

An Alternative Method for Measuring Plant Available Water in Inorganic Amendments

Matthew J. Curtis* and Victor P. Claassen

ABSTRACT

Inorganic amendments (IA) added to the rootzone of turfgrass are used to increase plant available water (PAW), however conflicting amounts of PAW contents have been reported for some of these amendments. The concept of PAW and the common technique used to estimate PAW in IAs have been reviewed. We hypothesized that hydraulic nonequilibrium in pressure-plate measurements results in an underestimation of PAW. An alternative standardized method of measuring PAW in coarse-textured inorganic amendments is proposed using a combination of pressure plates, saturated salt solutions and a dew-point potentiometer. Water release curves were measured for four IAs (calcined clay, calcined diatomaceous earth, calcined volcanic ash mixed with diatomaceous earth, and zeolite) and their PAW contents determined. Results show that the proposed method provides a more accurate -1500 J kg^{-1} water content measurement than the pressure-plate method. Pressure-plate hydraulic nonequilibrium at -1500 J kg^{-1} resulted in a 0.002 to $0.012 \text{ m}^3 \text{ m}^{-3}$ underestimation of PAW. The IAs examined in this study did not release appreciable amounts of internally held water until they were exposed to matric potentials more negative than usual in turfgrass management ($<-300 \text{ J kg}^{-1}$). The use of a standardized methodology for estimating PAW in IAs, such as the one described in this paper, will help to provide needed consistency and accuracy in information to practitioners.

M.J. Curtis and V.P. Claassen, University of California, Davis, LAWR, 1110 PES BLDG, One Shields Ave., Davis, CA 95616-8627. Received 31 Jan. 2008. *Corresponding author (mjcurtis@ucdavis.edu).

Abbreviations: IA, inorganic amendment; PAW, plant available water; CVAD, calcined volcanic ash and diatoms; CC, calcined clay; CDE, calcined diatomaceous earth; Zeo, zeolite; FC, field capacity; PWP, permanent wilting point.

INORGANIC AMENDMENTS such as calcined clays (CC) and calcined diatomaceous earth (CDE) have commonly been added to the rootzone of turfgrasses as an alternative to organic soil conditioners. The ability of IAs, in general, to reduce a soil's bulk density while increasing its cation-exchange capacity has been well documented (Bigelow et al., 2001; Bigelow et al., 2004; Li et al., 2000; Waltz et al., 2003). Conflicting data, however, have been reported about the influence of IAs on plant available water (PAW) [defined as the water held between field capacity (FC, -10 J kg^{-1}) and permanent wilting point (PWP, -1500 J kg^{-1}) (Cassel and Nielsen, 1986; where $\text{FC} \sim -10 \text{ J kg}^{-1}$ for coarse-textured soil)]. It is important to note here that the difference between FC and PWP gives only an estimate of PAW since each plant type behaves differently in terms of water use and regulation depending on its phenology and environmental conditions. For this reason, the term PAW should be regarded as an estimate for a generalized plant. Differences in soil texture, methodologies, and materials used to estimate PAW make comparing the results of the following studies difficult. van Bavel et al. (1978) reported that fritted clay (1–2 mm in size) held $0.31 \text{ m}^3 \text{ m}^{-3}$ PAW. Both Li et al. (2000) and Bigelow et al. (2004), however, found very little available water at pressure potentials less than -10 J kg^{-1} in IA-soil

Published in *Crop Sci.* 48:2447–2452 (2008).

doi: 10.2135/cropsci2008.01.0069

© Crop Science Society of America

677 S. Segoe Rd., Madison, WI 53711 USA

All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Permission for printing and for reprinting the material contained herein has been obtained by the publisher.

mixtures. Bigelow et al. (2004) noted the unexpectedly low PAW and devised another method of measuring the PWP water content in a pure IA growing media by using a bioassay. The data from the bioassay indicated a lower -1500 J kg^{-1} water content than was determined using the pressure plate method, and resulted in an estimated PAW content of $\sim 0.22 \text{ m}^3 \text{ m}^{-3}$.

