Particle density of substrate components measured by gas pycnometer

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Abstract

The particle density (ρ_s) of a porous medium represents one of its basic physical properties. Understanding the ρ_s of a substrate allows for the most accurate calculation of total porosity (TP). However, there are difficulties in determining the ρ_s of organic compounds with traditional liquid pycnometer procedures. Direct ρ_s measurements were conducted on five substrate components (coir, peat, pine bark, perlite, and wood) using a helium gas pycnometer. This method resulted in consisted ρ_s measurements with low deviations. Coir yielded the highest ρ_s of the five materials at 1.47 g cm^{-3}. Peat and wood had similar ρ_s at 1.41 and 1.38 g cm^{-3}, respectively. Of the organic materials, pine bark yielded the lowest measured ρ_s at 1.29 g cm^{-3}. Perlite yielded the lowest ρ_s at 0.67 g cm^{-3}. Differences observed between particle density-derived TP and saturation method-derived TP could provide valuable insights with respect to substrate water capture and retention. Due to compounding errors with increasing bulk density, use of a single, "generic" ρ_s value for a component or a mix of materials to determine TP should be avoided. Further measurements of particle density should be made across a wider range of organic and inorganic components to reduce our reliance upon inconsistent techniques and unreferenced values.

Keywords: porous medium, helium gas pycnometer, saturation method

INTRODUCTION

The particle density (ρ_s) of a porous medium represents one of its basic physical properties. Understanding the ρ_s and bulk density (ρ_b) of a material allows the most accurate calculations of total porosity (TP) to be made (Blake and Hartge, 1986). This is of particular importance in horticultural container substrates as the fractions of air and water filled pores are considered to be among its most important characteristics (Beardsell et al., 1979; DeBoodt and Verdonck, 1972; Jenkins and Jarrell, 1989). However, the determination of a substrate's TP is largely conducted by means of saturation methods, such as the NCSU Porometer Method (Fonteno et al., 1995).

A material's ρ_s can be determined by volume displacement techniques using a fluid of known density (liquid pycnometry) or by application of Boyle's gas law (gas pycnometry). Previous attempts to measure the ρ_s of organic and inorganic substrate components have yielded variable results (Table 1). The inconsistencies between saturation and ρ_s derived total porosities have sparked some debate as to which method should be preferred (Hershey, 1990).

The accurate determination of TP by saturation method or ρ_s by liquid pycnometry depends on a liquid's ability to fill the voids of the porous medium. The interpretation of inconsistencies in saturation method results is discussed by Bunt (1984) in terms of "active" and "inactive" porosity, a consequence presumably due to isolated pores trapped within particles or the well-documented hydrophobic tendencies of some organic components such as peat and bark (Fields et al., 2014). Modifications, such as boiling the sample, applying a vacuum, or using a low-density liquid, can be included in liquid pycnometer procedures to overcome the issues of hydrophobicity and trapped air (Flint and Flint, 2002). However, the variability observed in reported ρ_s determined by this method suggest that alternative methods are needed.

Table 1. Published particle density values (ρ_s) for organic and inorganic substrate components. Descriptions of the material types and methods are taken from the original source when available.

Component	Material description	ρ_s (g cm^{-3})	Method	Source
Peat	White peat	1.45	Pycnometer[a]	DeBoodt and Verdonck (1972)
	Peat	1.51	Pycnometer[a]	Arenas et al. (2002)
	Jiffy-7	1.60	Pycnometer[a]	Gislerod (1982)
	Sphagnum peat	1.40	Pycnometer (alcohol)	Paivanen (1973)
	Peat moss	2.00	Pycnometer (water)	Beardsell et al. (1979)
	Sphagnum peat	1.51	Pycnometer (water)	Heiskanen (1992)
Bark	Pine bark (*P. radiata*)	1.28	Pycnometer (water)	Beardsell et al. (1979)
	White fir bark	1.19	Pycnometer[a]	Jenkins and Jarrell (1989)
Wood	Sawdust	1.50	Pycnometer[a]	DeBoodt and Verdonck (1972)
	Sawdust (*E. regnans*)	1.12	Pycnometer (water)	Beardsell et al. (1979)
	Sawdust (*P. radiata*)	1.42	Pycnometer[a]	Goh and Haynes (1977)
Coconut coir	Coir	1.54	Pycnometer[a]	Arenas et al. (2002)
	Coir dust	0.76	Pycnometer (water)	Asiah et al. (2004)
Perlite	Perlite	2.30	Pycnometer[a]	DeBoodt and Verdonck (1972)

[a]indicates the method of liquid pycnometry to derive ρ_s was not specified by the author(s).

Particle density estimations by gas pycnometry would be less impeded by the hydrophobicity of organic compounds. However, interactions between the surface of the material and the gas species should be considered. Helium is a noble gas of small molecular size and is generally considered inert (Flint and Flint, 2002). In order to determine the viability of helium gas pycnometry and its implications to horticultural substrate science, five substrate components, coir, peat, pine bark, perlite, and wood, were examined.

