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Research completed at North Carolina State University evaluated several diverse commercially available inorganic amendments as potential peat moss substitutes in newly constructed putting green rootzones.

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PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 290 projects at a cost of $25 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

Editor

Jeff Nus, Ph.D.
904 Highland Drive
Lawrence, KS 66044
jnus@usga.org
(785) 832-2300
(785) 832-9265 (fax)

Research Director

Michael P. Kenna, Ph.D.
P.O. Box 2227
Stillwater, OK 74076
mkenna@usga.org
(405) 743-3900
(405) 743-3910 (fax)

Physical Properties of Sand Amended with Inorganic Materials or Sphagnum Peat Moss

Cale A. Bigelow, Daniel C. Bowman and D. Keith Cassel

SUMMARY

Researchers at North Carolina State University investigated the effects of mixing four commercially available inorganic amendments and a sphagnum peat moss on three sand size classes at two incorporation rates on rootzone physical properties. Some of their findings were:

- Bulk density decreased, total porosity increased, and percolation rates generally declined with amendment rate, but varied considerably depending on amendment and sand size.
- The inorganic amendments significantly altered the physical properties of the three sands, but they were not as effective as sphagnum peat at improving water retention in coarse textured, drought-prone sand sizes.
- Based on standard pressure plate methods, inorganic amendments 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 inorganic amendments may contain appreciably more available water than measured by the pressure plate technique.
- Inorganic amendments may be suitable peat substitutes for putting green rootzone mixtures, however, they cost several times more than peat.

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 (2). 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 peat moss have been mixed with sand to improve water and nutrient retention (1, 10). 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 to a uniform unamended sand (9, 13). One disadvantage of organic amendments is that they decompose with time, reducing their beneficial effects. Additionally, depending on the organic source, decomposition of organic matter may dramatically reduce percolation rates or hydraulic conductivity compared to unamended sand (13). The ideal amendment would be relatively stable, while providing water retention and release comparable to organic amendments.

A number of inorganic materials, including porous ceramics, diatomaceous earth, and zeolites, are currently marketed as alternatives to peat moss 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 to sand (< 2 mm) to maintain high percolation rates and mix uniformly when combined with sand.

Laboratory procedures were used to evaluate several inorganic amendments compared to sphagnum peat for their ability to affect water retention and percolation in sand-based rootzones.

C.A. BIGELOW, Ph.D., Department of Agronomy, Purdue University. West Lafayette, IN; D.K. CASSEL, Ph.D., Department of Soil Science, North Carolina State University, Raleigh, NC; D.C. BOWMAN, Ph.D., Department of Crop Science, North Carolina State University, Raleigh, NC.

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Particle sizes established by the US Department of Agriculture include clay, very fine sand, fine sand, medium sand, coarse sand, very coarse sand, and fine gravel.

Many products have been evaluated with mixed success (6, 12, 14, 15, 19, 21, 25, 26, 27). The major criticism of inorganic amendments is that much of the internally held water does not seem to be plant-available (5, 25). By contrast, Van Bavel (24) reported that fritted clay was an excellent medium for plant growth, providing good aeration and containing 31% of available water, much of it held internally. Unfortunately, few of the aforementioned studies contain results that directly compare inorganic amendments to an appropriate peat moss control, which makes data interpretation difficult.

The overall objective of this study was to evaluate several diverse commercially available inorganic amendments as potential peat moss substitutes in newly constructed putting green rootzones. Specifically we wanted to: 1) to evaluate the physical properties of inorganic amendments alone and when mixed with fine, medium and coarse sand, and compare the physical properties of inorganically amended sands to sand amended

Rootzone Component	**Particle size** ---- mm ---- > 2.0	1.0	0.5	0.25	0.10	0.05	< 0.05	**Geometric† mean diameter**	**Particle density**
	---- % ----							mm	g cm^{-3}
Fine sand	0	0	0	0	100	0	0	0.01	2.62
Medium sand	0	0	0	100	0	0	0	0.25	2.62
Coarse sand	0	0	100	0	0	0	0	0.50	2.62
Zeolite	0	< 0.1	24.2	61.5	13.9	0.1	0.3	0.67	2.32
Vitrified clay	0	0.3	87.1	10.8	1.1	0.7	< 0.1	0.84	2.15
Diatomaceous earth	0	0.5	44.6	53.4	1.0	0.5	< 0.1	0.74	2.27
Calcined clay	< 1	0	71.4	27.2	1.4	< 0.1	< 0.1	0.59	2.50
Sphagnum peat	-	-	-	-	-	-	-	NA	0.63

† Geometric mean diameter calculated according to method of Hillel (9).

