ASSESSING ROOT ZONE MIXES FOR PUTTING GREENS OVER TIME UNDER TWO ENVIRONMENTAL CONDITIONS

Progress Report to the United States Golf Association

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J. Murphy, S. Murphy, J. Honig, H. Motto, B. Clarke, R. Tate and E. Gaulin
Rutgers, The State University of New Jersey
Cook College, New Brunswick, NJ 08901-8520

Executive Summary

Project Title: Assessing Root Zone Mixes for Putting Greens over Time under Two Environmental Conditions

This project is designed to i) improve recommendations for sand particle size distribution and the depth of the root zone by consideration of the microenvironment, ii) evaluate composts as organic additives and inorganic products for root zone mixes compared to peat sources, iii) assess the potential of various root zone mixes to reduce management and resource inputs, and iv) monitor the physical, chemical, and biological changes that occur in root zones as greens mature for understanding factors that contribute to the success or failure of greens.

Field Research

The primary objective of the 1998 growing season was to evaluate the establishment of creeping bentgrass as affected by the sand size distribution and amendment used in root zone mixes. The 37 root zone treatments constructed in either one or two microenvironments of the field research facility at North Brunswick, NJ were seeded to 'L-93' creeping bentgrass turf on 31 May 1998.

Location Effect

- Environment (location) did affect establishment ratings for a few observation dates, however, there was not a strong influence on the establishment of creeping bentgrass in these two studies. It is expected that environment will have a greater effect on performance of turf maintained at a lower cutting height (< $^{5}/_{32}$-inch) and receiving compaction treatment during 1999.
- No significant interaction between location and root zone treatment was observed during the 60 days evaluation period of bentgrass establishment.

Sand Size Distribution Study

- Two finer sand size distributions (not meeting USGA guidelines) had a better rate of establishment than coarser sands. This was likely due to better moisture retention and subsequently better nutrient availability in those finer sands.
- The coarsest sand size established well, however, after 60 days, the performance of the plots declined. This may be an initial indication of the limitations of coarser sands.

Amendment Study

- A greater affect on the establishment of bentgrass was observed in the amendment study compared to sand size distribution study.
- Generally, increasing the rate of amendment with soil and peats enhanced establishment. This was likely due to increased fertility and/or moisture retention in these mixes. However, establishment ratings for the 20% soil and 20% peat treatments after 40 DAS became similar to respective lower amendment rate plots. This may indicate the development of stresses associated with low air-filled porosity in the root zone.
- As expected, the greater fertility of ZeoPro plots enhanced establishment. Both ZeoPro and Profile (inorganic) amendments enhanced establishment up to 40 DAS compared to unamended sand.

- ZeoPro maintained high establishment ratings up to 60 DAS; whereas, Profile plots were more similar to the unamended sand after 40 DAS.
- Additional establishment data for all amendment treatments constructed in the enclosed environment are currently being summarized.

Plan of Work for 1999

- A preventative fungicide program will be employed during the winter of 1998/1999; however, a curative program will be used periodically during the 1999 growing season to assess differences in disease incidence.
- Mowing height will be reduce from the current 0.325-inch to 0.15-inch or lower.
- Compaction will be applied with a water-filled roller on a weekly basis.
- Plots will be routinely rated for performance (i.e., quality, density, color, and stress).
- Plots will be evaluated for biological, chemical and physical properties.

Laboratory Research

Additionally, research studies in the laboratory have been conducted to evaluate the influence of sample preparation on saturated hydraulic conductivity (Ksat). The saturated hydraulic conductivity (Ksat) measurement continues to be a highly variable measurement within and among USGA testing. An understanding of the source of this variability would improve testing procedures and benefit the golf course construction industry. A possible source of the variability is the phenomenon of air entrapment within "saturated" laboratory packed cores. Four studies assessed the influence of core diameter, antecedent moisture content prior to saturation, and saturation method on Ksat variability, as affected by air entrapment.

Effects on Ksat

- Increasing core sample diameter (2- to 3-inches) resulted in higher sample densities and lower Ksat rates.
- Ksat rates for sand:peat and sand samples increased as the sample moisture content at time of saturation decreased. Greater sample moisture content at saturation apparently results in a sufficient amount of "pore necks" being filled with water that subsequently encloses air-filled pores during saturation (entrapped air). Conversely, a relatively dry sample provides open passages for the expulsion of air during saturation. Thus, dry sample cores did not entrap as much air during saturation and have higher Ksat.
- Vacuum saturation procedure demonstrated the importance of removing entrapped air from core samples. Vacuum saturation of sample cores increased Ksat rates compared to saturation at standard air pressure.

Temperature affects the solubility of gases in water. Water and room temperature can vary greatly within and between laboratories over time, and consequently could influence the air entrapment and Ksat of core samples. These factors are currently being evaluated for their effect on Ksat by varying water temperatures relative to ambient air temperatures in the lab.

Field Plot Research: Establishment of Creeping Bentgrass as Affected by Root Zone Mixtures and Microenvironment

Objective: Field study was conducted to examine the effects of sand size distribution, amendment material, and environment on the establishment of creeping bentgrass putting green turf.

Materials and Methods:

- Root zones mixed, and plots constructed in 2 locations (open and enclosed environments) in 1997.4 replications per location
- 6 sand size distributions, conforming to and finer than USGA guidelines, were amended with sphagnum peat at 9:1 volume ratio.
- A silt loam, 2 organic and 2 inorganic materials were used to amend a USGA-sized sand, at varying volume ratios.
- Plots settled during winter of 1997/1998.
- Plot depth reduced to 30-cm (12-in.) during spring 1998.
- Pre-plant fertilization (total N = 2-lb 1000ft^{-2} or 9.8 g m^{-2}) using a 10-4.4-8.3 and 12-10.5-11.6 (N-P-K) fertilizer each at a N rate of 1-lb 1000ft^{-2} (or 4.9 g m^{-2})
- Plots seeded with 'L-93' creeping bentgrass at 1-lb 1000-ft^{-2} (4.9 g m^{-2}) on 31 May 1998.

Date and N application rate used for post-plant fertilization during the establishment of 'L-93' creeping bentgrass on root zone mixes in both microenvironments during 1998.

