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GREENS MANAGEMENT

Physical and Hydraulic Properties of Rootzone Mixes Amended with Inorganics for Golf Putting Greens

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ABSTRACT

A trend to replace peat with inorganic amendments such as calcined clay (CC) and diatomaceous earth (DE) is occurring for athletic fields and golf course putting greens. For laboratory experiments, washed rootzone sand was amended at 15% (v/v) with either Canadian sphagnum peat (CSP), CC, or DE. Amendments reduced the bulk density and increased the total porosity of all mixtures. The DE mixture had the lowest K_{sat} (41.9 cm h^{-1}), which was attributed to the 2% by weight of particles <0.05 mm in diameter. The inorganic mixtures retained 0.021 to 0.084 cm^3 cm^{-3} less water than the CSP mixture at pressures less than −2.5 kPa. The CSP mixture held significantly more water in the entire profile and in the upper 15 cm compared with the inorganic mixtures and straight sand. Approximately 75% of the total water was lost within the first 15 min after drainage initiation for sand alone and the inorganic mixtures; only 65% was lost in the first 15 min for the CSP mixture. After 24 h of free drainage, the CC mixture lost the most water, while the DE mixture lost the least. Differences among the rootzone mixtures were measured in the first 3 min of drainage, with straight sand and the CC mixture having the greatest flow rate compared with DE and CSP mixtures. After 24 h of free drainage, the gravel layer remained saturated. For improved water retention in the rootzone, CSP remains the preferable amendment to sand when mixed at these ratios.

Since 1960, when the U.S. Golf Association (USGA) released the first specifications for golf putting green construction (U.S. Golf Assoc. Green Section Staff, 1960), many golf greens and athletic fields have been constructed with sand-based rootzone mixes. High sand content provides rapid drainage, limits soil compaction, and promotes aeration for root growth, despite sand's inefficiency in retaining moisture and nutrients (Beard, 1973). Also, with years of continuous traffic, individual sand particles within a putting green can move and become tightly packed (Taylor and Blake, 1981). Amendments, organic and inorganic, are possible means to reduce soil compaction and leaching, while increasing plant available water and nutrient holding capacity.

Peat, reed sedge or sphagnum, are the most common amendments used in putting green construction (Waddington, 1992). The benefits of peat include reduced soil bulk density, improved rootzone aeration, increased soil moisture retention, gradual release of plant-available water, and improved turfgrass germination (Letey et al., 1966; McCoy, 1992; Juncker and Madison, 1967; Bigelow et al., 1999). Because peat is an organic material and subject to natural decomposition, it may eventually lose its desirable characteristics (Huang and Petrovic, 1995). Also, because peat is a naturally occurring resource, the supply is limited. Therefore, the amendment of putting green rootzones with a possible peat replacement material that will retain its physical properties for many years is desired. Inorganic soil amendments such as calcined clay (CC) and diatomaceous earth (DE) have been identified as possible substitutes for peat in high sand content rootzones.

Positive characteristics of inorganic amendments include resistance to degradation (4 and 9.5%, respectively, using impact/abrasion tests) and low bulk densities (0.56–0.64 g cm^{-3} and 0.39–0.59 g cm^{-3} respectively) (Wasura and Petrovic, 2001; Petrovic et al., 1997; Waddington, 1992). Additional attributes include high porosity and greater water holding capacity than sand (Bigelow et al., 2000; Li et al., 2000). These physical properties allow inorganic amendments to withstand compaction and improve infiltration and aeration.

A reported disadvantage of inorganic amendments is adsorbed water being bound too tight within the internal pore space of the particle to be available to the turfgrass plant (Waddington, 1992). For straight CC, Bigelow et al. (2000) reported 0.35 cm^3 cm^{-3} capillary water retention at −4.0 kPa tension and 0.33 cm^3 cm^{-3} water retention at −50.0 kPa tension, resulting in a 2% available water holding capacity. Similar properties were reported for DE. With large amounts of water retained at high tensions, it was concluded that these amendments were composed of very small pores. Likewise, Li et al. (2000) reported a DE product to have greater internal porosity than CC. To the contrary, McCoy and Stehouwer (1998) concluded a CC amendment released water from internal pores at tensions (−12.8 kPa) below reported first signs of turfgrass wilt.

The objectives of this research were (i) to evaluate selected hydraulic properties of a rootzone sand amended with peat, calcined clay, or diatomaceous earth; and (ii)

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Abbreviations: BD, bulk density; CC, calcined clay; CSP, Canadian sphagnum peat; DE, diatomaceous earth; USGA, United States Golf Association; VHP, Vitel HydraProbe.

Table 1. Particle-size distribution of rootzone sand and rootzone media amended with Canadian sphagnum peat (CSP) and inorganic amendments, calcined clay (CC), and diatomaceous earth (DE) at 15% by volume along with the gravel used to construct simulated golf greens.

	Particle size, mm						
Rootzone media	**>2.0**	**1.0**	**0.50**	**0.25**	**0.10**	**0.05**	**<0.05**
	% by wt.						
Sand	0.0	4.9	37.1	43.8	13.7	0.4	0.2
CC	0.0	0.0	59.2	40.0	0.7	0.2	–
DE	0.0	23.3	68.9	5.9	1.4	0.6	–
Sand: CSP	0.0	6.9	35.6	41.4	15.1	0.5	0.5
Sand: CC	0.0	2.9	28.9	46.2	21.1	0.6	0.3
Sand: DE	0.0	3.4	30.3	44.6	19.0	0.6	2.0
USGA† specifications	<10		>60		<20	<10	
		Particle size, mm					
		12.7	**6.3**	**4.0**	**2.0**	**<2.0**	
		% by wt.					
	Gravel	0.0	86.2	12.9	0.4	0.6	

† U.S. Golf Association.

to establish a basis for choice of a particular amendment for rootzone sand.

MATERIALS AND METHODS

Rootzone media were constructed using washed quartz sand (Golf Agronomics, Lugoff, SC) commonly used for putting green construction in South Carolina. Various rootzone media were prepared using one of three amendments, Canadian sphagnum peat (93.4% organic matter loss on ignition at 800°C), a calcined clay product (PROFILE, Aimcor Consumer Products, Buffalo Grove, IL), and a diatomaceous earth product (PSA, Golf Ventures, Lakeland, FL). To prepare media, amendments were added to sand on a 15% v/v basis using bulk densities of 0.13, 0.59, and 0.46 g cm^{-3} for peat, CC, and DE, respectively.