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.

with a traditional organic amendment, sphagnum peat moss, 2) investigate plant-available water using laboratory values versus a greenhouse bioassay experiment.

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 sphagnum peat moss. 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, using a standard mechanical shaker sieve.

The four inorganic amendments were Ecolite (a clinoptilolite zeolite, Western Organics, Inc., Tempe, AZ), Isolite (an extruded diatomaceous earth, 78% SiO_2, 12% Al_2O_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_2O_3; 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 inorganic amendment was determined by sieving and

Rootzone component	Porosity Total	Porosity Macro	Porosity Capillary†	Water retention 500‡	Water retention AWHC§	Bulk Density
	%					$g\ cm^{-3}$
Fine sand	45.0 c	18.2 b	26.8 bc	2.5 c	24.4 a	1.42
Medium sand	42.9 c	37.8 a	5.1 d	2.9 c	2.2 c	1.47
Coarse sand	38.4 c	34.7 a	3.7 d	0.6 c	3.1 c	1.59
Zeolite	60.6 b	37.2 a	23.4 c	20.6 b	2.8 c	0.87
Vitrified clay	56.7 b	32.1 a	24.6 c	20.8 b	3.8 c	0.84
Diatomaceous earth	72.2 a	36.4 a	35.8 b	34.2 a	1.6 c	0.59
Calcined clay	73.4 a	38.0 a	35.4 b	33.2 a	2.2 c	0.64
Sphagnum peat	74.4 a	22.4 b	52.0 a	34.3 a	17.7 b	0.15

†Capillary porosity refers to water retained at -0.004 MPa or 40 cm.
‡ 500 equals water retained at -0.05 MPa or 500 cm.
§Available water holding capacity (AWHC) equals Capillary water retention minus 500.
Means followed by the same letter in the same column are not significantly different under Fisher's protected LSD (P = 0.05).

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

the geometric mean diameter (Table 1) was calculated according to methods of Hillel (9). Sphagnum peat moss referred to hereafter as "peat" (Bordnamona Co., Dublin, Ireland, 97.3 % organic matter by loss on ignition) was used as a standard for inorganic amendment 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 peat were equivalent to 0.51 and 1.20% organic matter by weight, respectively. Physical properties of the sands, amendments and their respective mixtures were determined by placing air-dry portions of each mixture in stainless steel cylinders (1.5 in tall x 2.23 in 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 (8). These measurements were made at a constant temperature of 20 C. Water retention of the inorganic amendments and three sands was also measured at pressures of -0.05, -0.1 and -1.5 MPa by the pressure plate method (4) Three replications of each sand or amendment were used in a completely random experimental design for all measurements.

Total porosity was calculated using measured bulk density and particle density as determined by the pycnometer method (7). 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 (23). Available water holding capacity 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* using 12-inch deep rootzone mixtures, equivalent to the compacted depth of most sand-based putting green rootzones. Columns (3 in. I.D. x 14 inch tall) were constructed from acrylic tubing and equipped with access measurement ports (0.7 in diam.) located at 0.8-inch intervals in a spiral arrangement down the sides of each column corresponding to depth intervals from 0.8 to 10 inches 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 prior to 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 (23). These tests are normally conducted using small steel cylinders (2- or 3-inch diam. x 3-4 inch tall), not the full 12-inch rootzone depth. Because of the unique *in situ* column approach used to determine moisture content with depth, a preliminary study was conducted to determine the most effective packing method which would not disturb the side-wall 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 12-inch deep rootzone. Based on these measurements, air-dry sand or sand/amendment were pre-weighed, 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 12 inches deep.

In addition to the 10 and 20% rates, each amendment was also evaluated at two incorporation depths: throughout the entire 12-inch depth, (referred to as "throughout") and incorporated only in the top one-half of the 12-inch 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 6 inches 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 hours, saturated hydraulic conductivity (K_{sat}) was determined by the constant head method (11), 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 (0.4-inch diameter x 3 inches) of the media were then sampled at each access port and oven dried for 24 hours at 105 C to determine volumetric water content.