Date	Fertilizer† N - P - K	N Application Rate	
	------- % -------	g m^{-2}	lb 1000ft^{-2}
9 Jun	10 - 4.4 - 8.3	3.1	0.62
15 Jun	12 - 10.5 - 11.6	1.3	0.26
22 Jun	12 - 10.5 - 11.6	2.1	0.42
29 Jun	16 - 1.7 - 6.6	1.6	0.32
4 Jul	16 - 1.7 - 6.6	1.5	0.30
25 Jul	46 - 0 - 0	1.2	0.25
12 Aug	46 - 0 - 0	1.2	0.25
	Cumulative	12.0	2.42

†, Sand (no amendment) and Kaofin root zone plots received supplemental fertilization on 7 July using 46 - 0 - 0 at a N rate of 1.5 g m^{-2} (0.3-lb 1000-ft^{-2}) to sufficiently enhance establishment and allow mowing of experimental area.

- Mowing was initiated on 4 July at 1.6-cm and lowered to 1.3-cm.
- All plots topdressed with respective root zone mix for leveling on 20-24 July at 4.8-ft^{3} 1000-ft^{-2} and 11-21 September at 6.0-ft^{3} 1000-ft^{-2}.

Data collection

- Pre-plant root zone fertility at the 0- to 10-cm depth zone, 12 subsamples combined per plot (Tables 1 and 3).
- Physical properties – see 1997 progress report for complete summary of data (Tables 2 and 4).
- Visual ratings of turf establishment , 9 representing the best turf characteristic and 5 to 6 representing acceptable establishment (Figures 1-6).
- Line-intersect counts (253 observations per plot) to estimate turf cover (data not presented).

Table 1. Pre-plant fertility characteristics of sand-size distribution treatments studied in two environments of the North Brunswick, NJ field research facility during 1998.

Root Zone Sand	Meets USGA Size	pH	P	K	Ca	Mg	O.M.
			------------ lb acre^{-1} ------------				%
Coarse	Yes	6.7	27	6	310	68	0.4
Medium	Yes	7.0	36	13	323	81	0.4
Fine	Yes	7.1	33	14	278	77	0.4
Extra Fine	No	7.2	33	14	311	83	0.5
Mason	No	7.0	34	12	305	78	0.4
CM-340	No	7.1	38	14	339	87	0.4

†, Mehlich 3 extraction for P, K, Ca, and Mg.

Table 2. Physical properties of sand-size root zone treatments studied in two environments of the North Brunswick, NJ field research facility (see previous progress report for more complete data).

Root Zone Sand	Meets USGA Size	Air Porosity	Capillary Porosity	Total Porosity
		------------------- % -------------------		
Coarse	Yes	29.5	7.3	36.8
Medium	Yes	22.2	14.0	36.2
Fine	Yes	17.5	17.6	35.2
Extra Fine	No	11.8	25.1	36.8
Mason	No	12.8	26.9	39.7
CM-340	No	24.2	13.9	38.0

Table 3. Pre-plant fertility of amended root zone mixes studied in two environments of the North Brunswick, NJ field research facility.

Root Zone Amendment	Amendment Volume	pH	P[†]	K	Ca	Mg	O.M.
	%		----------- lb acre^{-1} ------------				%
Sand	0	7.2	39	16	169	56	<0.1
Soil	2.5	6.8	55	19	198	60	0.1
Soil	5	6.7	55	20	240	60	0.2
Soil	20	6.9	86	54	462	111	0.4
Dakota	5	6.8	34	14	372	72	0.4
Dakota	10	6.7	31	13	601	93	0.7
Sphagnum	5	7.0	44	16	245	72	0.2
Sphagnum	10	7.0	42	15	336	92	0.4
Sphagnum	20	6.8	33	14	474	132	0.8
Profile	10	7.2	52	94	600	78	0.1
ZeoPro	10	6.4	83	153	538	96	0.3

[†], Mehlich 3 extraction for P, K, Ca, and Mg.

Table 4. Physical properties of amended root zone mixes studied in two environments of the North Brunswick, NJ field research facility.

Root Zone Amendment	Amendment Volume	Air Porosity	Capillary Porosity	Total Porosity
	%	---------------- %		----------------
None (sand)	0	15.5	23.6	39.1
Soil	2.5	18.2	21.4	39.6
Soil	5	15.0	21.1	36.1
Soil	20	13.0	23.1	36.1
Dakota	5	15.7	22.2	37.9
Dakota	10	7.4	32.9	40.3
Sphagnum	5	15.0	21.3	36.3
Sphagnum	10	16.7	24.1	40.7
Sphagnum	20	11.8	33.1	44.9
Profile	10	22.1	21.2	43.3
ZeoPro	10	22.8	19.8	42.6

Summary:

Location Effect

- Environment (location) did affect establishment ratings for a few observation dates, however, there was not a strong influence on the establishment of creeping bentgrass in these two studies (Figures 1 and 2). It is expected that environment will have a greater effect on performance of turf maintained at a lower cutting height (< $^{5}/_{32}$-inch) and receiving compaction treatment during 1999.
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Sand Size Distribution Study

- Two finer sand size distributions (not meeting USGA guidelines) had a better rate of establishment than coarser sands (Figure 3). This was likely due to better moisture retention and subsequently better nutrient availability in those finer sands (Table 2).
- The coarsest sand size established well, however, after 60 days the performance of those plots declined.

Amendment Study

- A greater affect on the establishment of bentgrass was observed in the amendment study compared to sand size distribution study.
- Generally, increasing the rate of amendment with soil and peats enhanced establishment (Figures 4 and 5). This was likely due to increased fertility and/or moisture retention in these mixes (Table 3 and 4). However, establishment ratings for the 20% soil and 20% peat treatments after 40 DAS became similar to respective lower amendment rate plots. This may indicate stress associated with low air porosity (Table 4).
- As expected, the greater fertility of ZeoPro plots (Table 3) enhanced establishment (Figure 6). Both ZeoPro and Profile (inorganic) amendments enhanced establishment up to 40 DAS compared to unamended sand.
- ZeoPro maintained high establishment ratings up to 60 DAS; whereas, Profile plots were more similar to the unamended sand after 40 DAS.
- Additional establishment data for all amendment treatments constructed in the enclosed environment are currently being summarized.

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- Plots will be evaluated for biological, chemical and physical properties.

425

Figure 1.