Particle-size distribution of the sand, individual inorganic amendments, and various rootzone media are presented in Table 1. For the sand and gravel fraction, particle-size distribution was determined by mechanical sieving, while the pipet method was used to separate the fine fraction (<0.05 mm) (Gee and Bauder, 1986). Physical properties of the rootzone media were determined by standard methods and presented in Table 2 (Hummel, 1993). Total porosity was calculated using measured bulk density and particle density. Macroporosity, or air-filled porosity, was calculated by subtracting the −4.0 kPa water content from the total porosity, while microporosity was determined as the volumetric water content at −4.0 kPa. These physical data were derived from the average of five replications.

Saturated hydraulic conductivity (K_{sat}) of prepared rootzone mixes was measured using a mariotte tube (Klute and Dirksen, 1986) to maintain a constant water head of 11.3 cm with water flow upward through the soil. Eight replications of each rootzone mixture were hand packed into 4.8-cm diameter plastic tubes and sealed with a plastic cap and liquid electrical tape to ensure the columns were airtight. The outer reservoir of the mariotte tube was filled with distilled deionized water and the top of the tube was open to the atmosphere for soil columns to slowly saturate from the bottom to the top. Once saturated, the outer reservoir of the mariotte tube was capped and a constant head was established as the difference in elevation between the inner mariotte tube and the outlet tube. Water flowing through the sample for the first 10 min was discarded. Thereafter, water was allowed to flow through the sample for 12 min with 4 subsamples collected on 3-min intervals. The volumes of water were collected, measured, and K_{sat} calculated. All data were averaged using the SAS general linear model procedure with means separated using least significant difference (LSD) at $\alpha = 0.05$ (SAS Inst., 2001).

Water Retention Curves

To establish water retention characteristic for straight sand, samples of dry sand were packed into 5.4-cm diameter metal rings. After slowly saturating the samples from the bottom up, water retention of each mixture was determined by the water desorption method using a hanging water column (Jury et al., 1991). For straight sand, natural saturation was 0.081 $\text{cm}^3\ \text{cm}^{-3}$ less than total porosity. To check the pressure applied on the sample by the water column, a hole was drilled into the metal ring, a 0.95-cm ceramic tensiometer was inserted, and then connected to a mercury manometer by a 0.18-cm i.d. nylon tube. Rings were filled with sand and water retention was determined as before with pressure measurements taken at each lowering of the water column. A 1:1 relationship would

Table 2. Physical properties of rootzone sand and rootzone media amended with peat and inorganic amendments at 15% by volume used for simulated putting greens.

Rootzone media	Particle density	Bulk density	Total porosity†	Air-filled porosity‡	Capillary porosity§	K_{sat}¶
	g cm^{-3}		$\text{cm}^3\ \text{cm}^{-3}$			cm h^{-1}
Sand	2.65	1.61	0.392	0.191	0.201	64.1b
Sand: peat	2.62	1.41	0.460	0.152	0.308	62.6c
Sand: calcined clay	2.68	1.48	0.449	0.191	0.258	70.3a
Sand: diatomaceous earth	2.64	1.50	0.433	0.189	0.244	41.9d
USGA specifications	–	–	0.35–0.55	0.15–0.30	0.15–0.25	30–60

† Total porosity was calculated as Total porosity = [1 − (Bulk density ÷ Particle density)].

‡ Air-filled porosity was calculated as the difference between total porosity and capillary porosity.

§ Capillary porosity determined at −4.0 kPa pressure.

¶ Saturated hydraulic conductivity was determined using a mariotte tube to maintain a constant head. Means followed by the same letter in the same column are not significantly different at $P = 0.05$ (LSD = 1.3, CV = 7.51).

be expected between pressure applied by the water column and pressure measured by the tensiometer. However, measured pressures were consistently lower for the tested range (0 to −4.5 kPa). Therefore, the water retention curve for these rootzone mixtures were determined as described by Juncker and Madison (1967).

Columns 45 cm high were assembled by connecting 37 polyvinyl chloride (PVC) rings (5.2 cm i.d. with a wall thickness of 0.4 cm) together with vinyl electrical tape. Each ring was 1.3 cm high, except the next to last bottom ring, which was 2.5-cm high. To retain the rootzone mixture, four layers of cheesecloth covered the bottom ring. Each premixed, air-dried mixture was added and tamped as individual rings were attached until the full 45-cm column was constructed. Filled columns were placed in an equally high plastic container and saturated with distilled, deionized water from the bottom to the top until ponding at the surface was observed. After the columns were allowed to equilibrate overnight, most of the water was siphoned from the plastic container to the point that the bottom 3.8-cm remained below the waterline. During drainage, the top of each column was covered with plastic wrap to prevent evaporation. Columns were allowed to drain for 72 h before they were sectioned from top to bottom by removing the tape and inserting a thin metal spatula between each ring. To determine water content, individual rings were placed in preweighed cans, weighed, oven-dried (105°C) overnight, and reweighed. Moisture content was determined for each ring and data were plotted as tension vs. gravimetric moisture content (θ_{wt}). Volumetric moisture content (θ_v) was calculated as the product of the θ_{wt} and the bulk density. This experiment was repeated three times with two columns included in each run for each rootzone mixture and data were analyzed using the SAS general linear model procedure with means separated using least significant difference (LSD) at $\alpha = 0.05$ (SAS Inst., 2001).

Drainage Columns

Similar to columns constructed for moisture retention curves, experimental rootzones were built as nine-ring columns. The entire 38.1-cm columns were constructed from PVC rings. The bottom ring (7.6 cm) was filled with gravel meeting USGA specifications for golf putting greens (Table 1) and the remainder of the columns was filled with the various rootzone mixes (U.S. Golf Assoc. Green Section Staff, 1993). The rootzone was eight total rings, four 1.3-cm rings overlay the gravel ring, one 2.5-cm ring followed, and three 7.6-cm rings extending to the surface, giving a total depth of 30.5 cm of rootzone media. Rootzone columns were constructed, filled, and wet as described for moisture retention columns.