McCoy and Stehouwer (1998) evaluated the water release curves of IA and sand mixtures from saturation to $\sim -10000 \text{ J kg}^{-1}$. They found a bimodal distribution of water release, where water held between sand and IA particles was released between saturation and $\sim -3 \text{ J kg}^{-1}$. Water held within the IA particles began to be released at a matric potential of -12.6 J kg^{-1} , but did not begin to release appreciable water until a matric potential of -53 J kg^{-1} . The internal pores drained fairly uniformly between -53 and -1000 J kg^{-1} . This information shows that the majority of internally held water in the IAs that they studied was available within the range of PAW.

The pressure plate method is the standard method used to assess soil water at pressures lower than -80 J kg^{-1} (Klute, 1986). Gee et al. (2002), however, showed that hydraulic nonequilibrium can occur between soil cores and the ceramic plates used in this method. Hydraulic nonequilibrium results when there is a loss of hydraulic connectivity (shrink-swell soils may pull away from the pressure plate) or the unsaturated hydraulic conductivity of the soil decreases in magnitude so that the soil does not reach the intended matric potential during the recommended minimum equilibration time of 2 d (Klute, 1986).

Inorganic amendments do not generally shrink and swell but their coarse texture does cause their unsaturated hydraulic conductivity to be low in magnitude. Hydraulic nonequilibrium results in artificially high water contents for the intended matric potentials. Gee et al. (2002) found that this was most pronounced at low matric potentials ($< -1000 \text{ J kg}^{-1}$). Estimates of PAW in IAs rely on accurate -1500 J kg^{-1} values; however, it appears that when this value is determined using the pressure-plate method, the water content may be overestimated. The result of this overestimation in water content is an underestimation in PAW. Dew-point potentiometers can be used to measure the relative humidity of soil samples. The relative humidity of a soil sample is related to its matric potential, and at low matric potentials (-1500 J kg^{-1}) dew-point potentiometers are very accurate if properly calibrated. The objective of this research was to estimate the PAW of four IAs using the pressure-plate method and a proposed alternative method (using a dew-point potentiometer) to determine if there was a difference between methods in estimated PAW.

METHODS AND MATERIALS

We evaluated the water release curves of four IAs [calcined volcanic ash and diatoms (CVAD) (Lassenite ATS, Western Pozzolan Corp., Doyle, CA), calcined clay (CC) (Soil-Life, Balcones Minerals Corp., Flatonia, TX), calcined diatomaceous earth (CDE) (Axis regular, EP Minerals LLC., Reno, NV), and zeolite (Zeo) (Ecosand, Zeo Inc., McKinney, TX)] using a combination of the pressure-plate method and a constant-humidity chamber. The difference in water content between -10 and -1500 J kg^{-1} was used to determine the PAW of each IA. The IA particle sizes ranged from 1 to 2 mm. Three replicates of each IA were measured over a range of matric potentials. All IAs were wetted from the bottom using DI water and allowed to soak for 24 h.

Pressure-Plate Method

The pressure-plate method was used to determine water contents at -10 , -30 , and -50 J kg^{-1} (Klute, 1986). Approximately 20 to 40 g of IA was placed in preweighed 2 cm tall \times 6 cm diameter rings and the bulk density of each IA was adjusted (i) to meet either the manufacturer's specification or (ii) by gradually filling the ring while tapping the side of the ring to settle the IA (Klute, 1986). The bulk densities of the IAs are presented in Table 1. Cheesecloth was placed on the bottom of the rings and attached with a rubber band so that all three matric potentials could be measured consecutively on the same sample. Rings were placed on pressure plates and deionized water was used to saturate the samples. After 24 h, excess water was drained from the plates and then they were placed into the pressure chamber (Soilmoisture Equipment Corp., Goleta, CA) at each specified pressure potential for 48 h. At the end of this time, pressure plates were removed and samples were weighed. After the -50 J kg^{-1} samples were weighed, they were placed in an oven at 105°C for 24 h, after which time they were placed in a desiccator and allowed to cool. The dry weight of the samples were then measured and the volumetric water contents of the IAs at -10 , -30 , and -50 J kg^{-1} were calculated based on wet weights measured at each matric potential.

