Physical Properties of Three Sand Size Classes Amended with Inorganic Materials or Sphagnum Peat Moss for Putting Green Rootzones

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ABSTRACT

Modern putting green rootzones are typically constructed using sands to avoid compaction and facilitate rapid drainage. Sands are often amended with organic matter (OM) such as sphagnum peat moss (SP) to increase moisture holding capacity. However, OM decomposition into finely divided material may negatively affect long-term soil physical properties. Inorganic amendments (IAs) having high water retention may be more suitable because of their resistance to biodegradation. A laboratory study determined the physical properties [bulk density, saturated hydraulic conductivity (K_{sat}), water retention, and pore size distribution] of three USDA sand size classes (fine, medium, and coarse) with and without amendment. Amendments used were calcined clay, vitrified clay, extruded diatomaceous earth, a processed zeolite, and SP. Amendments were tested at two incorporation rates (10 and 20% v/v), and in situ in 30-cm-deep rootzones at two incorporation depths (15 and 30 cm). Bulk density decreased, total porosity increased, and K_{sat} declined with amendment rate, but varied considerably depending on amendment, sand size, and incorporation depth. The K_{sat} was high for all mixtures, averaging 250 cm h^{-1}, probably because of the very uniform sands. On the basis of standard pressure plate methods, IAs increased total water holding capacity (WHC) of all three sands but did not increase available water. However, a unique bioassay for available water indicated that porous IAs may contain appreciably more available water than measured by the pressure plate technique. Although the IAs significantly altered the physical properties of the three sands, they were not as effective as SP at improving water retention in coarse-textured, drought-prone sands.

Golf course putting green rootzones must resist compaction, drain rapidly, and provide adequate moisture, nutrition, and aeration to produce high-quality turfgrass. Sand-based rootzones generally meet the first two criteria (Bingaman and Kohnke, 1970). However, many sands have inherently low water and nutrient retention capacities, which can lead to water and nutritional stresses, thus reducing turf quality. Historically, organic materials such as SP have been mixed with sand to improve water and nutrient retention (Juncker and Madison, 1967; Beard, 1982). Organic materials partially fill the voids in coarse-textured sands, creating a variety of pore sizes. This increases water retention and permits gradual water release compared with a uniform, unamended sand (Hillel, 1982; McCoy, 1992). One disadvantage of organic amendments is that they decompose with time, reducing their beneficial effects. Additionally, depending on the organic source, decomposition of OM may dramatically reduce hydraulic conductivity compared with unamended sand (McCoy, 1992). The ideal amendment would be relatively stable, while providing water retention and release comparable with organic amendments.

A number of inorganic materials, including porous ceramics, diatomaceous earth, and zeolites, are currently marketed as alternatives to SP for construction of sand-based rootzones. These products are generally stable, very porous, and are designed to increase microporosity and, thereby, water retention. Most are sized comparable with sand (≤2 mm) to maintain high percolation rates. Many have been evaluated with mixed success (Waddington et al., 1974; Schmidt, 1980; Ferguson et al., 1986; Nus and Brauen, 1991; Kussow, 1996; McCoy and Stehouwer, 1998; Miller, 2000; Waltz et al., 2003; Wehtje et al., 2003). The major criticism of IAs is that much of the internally held water is not plant-available (Davis et al., 1970; Waddington et al., 1974). By contrast, Van Bavel et al. (1978) reported that fritted clay was an excellent medium for plant growth, providing good aeration and containing 0.31 cm^3 cm^{-3} of available water, much of it held internally. Unfortunately, few of the aforementioned studies contain results that directly compare IAs to an appropriate SP control, which makes data interpretation difficult.

Therefore, the overall objective of this study was to evaluate several commercially available IAs for potential use in newly constructed putting green rootzones. Specific objectives were (i) to evaluate selected physical properties of several currently marketed IAs alone and when mixed with fine, medium, and coarse sand; and (ii) to compare physical properties of inorganically amended sands with sand amended with a traditional organic amendment, SP.

MATERIALS AND METHODS

Rootzone Mixture Components

A series of laboratory experiments measured the physical properties of sands varying in size class with and without amendment using several inorganic materials and SP. Fine (0.10–0.25 mm), medium (0.25–0.50 mm), and coarse (0.50–1.00 mm) USDA sand classes were isolated from a locally available (Conway, SC) washed quartz sand by a standard mechanical shaker sieve. The four IAs included Ecolite (a clinoptilolite zeolite, Western Organics, Inc., Tempe, AZ), Isolite (an extruded diatomaceous earth, 78% SiO$_2$, 12% Al$_2$O$_3$, containing 5% by weight of a clay binder, Sundire Enterprises, Arvada, CO), and two heat-treated porous ceramic products of differing mineralogy: Greenschoice (a heat-treated, unspecified high-temperature, shale-based clay, 64% SiO$_2$, 16% Al$_2$O$_3$;

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Abbreviations: AWHC, available water holding capacity; IA, inorganic amendment; K_{sat}, saturated hydraulic conductivity; OM, organic matter; SP, sphagnum peat moss; SWP, soil water pressure; WHC, water holding capacity.