To determine total cumulative drainage and drainage flux characteristics, each column was allowed to freely drain with drainage being caught at specific time intervals (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4, 5, 10, 15, 20, 30, 60, 120, and 1440 min) for the first 24 h. After 24 h, the column was sectioned as described for water retention columns to determine θ_{wt} and θ_v. This experiment was repeated four times with two columns included in each run for each rootzone mixture, data were analyzed as previously described.

Tension Readings

In a process similar to Morgan et al. (1966), columns were constructed from 25.4-cm i.d. (0.8 cm thick wall) PVC pipe (Fig. 1). Individual columns were 40 cm high with a 2.0 cm i.d. hole drilled at the bottom for drainage and wetting. A 10-cm layer of gravel (Table 1) was placed in the bottom of the columns (approximately 8.5 kg, giving a bulk density of 1.69 g cm^{-3}). Thirty centimeters of air-dry rootzone media (Table 1) were added in several stages. The surface of each stage was tamped and scarified before additional media was

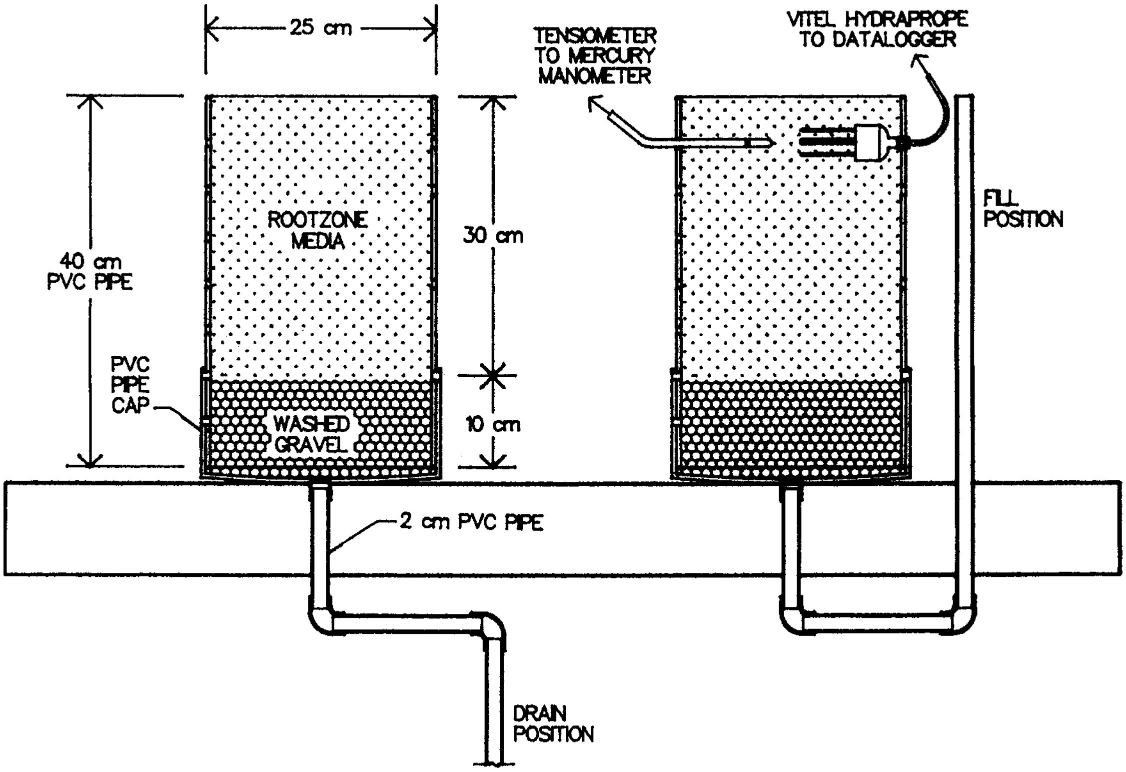

Fig. 1. Schematic diagram of columns used for tension and moisture probe measurements.

added until a 30-cm height was reached. No separation of the amendments during the filling process was evident.

Ceramic tensiometers (0.95 cm o.d.) were inserted through holes on the side of the column at depths of 5, 10, 15, 20, 25, 30, and 35 cm below the soil surface. The tensiometer at the 35-cm depth was constructed into the gravel layer when the gravel was added; the other tensiometers were pressed into place after the filling process to ensure good soil contact. A 0.18-cm i.d. nylon tube ran from the tensiometer to a mercury manometer board.

The tensiometers at 5, 10, 20, and 30 cm were positioned opposite from Vitel HydraProbes (VHP) (Vitel, Chantilly, VA), which were inserted during construction. The VHP were multiplexed (AM416 Relay Multiplexer, Campbell Scientific, Logan, UT) and connected to a data logger (Campbell 21X Micrologger, Campbell Scientific, Logan, UT) with readings taken on 1-min intervals (due to size of data set only selected intervals will be presented). Raw probe output voltages were downloaded and transformed to volumetric water content using manufacturer-supplied software. Once VHP calculated water contents were derived, water contents were adjusted using calibration curves derived from preliminary studies.

By extending the drainpipe to an up position, columns were saturated from the bottom up to minimize entrapped air. Once wetting was complete, a 0.5-cm head was established and columns were allowed to equilibrate for 0.5 h. To initiate drainage, the drainpipe was capped, rotated to a down position, and uncapped. Drainage was caught 5, 10, 15, 30, 60, 120, and 1440 min after the initiation of drainage and determined on a mass basis. To reduce evaporation and ensure loss of water through drainage alone, columns were covered with plastic. Corresponding tension readings were made at each time and soil pressure potential was calculated using the equation:

$$\psi_m = -[(12.55x) - y - z] \qquad [1]$$

where ψ_m is the pressure potential (cm), x is the height of mercury rise (cm), y is the height from the soil surface to the mercury surface (cm), and z is the depth of the tensiometer below the soil surface (cm) (Cassel and Klute, 1986).

Due to space and equipment constraints, one column of each mix was prepared but was wetted and allowed to drain three times. Pressure potential, 24 h flux, and volumetric water content by depth data were the average of the three runs for each material.

