PORE FRACTION ANALYSIS: A NEW TOOL FOR SUBSTRATE TESTING

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Keywords: particle size, pore size distribution, moisture retention

Abstract

Pore sizes have traditionally been divided into macropores and micropores with the division between the two being arbitrary. Since most mixes used in container production are ≥ 80% pores by volume, a more detailed pore-fraction analysis seems warranted. Taking into account hydraulic properties and irrigation parameters, pore-size distribution curves were separated into four ranges. Macropores were selected as pore sizes > 416 μ. Pore sizes within the macropore range cannot hold water under tension induced by gravity when allowed to drain after saturation. Mesopores were selected as being in the pore size range of ≤ 416 to ≥ 10 μ. Micropores were categorized into the pore-size range of 0.2 to 10 μ. This would be equivalent to volumes of water held between 30 kPa and 1.5 MPa. The water in these pores may be viewed as a type of water stress "buffer" not commonly used under normal irrigations but extracted by plant roots when suctions exceed 30 kPa. Ultramicropores hold water at suctions > 1.5 MPa and would be found in pores with effective pore diameters < 0.2 μ. This water would be considered unavailable to plants. Data derived from this analysis were in good agreement with traditional measures of pore space and particle size distributions for peat-based, bark-based, and soil-based substrates.

1. Introduction

The measurement of substrate physical properties usually describes capacity and transport characteristics. Capacity measurements include the ability to hold and release water and air space available under various conditions. There are many methods and characteristics that describe these parameters (Gardner, 1986, Klute, 1986). Transport characteristics involve aspects of water movement, such as drainage and hydraulic conductivity. While fewer in number and less frequently measured, several methods are available to describe water movement (Klute and Dirksen, 1986). All of these methods give indirect measurements of substrate structure. Direct measurements are limited to bulk density, particle density and particle size distribution.

Proc. Int. Sym. Growing Media and Hydroponics
Ed. A.P. Papadopoulos
Acta Hort. 481, ISHS, 1999.

Measurement of structure is complicated by the fact that structure is not created at the time of component blending. Structure is created through a three-step process of component blending, container filling, and initial watering/settling of the substrate in the container (Fonteno, 1996). Factors such as bulk density and moisture content of the substrate during blending and filling can alter the structure significantly (Milks, et al., 1989c). Therefore, structure does not “come in the bag,” but rather is created at the point of use.

The most common measures of substrate structure are bulk density and particle size distribution. Both of these parameters measure the weight and volume fractions of the solid particles in the substrate. However, most substrates that do not contain mineral soil have solid fractions between 10 and 20 percent (by volume). These two parameters do not describe the 80 to 90 percent of the substrate volume which contains pores. A technique is necessary to accurately and adequately describe the physical nature of the pore fraction in substrates.

Pore volumes have been described as containing “micropores” and “macropores.” Hillel (1982) has defined macropores as consisting mostly of interaggregate cavities serving as the major pathways for the infiltration and drainage of water and for aeration. Micropores have been defined as the intraggregate spaces responsible for water retention (Hillel, 1982). Skopp (1981) has expanded the definition of macropores to include pores which provide preferential paths of flow so that mixing and transfer of water between macropores and smaller pores is limited. While useful, these designations are somewhat arbitrary (Puustjarvi, 1974), because a macropore large enough to drain when in the top portion of a 15-cm tall container may not drain at all when found in the middle of a 2-cm plug cell.

A more detailed analysis can be obtained by developing a pore-size distribution curve. Pore-size distribution is directly correlated to moisture retention curves (Childs, 1940; Danielson and Sutherland, 1986; Milks et al., 1989a). Pore-size distribution curves may allow one to visualize ‘internal’ structure of the substrate.

More detailed evaluations of the influence of pore-size on physical properties of the substrates would require an expanded separation of pore size ranges for container substrates. Taking into account hydraulic properties and irrigation parameters, pore-size distribution curves were separated into four ranges as discussed below.