Table 1. Particle size distribution, geometric mean diameter and particle density of three sand size classes and five rootzone amendments used for the simulated putting green rootzone mixtures.

Amendment	Particle size, mm							Geometric mean diam.†	Particle density
	>2.0	1.0	0.5	0.25	0.10	0.05	<0.05		
	g kg^{-1}							mm	g cm^{-3}
Fine sand	0	0	0	0	1000	0	0	0.01	2.62
Medium sand	0	0	0	1000	0	0	0	0.25	2.62
Coarse sand	0	0	1000	0	0	0	0	0.50	2.62
Zeolite	0	<1	242	615	139	1	3	0.67	2.32
Vitrified clay	0	3	871	108	11	7	<1	0.84	2.15
Diatomaceous earth	0	5	446	534	10	5	<1	0.74	2.27
Calcined clay	<1	0	714	272	14	<1	<1	0.59	2.50
Sphagnum peat	–	–	–	–	–	–	–	na‡	0.63

† Geometric mean diameter calculated according to method of Hillel (1982).
‡ na = not applicable.

Premier Environmental Products, Inc., Houston, TX), and Profile (a heat-treated, 865°C, illite clay, 74% SiO_2; Applied Industrial Materials Corp., Buffalo Grove, IL), hereafter referred to as zeolite, diatomaceous earth, vitrified clay, and calcined clay, respectively. The particle size distribution for each IA was determined by sieving and the geometric mean diameter (Table 1) was calculated according to methods of Hillel, (1982). Sphagnum peat moss (Bordnamona Co., Dublin, Ireland, 973 g kg^{-1} OM by loss on ignition, 0.70 g water g^{-1} SP during mixing) was used as a standard for IA comparison.

Amendment and Sand Mixture Evaluations

The five different amendments were each combined at 10 and 20% by volume with the three sand size classes. The 10 and 20% additions of SP were equivalent to 0.51 and 1.20% OM by weight, respectively. On a dry-weight basis the IA additions were equivalent to 3.4, 3.5, 4.5, and 4.8% at the 10%-by-volume rate and 6.6, 6.8, 8.7, and 9.2% at the 20%-by-volume rate for calcined clay, extruded diatomaceous earth, vitrified clay, and zeolite, respectively. Physical properties of the sands, amendments, and their respective mixtures were determined by placing air-dried portions of each mixture in stainless steel cylinders (3.9 cm tall × 5.66-cm i.d.). After slowly saturating the samples from the bottom up, water retention of each mixture was determined at −0.001, −0.002, −0.004, −0.006, −0.01, and −0.02 MPa by the water desorption method (Flint and Flint, 2002b). These measurements were made at a constant temperature of 20°C. Water retention of the IAs and three sands was also measured at pressures of −0.05, −0.1, and −1.5 MPa by the pressure plate method (Dane and Hopmans, 2002). Three replications of each sand or amendment were used in a completely random experimental design for all measurements.

Total porosity was calculated with measured bulk density and particle density as determined by the pycnometer method (Flint and Flint, 2002a). Macroporosity (air-filled) was calculated by subtracting the water content at −0.004 MPa from total porosity. Microporosity (capillary water) was defined as the amount of pores retaining water at −0.004 MPa (USGA, 1993). Available water holding capacity (AWHC) of each material was calculated as the difference between water retained at −0.004 MPa and −0.05 MPa.

Additional physical properties were determined in situ with 30-cm-deep rootzone mixtures, equivalent to the compacted depth of most sand-based putting green rootzones. Columns (7.6-cm i.d. by 35 cm tall, with a wall thickness of 0.42 cm) were constructed from acrylic tubing and equipped with access measurement ports (1.8-cm diam.) located at 2-cm intervals in a spiral arrangement down the sides of each column corresponding to depth intervals from 2 to 26 cm below the surface of the media. During use, each measurement port was covered by a rubber stopper. Additionally, stainless steel mesh was embedded into the base of each column and before packing the columns, the steel mesh base was fitted with a single sheet of porous glass wool to retain the sand mixtures in the columns.

Conventional laboratory methods for determining the physical properties of potential sand-based rootzone media require samples to be compacting from the top using a weighted hammer apparatus (USGA, 1993). These tests are normally conducted with small steel cylinders (5-cm diam. by 7.6–10 cm tall), not the full 30-cm rootzone depth. Because of the unique in situ column approach (7.6-cm diam. by 30 cm tall) used to determine moisture content with depth, a preliminary study was conducted to determine the most effective packing method which would not disturb the sidewall measurement ports. Sand and amended sands were installed in smaller, more traditional columns and compacted to determine the mass of sand or sand + amendment required to produce a compacted 30-cm-deep rootzone. On the basis of these measurements, air-dry sand or sand + amendment were preweighed, mixed, and installed into the larger columns by slowly pouring in one continuous step. This process minimized layering and maintained the integrity of the measurement ports. The media was further compacted by hand through repeated tapping on a hard surface until the rootzone mixtures were exactly 30 cm deep.