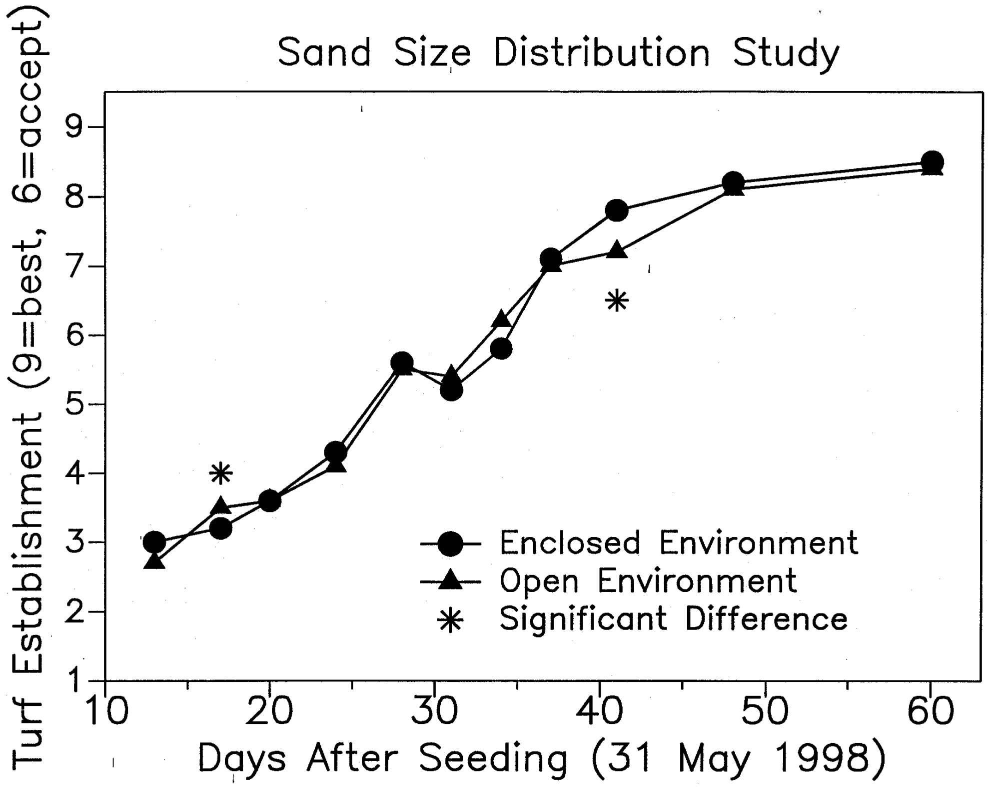
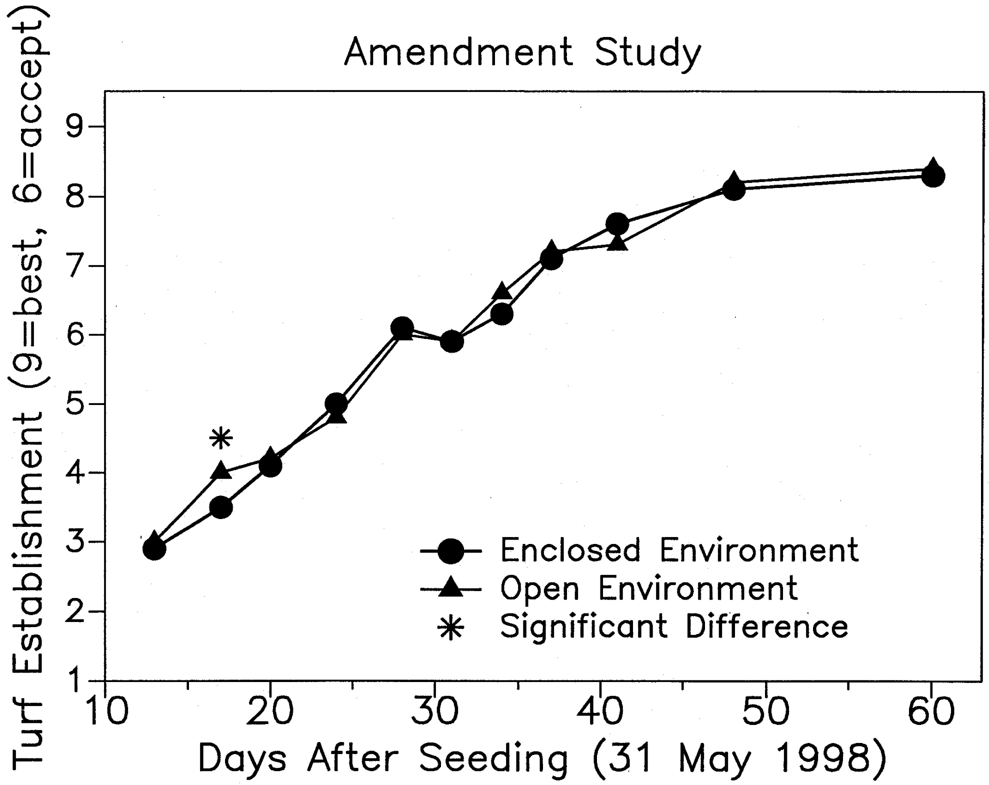
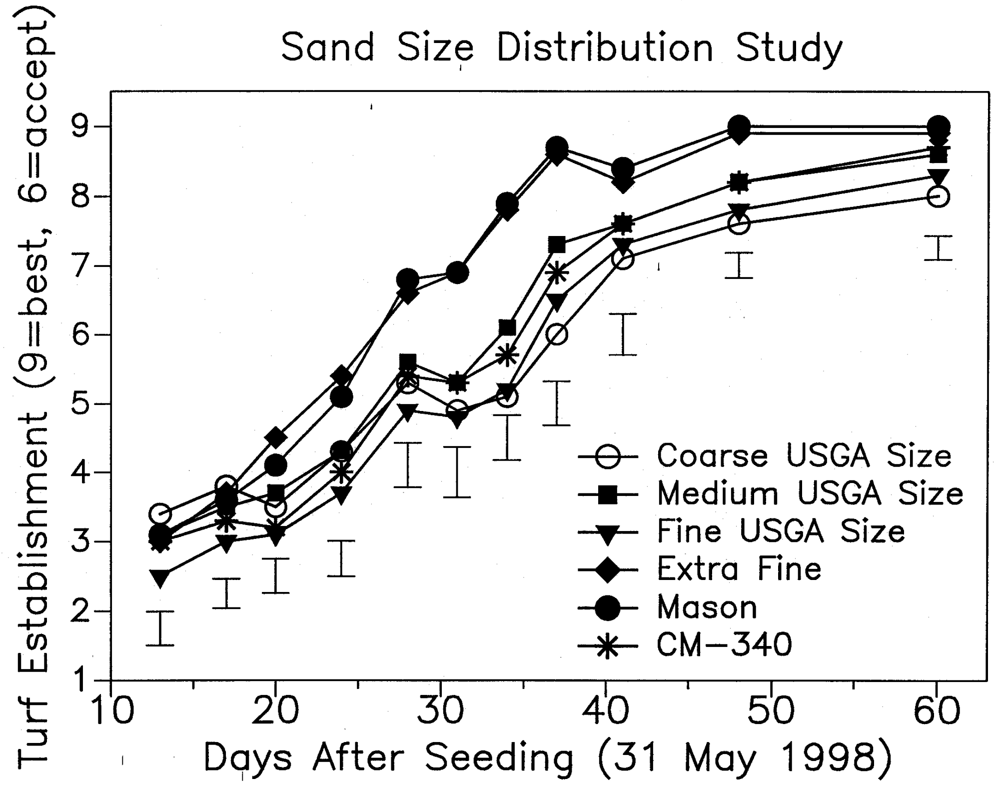

Sand Size Distribution Study
Turf Establishment (9=best, 6=accept)
Days After Seeding (31 May 1998)
Enclosed Environment
Open Environment
Significant Difference
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60

Figure 2.


