 to 80% for biosolids samples. The data for the rigorous digestion method show that all the biosolids samples, except the SULS are classified as silt loams. The data for the mild treatment (Table 2) show that incomplete oxidation of OC before the determination of particle size distribution tend to cause over estimation of the sand sized fraction. This is because that OC and other cementing agents tend to hold biosolids particles as stable aggregates.

Table 2. Textural analysis of biosolids and soil samples as performed by the pipette method following a rigorous and mild hydrogen peroxide digestion pretreatment.

	Rigorous H_2O_2 Digestion [a]				Mild H_2O_2 Digestion [b]			
Sample	sand	silt	clay	Textural Class	sand	silt	clay	Textural Class
	------------ %--------------				------------- %-------------			
SALS	18	72	10	Silt loam	49	44	7	Loam
SAHS	30	63	7	Silt loam	50	45	5	Loam
SULS	11	80	9	Silt	53	40	7	Sandy loam
SUHS	15	74	11	Silt loam	54	38	8	Sandy loam
CAHS	13	79	8	Silt loam	53	40	7	Sandy loam
CALS	14	79	7	Silt loam	59	36	6	Sandy loam
Soil	10	69	21	Silt loam	10	66	24	Silt loam

[a] Peroxide treatment at 50°C for 96 hrs or until foaming due to oxidation ceased.
[b] Peroxide treatment at 25°C for 48 hrs.

Particle Density

Volatile solids and the estimated organic carbon contents were lower for the aged Stickney samples (Table 3). Particle density was determined on both untreated and samples oxidized at 430°C for 24 hours. The oxidized samples give a more reliable particle density of the mineral matter of the soil after volatile solids have been removed. It appears that the inherent particle density of the biosolids mineral matter (2.80 to 2.95 g cm^{-3}) is slightly higher than that of the soil (2.77 g cm^{-3}). Particle density data of the untreated sample reflect density of both mineral and organic matter and they may be used together with bulk density data to calculate the porosity of samples.

Table 3. Oxidizable carbon and particle density of oxidized and untreated biosolids and soil samples[a]

Sample	Oxidizable Carbon		Particle Density	
	Volatile Solids	OC[b]	Oxidized	Untreated
	------------- % -------------		------------ $g\ cm^{-3}$ ------------	
SALS	31.4	18.3	2.83	2.07
SAHS	26.8	15.6	2.82	2.14
SULS	36.5	21.2	2.80	1.98
SUHS	35.9	20.9	2.92	1.92
CAHS	39.0	23.1	2.95	1.93
CALS	40.8	23.7	2.90	1.94
Soil	3.8	2.2	2.77	2.48

[a] Oxidation conducted in a muffle furnace at 430°C for 24 hrs.
[b] OC = volatile solids/1.71.

Bulk Density

Bulk densities of biosolids ranged from 0.52 to 1.01 g cm^{-3} and from 0.69 to 1.01 g cm^{-3} for the loose and repacked samples, respectively (Table 4). The bulk densities observed for the field cores collected at the Waters Edge Golf Course (0.83 to 0.94 g cm^{-3}) were within the range of the repacked samples. Cores could be more densely packed with an 85:15 ratio of soil to biosolids than they could for either the soil or biosolids alone (Table 4.). The 75:25 and 50:50 mix were both less dense than the soil sample at the highest level of densification (repacked).

Loosely packed cores represent consolidation of material caused only by forces involved with adhesion and capillarity of water. This condition might represent a site where biosolids were land applied as a thin layer and not compacted by elements such as traffic or long-term subsidence. Packed and re-packed cores represent conditions that might be found at a site where moist biosolids are subject to light compaction such as foot traffic or light vehicle traffic. Together the loose, packed, and repacked bulk densities give a range of expected bulk density values over a range of typical field conditions.

Table 4. Bulk Density of biosolids, and soil and soil:biosolid mix measured on packed cores with increasing packing density applied.