In addition to the 10 and 20% rates, each amendment was also evaluated at two incorporation depths: throughout the entire 30-cm depth, (referred to as *throughout*) and incorporated only in the top one half of the 30-cm rootzone (hereafter called *top half*) with three replications of each treatment for all measurements.

When the amendment mixture was placed only in the top half of the rootzone, it was subtended by 15 cm of unamended sand of the same size class. Packed columns were incrementally saturated with tap water from the bottom up until ponding at the rootzone surface was observed. After 24 h, K_{sat} was determined by the constant head method (Klute and Dirksen, 1986), with results adjusted to 20°C.

After K_{sat} was measured, each column was loosely capped to prevent evaporation, placed on a screen drying rack, and allowed to drain for 24 h. Horizontal cores (1-cm diam. × 7.5 cm tall) of the media were then sampled at each access port and oven dried for 24 h at 105°C to determine gravimetric water content.

Bioassay for Available Water

The amount of available water held by some of the amendments, as obtained with standard desorption techniques (see above), seemed surprisingly low and were in direct conflict with results documenting considerable available water in other calcined clays (Van Bavel et al., 1978). Consequently, a bioassay was designed to estimate plant available water in fine sand and calcined clay, with a combination of tensiometers for soil water potentials <100 kPa, and leaf water potential as a lagging indicator of more negative soil water potential. Plastic pots (15.2-cm diam. by 11.1 cm deep) were fitted with two 1-cm diam. tensiometers (Soil Moisture Systems, Las Cruses, NM) located on each side of the pot, 5 cm above the bottom. A layer of cheesecloth was placed in the bottom of the pot which was then filled to a depth of 10 cm with the fine sand or the calcined clay. Perennial ryegrass (*Lolium perenne* L. 'Competitor') was seeded at 250 kg ha^{-1} and grown in the greenhouse (36/21°C day/night) for 10 wk, during which the plants were well watered and fertilized with 14 kg N ha^{-1} wk^{-1} from a soluble (20-20-20 N-P-K) fertilizer. The grass was unmowed during the study to maximize transpiration.

With the grass well established, a 4-d drought stress period was imposed. Soil water content was determined gravimetrically each day (corrected for plant biomass), and soil matric potential was determined directly with the tensiometers (low tensions) and indirectly by measuring leaf water potential (higher tensions). Leaf water potential was measured with a hydraulic press (J-14 Leaf Press, Decagon Devices, Pullman, WA) technique (White et al., 1992). Briefly, three representative leaves were removed at each sampling period, the lamina segments (approximate length of 5 cm) were placed on filter paper within the press and pressure applied until sap was expressed. Six replications of each rootzone amendment were used in a completely random experimental design and plants were moved every other day to offset effects of possible environmental gradients within the greenhouse.

All data was subjected to ANOVA with the Statistical Analysis System (SAS Institute, 1985). Separation of significantly different treatment means was accomplished by preplanned orthogonal contrasts (Steel et al., 1997). Means were separated with Fisher's protected LSD if the ANOVA *F* test indicated that source effects were significant. Amended sand rootzone mixtures within each sand class were compared with the unamended sand control by Dunnett's test (Steel et al., 1997). The laboratory experiments were conducted with a completely random factorial design. The pore size distribution and water retention data were analyzed as a two-factor study (sand size and incorporation rate) and the in situ study as a three-factor study (sand size, incorporation rate, and incorporation depth).

RESULTS AND DISCUSSION

Pore Size Distribution

Sand size affected macro- and capillary porosity as well as available water (Table 2). Fine sand held considerably more total and available water, 0.268 and 0.244 cm^3 cm^{-3} volumetric water, than either the medium or coarse sand, which only retained 0.051 to 0.037 cm^3 cm^{-3} volumetric water, respectively. Most successful sand-based rootzones contain ≥0.15 cm^3 cm^{-3} but <0.25 cm^3 cm^{-3} volumetric water (Bingaman and Kohnke, 1970; USGA, 1993), suggesting that both the medium and coarse sand might be difficult to manage without amending to improve water retention. However, it must also be considered that the sands used in this study were screened to a high uniformity not available in practice. Consequently, the medium sand discussed here, as an example, might not be easily compared with a predominantly medium sand from a commercial source.

Table 2. Porosity and water retention of three sand size classes and five rootzone amendments.