Amendment Study
Turf Establishment (9=best, 6=accept)
9
8
7
6
5
4
3
2
1
10
20
30
40
50
60
Days After Seeding (31 May 1998)
Enclosed Environment
Open Environment
Significant Difference

426

Figure 3.


Sand Size Distribution Study
Turf Establishment (9=best, 6=accept)
Days After Seeding (31 May 1998)
1
2
3
4
5
6
7
8
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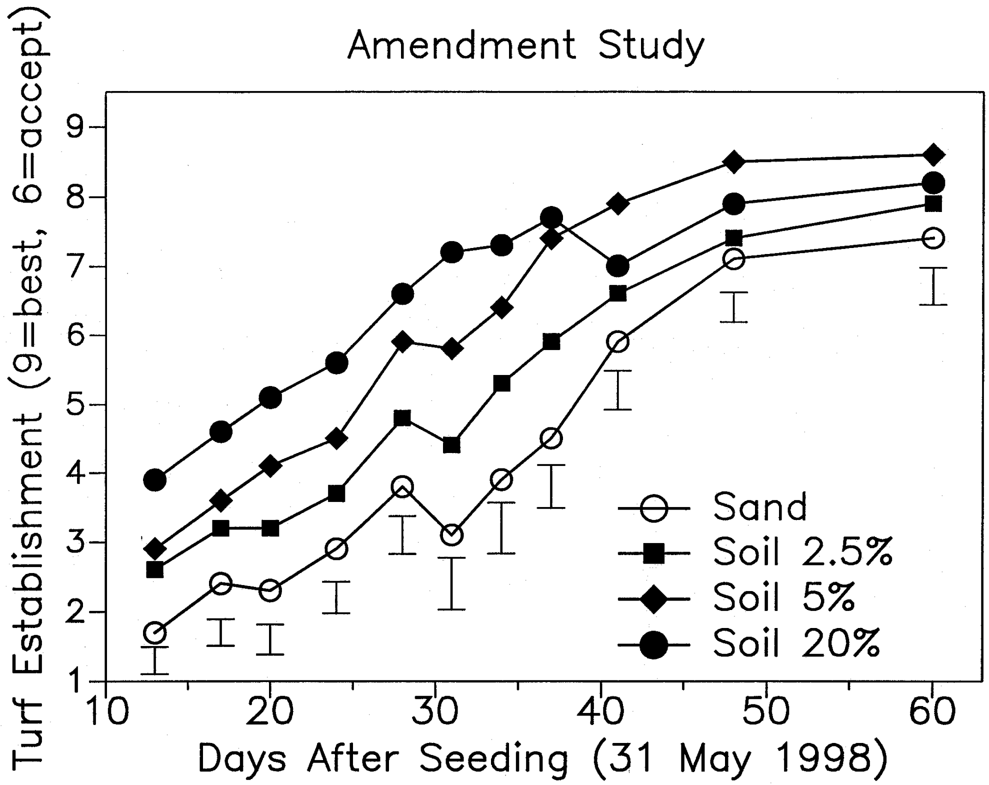
30
40
50
60
Coarse USGA Size
Medium USGA Size
Fine USGA Size
Extra Fine
Mason
CM-340

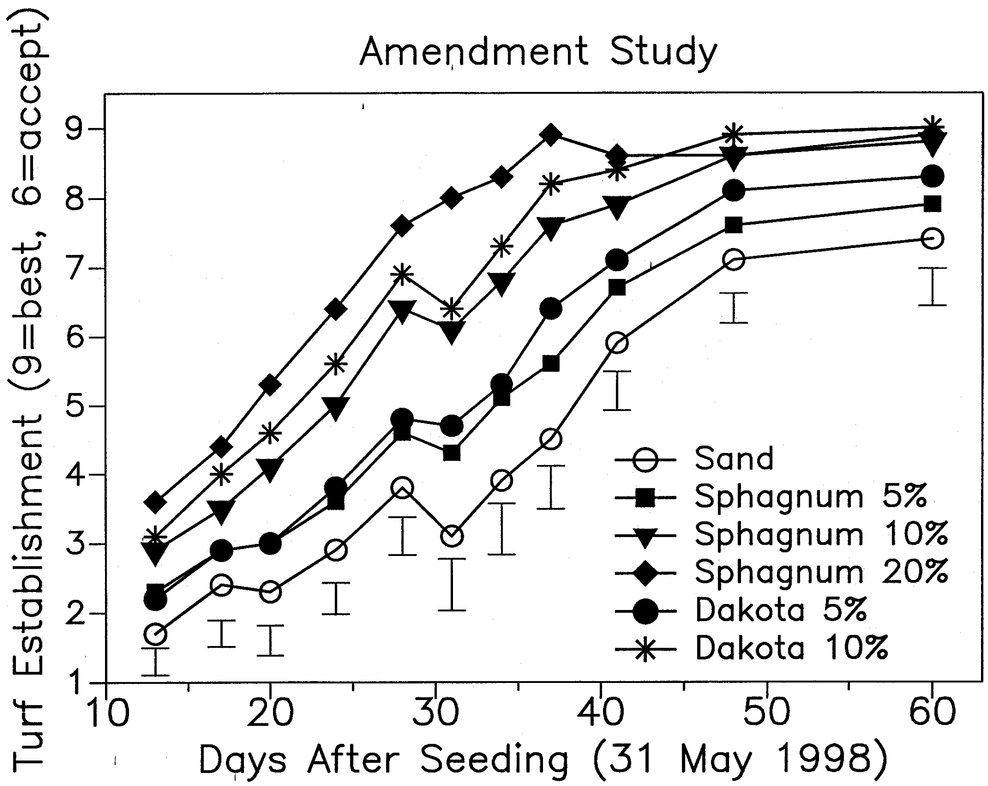
Figure 4.