Below -50 J kg^{-1} , the pressure plate method was used to bring the IAs to the approximate matric potentials of -300 , -1000 , and -1500 J kg^{-1} , after which the matric potential was measured on a dew-point potentiometer (WP4-T, Decagon Devices, Pullman, WA). Dew-point potentiometers work best at matric potentials below -100 J kg^{-1} , since above this matric potential the relative humidity is very close to saturation [0.999261 at -100 J kg^{-1} (20°C)] and measurements are too imprecise. Dry IAs were placed on a pressure plate within 1 cm tall \times 5 cm diameter rings (20 g) for determining the -300 , -1000 , and -1500 J kg^{-1} matric potentials. All samples were allowed to saturate as described above. The IAs were placed loosely in the rings and the bulk density was not adjusted. The soil structure achieved by adjusting the bulk density is not important at matric potentials below -100 J kg^{-1} since at these potentials, water is located on particle surfaces or interior pores (Hillel, 1982). After the samples had been in the pressure chamber for 48 h, the actual matric potential was measured on a subsample (~ 5 g) of each IA using a dew-point potentiometer. The matric potential of each sample was continuously measured in the dew-point potentiometer at 25°C until the readings became

stable (~10 minutes). After determining a sample's matric potential, it was transferred to a tared tin and then weighed. Samples were then placed in an oven at 105°C for 24 h, after which they were placed in a desiccator and allowed to cool. The dry weights of the samples were then measured and the gravimetric water content for each matric potential was calculated. Gravimetric water content of these samples was then converted to volumetric water content by multiplying the gravimetric water content by the IA bulk density.

Equilibration-Chamber Method

To reduce the matric potential of the IAs below -1500 J kg^{-1} , approximately 5 g of each IA (which had been previously placed in a pressure chamber at -1500 J kg^{-1} for 48 h) was placed above a saturated K_2SO_4 solution in a closed, airtight chamber at room temperature. The relative humidity above this solution is fairly constant over a range of temperatures and has a corresponding matric potential of -2800 J kg^{-1} (Wexler and Hasegawa, 1954). After 24 h the matric potential of the IA sample was measured using a dew-point potentiometer and the water content was determined by oven-dried weight loss (105°C for 24 h). Although many of the samples did not desorb enough water to reach equilibrium above the saturated salt solution within 24 h, the measured matric potential of all the samples was reduced to below -1500 J kg^{-1} . Gravimetric water content of these samples was then converted to volumetric water content by multiplying the gravimetric water content by the IA bulk density. The water content at -1500 J kg^{-1} was determined by assuming a linear relationship between the matric potentials and IA water

contents near the target potential of -1500 J kg^{-1} . In general, the portion of the water release curve below -300 J kg^{-1} (~2.5 in log scale) was linear (Fig. 1).

One-way ANOVA was used to determine differences between treatments and a Tukey test was used to separate differences between means ($n = 3$). Evaluation of means was performed using a $p = 0.05$ level of statistical significance with Statistica (Version 6, 2003) (Tulsa, OK).

RESULTS AND DISCUSSION

The -10 J kg^{-1} water contents ranged in the IAs from 0.216 to $0.456 \text{ m}^3 \text{ m}^{-3}$ (Table 1). The IAs are ranked in terms of pore volume as follows, $\text{CDE} > \text{CVAD} > \text{CC} > \text{Zeo}$. A majority of the interior pore volume of the CDE appears to be composed of pore sizes that correspond to PAW matric potentials. The PAW in the CDE accounts for ~72% of the total water holding capacity below FC. Approximately 50% of the interior pore volume in the CVAD and CC IAs corresponded to PAW matric potentials. Zeolite released very little water between FC and PWP. The internal porosity of IAs is a property that is very different than the media which they are often used to amend. Cassel and Nielsen (1986) found that coarse sand (0.5–1 mm in diameter) held very little ($0.006 \text{ m}^3 \text{ m}^{-3}$) water below -50 J kg^{-1} , indicating that this material was not internally porous. In contrast, Fig. 1 shows that significant water depletion in most of the IAs occurred at matric potentials below -50 J kg^{-1} . Notably, the CDE did