Sample	Loose [a]	Packed [b]	Repacked [c]
	g cm^{-3}		
SALS	0.64	0.71	0.72
SAHS	0.76	0.99	0.99
SULS	0.51	0.66	0.77
SUHS	0.52	0.78	0.79
CAHS	0.68	0.80	0.82
CALS	0.67	0.72	0.80
Soil	1.10	1.11	1.27
85:15 [d]	1.18	1.25	1.36
75:25	1.12	1.19	1.25
50:50	0.98	1.10	1.15

[a] Cores were initially filled under water tension and settled in water then allowed to dry.
[b] Samples were packed in 1-cm increments using a pestle.
[c] Cores were wet, dried then additional soil was packed into crevices formed by drying.
[d] Soil:SALS biosolids mixes prepared on a volumetric basis

Porosity

Biosolids samples ranged in porosity from 64-74% when not mechanically consolidated and from 54-65% when packed in laboratory conditions (Table 5). The soil and soil:biosolids mixtures had similar porosities that were slightly lower than those of 100% biosolid samples. Ample pore space to facilitate water movement and gas exchange between soil and the atmosphere existed for all biosolids and soil:biosolids mixes.

Moisture/Suction Relationship

The soil water release data (Table 6) show that compared to the soil, the moisture content at all suction was high in the biosolids. The SUHS sample contained the most water at all suctions. At the permanent wilting point (PWP) suction (15 bar), moisture content in the biosolids was even higher than the soil moisture content at the field capacity (FC) suction (0.33 bar). Plant available water estimated as the difference between moisture contents at FC and at PWP was higher than soil (14.9%) in only the SALS and CALS samples. The SAHS sample had very little water held between the 0.33 bar and 15 bar suctions and PAW was only 2.5%.

Table 5. Porosity of packed cores of biosolids, soil, and soil:biosolids mixtures at three different packing densities [a].

Sample [b]	Loose [c]	Packed [d]	Repacked [e]
	----------	%	----------
SALS	69	66	65
SAHS	64	54	54
SULS	74	67	61
SUHS	73	59	59
CAHS	65	59	58
CALS	65	63	59
Soil	56	55	49
85:15 [f]	51	59	43
75:25	52	47	47
50:50	56	46	48

[a] Porosity calculated using the formula: PS (%) = (1-BD/PD) * 100, where PD = Particle density of unoxidized (untreated) samples.
[b] Ratios represent percent soil:SALS biosolids by volume mixtures.
[c] Cores were initially filled under water tension and settled in water then allowed to dry.
[d] Samples were packed in 1-cm increments using a pestle.
[e] Cores were wet, dried then additional soil was packed into crevices formed by drying.
[f] Soil:SALS biosolids mixtures prepared on a volumetric basis

Plant available water content was similar for biosolids mixes and the LASMA sample. This may not accurately represent the potential increase in plant available water in biosolids-amended soils because it does not account for improved rooting and tilth that would allow for the increase in root exploration of additional soil volume and water.

Water Repellency (Hydrophobicity)

Hydrophobicity is a concern when biosolids are used as a soil amendment because it can prevent intake of rainfall in a climate or season where water deficits occur. Hydrophobicity can limit plant availability of irrigation and rainfall water because it can reduce the rate of water intake into soil peds and lead to offsite movement of water by leaching or runoff. Hydrophobicity can be advantageous in that it can reduce moisture loss through evaporation by the 'dry mulch' effect of a repellent surface layer.

Table 6. Soil water content at various suction (moisture-suction relationship) determined on repacked cores of biosolids, soil, and soil:biosolids mix [a]

	Suction (bar)							PAW[b]	
Sample	0.10	0.33	0.50	1.0	5.0	10	15	(0.33 bar)	(0.10 bar)
	Gravimetric Water Content (%)								
SALS	78	78	69	67	63	61	60	17.6	17.6
SAHS	60	45	44	43	43	42	42	2.5	17.5
SULS	96	88	77	77	75	75	75	13.0	21.0
SUHS	103	97	89	89	85	85	83	14.4	20.4
CAHS	78	73	68	64	64	63	63	10.6	15.6
CALS	94	83	71	71	67	65	58	24.3	35.3
Soil	40	31	26	22	20	17	16	14.9	24.0
85:15[d]	31	28	27	25	18	16	15	13.1	16.1
75:25	32	29	29	27	19	18	16	12.9	15.9
50:50	41	36	33	30	25	24	22	14.6	19.6

[a] Analysis conducted on ceramic plates in pressure chambers at specified suctions.
[b] PAW = Plant available water at the 0.33 and 15 bar estimated as moisture contents at 0.33 minus 15 bar and 0.1 bar minus 15 bar suction, respectively.
[c] PAW = plant available water determined as the difference between 0.10 and 15 bar suction.
[d] Soil:SALS biosolids mixes prepared on a volumetric basis

The SUHS sample had the highest degree of hydrophobicity (Table 7). Generally, hydrophobicity decreased as moisture content of the biosolids increased from oven-dry to FC (0.33 bar). The soil sample was not hydrophobic under any moisture condition. Hydrophobicity is less likely to develop if biosolids are not allowed to dry to near air-dry status (80 – 90% solids) before biosolids are land applied either as a monolayer or mixed with soil.