MATERIALS AND METHODS

A variety of organic and inorganic materials are used in horticultural container substrates. In time, all substrate components should be considered for ρ_s analysis. For this initial work, only the most common base components (coir, peat, and pine bark) as well as common and immerging additives (perlite and wood) were analyzed. Coir (Oldcastle; Anderson, SC, USA) was obtained in brick form, hydrated to 60% moisture content by mass, and broken up by hand. In a similar fashion, sphagnum peat (BPP; Berger, Saint-Modeste, QC, Canada) was acquired and prepared. The pine bark analyzed in this study was obtained from the species *Pinus palustris* and was aged for three months. In order to obtain the purest measurements for each material, wood particles associated with the pine bark material were removed by hand. To remove any soil collected during the aging process, the pine bark substrate was dried, bathed in deionized water, and stirred aggressively to allow the soil to disassociate from the pine bark particles and settle to the bottom. This process was repeated six times (Kaderabek, 2017). Wood chips (*P. taeda*) were used in this study to obtain ρ_s measurements for wood. Pine trees located in Raleigh, NC were harvested, chipped, and sieved to acquire chips (bark removed) between a 1- and 4-mm screen size. Horticultural perlite (Krum; Carolina Perlite Company, Gold Hill, NC, USA) was analyzed for this study.

Following sample acquisition and preparation, four 0.5-L samples from each material were oven-dried at 105°C for one week. In order for the samples to remain dry, a desiccator was used to store the samples between analyses. Particle density measurements were made using a gas pycnometer (AccuPyc II 1340; Micromeritics Instrument Corp., Norcross, GA, USA) with helium gas. The 100-cm^3 sample container was loose-filled with approximately 80 cm^3 of material. The sample weight was obtained prior to placement in the gas pycnometer. Each sample was analyzed 10 times with an equilibration rate of 0.005 psig min^{-1}. The mass of each sample was divided by the mean volume of its 10 runs to obtain the sample's ρ_s.

To observe differences in total porosities determined by gas pycnometry, a saturation method (NCSU Porometer), or liquid pycnometry, data were pulled from the NCSU Substrates Lab database on single component analysis for each substrate type. The data from each component was selected from the database to obtain the TP and ρ_b (calculated in the procedure). Using the ρ_b from the porometer data, the TP for each sample could be determined by ρ_s values obtained from gas or liquid pycnometry through the equation:

$$Total\ porosity = 1 - \rho_b/\rho_s \quad (1)$$

since the particle density of a material (or a range of values for particle density) remain constant for each substrate component.

All statistical analyses were performed using SAS 9.4 (SAS Institute, Cary, NC, USA). Data were subjected to one-way analysis of variance (ANOVA) procedure. Within the ANOVA procedure, Tukey's multicomparison test was used to compare the means of all substrate component types (coir, peat, pine bark, perlite, and wood).

RESULTS AND DISCUSSION

Differences were observed ($p \leq 0.0001$) in the ρ_s values determined by helium gas pycnometry for substrate type (Table 2). Of all five materials, coconut coir had the highest ρ_s of 1.47 g cm^{-3}. Sphagnum peat and wood had a measured ρ_s of 1.41 and 1.38 g cm^{-3}, respectively. Of the organic materials analyzed, pine bark had the lowest ρ_s with a value of 1.29 g cm^{-3}. However, of all measured components, perlite was observed to have the lowest ρ_s value at 0.62 g cm^{-3}.

Table 2. Particle density (ρ_s) values of five horticultural substrate components as measured by a helium gas pycnometer.

Component	ρ_s (g cm^{-3})	Std. dev.
Coconut coir	1.47a[a]	0.018
Sphagnum peat	1.41b	0.008
Pine bark[b]	1.29c	0.031
Perlite[c]	0.62d	0.044
Wood[d]	1.38b	0.002

[a]Data subjected to one-way analysis of variance (ANOVA) procedure. Within the ANOVA procedure, Tukey's multicomparison test was used to compare the means of all substrate component types (n=4). Means followed by the same letter are not significantly different (α=0.05).
[b]Bark was obtained from the species *P. palustris* and aged for 3 months.
[c]Horticultural grade perlite.
[d]Wood chips (between 1 and 4 mm screen size) from the species *P. taeda*.

The ρ_s values obtained by helium gas pycnometry differed from most reported values obtained from liquid pycnometry. For coconut coir, the results from Arenas et al. (2002) were similar to the value obtained by gas pycnometry, a difference of 0.07 g cm^{-3}. For peat, the value obtained from gas pycnometry is lower than most reported values but is most similar to the results obtained by Paivanen (1973) who used alcohol to measure ρ_s instead of water. For bark, the ρ_s value from gas pycnometry and Beardsell et al. (1979) are nearly identical but slightly higher than those reported by Jenkins and Jarrell (1989) from a different species from a different genus. Similar inferences could be made when comparing the ρ_s values of wood. The reported ρ_s value for *P. radiata* wood by Goh and Haynes (1977) is closest to the measured ρ_s for *P. taeda* wood in this study. These results indicate that the ρ_s of bark and wood within the same genus may be similar but different between genera. The greatest disparity between gas pycnometer and liquid pycnometer ρ_s values is observed for perlite. The ρ_s reported by DeBoodt and Verdonck (1972) for perlite (2.30 g cm^{-3}) is nearly 4 times greater than the ρ_s measured in this study. Since the initial gas pycnometer samples were analyzed, further analyses have been conducted with ground materials (data not shown). The results from these

ground samples indicate that the ρ_s reported by DeBoodt and Verdonck (1972) was likely pulverized prior to analysis. A higher measured ρ_s as a result of grinding or pulverizing could be indicative of the presence of closed pores within the non-ground material, a theory previously proposed by Bunt (1984) in terms of "effective" and "ineffective" porosity.