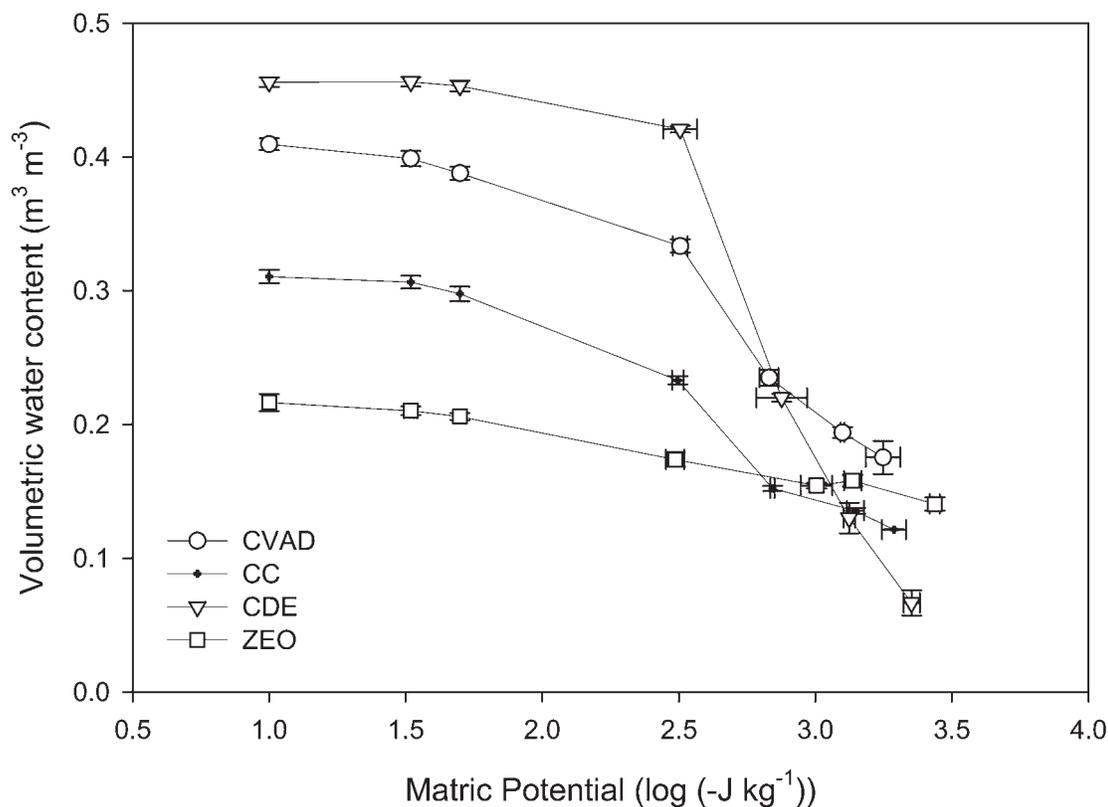


Figure 1. Water release curves for four inorganic amendments determined using both the pressure-plate method and a constant-humidity chamber: Calcined volcanic ash and diatoms (CVAD), calcined clay (CC), calcined diatomaceous earth (CDE), and zeolite (Zeo). Error bars indicate the standard deviation between replicates within a treatment.

Table 1. Comparison of the traditional pressure plate method and an alternative pressure plate/potentiometer method used for estimating plant available water (PAW): results from four inorganic soil amendments.

Inorganic amendment [†]	Bulk density Mg m ⁻³	-10 J kg ⁻¹ m ³ m ⁻³	Values determined on pressure plate			Dew-point potentiometer method		Difference in PAW Between methods m ³ m ⁻³
			SMP [‡] J kg ⁻¹	-1500 J kg ⁻¹ m ³ m ⁻³	PAW m ³ m ⁻³	-1500 J kg ⁻¹ m ³ m ⁻³	PAW m ³ m ⁻³	
CVAD	0.74	0.410	-1260	0.193	0.217 b	0.185	0.224 b	0.007 a [¶]
CC	0.65	0.311	-1400	0.135	0.176 c	0.133	0.178 c	0.002 a
CDE	0.39	0.456	-1330	0.130	0.326 a	0.118	0.338 a	0.012 b
Zeolite	0.94	0.216	-1370	0.158	0.058 d	0.154	0.062 d	0.004 a

[†]Calced volcanic ash and diatoms (CVAD), calced clay (CC), and calced diatomaceous earth (CDE).

[‡]Soil Matric Potential (SMP) of inorganic amendments at -1500 J kg⁻¹ on pressure plates. Means in the same column followed by the same letter are not significantly different, where $p < 0.05$ using a Tukey HDS test.