Amendment Study
Turf Establishment (9=best, 6=accept)
Days After Seeding (31 May 1998)
Sand
Soil 2.5%
Soil 5%
Soil 20%
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60

428

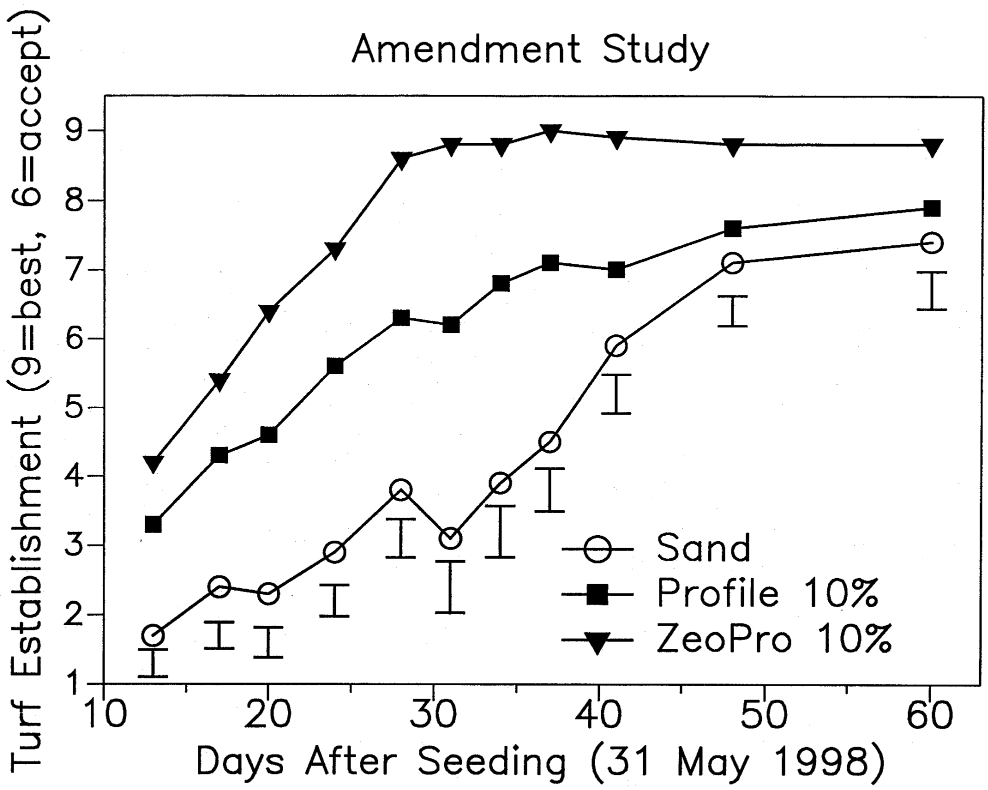
Figure 5.



Amendment Study
Turf Establishment (9=best, 6=accept)
9
8
7
6
5
4
3
2
1
10
20
30
40
50
60
Days After Seeding (31 May 1998)
Sand
Sphagnum 5%
Sphagnum 10%
Sphagnum 20%
Dakota 5%
Dakota 10%

429

Figure 6.



Amendment Study
Turf Establishment (9=best, 6=accept)
9
8
7
6
5
4
3
2
1
10
20
30
40
50
60
Days After Seeding (31 May 1998)
Sand
Profile 10%
ZeoPro 10%

430

Studies of the Variability of the Saturated Hydraulic Conductivity Measurement

The saturated hydraulic conductivity (Ksat) measurement continues to be a highly variable measurement within and among USGA testing laboratories (Miller and Kotuby-Amacher, 1997). An understanding of the source of this variability would improve testing procedures and benefit the golf course construction industry. A possible source of the variability is the phenomenon of air entrapment within "saturated" laboratory packed cores. Entrapped air has been shown to affect saturated hydraulic conductivity (Gupta and Swartzendruber, 1964), as well as other soil physical properties including infiltration (Bond and Collis-George, 1981) and the moisture characteristic curve (Davidson et al., 1966). Fayer and Hillel (1986) showed that initial moisture content prior to saturation influenced the amount of entrapped air retained within pores of a field soil. This report summarizes four studies of Ksat variability as affected by air entrapment, and influenced by antecedent moisture content and saturation method.

Ksat Variability Study #1

Objective: To investigate the affects of antecedent moisture content, saturation method, and core size on Ksat, porosity, and bulk density.

Methods:

- 2 and 3-inch cores packed with a 90:10 sand:sphagnum peat initially brought to moisture equilibrium in a 30°C oven.
- Moisture contents varied prior to final saturation before Ksat measurement.
- Saturated for Ksat slowly ($^1/_2$-inch water added every 30 minutes until saturated), quickly (approximately 30 seconds to saturation), or vacuum saturated.
- Repeated as above for the same sand without amendment.

Preparation of laboratory packed samples in Study 1 compared to USGA procedures.

Green Section Procedure	Ksat Variability Study 1 Procedure
1. Fill cores	1. Fill cores (2- and 3-inch diameters)
2. Saturate cores	2. Dry cores at 30°C
3. Drain cores at 40-cm tension	3. Saturate cores
4. Compact cores	4. Drain cores at 40-cm tension
5. Saturate cores	5. Compact cores
6. Test Ksat of cores	6. Drying and saturation cores (Treatments):
	Drying method — Saturation method
	-40cm — Slow, Quick, Vacuum
	30°C — Slow, Quick, Vacuum
	70°C — Slow, Quick, Vacuum
	7. Test Ksat of cores

Results and Discussion:

- Ksat rates increased in response to decreasing antecedent sample moisture content at time of saturation for Ksat (Table 1)
- Vacuum saturation resulted in higher Ksat rates for all drying treatments except 70°C in the 2-inch cores (Table 1)
- The difference between measured total porosity and calculated total porosity represents the amount of air entrapment within soil pores. The difference between measured total porosity and calculated total porosity was greater with increasing moisture content in the slowly and quickly saturated cores. There was not a great difference between measured total porosity and calculated total porosity in the vacuum saturated cores over the 3 moisture contents. Thus, decreasing moisture content at the time of saturation in the slowly saturated and quickly saturated treatments, and vacuum saturation resulted in less air entrapment and greater Ksat rates (Table 1).
- Capillary porosity increased with decreasing moisture content at the time of saturation in the slowly saturated and quickly saturated cores. Capillary porosity was greater in vacuum saturated cores, but decreased with increasing moisture content. The greater capillary porosity may indicate that there was greater water film continuity and therefore greater drainage of pores in treatments least affected by air entrapment (Table 1).
- Bulk density increased with decreasing moisture content at the time of saturation, and with vacuum saturation. Greater air entrapment may result in an expansion of the sample cores, while vacuum saturation settles material within a packed core (Table 1).
- Bulk density was greater in 3-inch cores and affected porosity measurements independent of moisture content and saturation method (Table 1).
- The Ksat response of the unamended sand (Table 2) was similar to the Ksat response of the sphagnum-amended sand (Table 1). This indicates that the Ksat response of the amended sand was not influenced by hydrophobicity that may have developed by oven drying.