Bioassay for Available Water

The amount of available water held by some of the amendments, as obtained using standard desorption techniques (see above) seemed surprisingly low, and were in direct conflict with results documenting considerable available water in other calcined clays (24). Consequently, a bioassay was designed to estimate plant-available water in fine sand and calcined clay, using 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 (6-inch diam. x 4.5 inches deep) were fitted with two small tensiometers (Soil Moisture Systems, Las Cruses, NM) located on each side of the pot 2 inches above the bottom. A layer of cheese-cloth was placed in the bottom of the pot which was then filled to a depth of 4 inches with the fine sand or the calcined clay. Perennial ryegrass (*Lolium perenne* L. 'Competitor') was seeded at 5 lbs per 1000 ft^2 and grown in the greenhouse for 10 weeks in the spring, during which the plants were well watered and fertilized with 1/4 lb N per week 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-day 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 meas-

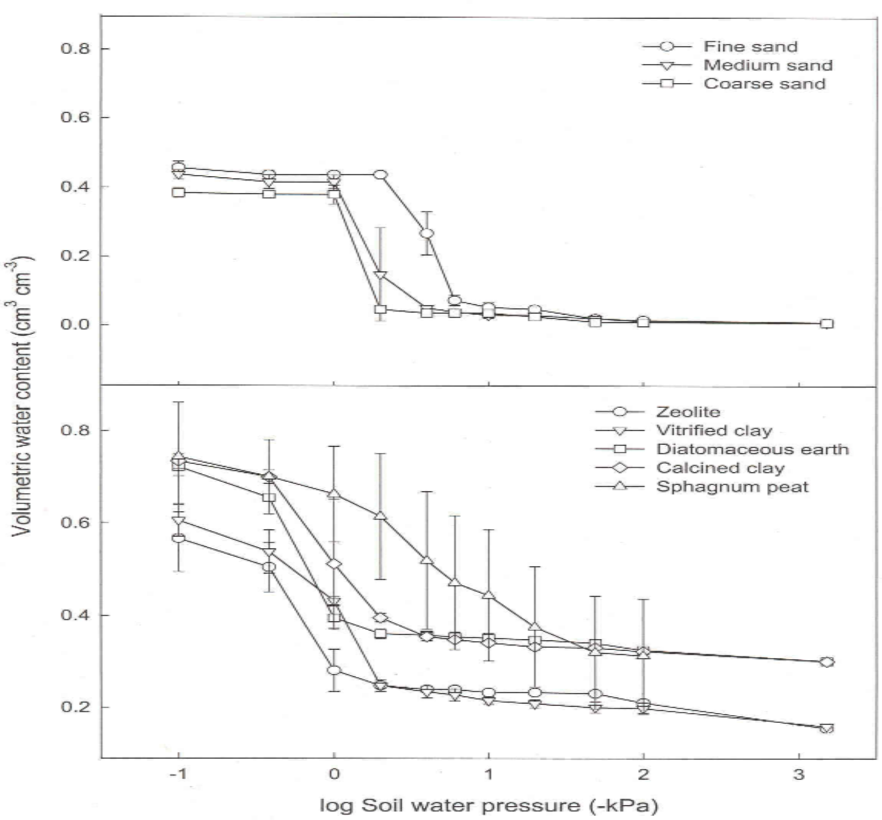

Figure 1. Moisture release curves (0 to -1500 kPa) for three USDA sand size classes and five amendments.

uring leaf water potential (higher tensions).

Leaf water potential was measured using a hydraulic press (J-14 Leaf Press, Decagon Devices, Pullman, WA) technique (28). Briefly, three representative leaves were removed at each sampling period, the lamina segments (approx. 2 inches) 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 analysis of variance (ANOVA) using the Statistical Analysis System (SAS Institute, Inc.). Separation of significantly different treatment means was accomplished using pre-planned orthogonal contrasts (22). Means were separated with Fishers protected LSD if the ANOVA F-test indicated that source effects were significant. Amended sand rootzone mixtures within each sand class were compared to the unamended sand control using Dunnett's test (22).