[¶]Differing letters following means in this column indicate significant differences in PAW estimates between methods (pressure plate method vs. the dew-point potentiometer method).

not release appreciable water until -300 J kg⁻¹. For turf-grass managers, this water release characteristic may not be desirable since plants may begin to reduce transpiration at soil matric potentials as high as -20 J kg⁻¹ when under high evaporative demand (Denmead and Shaw, 1962).

All IAs were influenced by hydraulic nonequilibrium on the pressure plates at the -1500 J kg⁻¹ matric potential. Actual matric potentials ranged from -1260 J kg⁻¹M (CVAD) to -1400 J kg⁻¹ (CC), which resulted in erroneously high -1500 J kg⁻¹ water contents (Table 1). The differences between methods in terms of PAW were between 0.002 and 0.012 m³ m⁻³ (Table 1). In comparison to the dew-point potentiometer method proposed above, the

pressure-plate method underestimated PAW by between 1.1 to 6.5% depending on IA. The pressure-plate method worked well to bring the IA samples to the -300 J kg⁻¹ matric potential, however at -1000 J kg⁻¹, all the IA samples except zeo failed to reach equilibrium (Fig. 2). The deviation in matric potentials between replications also increased at matric potentials below -300 J kg⁻¹, as seen by the magnitude of the error bars in Fig. 2.

These data indicate that discrepancies in the reported PAW water contents of IAs may partially be explained by pressure-plate nonequilibrium. Other possible sources of variation in PAW contents of similar IAs, however, could include differences in clay mineralogy between manufacturers and different definitions of FC. Both this study and van Bavel et al. (1978) used CC from Soil-Life (Balcones Mineral Corp., Flatonia, TX) consisting of mostly smectite, however, Bigelow et al. (2004) and Li et al. (2000) used CC from Profile (Applied Industrial Materials Corp., Buffalo Grove, IL) consisting mostly of illite. This study found that CC had a PAW content of 0.178 m³ m⁻³ compared to 0.31 m³ m⁻³ reported by van Bavel et al. (1978) for material from the same manufacturer (Table 1). The main reason for this discrepancy lies in the concept of FC. van Bavel et al. (1978) reported that after drainage, the volumetric water content of CC was 0.45 m³ m⁻³. However, according to