Rootzone component	Porosity			Water retention		Bulk density
	Total	Macro	Capillary†	Θ_{500}‡	AWHC§	
	Volumetric content cm^3 cm^{-3}					g cm^{-3}
Fine sand	0.450c¶	0.182b	0.268bc	0.025c	0.244a	1.42
Medium sand	0.429c	0.378a	0.051d	0.029c	0.022c	1.47
Coarse sand	0.384c	0.347a	0.037d	0.006c	0.031c	1.59
Zeolite	0.606b	0.372a	0.234c	0.206b	0.028c	0.87
Vitrified clay	0.567b	0.321a	0.246c	0.208b	0.038c	0.84
Diatomaceous earth	0.722a	0.364a	0.358b	0.342a	0.016c	0.59
Calcined clay	0.734a	0.380a	0.354b	0.332a	0.022c	0.64
Sphagnum peat	0.744a	0.224b	0.520a	0.343a	0.177b	0.15

† Capillary porosity refers to water retained at −0.004 MPa.

‡ Θ_{500} = water retained at −0.05 MPa.

§ Available water holding capacity (AWHC) = capillary water retention − Θ_{500}.

¶ Means followed by the same letter in the same column are not significantly different under Fisher's protected LSD ($P = 0.05$).

The amendments had significantly greater total porosity (macro + capillary) than any of the three sands, with the following ranking: SP = calcined clay = diatomaceous earth > zeolite = vitrified clay > fine sand = medium sand = coarse sand. Peat, calcined clay, and diatomaceous earth had >0.70 cm^3 cm^{-3} total porosity, compared with 0.40 to 0.45 cm^3 cm^{-3} for the sands. Macroporosity was generally similar, >0.30 cm^3 cm^{-3}, for all amendments and the medium and coarse sands, reflecting similar particle sizes. It is apparent that the IAs have a much higher capillary porosity than the medium and coarse sands, primarily because of the relatively large internal pore space in the amendments.

The moisture characteristic of the substrate is extremely important for successful putting green rootzones. Consequently, data on moisture release from IAs should help in selecting appropriate amendments for sand-based rootzones. For example, if an amendment releases most of its water at a relatively low tension and retains little at a moderate tension, it may contribute little benefit to a coarse-textured sand. Conversely, if an amendment releases little water at low tensions and retains significant quantities at higher tensions, making it unavailable to the turf, it may be equally unsuitable. In the present study, all amendments except fine sand released 0.28 to 0.36 cm^3 cm^{-3} water between saturation and −0.002 MPa. In constructed rootzones deeper than 20 cm, this water would be lost through gravitational drainage and thus unavailable for plant use. In contrast, fine sand released only 0.004 cm^3 cm^{-3} water at this low tension. Thus, the fine sand retains a substantial amount of water that may be available for plant growth.

To characterize further the moisture release properties of the amendments and three sands, water retention data were collected for a range of soil water pressures (SWPs). Each sand and amendment generally had a characteristic tension at which much of the water was released (Fig. 1). For the sands, this critical SWP is related to the particle size, with coarse sand abruptly releasing water between −0.001 and −0.002, medium sand between −0.001 and −0.004, and fine sand between −0.002 and −0.01 MPa. Compared with the sands, the IAs and SP contained significantly more water at saturation, >0.55 cm^3 cm^{-3}, and released this water more grad-

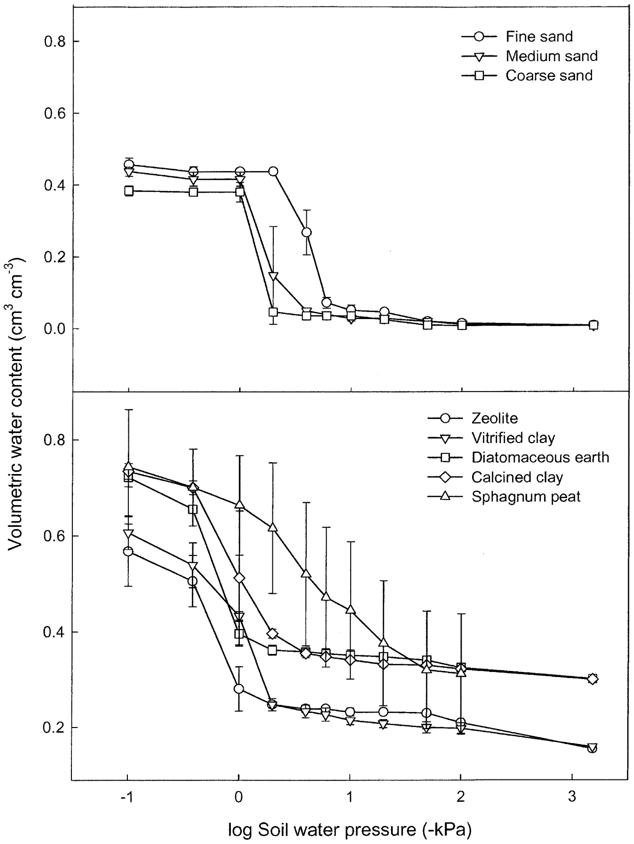

Fig. 1. Moisture release curves for three USDA sand size classes and five amendments. Vertical bars represent ±1 SE of the mean where the bars exceed the size of the symbol.

ually with decreasing SWP up to −0.006 MPa. At SWP < −0.006 MPa, water release from the IAs leveled off and remained relatively constant to −1.5 MPa SWP. Peat moss had the most gradual release for any of the rootzone components.