Table 1. Saturated hydraulic conductivity of a USGA size sand (Unimin 313) as affected by core size, method of saturation, and antecedent moisture content at time of saturation before Ksat.

Amendment	Core Diameter (inches)	Saturation Method	Drying Method	Volumetric water content at time of saturation %	Ksat (cm hr^{-1})	Calculated Air-filled porosity (%)	Calculated Capillary porosity (%)	Calculated Total porosity (%)	Measured Air-filled porosity (%)	Measured Capillary porosity (%)	Measured Total porosity (%)	Bulk Density (g cm^{-1})
Sph10%	2	Slow	40cm	11.1	30.3	19.1	20.4	39.5	12.9	20.4	33.3	1.60
Sph10%	2	Slow	30°C	2.6	54.4	18.8	20.5	39.4	14.0	20.5	34.6	1.61
Sph10%	2	Slow	70°C	0.5	95.9	18.1	21.0	39.2	18.2	21.0	39.3	1.61
Sph10%	2	Quick	40cm	11.2	24.8	19.4	20.3	39.7	12.9	20.3	33.2	1.60
Sph10%	2	Quick	30°C	2.4	56.5	18.9	20.7	39.6	14.9	20.7	35.6	1.60
Sph10%	2	Quick	70°C	0.1	98.3	17.7	21.1	38.8	19.3	21.1	40.3	1.62
Sph10%	2	Vacuum	40cm	10.4	42.9	12.5	26.0	38.4	15.9	26.0	41.8	1.63
Sph10%	2	Vacuum	30°C	2.5	74.1	13.2	25.2	38.5	16.6	25.2	41.8	1.63
Sph10%	2	Vacuum	70°C	0.3	72.2	16.0	22.4	38.4	19.2	22.4	41.6	1.63
Sph10%	3	Slow	40cm	10.8	28.6	16.6	22.0	38.6	13.1	22.0	35.1	1.63
Sph10%	3	Slow	30°C	2.5	52.9	15.9	22.2	38.1	13.1	22.2	35.2	1.64
Sph10%	3	Slow	70°C	0.2	91.6	14.7	23.1	37.7	16.4	23.1	39.5	1.65
Sph10%	3	Quick	40cm	10.9	26.2	16.2	21.9	38.1	12.8	21.9	34.7	1.64
Sph10%	3	Quick	30°C	2.3	58.4	15.4	22.6	37.9	14.0	22.6	36.6	1.64
Sph10%	3	Quick	70°C	0.1	93.5	14.2	23.4	37.6	18.0	23.4	41.4	1.65
Sph10%	3	Vacuum	40cm	11.5	49.6	9.1	28.0	37.1	15.4	28.0	43.4	1.67
Sph10%	3	Vacuum	30°C	2.4	75.8	9.0	28.2	37.1	14.9	28.2	43.1	1.67
Sph10%	3	Vacuum	70°C	0.1	85.1	12.5	24.4	36.9	19.0	24.4	43.3	1.67
C.V.(%)					23.6	8.4	3.1	2.1	7.7	3.1	3.0	1.3

ANOVA Source	P>F							
Rep	***	***	***	***	***	***	***	***
Core diameter	NS	***	***	***	***	***	***	***
Saturation method	**	***	***	***	***	***	***	***
Drying method	***	NS	***	**	***	***	***	**
Core diameter*Saturation method	NS	NS	NS	NS	NS	NS	NS	NS
Core diameter*Drying method	NS	NS	NS	NS	*	NS	NS	NS
Saturation method*Drying method	***	***	***	NS	**	***	***	NS
Core dia.*Sat. method*Drying method	NS	NS	NS	NS	NS	NS	NS	NS

*,**, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; NS = not significant at $P \leq 0.05$.

Table 2. Saturated hydraulic conductivity of a non-amended USGA size sand (Unimin 313) as affected by core size, method of saturation, and antecedent moisture content at time of saturation before Ksat.

Amendment	Core Diameter	Saturation Method	Drying Method	Volumetric water content at time of saturation	Ksat	Calculated Air-filled porosity	Calculated Capillary porosity	Calculated Total porosity	Measured Air-filled porosity	Measured Capillary porosity	Measured Total porosity	Bulk Density
	(inches)			%	cm hr^{-1}	(%)	(%)	(%)	(%)	(%)	(%)	(g cm^{-1})
None	2	Slow	40cm	11.9	53.4	16.5	22.6	39.1	11.1	22.6	33.7	1.61
None	2	Slow	30°C	1.4	74.9	16.2	22.5	38.7	11.7	22.5	34.3	1.63
None	2	Slow	70°C	0.0	88.2	14.8	24.0	38.8	11.0	24.0	35.0	1.62
None	2	Quick	40cm	11.8	54.6	17.5	22.1	39.6	11.1	22.1	33.2	1.60
None	2	Quick	30°C	1.1	73.2	16.4	23.0	39.3	10.4	23.0	33.4	1.61
None	2	Quick	70°C	0.0	89.9	13.4	24.7	38.0	10.5	24.7	35.2	1.64
None	2	Vacuum	40cm	11.1	61.0	2.5	34.2	36.7	3.4	34.2	37.6	1.68
None	2	Vacuum	30°C	1.5	83.1	1.4	34.0	35.3	4.9	34.0	38.9	1.71
None	2	Vacuum	70°C	0.0	87.6	4.9	31.6	36.5	7.1	31.6	38.7	1.68
None	3	Slow	40cm	12.2	52.1	13.7	24.6	38.3	9.6	24.6	34.2	1.63
None	3	Slow	30°C	2.0	66.7	11.2	25.8	37.0	9.3	25.8	35.1	1.67
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None	3	Quick	30°C	1.8	73.4	12.4	25.2	37.6	9.6	25.2	34.8	1.65
None	3	Quick	70°C	0.1	95.4	8.9	27.6	36.6	9.0	27.6	36.6	1.68
None	3	Vacuum	40cm	11.8	67.9	0.0	36.0	35.7	2.4	36.0	38.4	1.70
None	3	Vacuum	30°C	1.8	82.3	0.2	34.6	34.8	6.2	34.6	40.8	1.73
None	3	Vacuum	70°C	0.1	82.3	0.0	34.6	34.6	4.6	34.6	39.2	1.73
C.V.(%)					13.0	18.6	5.7	2.0	24.5	5.7	2.5	1.2