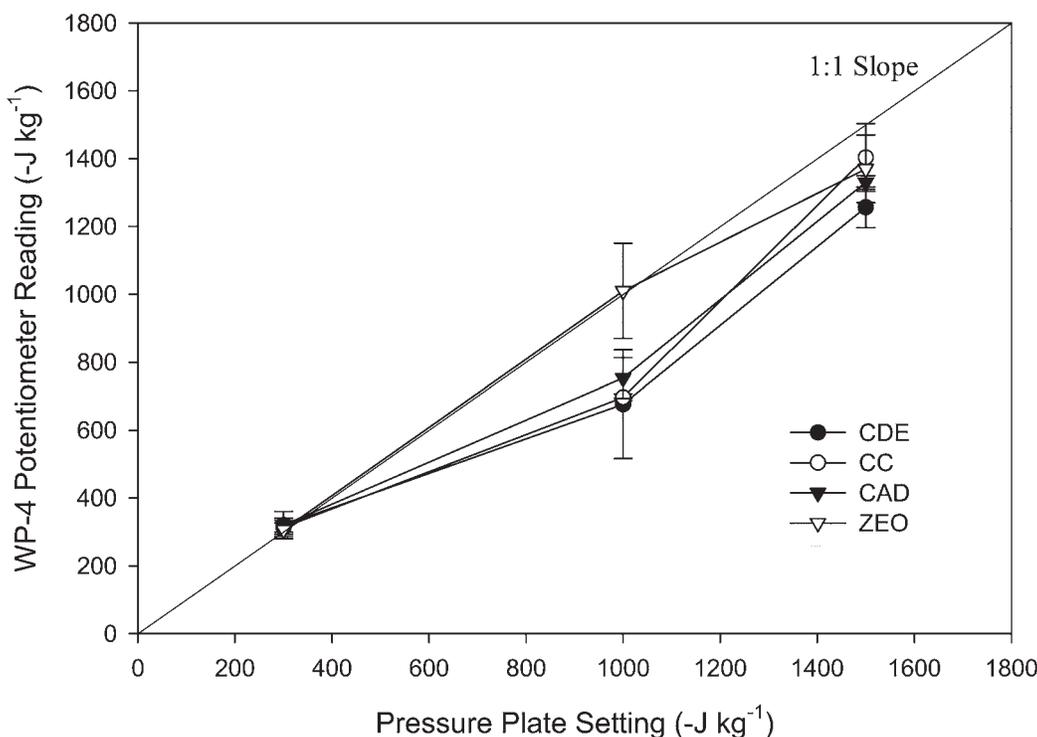


Figure 2. Comparison of pressure plate setting to potentiometer readings at three matric potentials for four inorganic amendments: Calced volcanic ash and diatoms (CVAD), calced clay (CC), calced diatomaceous earth (CDE), and Zeolite (Zeo). Error bars indicate the standard deviation between replicates within a treatment.

their water release curve data, that water content corresponds to a matric potential of -1 to -2 J kg^{-1} rather than the -10 J kg^{-1} value used in this study. McCoy and Stehouwer (1998) reported that a matric potential of -10 J kg^{-1} corresponds to the release of water held between particles and not internally held water. Based on van Bavel's (van Bavel et al., 1978) water release curve, the difference in water content between the -10 and -1500 J kg^{-1} is $\sim 0.20 \text{ m}^3 \text{ m}^{-3}$. When the definition of FC (-10 J kg^{-1}) is standardized between studies, the magnitude of difference between the reported PAW values for CCs is diminished [this study $-0.178 \text{ m}^3 \text{ m}^{-3}$, van Bavel et al. (1978) $-0.20 \text{ m}^3 \text{ m}^{-3}$, and Bigelow et al. (2004) $-0.22 \text{ m}^3 \text{ m}^{-3}$ (determined by bioassay)]. In the future, standardizing the definition of FC in IAs would help to provide accurate information to practitioners.

The difference in error of PAW estimates that is caused by hydraulic nonequilibrium at -1500 J kg^{-1} may not be problematic for turfgrass managers who often do not let soil matric potentials drop below -50 J kg^{-1} . Given that a majority of the internally held water in IAs is released at matric potentials below -50 J kg^{-1} , other soil properties that are amended by IA application, such as an increase in CEC and reduction in bulk density, may produce the primary benefit of IAs for turfgrass.

The type of soil or sand that is to be amended will also influence the impact of the difference in estimated IA PAW between estimate methods. Inorganic amendments are often applied at volumetric ratios of between 1:10 and 1:5 (IA to soil). Bigelow et al. (2004) reported that a fine sand (0.10–0.25 mm in diameter) held $0.244 \text{ m}^3 \text{ m}^{-3}$ while medium (0.25–0.50 mm) and coarse (0.50–1.00 mm) sands held $\sim 0.027 \text{ m}^3 \text{ m}^{-3}$ available water (-4 J kg^{-1} minus -50 J kg^{-1} water content). Since sand has no internal pore space very little water is expected to be available below -50 J kg^{-1} . Given this, these values for available water can be compared to our estimates of PAW. If CDE was applied at a 1:5 ratio to the fine sand, then the error between PAW estimate methods would result in a $0.0024 \text{ m}^3 \text{ m}^{-3}$ difference in whole soil (IA + sand) PAW. This does not make much of a difference when the total PAW is nearly $0.25 \text{ m}^3 \text{ m}^{-3}$ ($\sim 1\%$), or even when the soil media's PAW is low. In the medium sand where the PAW is $\sim 0.09 \text{ m}^3 \text{ m}^{-3}$, there is only a slight increase in the difference between methods (3% of PAW). This example shows that the difference between methods is minimal but the magnitude of this difference will depend on the application rate as well as the water holding properties of the amended substrate.

The emerging field of xeriscape horticulture is expected to make greater use of water retentive amendments. Drought-resistant plant types have been shown to access water below the -1500 J kg^{-1} matric potential used as the definition of PWP in this study (Holmes and Rice, 1996). Inorganic amendments releasing water

at lower matric potentials may be useful for the development of drought-resistant landscaping where plants often have reduced water use (Henson et al., 2006; Zollinger et al., 2006).