RESULTS AND DISCUSSION

Physical Properties

Compared to straight sand, the addition of CSP decreased bulk density by 12.4%, while the addition of an inorganic amendment reduced bulk density by a maximum of 8.1% (Table 2). This was anticipated since CSP had the lowest BD (0.13 g cm^{-3}) of the three amendments. Likewise, the addition of an amendment increased the total porosity of the sand mixtures as much as 0.068 cm^3 cm^{-3}. At a water potential of −4 kPa, sand modified with CSP had 0.107 cm^3 cm^{-3} more capillary water than sand alone. Compared with sand, the addition of an inorganic amendment increased capillary porosity by 0.043 to 0.057 cm^3 cm^{-3} for DE and CC mixtures, respectively. These results agree with those of Li et al. (2000) and McCoy and Stehouwer (1998).

The K_{sat} for three of the four combinations (sand alone and sand amended with CSP or CC) exceeded the U.S. Golf Assoc. Green Section (1993) accelerated infiltration range specifications of 30 to 60 cm h^{-1} (Table 2). Rootzone sand amended with DE was the only mixture within this range. Amendment of sand with CC increased K_{sat} 9.7%, while the addition of CSP and DE decreased K_{sat}, 2.3 and 34.6% respectively, compared with unamended RZS. Similarly, increased K_{sat} with the addition of CC to sand was reported by Smalley et al. (1962). Also, others (Li et al., 2000; McCoy and Stehouwer, 1998) have reported depressed K_{sat} values with DE amended sand, however, not as extreme as in this research. Relative to the other rootzone mixtures, a possible reason for lower K_{sat} values when sand is amended with DE could be attributed to the dusty nature of the DE product. The sand–DE combination had a greater number (four times greater than other combinations) of fines, particles below the 0.05-mm size fraction (Table 1). However, the amount of fines remaining after successive leaching of water through the rootzone was not determined; therefore, K_{sat} might increase in these media as the fine particles are leached from the rootzone.

Bigelow et al. (2001) reported greater (about five times higher) K_{sat} measurements of a sand with similar particle-size distribution as used in our experiments. Like the columns of Bigelow et al. (2001), our columns were packed with dry material. However, columns in our study were allowed to saturate at the time of testing compared with being saturated and drained to −4 kPa before being packed, as described by the Hummel (1993) procedure. Also, in our experiments, a constant head was maintained with a mariotte tube. Our results were similar to the ranges prescribed by the USGA and congruent to results of others (Li et al., 2000; McCoy and Stehouwer, 1998).

Water Retention and Drainage

The saturated volumetric water content (θ_{vsat}), θ_v at 0 kPa, and the total porosity (Table 2) should be identical. However, using the Juncker and Madison (1967) method to determine the moisture release characteristic (Fig. 2), the measured θ_{vsat} was less than the calculated θ_{vsat} from the total porosity for each mixture. The natural saturation was 0.063, 0.015, 0.076, and 0.034 cm^3 cm^{-3} lower than total porosity for sand and mixtures of CSP, CC, and DE, respectively. The difference between the two measurements was considered a measure of air entrapment (Klute, 1986).

Gravimetric and volumetric water retention curves for sand and sand amended with CSP, CC, and DE are presented in Fig. 2. At all tensions, sand amended with CSP or an inorganic amendment retained 0.015 to 0.116 cm^3 cm^{-3} more water than unamended sand. Compared with sand amended with CSP, inorganic amendment mixtures retained 0.021 to 0.084 cm^3 cm^{-3} less water at pressures >-2.5 kPa, while at more negative pressures no differences were measured.

Water holding properties of the amended sand overlaying gravel followed a similar trend as water retention curves (Fig. 3). On a volumetric basis in the upper 25 cm,

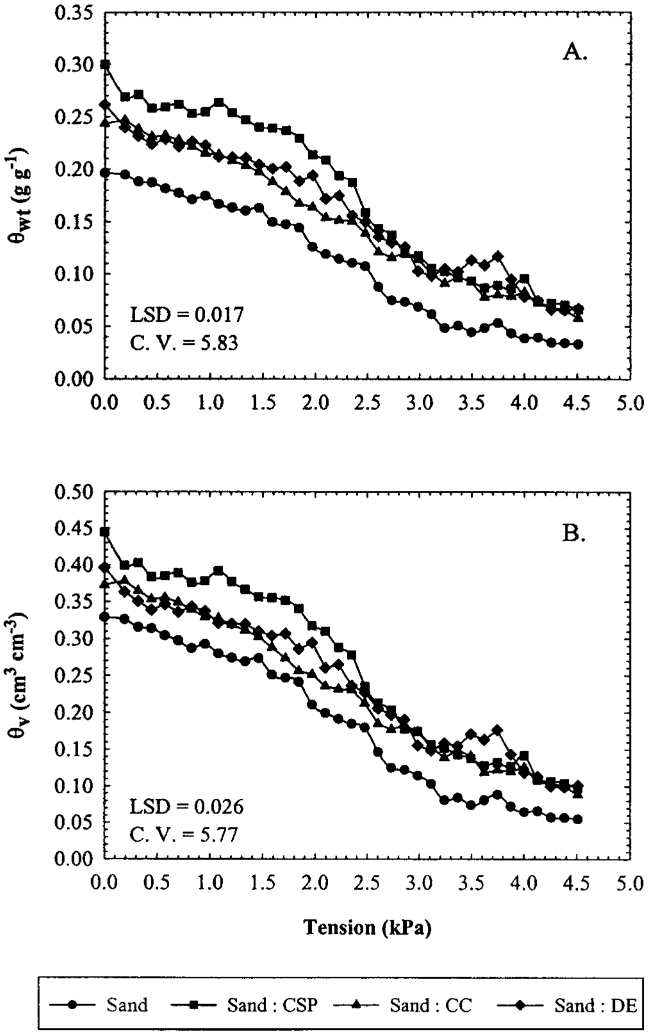

Fig. 2. (*A*) Gravimetric and (*B*) volumetric water retention curves for rootzone sand, and sand amended with 15% v/v Canadian sphagnum peat (CSP), calcined clay (CC), or diatomaceous earth (DE).