Water retained at −0.05 MPa (taken to represent plant unavailable water for bentgrass grown on sand-based rootzones) was greatest for amendments, ranging from 0.20 to 0.34 cm^3 cm^{-3} (Table 2), and lowest in unamended sands (0.006 to 0.03 cm^3 cm^{-3}). The AWHC was highest for the fine sand (0.24 cm^3 cm^{-3}), whereas the other sands and IAs had AWHCs < 0.04 cm^3 cm^{-3}. This suggests that particle size and pore size architecture, rather than total internal pore space, may be the overriding factor for AWHC determination in a 30-cm-deep rootzone.

Amendments had little effect on macroporosity in all three of the sands, but increased capillary porosity in the medium and coarse sand classes (Table 3). Amendments also increased the moisture held at −0.05 MPa. However, increased capillary porosity did not translate into increased AWHC. Inorganic amendments either had no effect on AWHC (medium and coarse sands) or, as in the fine sand, actually decreased AWHC. Not surprisingly, 20% SP increased AWHC in the medium and coarse, but not the fine sand. It should be noted that AWHC was extremely low for both the medium and coarse sands, even with amendment addition. This is probably because of the very high uniformity of the sands used, and suggests that some highly sorted sands might actually have too narrow a particle size distribution for adequate moisture-holding capacity. Thus, these sands would benefit from a small quantity of finer-sized particles.

Fine sand and amended fine sand were the only media that consistently met USGA guidelines for pore size distributions, namely 0.15 to 0.30 cm^3 cm^{-3} and 0.15 to 0.25 cm^3 cm^{-3} for macropores and capillary water retention, respectively (USGA, 1993). The medium and coarse sand classes failed to meet specifications because of a preponderance of macropores, which would promote droughty conditions and difficulty in establishing turf by seed. The only exception was the medium sand amended with 20% SP, which met USGA guidelines. Several fine sand mixtures failed to meet guidelines (10 and 20% SP; 20% diatomaceous earth and calcined clay) because of excessive capillary water, which could contribute to poor rooting and inadequate gas exchange.

Bulk Density

Amendments decreased bulk density (Table 3) for all three sand classes, with SP having the greatest effect. Similar results were observed by Juncker and Madison (1967), Waddington et al. (1974), and Waltz et al. (2003). Bulk density alone, however, is not considered to be an adequate indicator of a successful rootzone mixture (USGA, 1993).

Saturated Hydraulic Conductivity

The K_{sat} values were very high for all three sands, and increased with coarseness (89, 211, and 505 cm h^{-1} for the fine, medium, and coarse sand, respectively, data not shown). Amendments decreased K_{sat} 13 to 50% in the medium sand, with the reduction directly related to the geometric mean diameter of the incorporated amendment. There was less effect of amendment on fine sand, and essentially no effect on the coarse sand. Mean K_{sat} values for each amendment across all three sand classes ranked in the following order: vitrified clay = zeolite ≥ unamended sand ≥ diatomaceous earth ≥ calcined clay > SP. Amending only the top 15 cm had less impact on K_{sat} than incorporation throughout the entire 30-cm rootzone; the 20% amendment rate decreased conductivity more than the 10% rate (data not shown).

These K_{sat} values are much higher than the USGA guidelines of 15 to 30 cm h^{-1} (USGA, 1993), most likely because of our use of highly uniform sands. This is consistent with results of Bingaman and Kohnke (1970), who reported similar high K_{sat} values for several well-graded fine and medium sands.

Water Retention and Availability of Simulated Rootzones

Soil moisture profiles (Fig. 2) varied considerably, depending on sand size. All three sands were close to saturation (≈0.45 cm^3 cm^{-3}) at the bottom of the 30-cm

Table 3. Porosity, water retention, and bulk density of sand mixtures from three sand size classes.