There are some research applications for IAs which require a greater degree of product knowledge. Researchers who examine water stress in greenhouse studies rely on accurate water release curves of potting media (which often consist or contain IAs) so that soil matric potentials can be maintained based on water content (Sathyan et al., 2005). Furthermore, in nonirrigated landscapes accurate estimates of PAW will help practitioners to increase soil water resources to meet the water use needs of the desired vegetation. The dew-point potentiometer method used to measure water content of IAs at low matric potentials that was described in this paper will help to provide more accurate PAW contents and water release curves for IA materials. Even if the accuracy of these improved methods is not needed, a standardization of the parameters used to compare PAW will help users more accurately interpret product performance.

Acknowledgement

This research was supported by California Department of Transportation RTA #65A0182. We thank several inorganic amendment producers for providing samples of their products.

References:

- Bigelow, C.A., D.C. Bowman, D.K. Cassel, and T.W. Rufty, Jr. 2001. Creeping bentgrass response to inorganic soil amendments and mechanically induced subsurface drainage and aeration. *Crop Sci.* 41:797–805.
- Bigelow, C.A., D.C. Bowman, and D.K. Cassel. 2004. Physical properties of three sand size classes amended with inorganic materials of sphagnum peat moss for putting green rootzones. *Crop Sci.* 44:900–907.
- Cassel, D.K., and D.R. Nielsen. 1986. Field capacity and available water capacity. p. 901–926. *In* A. Klute (ed.) *Methods of soil analysis. Part 1. Physical and mineralogical methods.* 2nd ed. Agron. Monogr. no. 9. ASA and SSSA, Madison, WI.
- Denmead, O.T., and R.H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. *Agron. J.* 45:385–390.
- Gee, G.W., A.L. Ward, Z.F. Zhang, G.S. Campbell, and J. Mathison. 2002. The influence of hydraulic nonequilibrium on pressure plate data. *Vadose Zone J.* 1:172–178.
- Henson, D.Y., S.E. Newman, and D.E. Hartley. 2006. Performance of selected herbaceous annual ornamentals grown at decreasing levels of irrigation. *Hortsci.* 6:1481–1486.
- Hillel, D. 1982. *Introduction to soil physics.* p. 76. Academic Press, San Francisco, CA.
- Holmes, T.H., and K.J. Rice. 1996. Patterns of growth and soil-water utilization in some exotic annuals and native perennial bunchgrasses of California. *Ann. Bot. (Lond.)* 78:233–243.
- Klute, A. 1986. Water retention: Laboratory methods. p. 635–662. *In* A. Klute (ed.) *Methods of soil analysis. Part 1. Physical and mineralogical methods.* 2nd ed. Agron. Monogr. no. 9. ASA and SSSA, Madison, WI.

- Li, D., Y.K. Joo, N.E. Christians, and D.D. Minner. 2000. Inorganic soil amendment effects on sand-based sports turf media. *Crop Sci.* 40:1121–1125.
- McCoy, E.L., and R.C. Stehouwer. 1998. Water and nutrient retention properties of internally porous inorganic amendments in high sand content root zones. *J. of Turfgrass Manage.* 2(4):49–69.
- Sathyan, P., R.J. Newton, and C.A. Loopstra. 2005. Genes induced by WDS are differentially expressed in two populations of aleppo pine (*Pinus halepensis*). *Tree Genetics & Genomes* 1:166–173.
- van Bavel, C.H.M., R. Lascano, and D.R. Wilson. 1978. Water relations of fritted clay. *Soil Sci. Soc. Am. J.* 42:657–659.
- Waltz, F.C., V. Quisenberry, and L.B. McCarty. 2003. Physical and hydraulic properties of rootzone mixes amended with inorganics for golf putting greens. *Agron. J.* 95:395–404.
- Wexler, A., and S. Hasegawa. 1954. Relative humidity-temperature relationships of some saturated salt solutions in the temperature range 0° to 50°. *J. Res. Nat. Bureau of Standards.* 53(1):19–26.
- Zollinger, N.R., T. Kjelgren, K. Cerny-Koenig, and R. Koenig. 2006. Drought responses of six ornamental herbaceous perennials. *Sci. Hortic. (Amsterdam)* 109:267–274.