The laboratory experiments were conducted using a completely random factorial design. The pore size distribution and water retention data were analyzed as a two-factor study (sand size, incorporation rate) and the *in situ* study as a three-factor study: (sand size, incorporation rate, and incorporation depth).

			Porosity			**Water retention**		**Bulk density**
Sand size	Amendment	Incorp. Rate (v/v)	Total	Macro	Capillary†	Θ_{500}‡	AWHC§	
			------------- Volumetric content (%)			----------------		g cm^{-3}
Medium (0.25-0.50 mm)	Unamended	0	42.9	37.8	5.1	2.9	2.2	1.47
	Zeolite	10	43.5	37.2	6.3	2.8	3.5	1.44
		20	44.5	36.5	8.0 **	5.1 *	2.9	1.39
	Vitrified clay	10	43.2	37.0	6.2	4.4	1.7	1.41
		20	43.3	34.8	8.5 ***	6.5 **	2.0	1.44
	Diatomaceous earth	10	43.2	35.7	7.5 **	3.8	3.7	1.43
		20	46.2 *	34.1 **	12.1 ***	7.2 ***	4.9 *	1.36
	Calcined clay	10	44.5	36.9	7.6 **	5.1	2.5	1.43
		20	46.7 **	37.2	9.5 ***	6.9 ***	2.6	1.35
	Sphagnum peat	10	43.9	34.6 *	9.3 ***	5.2 *	4.1	1.38
		20	46.1 *	27.7 ***	18.4 ***	7.9 ***	10.5 ***	1.23

†Capillary equals water retained at -0.004 MPa or 40 cm.

‡ Θ_{500} equals water retained at -0.05 MPa or 500 cm.

§ Available water holding capacity (AWHC) equals capillary minus Θ_{500}.

*,**,*** represents significant, at 0.05, 0.01, 0.001 levels respectively compared to unamended sand.

Table 3. Porosity, water retention and bulk density of a medium sand and medium sand/amendment mixtures.

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 (26.8 %, 24.4%, respectively) than either the medium or coarse sand which only retained 5.1 to 3.7 % volumetric water, respectively. Most successful sand-based rootzones contain > 15 % but less than 25 % (2, 23), 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 to a predominantly "medium" sand from a commercial source.

The amendments had significantly greater total porosity (macro + capillary) than any of the three sands, with the ranking: peat = calcined clay = diatomaceous earth > zeolite = vitrified clay > fine sand = medium sand = coarse sand. Peat, calcined clay, and diatomaceous earth had greater than 70 % total porosity, compared to 40-45 % for the sands. Macroporosity was generally similar, greater than 30 %, for all amendments and the medium and coarse sands, reflecting similar particle sizes. It is apparent that the inorganic amendments have a much higher capillary porosity than the medium and coarse sands, primarily due to 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 inorganic amendments should help in selecting appropriate amendments