Sand size	Amendment	Incorp. rate	Porosity			Water retention		Bulk density
			Total	Macro	Capillary†	Θ_{500}‡	AWHC§	
		v/v	Volumetric content, cm^3 cm^{-3}					g cm^{-3}
Fine (0.10–0.25 mm)	unamended	0	0.450	0.182	0.268	0.025	0.243	1.42
	zeolite	10	0.447	0.225	0.222	0.040	0.182*	1.41
		20	0.444	0.208	0.236	0.064**	0.175**	1.42
	vitrified clay	10	0.442	0.211	0.231	0.039	0.192	1.42
		20	0.430	0.196	0.234	0.062**	0.172**	1.41
	diatomaceous earth	10	0.458	0.228	0.230	0.056**	0.174**	1.39
		20	0.455	0.191	0.264	0.074***	0.190*	1.37
	calcined clay	10	0.452	0.203	0.249	0.049	0.200	1.39
		20	0.464	0.198	0.266	0.075***	0.192	1.34
	sphagnum peat	10	0.445	0.176	0.269	0.064**	0.205	1.36
		20	0.472	0.153	0.319*	0.089***	0.230	1.22
Medium (0.25–0.50 mm)	unamended	0	0.429	0.378	0.051	0.029	0.022	1.47
	zeolite	10	0.435	0.372	0.063	0.028	0.035	1.44
		20	0.445	0.365	0.080**	0.051*	0.029	1.39
	vitrified clay	10	0.432	0.370	0.062	0.044	0.017	1.41
		20	0.433	0.348	0.085***	0.065**	0.020	1.44
	diatomaceous earth	10	0.432	0.357	0.075**	0.038	0.037	1.43
		20	0.462*	0.341**	0.121***	0.072***	0.049*	1.36
	calcined clay	10	0.445	0.369	0.076**	0.051	0.025	1.43
		20	0.467**	0.372	0.095***	0.069***	0.026	1.35
	sphagnum peat	10	0.439	0.346*	0.093***	0.052*	0.041	1.38
		20	0.461*	0.277***	0.184***	0.079***	0.105***	1.23
Coarse (0.50–1.00 mm)	unamended	0	0.384	0.347	0.037	0.006	0.031	1.59
	zeolite	10	0.414	0.361	0.053	0.019	0.034	1.45
		20	0.428**	0.360	0.068***	0.036**	0.032	1.41
	vitrified clay	10	0.420*	0.369	0.051	0.022*	0.029	1.47
		20	0.424**	0.358	0.066**	0.040***	0.026	1.43
	diatomaceous earth	10	0.438***	0.365	0.073***	0.038***	0.035	1.46
		20	0.450***	0.374	0.076***	0.053***	0.023	1.36
	calcined clay	10	0.418*	0.360	0.058*	0.033**	0.025	1.47
		20	0.457***	0.371	0.086***	0.062***	0.024	1.39
	sphagnum peat	10	0.425**	0.342	0.083***	0.035**	0.048	1.40
		20	0.454***	0.329	0.125***	0.071***	0.054*	1.26
Orthogonal contrast								
Peat vs. inorganic amendment			**	***	***	***	***	na¶
Source of variation								
Sand size (S)			***	***	***	***	***	na
Amendment (A)			***	***	***	***	***	na
S × A			**	***	**	ns#	***	na
Rate			***	**	***	***	ns	na
S × R			*	ns	ns	ns	ns	na
A × R			**	ns	***	ns	**	na
S × A × R			ns	ns	ns	ns	ns	na

* Significant at the 0.05 level compared with unamended sand.
** Significant at the 0.01 level compared with unamended sand.
*** Significant at the 0.001 level compared with unamended sand.
† Capillary porosity equals water retained at −0.004 MPa.
‡ Θ_{500} = water retained at −0.05 MPa.
§ Available water holding capacity (AWHC) = capillary water retention − Θ_{500}.
¶ na = not applicable.
# ns = not significant.

sand column, where the gravitational head was zero. There was a curvilinear decrease in soil moisture with height, with the greatest change occurring in the coarse sand and the least in the fine sand. At the top of the column, soil moisture had declined to 0.04, 0.17, 0.36 cm^3 cm^{-3} for the coarse, medium, and fine sand, respectively. The coarse sand held very little water in the top 15 cm of the 30-cm rootzone, whereas the fine sand remained relatively wet throughout the entire rootzone. If used unamended, both sands would present management challenges, with the coarse sand being too droughty and the fine sand lacking adequate aeration, except perhaps in the upper 5 cm of the soil profile. The medium sand appears best suited for shallow (<30 cm) rootzones, based on the balance of water-filled and air-filled pores throughout much of the rootzone.

The shape of the moisture retention curves for drained sand-amendment mixtures (data for 20% incorporation rate, Fig. 3) was generally similar to that for the drained, unamended sands (compare Fig. 2 and 3, for medium sand). All rootzone mixtures were nearly saturated at the bottom of the rootzone. Amended fine sand was nearly saturated at most depths (data not shown), similar to the unamended fine sand. Amendment generally increased water retention compared with unamended sands; SP increased water retention more than IAs (Fig. 3).

Peat amendment rate and incorporation depth had a dramatic effect on water retention of medium sand (Fig. 4). Mixing 20% SP in the top 15 cm increased water retention approximately 0.15 cm^3 cm^{-3}, but only in the top half of the rootzone. Water content in the unamended lower half was similar to that of unamended sand. This might be desirable in terms of soil aeration,