Saturated Hydraulic Conductivity (permeability)

Over the range of bulk densities we used for permeability, some samples could not hold water above the surface of the core when it was delivered at an equivalent rate of 35 inches per hr. These cores were assigned a permeability value of 35 In hr^{-1} and averaged with the other cores, thus resulting in conservative estimates of permeability (Table 8).

The data in Table 8 show that hydraulic conductivity or permeability of the biosolids is very high compared to the soil. The highest conductivity observed was in the SALS sample. Practically speaking permeability of biosolids would not be a limitation to water movement through the soil.

Table 7. Hydrophobicity of biosolids and soil:biosolid mix samples as determined by time of entry of a range of ethanol molarity solutions into samples pretreated under different drying regimes. [a]

Sample	Oven Dry	Air Dry	0.33 bar	Hydrophobicity Rating
	---------- MED ----------			
SALS	2	1	1	Slightly hydrophobic
SAHS	4	4	2	Moderately hydrophobic
SULS	5	>5	>5	Hydrophobic
SUHS	4	4	4	Hydrophobic
CAHS	5	4	0	Moderately Hydrophobic
CALS	5	5	1	Moderately Hydrophobic
Soil	0	0	0	Not Hydrophobic
85:15	0	0	0	Not Hydrophobic
75:25	0	0	0	Not Hydrophobic
50:50	0	0	0	Not Hydrophobic

[a] Single drops time of entry into peds observed on 5 separate samples

[b] MED = lowest molarity of ethanol drop required to penetrate biosolids samples in less than 10 seconds.

[c] Subjective rating scale on the average of air dry and 0.33 bar values, 4-5 = hydrophobic, 2-3 = moderately hydrophobic, 1 = slightly hydrophobic.

Table 8. Permeability and final bulk density of packed cores [a]

Sample	Bulk Density	Permeability	Permeability Class
	g cm^{-3}	In hr^{-1}	
SALS[b]	0.68	30 ± 16	Very rapid
SAHS[b]	0.89	17 ± 18	Rapid
SULS[b]	0.65	20 ± 18	Rapid
SUHS[b]	0.69	21 ± 17	Rapid
CAHS	0.75	17 ± 15	Rapid
CALS	0.74	9 ± 5	Moderate
Soil	1.18	0.07 ± 0.1	Slow

[a] Cores were packed by layering biosolids in 1 inch segments and packing with a pestle then were placed in a constant head device and allowed to flow freely for 2 hrs before measurements began.

[b] These biosolids samples had one or more of the 9 reps for which positive head could not be developed above the core resulting in an estimate of 35 inches hr^{-1}

SUMMARY

The physical characteristics and their impact on moisture relations was evaluated on some District biosolids samples and soil:biosolids mixtures. The samples were analyzed using methods approved by the American Society of Agronomy or, in the case of hydrophobicity, a method from peer-reviewed publications. With respect to moisture relations, the properties of biosolids are similar to a silt loam. Except for the low solids aged sample generated from the Calumet WRP, permeability was high for all biosolids tested. Hydrophobicity ranking ranged from slightly hydrophobic to hydrophobic and the highest hydrophobicity was in the under aged biosolids samples. When the soil was mixed with up to 50 percent biosolids, there was no evidence of hydrophobicity. Soil-biosolids mixtures containing less than 20% biosolids had bulk densities equal to or greater than the silt loam soil used in the mixtures. The data obtained from this evaluation show that addition of biosolids to a silt loam soil might have little impact on physical parameters such as bulk density and total porosity. These potential of biosolids amendments to improve these soil properties would be greater for soils that are more clayey or sandy than the silt loam textured soil used in this evaluation. The greatest benefits from biosolids additions to a silt loam soil are most likely to be improvement of soil tilth and permeability, which can significantly improve the root environment.

RECOMMENDATIONS

- Biosolids have physical properties similar to silt loam soils. At low soil tensions close to saturation, biosolids or biosolids amended soils typically have an abundance of large pores that will freely drain. Plant available water holding capacity of biosolids is typically equal or superior to silt loam soils and would provide an improvement when added to either sandy or clayey soils. Addition of biosolids to clayey soils promotes development of macroporosity that increases natural permeability and aeration. When added to sandy soils, the silt loam textured biosolids increase the abundance of medium and small sized pores and increase the water holding capacity.