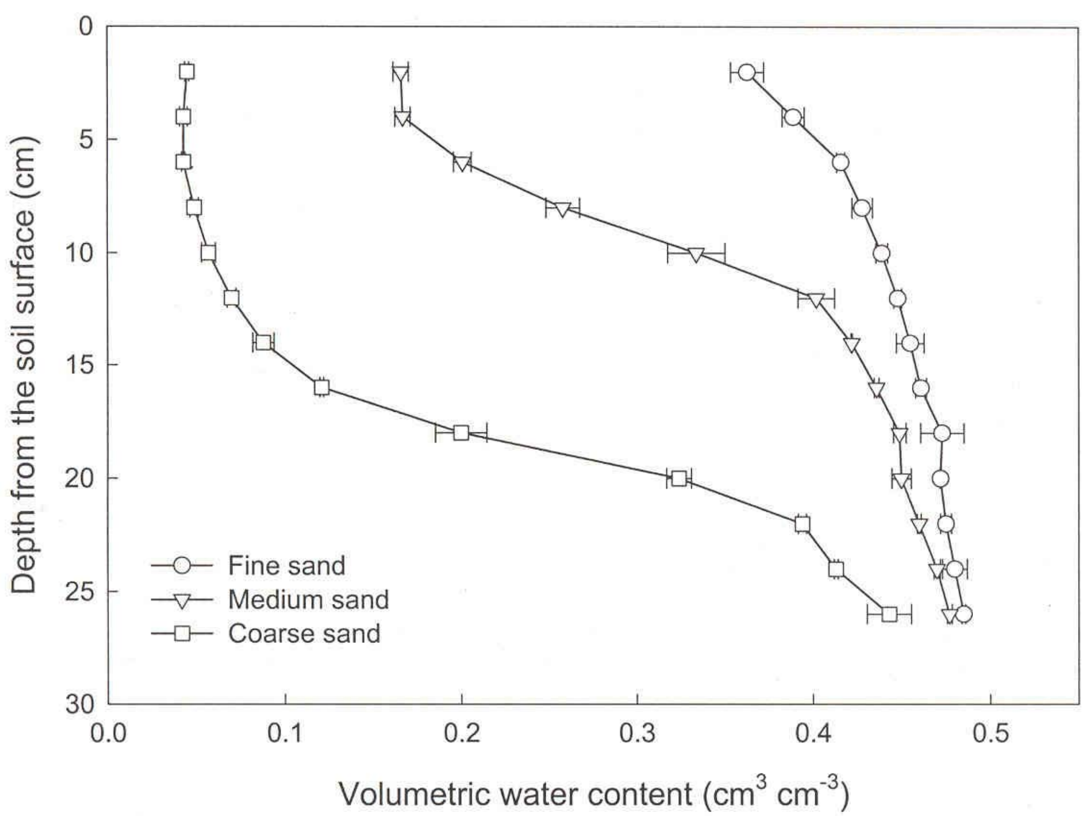

Figure 2. Moisture retention as a function of soil depth for three USDA sand sizes

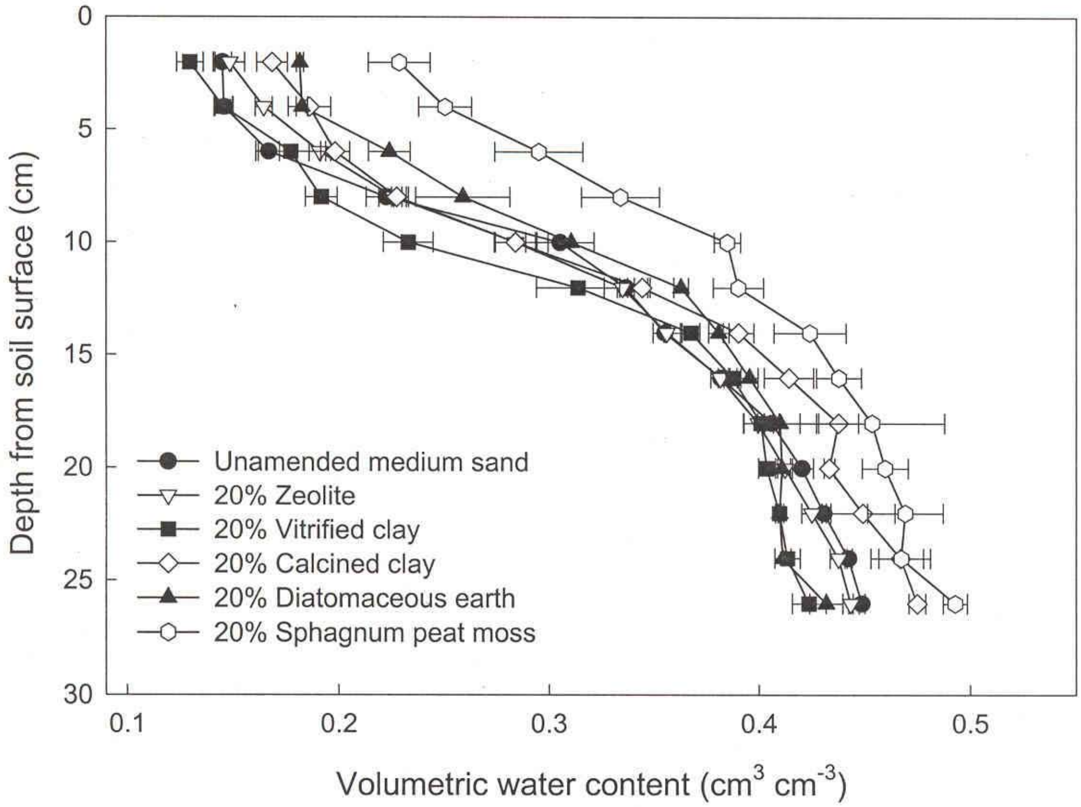

Figure 3. Moisture retention as a function of soil depth for a medium sand amended (20% by volume) with four inorganic amendments or sphagnum peat moss