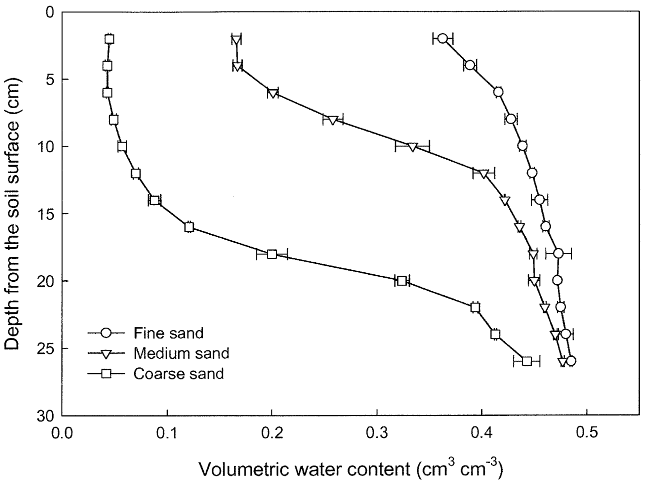

Fig. 2. Moisture retention as a function of soil depth for three USDA sand sizes. Horizontal bars represent ±1 SE of the mean where the bars exceed the size of the symbol.

since incorporating SP throughout the profile resulted in relatively high water content (low aeration) in the lower half. However, the practical considerations of constructing a layered rootzone might argue against this strategy, unless onsite incorporation were used. This practice is rarely recommended because of the tremendous variability in mixing equipment, potential for operator error, and lack of proper quality controls, which would ultimately result in rootzone failure.

Low water retention near the rootzone surface is one of the most limiting factors for turfgrass seed germination and development (USGA, 1993). Moisture retention $\geq$0.15 cm^3 cm^{-3} is necessary for seedling survival and establishment (Bingaman and Kohnke, 1970). Field studies with sand-based rootzones showed that volumetric water retention $<$0.09 cm^3 cm^{-3} resulted in poor turfgrass establishment and required careful maintenance (Carlson et al., 1998). On the basis of these results, moisture content at the surface of both the medium and fine sands, with or without amendments, would be considered adequate for successful turf establishment. Amendments also increased water retention at the surface of the coarse sand. However, with the exception of sand plus 20% SP, none of the coarse sand mixtures retained sufficient water at the surface ($>$0.15 cm^3 cm^{-3}) to assure success.

Available soil moisture is more important than total water content, at least for turfgrass performance. We calculated the amount of available water in the top 15 cm of the 30-cm rootzone for each sand mixture. This depth was chosen as it contains most of the root system. Available water was determined by subtracting the −0.05 MPa value (unavailable) from the volumetric water content measured at each sampling depth, and averaging the results for the entire 15 cm (data not shown). Amendments tended to increase total water retention but had little or no effect on available water. Some of the IAs actually decreased AWHC in the fine and medium sands. Peat was the only amendment that significantly increased available water, and then only in the coarse sand.

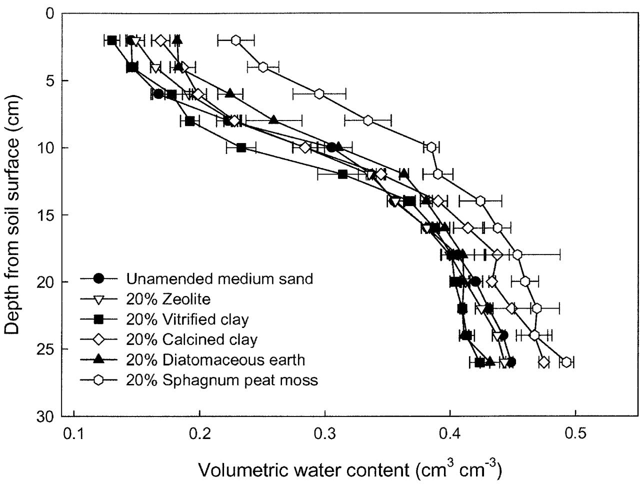

Fig. 3. Moisture retention as a function of soil depth for a medium sand amended (20% v:v) with four inorganic amendments or sphagnum peat moss. Horizontal bars represent ±1 SE of the mean where the bars exceed the size of the symbol.

Bioassay for Plant Available Water

As discussed above, IAs hold considerable moisture, but much of it appears to be unavailable, at least when determined with standard laboratory techniques. This conflicts with the results of Van Bavel et al. (1978) and McCoy and Stehouwer (1998), showing that much of the water contained by some porous IAs is released at tensions consistent with plant availability. One possible explanation for this disparity considers that the pore structure of the IAs might be discontinuous, and that some pores would thus be isolated and disconnected from the tension source of a pressure plate. As such, some fraction of the pores might not drain, even at high tensions. This would result in exaggerated values for unavailable moisture, and reduce the calculated values for available water.