- Soil-biosolids mixtures used in this study included silt loam soil and silt loam sized biosolids, therefore, the differences in bulk density and porosity observed were minimal when compared to native soil. Improvements to physical properties would likely be greater when biosolids were mixed with either sandy or clayey soils or sediments.

- Development of long term tilth and granularity due to biosolids application or biosolids mixing into soil material is another likely benefit due to the association of organic matter with mineral surfaces, which would increase flocculation and biological activity.

- The biosolids evaluated were all silt or silt loam sized textural class with favorable permeability and plant available water holding characteristics.

- Where biosolids are used as a soil substitute, the irrigation management required may be quite different from that of typical topsoil. Because of the high saturated conductivity of biosolids, a high rate of irrigation delivery may be inefficient since water is absorbed by biosolids aggregates relatively slowly. Therefore, when biosolids are used as a soil substitute, irrigation management requires lower amount of water and delivery rate compared to typical soils. The slow absorption of water cause rapid movement of water to below the root zone. For establishing turf by direct seeding, irrigation management should entail small frequent water application, so that the surface does not dry out and become hydrophobic.

- The hydrophobicity of biosolids can be beneficial because, as the surface of a biosolids layer dries and becomes more hydrophobic it creates a mulch effect, which reduces evaporative moisture loss from below the surface.

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Appendix

Table A1: Particle Size Analysis

	Mild Digestion				Rigorous Digestion		
Sample	Sand	Silt	Clay		Sand	Silt	Clay
	---------------- % --------------				---------------- % -------------		
SALS	18	72	10		49	44	7
	18	73	9		47	43	10
	19	72	9		51	44	5
	18	71	11		49	44	7
SAHS	30	63	7		50	45	5
	30	63	7		51	44	5
	30	62	8		52	45	3
	30	64	6		47	45	8
SULS	11	80	9		53	40	7
	11	79	10		53	39	8
	11	80	9		52	39	9
	11	80	9		54	41	5
SUHS	15	74	11		54	38	8
	15	72	13		52	41	7
	14	74	12		53	38	9
	15	75	10		57	35	8
CAHS	13	79	8		53	40	7
	12	77	11		53	38	9
	11	81	8		53	42	5
	15	79	6		53	40	7
CALS	14	79	7		59	36	6
	14	78	8		60	35	5
	15	78	7		60	36	4
	13	80	7		57	36	7
Soil	10	69	21		10	66	24
	10	69	21		11	65	24
	10	69	21		9	66	25
	10	69	21		10	66	24

Table A2: Volatile Solids, Organic Carbon, and Particle Density Analysis

Sample	Volatile Solids	OC	Particle Density	
			Oxidized	Untreated
	---------- % ----------		------- g/cm^3 ----------	
SALS	31.40	18.30	2.83	2.07
	30.80	18.01	2.82	2.04
	32.40	18.95	2.84	2.10
	31.00	17.94	2.83	2.07
SAHS	26.80	15.67	2.82	2.14
	27.90	16.32	2.82	2.12
	26.40	15.44	2.84	2.12
	26.10	15.26	2.80	2.18
SULS	36.50	21.20	2.80	1.98
	36.20	21.17	2.79	2.01
	35.90	20.99	2.81	2.00
	37.40	21.87	2.80	1.93
SUHS	35.90	20.90	2.92	1.92
	35.40	20.70	2.91	1.91
	34.90	20.41	2.93	1.91
	37.40	21.87	2.92	1.94
CAHS	39.00	23.10	2.95	1.93
	38.70	22.63	2.94	1.94
	40.10	23.45	2.93	1.92
	38.20	22.34	2.98	1.93
CALS	40.80	23.70	2.90	1.94
	39.70	23.22	2.91	1.94
	39.90	23.33	2.92	1.94
	42.80	25.03	2.87	1.94
Soil	3.80	2.20	2.77	2.48
	3.76	2.20	2.74	2.47
	3.77	2.20	2.76	2.49
	3.87	2.26	2.81	2.48