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 28 to 36 % water between saturation and -0.002 MPa. In constructed rootzones deeper than 8 inches, this water would be lost through gravitational drainage and thus would be unavailable for plant use. In contrast, fine sand released only 0.4 % water at this low tension. Thus, the fine sand retains a substantial amount of water that may be available for plant growth.

To further characterize the moisture release properties of the amendments and three sands, water retention data were collected for a range of soil water pressures (SWP). Each sand and amendment generally had a characteristic tension at which much of the water was released (Figure 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 to the sands, the inorganic amendments and peat contained significantly more water at saturation, > 55 %, and released this water more gradually with decreasing SWP up to -0.006 MPa. At SWP less than -0.006 Mpa, water release from the inorganic amendments leveled off and remained relatively constant to -1.5 MPa SWP. Peat moss had the most gradual release for any of

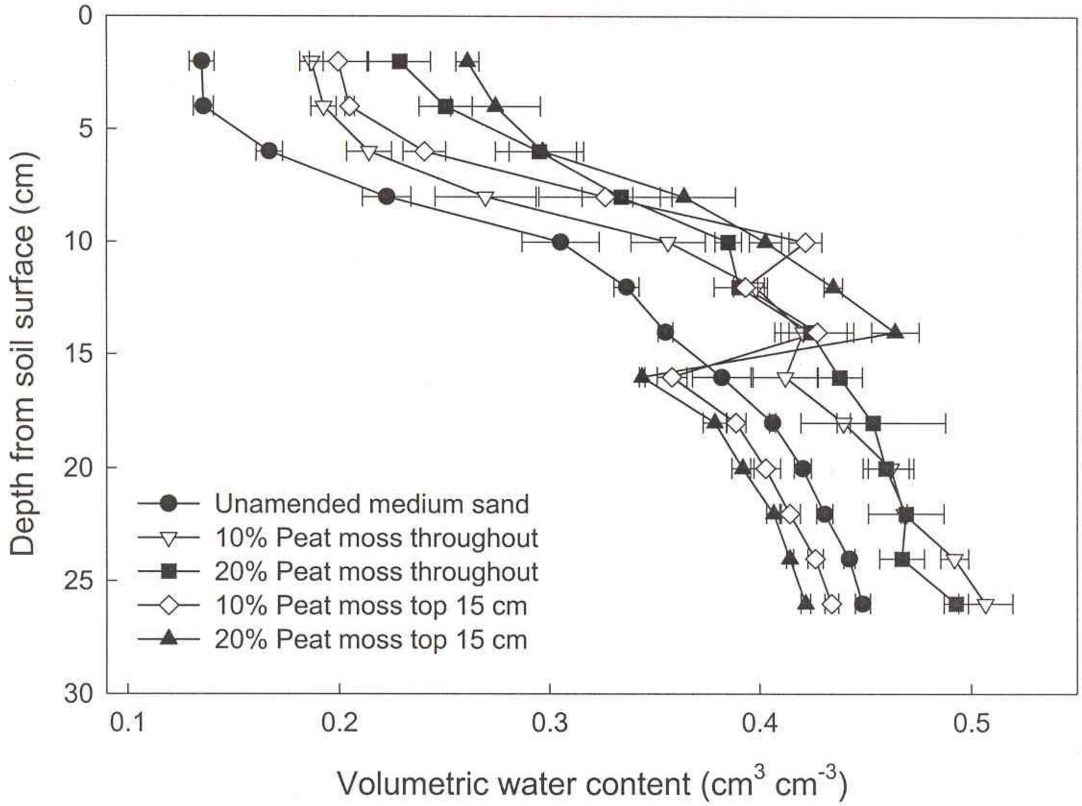

Figure 4. Moisture retention of a medium sand as a function of rate and depth of amendment with sphagnum peat moss

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 20 to 34 % (Table 2), and lowest in unamended sands (0.6 to 3 %). Available water holding capacity (AWHC) was highest for the fine sand (24 %) whereas the other sands and inorganic amendments had AWHC's less than 4 %. 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 12-inch deep rootzone.