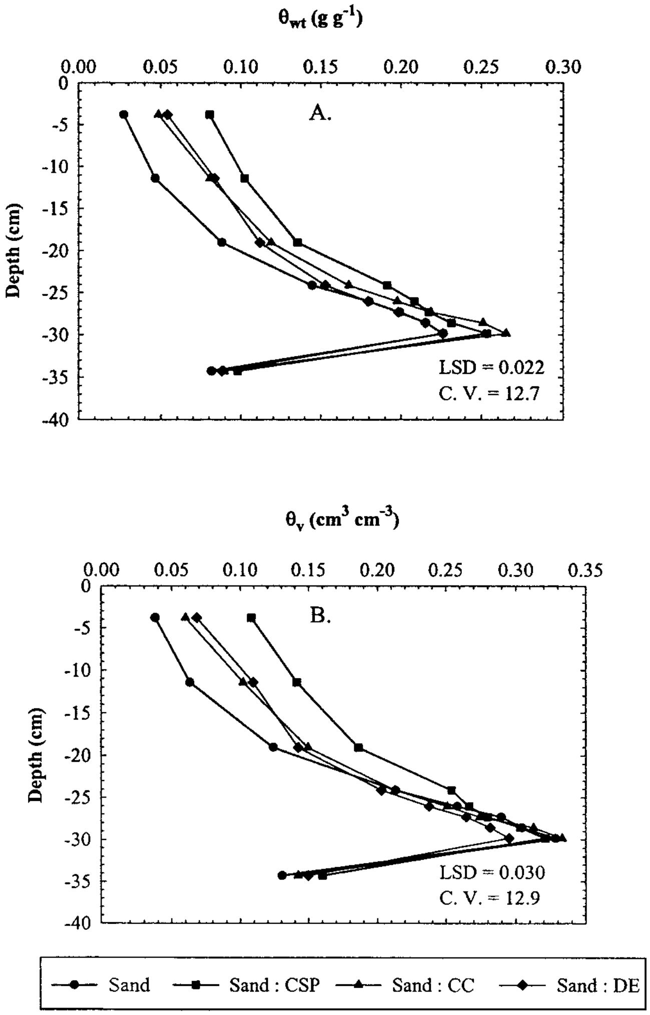

Fig. 3. (*A*) Gravimetric and (*B*) volumetric water content with depth for rootzone sand, and sand amended with 15% v/v Canadian sphagnum peat (CSP), calcined clay (CC), or diatomaceous earth (DE) overlaying 7.6 cm of gravel meeting U.S. Golf Association specifications.

the CSP mixture held 0.041 to 0.078 cm^3 cm^{-3} more water than sand and 0.032 to 0.051 cm^3 cm^{-3} more than the inorganic mixes. Similarly, sand amended with an inorganic amendment held 0.022 to 0.046 cm^3 cm^{-3} more water in the upper 17 cm of the rootzone. For all depths, differences were not measured between the inorganic mixtures; also, differences between sand and other mixtures were not detected below the 25-cm depth.

For each soil mixture, the addition of an amendment to sand caused significant differences in the amount of water retained at various depths (Table 3). After 24 h of free drainage, CSP-amended sand retained the most water (27.0 cm) within the profile, while straight sand retained the least (19.9 cm). Likewise, sand amended with CSP retained 3.5 to 7.1% more water in the upper 7.6 cm of the rootzone and 3.1 to 7.6% more at 7.6- to 15.0-cm intervals than unamended sand or the inorganic mixtures. In the upper half of the profile, straight sand retained the least water compared with amended mixtures; however, this trend was reversed in the bottom 15 to 30 cm of the profile. Rootzone sand retained 6.1

Table 3. Water retention following 24 h of free drainage of rootzone sand and rootzone media amended with Canadian sphagnum peat (CSP) and inorganic amendments, calcined clay (CC), and diatomaceous earth (DE) at 15% by volume. All mixtures overlay 7.6 cm of gravel meeting U.S. Golf Association specifications.

Rootzone media	Total water retained	Depth, cm 0–7.6	7.6–15	15–30	<30
	cm	% total water retained			
Sand	19.9c	6.1c	31.0c	43.3a	18.2b
Sand: CSP	27.0a	13.2a	38.6a	32.5c	15.7c
Sand: CC	23.1b	8.3bc	34.9b	37.2b	19.6a
Sand: DE	22.8b	9.7b	35.5b	34.0c	20.7a
SE	0.70	0.01	0.01	0.01	0.01

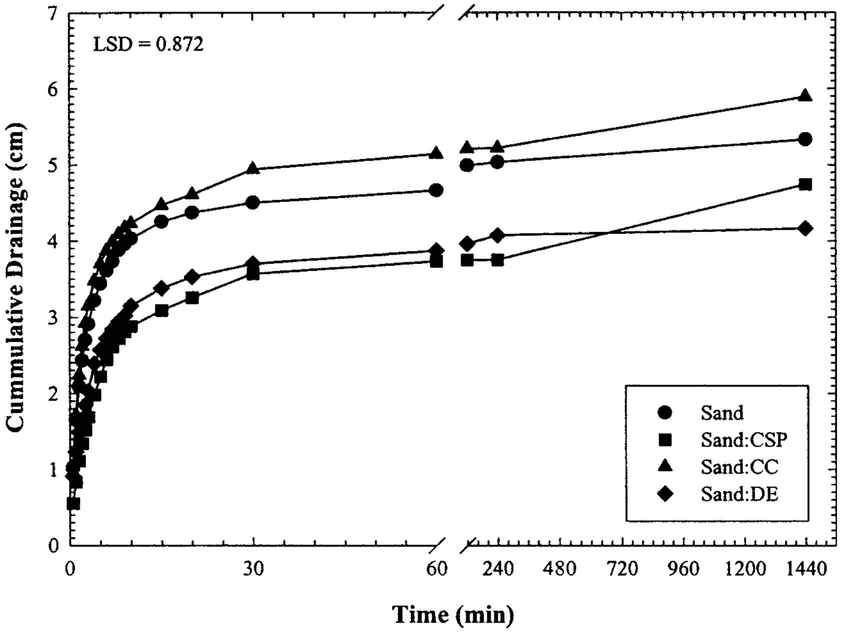

Fig. 4. Cumulative drainage with time for rootzone sand, and sand amended with 15% v/v Canadian sphagnum peat (CSP), calcined clay (CC), or diatomaceous earth (DE) overlaying 7.6 cm of gravel meeting U.S. Golf Association specifications.

to 10.8% more water than the amended mixtures. Below the 30-cm depth, sand amended with an inorganic amendment retained 1.4 to 5% more water than straight sand or the CSP mixture. The reason for water retention below the 30-cm depth can be attributed to the migration of rootzone media into the larger pores of the gravel layer; thus, a transition layer was formed (Elrick et al., 1981). Of the total water retained in the profile, 15 to 21% was found below the 30-cm depth.