Table A3: Moisture Retention Curve

	Moisture Suction (bars)						
Sample	0.1	0.33	0.5	1	5	10	15
	------------------------------ Moisture Content (%) ------------------------------						
SALS	77.09	68.57	67.40	68.53	62.78	61.45	60.45
	79.07	76.37	69.81	67.22	62.44	61.73	59.65
	77.74	88.53	69.34	67.05	64.11	59.97	60.52
SAHS	60.32	39.30	44.44	41.73	42.19	41.61	44.18
	60.45	47.34	43.55	44.11	42.17	42.36	40.47
	58.18	47.35	44.08	44.52	43.47	43.13	41.82
SULS	100.00	89.10	79.14	76.91	75.81	72.66	75.92
	94.30	88.17	75.44	75.90	72.50	76.36	75.68
	95.62	86.58	76.47	77.81	77.43	76.23	73.39
SUHS	101.01	97.88	84.79	86.11	87.86	85.17	78.79
	105.77	97.57	92.46	90.95	85.67	84.36	83.38
	101.06	96.02	89.61	89.26	82.13	84.09	86.24
CAHS	79.00	73.17	66.34	63.43	63.37	63.04	61.99
	77.21	72.89	70.91	64.52	63.48	63.06	63.93
	76.43	73.86	66.86	64.19	63.94	63.30	62.23
CALS	95.74	88.62	73.82	71.29	69.10	65.72	56.69
	89.95	81.21	70.54	70.86	65.57	64.48	58.03
	96.79	77.71	69.03	70.75	65.92	65.16	59.80
Soil	40.73	30.73	24.34	21.90	19.28	16.99	15.76
	40.46	30.89	26.62	22.43	20.80	16.55	15.86
	39.47	30.56	26.96	21.98	20.21	16.54	15.80

Table A4: Soil:biosolids mixtures moisture retention curve

	Moisture Suction (bars)						
Sample	0.1	0.33	0.5	1	5	10	15
	---------------------------- Moisture Content (percent) ----------------------------						
85:15	31.80	27.11	27.75	25.25	17.56	16.77	14.50
	30.46	29.00	27.11	25.26	17.45	16.30	15.39
	30.59	27.98	26.85	25.50	18.15	16.26	14.96
75:25	33.29	28.16	29.01	25.81	18.50	17.63	16.32
	32.06	29.02	28.37	27.42	18.28	17.79	16.03
	30.96	29.97	29.13	27.60	18.80	17.99	16.05
50:50	41.29	37.74	33.71	30.63	24.20	23.39	21.81
	41.73	36.01	33.65	30.57	24.13	24.41	21.58
	41.31	35.70	33.09	29.12	25.42	24.33	22.15

Table A5: Hydrophobicity – molarity of ethanol drop (MED) test

Sample	Oven Dry	Air Dry	0.33 bar	Hydrophobicity Rating
	------------	MED	------------	
SALS	2	1	1	Slightly hydrophobic
	2	1	2	
	2	1	1	
	2	1	1	
SAHS	4	4	2	Moderately hydrophobic
	4	4	2	
	4	4	2	
	4	4	2	
SULS	5	>5	>5	Hydrophobic
	5	>5	>5	
	>5	>5	>5	
	5	>5	>5	
SUHS	4	4	4	Hydrophobic
	4	4	3	
	4	4	4	
	5	4	4	
CAHS	5	4	0	Moderately Hydrophobic
	5	4	0	
	5	4	0	
	5	5	1	
CALS	5	5	1	Moderately Hydrophobic
	5	5	1	
	5	5	2	
	>5	5	0	
Soil	0	0	0	Not Hydrophobic
	0	0	0	
	0	0	0	
	0	0	0	
85:15	0	0	0	Not Hydrophobic
	0	0	0	
	0	0	0	
	0	0	0	
75:25	0	0	0	Not Hydrophobic
	0	0	0	
	0	0	0	
	0	0	0	
50:50	0	0	0	Not Hydrophobic
	0	0	0	
	0	0	0	
	1	0	0	

Table A6: Saturated hydraulic conductivity (Ksat)

Sample	Ksat (in/hr)
SALS	0.17
	24
	50
	35
	35
	35
SAHS	0.09
	2.8
	5.1
	11
	50
	35
SULS	0.52
	10
	11
	16
	50
	35
SUHS	5.9
	10
	14
	15
	50
	35
CAHS	0.09
	4.9
	13
	15
	35
	35
CALS	0.44
	6.8
	6.8
	11
	12
	15
Soil	0.01
	0.01
	0.01
	0.02
	0.13
	0.24