Amendments had little effect on macroporosity in all three of the sands, but had the most dramatic effect on capillary porosity in the medium and coarse sand classes (Table 3 data presented for the medium sand only). 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% peat 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 due to 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 15-30 % and 15-25 % for macropores and capillary water retention, respectively (23). This is largely due to the inherent ability of fine sand to retain moisture, even without amendment. The medium and coarse sand classes failed to meet specifications due to 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% peat, which met USGA guidelines. Several fine sand mixtures failed to meet guidelines (10% and 20% peat; 20% diatomaceous earth and calcined clay) due to 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 peat having the greatest effect. Similar results were observed by Junker and Madison(10), Waddington et al.(25), and Waltz et al. (26). These results are not surprising since the particle density of the amendments was somewhat less than sand. Bulk density alone however is not considered to be an adequate indicator of a successful rootzone mixture (23).

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity or percolation rates were very high for all three sands, and increased with amendment coarseness (35, 83 and 198 inches per hour for the fine, medium, and coarse sand, respectively, data not shown). Amendments decreased percolation 13-50% 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 percolation rates for each amendment across all three sand classes ranked in the following order: vitrified clay = zeolite > unamended sand > diatomaceous earth > calcined clay > peat. Amending only the top 6 inches had less impact on percolation than incor-

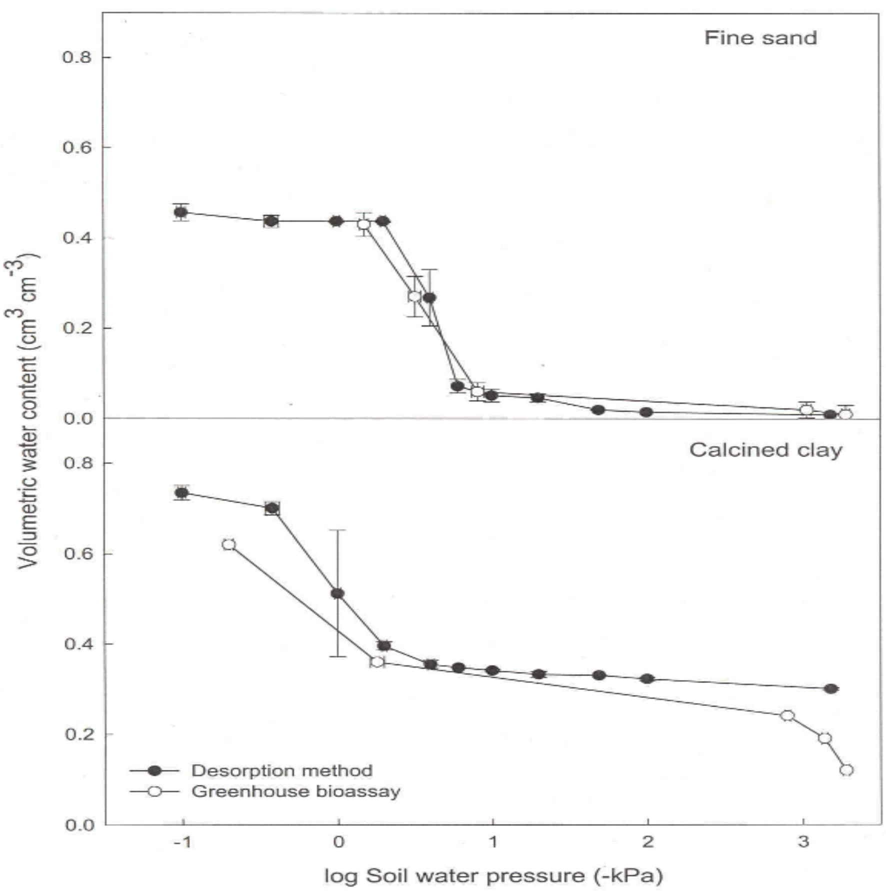

Figure 5. Moisture release curves for fine sand and calcined clay as determined by the standard desorption method and by a greenhouse bioassay method

poration throughout the entire 12-inch deep rootzone; the 20% amendment rate decreased conductivity more than the 10% rate (data not shown).