Another method of evaluating effective and ineffective porosity could be to examine the TP results obtained by saturation methods to reported ρ_s-derived results. An assumption could be made that the ρ_s measured by helium gas pycnometry may result in an accurate calculation of a substrate's "true" TP. On the other hand, TP calculated by saturation methods may indicate the percent porosity which was accessible/inaccessible by water. Any differences observed between these two methods could provide valuable insights with respect to substrate water capture and retention. For comparison, the TP from single component data were collected from the NCSU Porometer database and compared to the helium gas pycnometer-derived TP and TP derived from previously reported ρ_s values using Equation 1 (Table 3). The results obtained by the NCSU Porometer method differed only slight from the gas pycnometer-derived TP for coir, peat, and pine bark samples (<2% difference). However, the NCSU Porometer method measured slightly lower values of TP for perlite and wood, a difference of ~9 and ~6%, respectively. These differences could be a result of the fraction of porosity which was inaccessible by water. This fraction of inaccessible porosity could be due to in-trapped air bubbles or hydrophobic regions within the substrate. Future comparisons between saturation method-derived and particle density-derived TPs could be made as an estimation of the hydrophobicity of a material, an important topic in horticultural substrate science.

Table 3. The total porosity of single component container substrates derived from a saturation method (NCSU Porometer) and reported particle densities when bulk density (ρ_b) is constant[a].

	Coir	Peat	Pine bark[b]	Perlite[c]	Wood[d]
			ρ_b (g cm^{-3})		
Source	0.08	0.10	0.21	0.14	0.18
NCSU Gas Pycnometer	94.56%	92.91%	83.72%	77.42%	86.96%
NCSU Porometer	94.04%	93.01%	85.65%	68.85%	81.36%
DeBoodt and Verdonck (1972)	N/A[e]	93.10%	N/A	93.31%	88.00%
Beardsell et al. (1979)	N/A	95.00%	83.59%	N/A	83.93%
Arenas et al. (2002)	94.81%	93.38%	N/A	N/A	N/A
Gislerod (1982)	N/A	93.75%	N/A	N/A	N/A
Goh and Haynes (1977)	N/A	N/A	N/A	N/A	87.32%

[a]Data were collected from the NCSU Substrates Lab database. The ρ_b determined by the NCSU Porometer method was used to calculate the total porosity for each sample by the ρ_s values obtained from gas or liquid pycnometry through the equation: Total porosity = 1-ρ_b/ρ_s.
[b]Bark was obtained from the species *P. palustris* and aged for 3 months.
[c]Horticultural grade perlite.
[d]Wood chips (between 1 and 4 mm screen size) from the species *P. taeda*.
[e]N/A = particle density not reported.

Due to the linear relationship between ρ_b and ρ_s, it can be observed that slight deviations in reported ρ_s values can result in small, perhaps insignificant changes in the TP of a substrate when compared to gas pycnometer results. These small changes are the result of a small numerator, the ρ_b, in Equation 1. However, as ρ_b increases, differences in calculated total porosities increase linearly from the same deviations in ρ_s.

For example, using a ρ_s 2.00 g cm^{-3} (Beardsell et al. 1979) and 1.40 g cm^{-3} (Paivanen, 1973), the highest and lowest reported ρ_s values for peat, the differences in the calculated TP of a peat sample with a ρ_b of 0.1 g cm^{-3} is 2.1%. Using the same ρ_s values but a peat sample with a ρ_b of 0.2 g cm^{-3} (realistic or not), the difference in calculated TP increases to 4.3%.

For the sake of consistency and reproducibility, use of a single, "generic" value for a component or a mix of materials to determine TP should be avoided. This creates an error that

will only be compounded when using TP to derive other values, such as air-filled porosity, water content or available water content.

CONCLUSIONS

The results of this study demonstrate that helium gas pycnometry can provide accurate and reproducible results for determining the ρ_s of organic and inorganic substrate components. The objective of this work was not to call into question previous results and conclusions drawn from referenced and unreferenced texts but simply to provide researchers with a referenceable and reproducible option for the derivation of TP. In the future, we recommend that the results of this study be used to improve the measurement and modeling of substrate physical and hydrological properties. Further measurements of ρ_s should be made across a wider range of organic and inorganic components to reduce our reliance upon inconsistent techniques and undocumented values.

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