ANOVA Source	P>F							
Rep	NS	NS	**	**	*	**	NS	**
Core diameter	NS	***	***	***	NS	***	***	***
Saturation method	*	***	***	***	***	***	***	***
Drying method	***	*	NS	***	NS	NS	*	***
Core diameter*Saturation method	NS	NS	NS	NS	NS	NS	NS	NS
Core diameter*Drying method	NS	NS	NS	NS	NS	NS	NS	NS
Saturation method*Drying method	NS	**	**	NS	NS	**	NS	NS
Core dia,*Sat. method*Drying method	NS	NS	NS	NS	NS	NS	NS	NS

*,**, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; NS = not significant at $P \leq 0.05$.

Ksat Variability Study #2

Objectives: Study the affect of moisture content variation early in the laboratory preparation procedure (simulating moisture content differences in a sand mixture when material is added to the core) on Ksat, porosity, and bulk density.

Methods:

- 2 and 3-inch cores packed with a 90:10 sand:sphagnum peat initially brought to moisture equilibrium in a 30°C oven.
- Moisture contents varied at beginning of core preparation process.
- All treatments re-saturated and progress through normal preparation procedure.

Preparation of laboratory packed samples in Study 2 compared to USGA procedures.

Green Section Procedure	Ksat Variability Study 2 Procedure
1. Fill cores	1. Fill cores (2- and 3-inch diameters)
2. Saturate cores	2. Dry cores at 30°C
3. Drain cores at 40-cm tension	3. Saturate cores
4. Compact cores	4. Cores Treated:
5. Saturate cores	Drying method
6. Test Ksat of cores	40-cm tension
	30°C
	70°C
	5. Saturate cores
	6. Drain cores at 40-cm tension
	7. Compact cores
	8. Drying and saturation cores
	9. Test Ksat of cores

Results and Discussion:

- Ksat rates increased in response to decreasing antecedent moisture content varied early in the preparation procedure (Table 3).
- Air entrapment was evident immediately after the drying treatments were imposed and the cores were saturated (data not shown). The entrapped air remained evident through the entire procedure. The difference between calculated total porosity and measured porosity represents the amount of entrapped air at saturation immediately prior to Ksat (Table 3). Entrapped air content decreases with decreasing initial moisture content.
- Capillary porosity increased with decreasing initial moisture content. The greater capillary porosity may indicate that there was greater water film continuity and therefore greater drainage of pores in treatments least affected by air entrapment (Table 3).
- Bulk density increased with decreasing sample moisture content before compaction. Greater air entrapment may result in an expansion of cores thereby reducing bulk density (Table 3).
- Bulk density was greater in 3-inch cores and affected porosity measurements independent of initial moisture content (Table 3).

Table 3. Saturated hydraulic conductivity of a USGA size sand (Unimin 313) as affected by core size and antecedent moisture content varied after filling cores and before compaction.

Amendment	Core Diameter	Drying Meth.	Volumetric water content at time of 1st saturation	Volumetric water content at time of 2nd saturation for -40-cm compaction	Ksat	Calculated Air-filled porosity	Calculated Capillary porosity	Calculated Total porosity	Measured Air-filled porosity	Measured Capillary porosity	Measured Total porosity	Bulk Density
	(inches)				(cm hr^{-1})	----------	----------	---------- %	----------	----------	----------	(g cm^{-1})
Sph 10%	2	40cm	11.9	12.6	34.2	18.3	22.4	40.7	11.8	22.4	35.6	1.57
Sph 10%	2	30°C	3.0	12.4	41.3	16.1	23.5	39.6	11.7	23.5	36.0	1.60
Sph 10%	2	70°C	0.1	11.6	56.6	14.3	25.2	39.4	11.0	25.2	37.1	1.60
Sph 10%	3	40cm	12.4	12.9	30.6	14.2	24.4	38.6	11.0	24.4	36.5	1.63
Sph 10%	3	30°C	3.4	12.9	44.3	13.3	24.7	38.0	11.5	24.7	37.0	1.64
Sph 10%	3	70°C	0.3	11.9	58.7	12.4	25.8	38.1	11.6	25.8	38.3	1.64
C.V.(%)					16.2	11.3	3.4	2.6	8.3	3.4	1.7	1.7

ANOVA Source	P>F							
Rep	**	***	***	NS	***	***	***	NS
Core diameter	NS	***	***	***	NS	***	***	***
Drying method	***	***	***	*	NS	***	***	*
Core diameter*Drying method	NS	NS	NS	NS	NS	NS	NS	NS

*,**, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; NS = not significant at P≤ 0.05.

Ksat Variability Study #3

Objectives: Study the affect of moisture content variation (near 30-cm tension) at the time of saturation before the Ksat measurement on Ksat, porosity, and bulk density.

Methods:

- 2 and 3-inch cores packed with a 90:10 sand:sphagnum peat initially brought to moisture equilibrium in a 30°C oven.
- Moisture contents varied at final saturation before Ksat measurement.

Preparation of laboratory packed samples in Study 3 compared to USGA procedure.

Green Section Procedure	Ksat Variability Study 3 procedure
1. Fill cores	1. Fill cores (2 inch and 3 inch)
2. Saturate cores	2. Dry cores at 30°C
3. Drain cores at 40-cm tension	3. Saturate cores
4. Compact cores	4. Drain cores at 40-cm tension
5. Saturate cores	5. Compact cores
6. Test Ksat of cores	6. Cores Treated:
	Drying method
	20-cm tension
	30-cm tension
	40-cm tension
	7. Saturate cores
	8. Test Ksat of cores

Results and Discussion:

- Ksat rates decreased in response to decreasing antecedent moisture content at time of saturation for Ksat (Table 4). This response was different from the above studies. This may reflect that a percentage of the pore sizes that could potentially entrap air did not drain at 20-cm tension, but did drain at 30-cm and 40-cm tensions prior to saturation immediately before Ksat.
- The difference between calculated total porosity and measured total porosity represents the amount of entrapped air at saturation immediately prior to Ksat (Table 4). Entrapped air content was smallest at 20-cm tension (sample moisture content at saturation) and greatest at 40-cm tension in this study.
- Increases in moisture content above the recommended compaction moisture content (water tension) can influence Ksat rate.
- Capillary porosity decreased with decreasing moisture content at time of saturation. Increased capillary porosity suggests greater water film continuity, and therefore greater water flux in treatments least affected by air entrapment (Table 4).
- Bulk density was greater in 3-inch cores. This affected porosity measurements (Table 4).