These percolation rates are much higher than the USGA guidelines of 6 to 12 inches per hour (23), most likely due to our use of highly uniform sands. This is consistent with results of Bingaman and Kohnke (2), who reported similar high values for several well-graded fine and medium sands.

<u>*Water Retention and Availability of Simulated Rootzones*</u>

Soil moisture profiles (Fig. 2) varied considerably, depending on sand size. All three sands were close to saturation (~45 % moisture) at the bottom of the 12-inch 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 4, 17 and 36% for the coarse, medium and fine sand, respectively.

The coarse sand held very little water in the top 6 inches, 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 2 inches of the soil profile. The medium sand appears best suited for shallow (< 12 inches) 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, Figure 3) was generally similar to that for the drained, unamended sands (compare Figures 2 and 3, for medium sand). All rootzone mixtures were nearly saturated at the bottom of the rootzone. Amended fine sand was nearly saturated (45 % moisture) at most depths (data not shown), similar to the unamended fine sand. Amendment generally increased water retention compared to unamended sands; peat increased water retention more than inorganic amendments (Figure 3).

Peat amendment rate and incorporation depth had a dramatic effect on water retention of medium sand (Figure 4). Mixing 20 % peat in the top six inches increased water retention approximately by 15 %, 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, since incorporating peat 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 (23). Reasonable moisture retention > 15 % is necessary for seedling survival and establishment (2). Field studies with sand-based rootzones showed that volumetric water retention < 9 % resulted in poor turfgrass establishment and required careful maintenance (3). Based on 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% peat, none of the coarse sand mixtures retained sufficient water at the surface (> 15 %) 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 6 inches of the 12-inch 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 6 inches (data not shown). Amendments tended to increase total water retention, but had little or no effect on available water. Some of the inorganic amendments 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.

Bioassay for Plant Available Water

As discussed above, inorganic amendments hold considerable moisture, but much of it appears to be unavailable, at least when determined using standard laboratory techniques. This conflicts with the results of Van Bavel (24) and McCoy and Stehouwer (14) showing that much of the water contained by some porous inorganic amendments is released at tensions consistent with plant availability. One possible explanation for this disparity is that the pore structure of inorganic amendments 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 using evapotranspiration (and root absorption) as the driving force 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 inorganic amendment. Calcined clay was chosen for study, since it is highly porous and, as determined with the pressure plate, retained large amounts (> 25 %) 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 (Figure 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 (> 10 %) 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 inorganic amendments hold considerably more available water than standard pressure plate methods might suggest.

Major findings and implications

Highly graded sands amended with inorganic or organic amendments had lower bulk densities, generally higher water retention, and variable saturated hydraulic conductivity 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 due to its inherently high water retention.

Addition of inorganic amendments to sand significantly increased total and macro porosity and decreased AWHC. These effects appear to be related to amendment particle size and internal porosity of the inorganic amendments. Among the inorganic amendments tested, extruded diatomaceous earth and calcined clay resulted in higher total porosity and overall water retention compared to zeolite and vitrified clay. Only the fine sand plus amendment mixtures consistently met guidelines (23) for pore size distributions.

The medium and coarse sands failed due to 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. Although a large percentage of macropores seems undesirable due to the potential for drought, rootzones constructed on the slightly coarser side might be preferable to those constructed with extremely fine sands over the long-term. Declining percolation rates from initial values over time have been documented in several studies, sometimes as much as 33-90% in the first six months (16, 18, 25).

Finally, although inorganic amendments significantly altered the physical properties of unamended sands, compared to peat moss they were not as effective at sufficiently increasing the AWHC of sand rootzone mixtures. The dominant matrix in any successful sand-based rootzone starts with selecting a proper sand and modifying the particle size distribution to bring water retention and percolation rates in line with suggested USGA guidelines.

Lastly, in a cost comparison between peat moss and the two most common inorganic amendments, a calcined clay and a zeolite, it was discovered that to use the inorganic amendments at an equivalent incorporation rate it would cost as much as five times more (17).

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