Figure 4 shows cumulative drainage with time for each rootzone mixture. Although different amounts of water drained through each mixture, >75% of the total water lost through drainage occurred within the first 15 min for three (sand and the inorganic amendment mixtures) of the four rootzone mixtures. For the CSP mixture, only 65% of the total water drained from the rootzone at 15 min; an additional 15 min was required to reach 75%. Also at 15 min, sand amended with DE or CSP allowed 25 to 38% less water to pass through the soil column compared with straight sand. The CC mixture was not different from the unamended sand. Although at a slower rate, water continued to drain for 240 min. After 1440 min (24 h) of free drainage, the CC mixture lost 5.9 cm of water, while the DE mixture

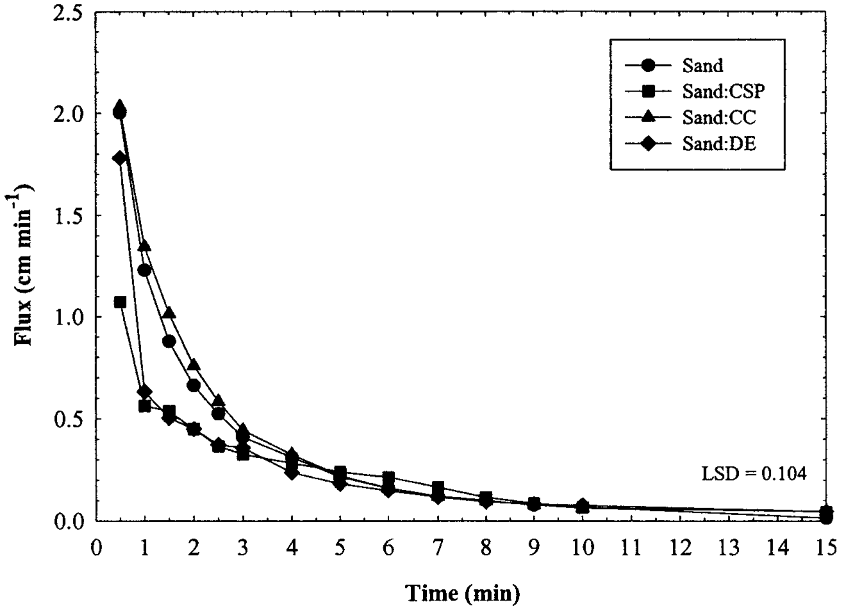

Fig. 5. Flux with time for rootzone sand, and sand amended with 15% v/v Canadian sphagnum peat (CSP), calcined clay (CC), or diatomaceous earth (DE) overlaying 7.6 cm of gravel meeting U.S. Golf Association specifications.