Table 4. Saturated hydraulic conductivity of a USGA size sand (Unimin 313) as affected by core size and antecedent moisture content at time of saturation before Ksat.

Amendment	Core Diameter	Drying Meth.	Volumetric water content at time of saturation	Ksat	Calculated Air-filled porosity	Calculated Capillary porosity	Calculated Total porosity	Measured Air-filled porosity	Measured Capillary porosity	Measured Total porosity	Bulk Density
	(inches)		%	cm hr^{-1}	----------	----------	---------- %	----------	----------	----------	(g cm^{-1})
Sph 10%	2	20cm	34.0	59.5	18.2	21.0	39.2	13.9	21.0	35.3	1.58
Sph 10%	2	30cm	19.7	48.9	19.3	20.4	39.7	13.8	20.4	34.9	1.53
Sph 10%	2	40cm	10.8	49.2	20.3	19.5	39.8	13.4	19.5	33.6	1.57
Sph 10%	3	20cm	34.6	60.8	13.5	23.3	36.8	12.9	23.3	36.4	1.60
Sph 10%	3	30cm	20.5	48.5	15.5	22.0	37.6	12.8	22.0	35.3	1.60
Sph 10%	3	40cm	11.5	46.8	17.5	20.8	38.3	13.4	20.8	35.1	1.60
C.V.(%)				4.9	3.1	1.4	1.0	3.7	1.4	1.6	1.9

ANOVA Source	P>F							
Rep	***	***	***	**	***	***	***	NS
Core diameter	NS	***	***	***	***	***	***	***
Drying method	***	***	***	***	NS	***	***	NS
Core diameter*Drying method	NS	***	***	*	*	***	NS	NS

*,**, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; NS = not significant at $P \leq 0.05$.

Ksat Variability Study #4

Objectives: Study the affect of moisture content variation (near 30-cm tension) early (before compaction) in the laboratory preparation procedure on Ksat, porosity, and bulk density.

Methods:

- 2 and 3-inch cores packed with a 90:10 sand:sphagnum peat initially brought to moisture equilibrium in a 30°C oven.
- Moisture contents varied at beginning of core preparation process.
- All treatments re-saturated and progress through normal preparation procedure.

Preparation of laboratory packed samples in Study 4 compared to USGA procedure.

Green Section Procedure	Ksat Variability Study 4 procedure
1. Fill cores	1. Fill cores (2 inch and 3 inch)
2. Saturate cores	2. Dry cores at 30°C
3. Drain cores at 40-cm tension	3. Saturate cores
4. Compact cores	4. Cores Treated:
5. Saturate cores	Drying method
6. Test Ksat of cores	20-cm tension
	30-cm tension
	40-cm tension
	5. Saturate cores
	6. Drain cores at 40-cm tension
	7. Compact cores
	8. Saturate cores
	9. Test Ksat of cores

Results and Discussion:

- Ksat rates were not different in response to moisture content variation near 30-cm tension when moisture content is varied early in the preparation process (Table 5).
- The differences between drying method treatments in the amount of entrapped air remaining at saturation immediately prior to Ksat is minimal, as would be expected from the Ksat data (Table 5).
- Capillary porosity was slightly greater in the 20cm treatments, possibly reflecting a small reduction in air entrapment (Table 5).
- Bulk density was greater in 3-inch cores. This affected porosity measurements (Table 5).

Table 5. Saturated hydraulic conductivity of a USGA size sand (Unimin 313) as affected by core size and antecedent moisture content varied after filling cores.

Amendment	Core Diameter	Drying Meth.	Volumetric water content at time of 1st saturation	Volumetric water at time of 2nd saturation for -40-cm compaction	Ksat	Calculated Air-filled porosity	Calculated Capillary porosity	Calculated Total porosity	Measured Air-filled porosity	Measured Capillary porosity	Measured Total porosity	Bulk Density
	(inches)				(cm hr^{-1})	------------------------		%			------------------------	(g cm^{-1})
Sph 10%	2	20cm	35.0	12.4	30.6	18.4	21.5	39.9	13.2	21.5	35.7	1.59
Sph 10%	2	30cm	17.5	12.4	34.6	19.1	20.8	39.9	13.7	20.8	35.2	1.59
Sph 10%	2	40cm	11.4	12.4	29.4	19.9	20.7	40.6	13.5	20.7	35.2	1.57
Sph 10%	3	20cm	36.0	13.0	29.0	15.3	23.4	38.7	12.2	23.4	36.7	1.62
Sph 10%	3	30cm	18.0	12.7	31.1	16.5	22.4	38.9	12.8	22.4	36.3	1.62
Sph 10%	3	40cm	11.7	12.7	28.8	16.4	22.4	38.8	12.6	22.4	36.1	1.62
C.V.(%)					14.0	3.1	1.5	1.0	3.5	1.5	1.4	0.6

ANOVA Source	P>F							
Rep	NS	NS	NS	NS	NS	NS	NS	NS
Core diameter	NS	***	***	***	***	***	***	***
Drying method	NS	***	***	NS	*	***	*	NS
Core diameter*Drying method	NS	NS	NS	NS	NS	NS	NS	NS

*,**, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; NS = not significant at P≤ 0.05.

Additional Studies of the Variability of the Saturated Hydraulic Conductivity Measurement

Temperature affects the solubility of gases in water, and has also been implicated in entrapped air bubble volume changes in soil (King, 1899). Water temperature and room temperature can vary greatly within and between laboratories according to time of year, and consequently could influence the relationship between Ksat and entrapped air. These factors are currently being evaluated for their affect on Ksat by varying water temperatures relative to ambient air temperatures in the lab.

Bulk density variability between laboratories has been implicated as influencing Ksat (Miller and Kotuby-Amacher, 1997). A study was conducted to investigate the affects of compaction on the stability of inorganic amendments, and the physical property data has been reported in previous progress reports. This study was expanded to include an organic amendment and a repeat set of amendments at an additional volume mixture ratio. Data for this expanded treatment set was completed, and is currently being analyzed. Results will be available for the May 1999 progress report.

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