In an attempt to reconcile this disparity, we designed a bioassay to determine available water with evapotranspiration (and root absorption) as the driving force

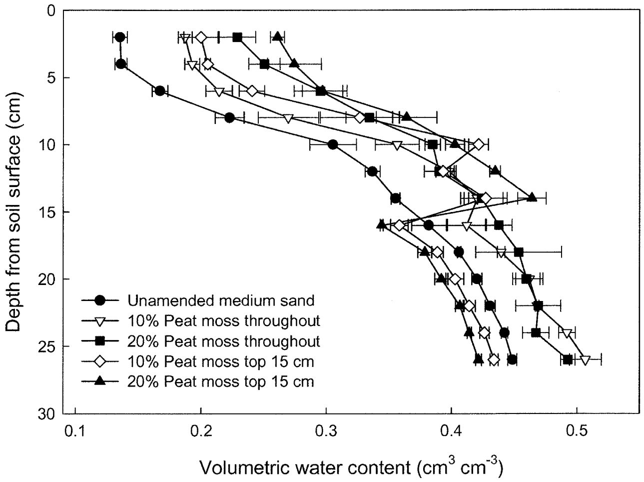

Fig. 4. Moisture retention of a medium sand as a function of rate and depth of amendment with sphagnum peat moss. Horizontal bars represent ±1 SE of the mean where the bars exceed the size of the symbol.

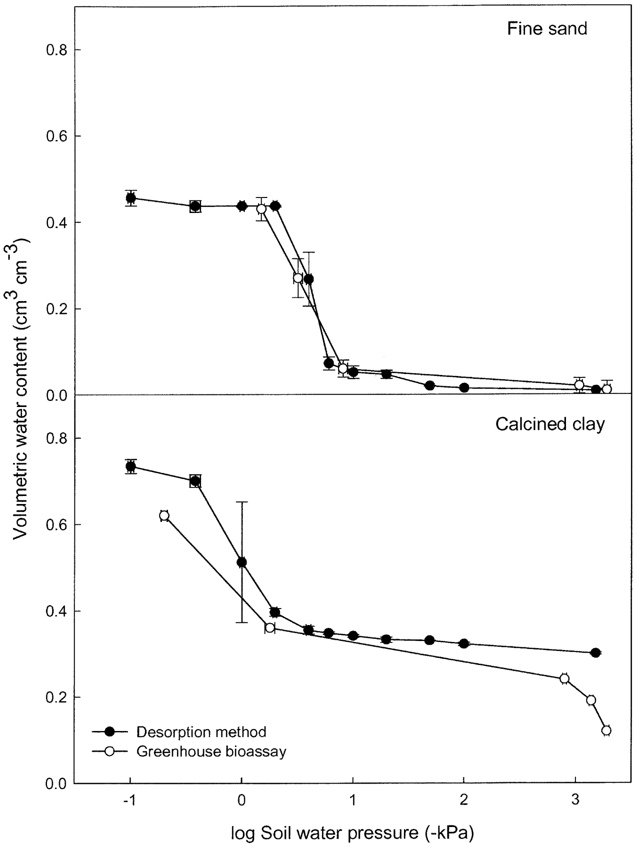

Fig. 5. Moisture release curves for fine sand and calcined clay as determined by the standard desorption method and by a bioassay method. Bars represent ±1 SE of the mean where the bars exceed the size of the symbol.

for water extraction. We hypothesized that the extensive turfgrass root system, including its profusion of root hairs, would be able to contact and access water held in isolated and disconnected pores of the IA. Calcined clay was chosen for study, since it is highly porous and as determined with the pressure plate, retained large amounts (>0.25 cm^3 cm^{-3}) of unavailable water. Perennial ryegrass was selected as a fast-growing species that develops a very dense root system.

The moisture release curves for the sand and Profile were similar in form to those generated with standard methods of physical analysis (Fig. 5). There was good agreement between the two methods for both the fine sand and calcined clay, particularly in the tension range at which most of the water was released. However, there was an important divergence between the two methods for calcined clay at SWP $>$ approximately -100 kPa, with the bioassay indicating greater water removal (>0.10 cm^3 cm^{-3}) than the pressure plate method. This result indicates that the ryegrass plants were able to access and extract much of the capillary water and implies that calcined clay, and perhaps the other porous IAs, hold considerably more available water than standard pressure plate methods might suggest.

CONCLUSIONS

Highly graded sands amended with inorganic or organic amendments had lower bulk densities, generally higher water retention, and variable K_{sat} that was 2- to 15-fold greater than USGA-recommended rates. Amendments had the greatest positive effect on water retention when used in the medium and coarse sands. The lack of effect in fine sand was probably because of its inherently high water retention. Addition of IAs to sand significantly increased total porosity and macroporosity and decreased the AWHC. These effects appear to be related to amendment particle size and internal porosity of the IAs. Among the IAs tested, extruded diatomaceous earth and calcined clay resulted in higher total porosity and overall water retention compared with zeolite and vitrified clay. Only the fine sand plus amendment mixtures consistently met guidelines (USGA, 1993) for pore size distributions. The medium and coarse sands failed because of the large percentage of macropores, which would result in droughty conditions. This result illustrates the advantage of a certain percentage of smaller-sized components in a sand-based rootzone mixture. Finally, although IAs significantly altered the physical properties of unamended sands, compared with SP they were not as effective at sufficiently increasing the AWHC of sand rootzone mixtures.

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