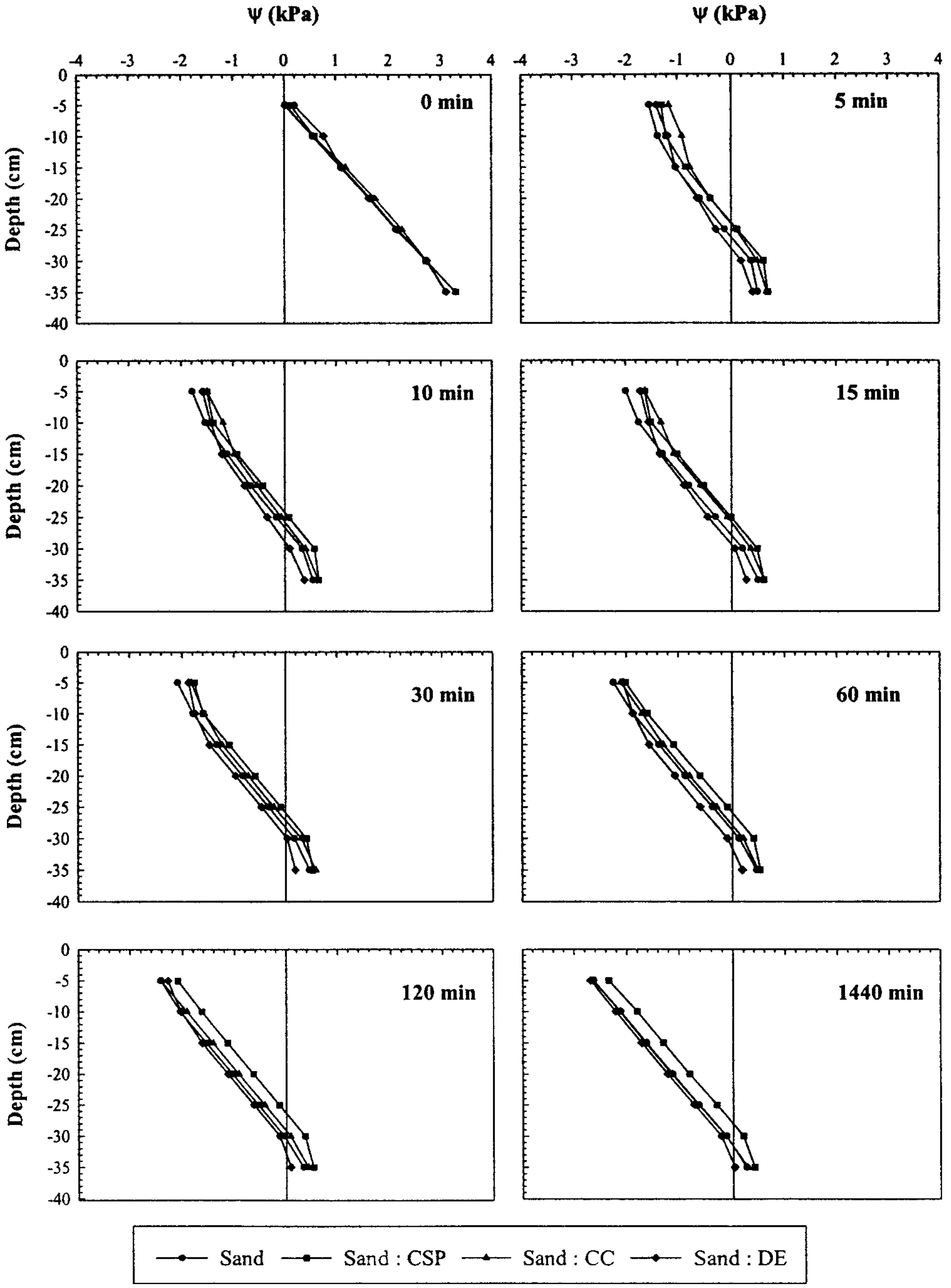

Fig. 6. Pressure potential with depth for rootzone sand, and sand amended with 15% v/v Canadian sphagnum peat (CSP), calcined clay (CC), or diatomaceous earth (DE) overlaying 7.6 cm of gravel meeting U.S. Golf Association specifications.

lost the least, 4.2 cm. Between 240 and 1440 min, the CSP mixture lost an additional 1 cm of water, indicating continual drainage. Others have noted a more gradual loss of water in sand amended with peat, compared with unamended sand or sand amended with an inorganic amendment (Bigelow et al., 2000; McCoy and Stehouwer, 1998).

Flux with time was plotted to determine the velocity of water movement through the rootzone mixes (Fig. 5). Differences between mixes were observed within the first 3 min following the onset of drainage. After 0.5 min, the downward flow of water for sand and the CC mixture was 2.0 cm min^{-1}, while DE and CSP mixtures were significantly less, 1.8 and 1.1 cm min^{-1}, respectively. As flow velocities decreased during the first 3 min, this trend continued; thereafter, no differences between any rootzone mixes were measured. After 15 min, the downward flow for all mixes was <0.05 cm min^{-1}. Water velocity measurements of these magnitudes were an indication the bulk of the drainage had concluded.

Water Potential

Pressure potential measurements within the various sand mixtures during a 1440-min (24 h) drainage period are shown in Fig. 6. At 0 min after drainage, positive

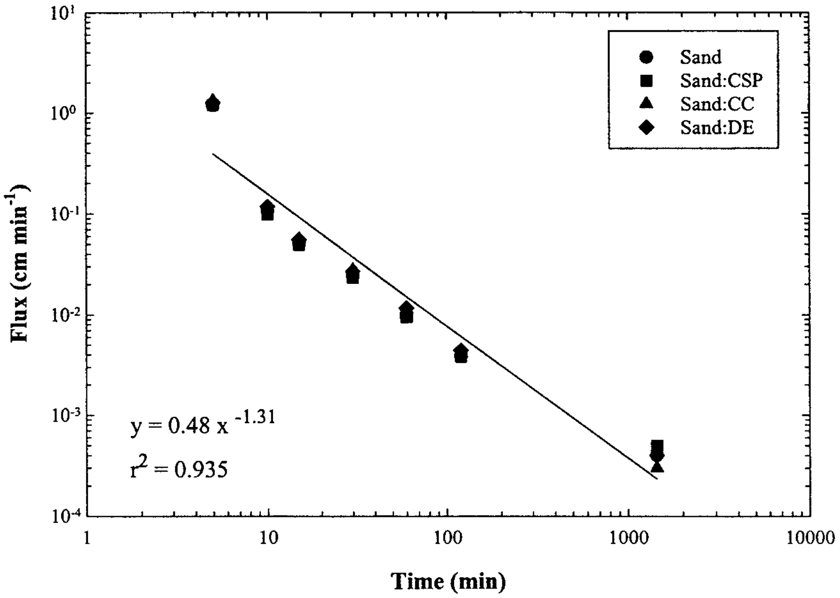

Fig. 7. Flux during a 24-h drainage period for rootzone sand, and sand amended with 15% v/v Canadian sphagnum peat (CSP), calcined clay (CC), or diatomaceous earth (DE).

pressure potentials were measured throughout the profile, indicating saturation. Drainage in the upper 5 cm from the columns was rapid in all soil mixtures, with pressure potentials falling to <-1.0 kPa within 5 min of the removal of surface water. Also, at 5 min, negative pressure potentials were measured for all mixtures to the 20-cm depth, while positive pressure potentials were recorded at the 25-cm depth for the CSP and CC mixtures and all mixtures at 30 and 35 cm. The drop in pressure potentials was followed by a gradual decrease in potential through the remainder of the drainage period.

Interestingly, at the 35-cm depth, positive pressure potentials were measured 1440 min for all mixtures, indicating free water within the gravel layer. At this same time, drainage flux for all amendments ranged from 0.0003 to 0.0005 cm min^{-1} (Fig. 7), indicating drainage had nearly ceased and columns had almost reached equilibrium. Previous reports have not indicated the presence of free water in the gravel layer of a rootzone profile constructed to USGA specifications.

By relating pressure potentials to the water retention curve (Fig. 2), θ_v at each depth was estimated (Fig. 8). At 5 min, decreases in θ_v were measured at the 5- through 20-cm depth, but were not discernible below the 25-cm depth; the exception was DE-amended sand, which had a 0.053 cm^3 cm^{-3} decrease. As would be expected, θ_v decreased through the remainder of the drainage period. After 1440 min of drainage, three of the four mixtures remained saturated at the 30- and 35-cm depths; the exception was the DE mixture, with a 0.040 cm^3 cm^{-3} decrease.

The amendments used in this study had different effects on the physical and hydraulic properties of sand. Despite the increase of total porosity when CSP and DE were added to sand, the addition of these amendments decreased the air-filled porosity and hindered water movement. Also, a high proportion of fine particles may influence water dynamics within the rootzone. The result was lower K_{sat} and flow rates compared with unamended sand. However, the addition of CC to sand increased the K_{sat} and flux, although the air-filled porosity for the CC mixture and unamended sand were identical.

In amended sand mixtures, 0.015 to 0.116 cm^3 cm^{-3} more water was retained compared with unamended sand. The location of water in the profile is important for turfgrass roots, especially in the upper portion of the rootzone. Of the water retained in the rootzone, the CSP mixture held >50% in the upper 15 cm, while straight sand held the least (37.1%). Comparing the inorganic amendments, the DE mixture held slightly more water in the upper 15 cm than the CC mixture, 45 and 43%, respectively. However, with the abruptness with which incipient wilt in turfgrass becomes severe wilt, the slightest increase of water in the rootzone may make a difference in turfgrass survival.

A USGA rootzone is conceptualized as a layered system; however, sand and amendments move into the pore space of the gravel, if only in the upper few millimeters (Baker and Binns, 2001). Therefore, a transition layer is formed and this layer may influence the distribution of water. Negative pressure potentials were measured at the 30-cm depth after 1440 min of drainage. However, at this depth, tensions were not great enough to remove water from the largest pores, resulting in a water-saturated zone at the 30-cm depth.

In every soil mixture, water content decreased from the surface to the gravel layer. It has long been believed that the construction of a layered profile to establish a reservoir of water in the lower portions of the rootzone is desirable for turfgrass survival. Often the roots of

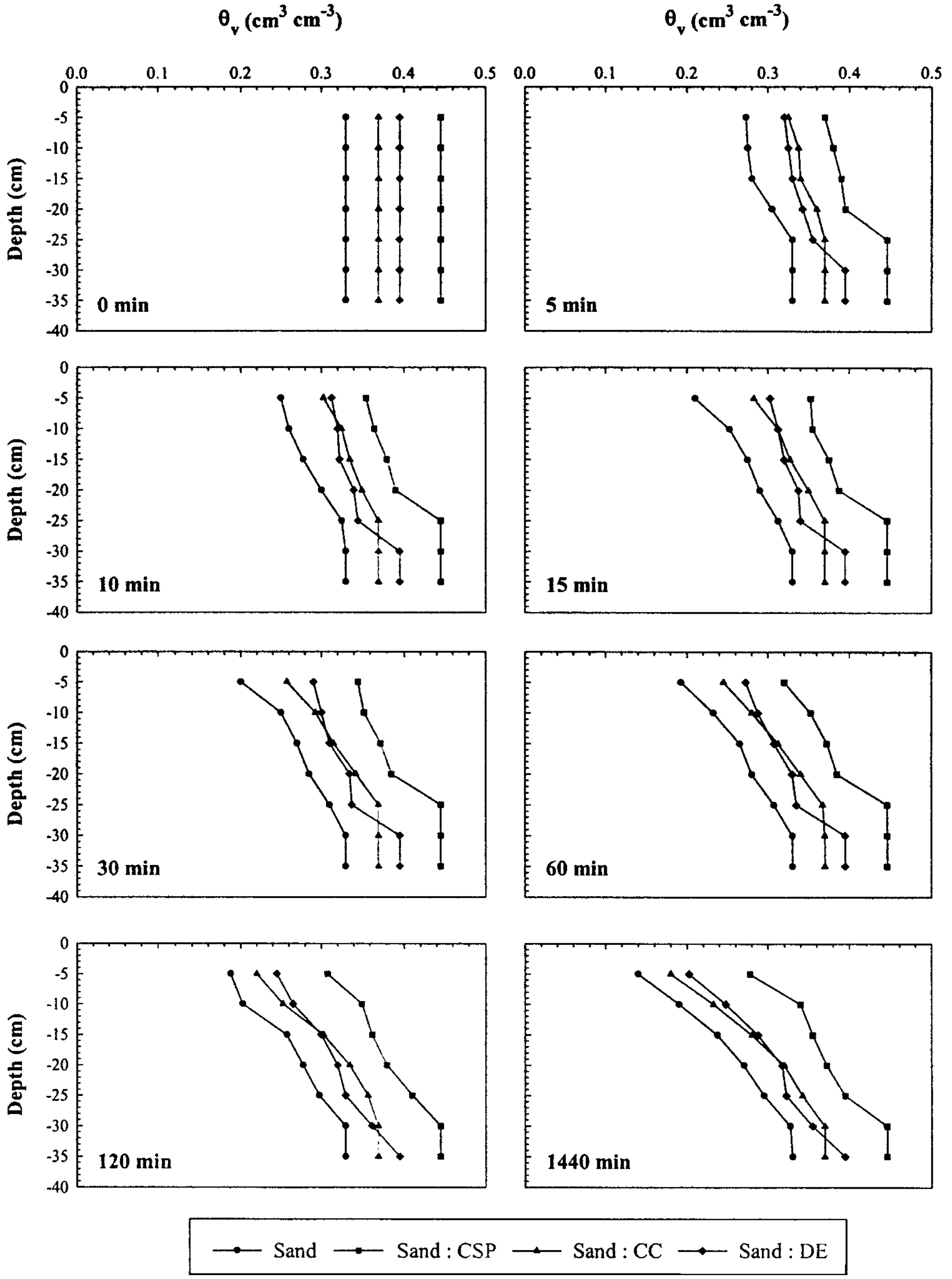

Fig. 8. Estimation of volumetric water content (θ_v) from the water retention curve at 7 depths within a 40-cm rootzone for the first 24 h following drainage for rootzone sand, and sand amended with 15% v/v Canadian sphagnum peat (CSP), calcined clay (CC), or diatomaceous earth (DE).

closely mowed turf do not extend into the lower depths; thus, this water is unavailable to the roots. Others have suggested the increased water retention in the lower sections of the rootzone may lead to reduced root growth and other problems associated with wet soils (Taylor et al., 1997).

Straight (100%) sand profiles built to USGA specifications retain water poorly in the upper half of the rootzone. Of the materials tested, peat had better overall attributes as an amendment to the sand used in this research. It could be assumed amendments that slow water movement and retain more water in the upper portion of the rootzone would result in turf with less water stress than turf grown on media that retained less water due to rapid drainage. By comparing the physical analysis and the hydraulic properties of the various rootzone media, it appears that sand amended with CSP would provide the most conducive rootzone for turfgrass growth. As with the conclusions of McCoy and Stehouwer (1998), the DE mixture had water retention and drainage characteristics most similar to the CSP mixture and of the two inorganic amendments evaluated; therefore, it would probably make the better substitute for peat in putting green rootzone media in terms of water relations.

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