The objectives of this study were: 1) to determine the physical properties of a peat-based, a bark-based, and a soil-based substrate; 2) to determine pore size distribution curves for these substrates from physical property data; and 3) to develop a pore fraction profile for each substrate.

2. Materials and methods

2.1. Substrates

The three substrates used were selected to cover the range of mixes used in container production. A peat-based substrate (peat mix) was created with 1 Canadian sphagnum peat moss (< 6 mm):1 horticultural grade vermiculite no. 2 (by volume). A bark-based substrate (bark mix) was formulated with 3 aged pine bark (< 13 mm):1 Canadian sphagnum peat moss (< 6 mm):1 concrete grade sand (by volume). A soil-based substrate (soil mix) was prepared with 1 sandy loam (75% sand: 15% silt 10% loam):1 Canadian sphagnum peat moss (< 6 mm):1 concrete grade sand (by volume).

2.2. Physical Properties.

Particle size distribution of each substrate was determined using three, 100 g oven dry samples. Each sample was placed on a series of twelve U.S. standard sieves (ranging from > 6.3 mm to < 0.106 mm) and shaken on a Rotap Shaker (Tyler Industrial Products, Combustion Engineering Inc., Menton, Ohio) for 5 min at 160 shakes per min. Portions of substrate samples remaining on each screen were weighed and expressed as the percentage of total sample weight.

Seven samples of each substrate were packed in aluminum cylinders (7.6 cm diameter, 7.6 cm height) to the same bulk density using procedures described by Bilderback and Fonteno (1987). Substrate water retention characteristics at increasing soil moisture tension (SMT) values were determined with seven replicate samples using a pressure plate apparatus described by Fonteno and Nelson (1990). Seven additional samples were used to determine substrate total porosity and volume water content at 0.38 kPa using the NCSU Porometer described by Fonteno and Bilderback (1993).

Volumetric water content (Θ) values at 0 kPa and 0.38 kPa from the NCSU Porometer were used with SMT values of 1, 2, 4, 5, 7.5, 10, 20, and 30 kPa, to develop a moisture retention characterization curve for each substrate using a nonlinear, five-parameter function developed by van Genuchten and Nielsen (1985) and adapted to horticultural substrates by Milks et al. (1989a). The nonlinear model is defined as

$$\Theta = \Theta_r + (\Theta_s - \Theta_r)/[1 + (\alpha h)^n]^m \qquad [1]$$

where Θ_s is the volumetric water content at saturation (0 kPa), Θ_r is the residual volumetric water content at 30 kPa of water tension, and a, n, and m are curve-fitting parameters estimated through iteration.

The equilibrium capacity variable (ECV) model described by Bilderback and Fonteno (1987) and refined by Milks et al. (1989b) combined the nonlinear moisture retention function [1] with container geometry. These models were used to provide accurate predictions of container capacity (CC), air space (AS), and available water (AW) for 11 cm height substrate in a 12.5 cm height azalea pot. Total porosity (TP) was equal to the sample volume wetness at saturation (0 kPa). Unavailable water (UW) was equal to the moisture content at 1.5 MPa, using a high pressure plate apparatus according to Cassel and Nielsen (1986) and modified for soilless substrates by Milks et al. (1989b).

2.3. Pore size distributions

Pore size distribution curves for a particular substrate were derived directly from moisture retention curve data. The effective diameter of the largest water-filled pore at each tension was calculated by

$$d_p = 4\sigma \text{ X } 10^5 / \rho_w gh \qquad [2]$$

where σ is surface tension ($J \cdot m^{-2}$) and ρ_w is the density ($Mg \cdot m^{-3}$) of water, g is gravitational acceleration ($m \cdot s^{-2}$), and h is the matric suction (cm of water) (Danielson and Sutherland, 1986).

2.4 Average effective suction determination

The pore size selected as the endpoint point for the macropore range in this study was equivalent to the maximum pore diameter to hold water at an <u>average</u> <u>effective</u> <u>suction</u> at container capacity (AES_{cc}).

The AES$_{cc}$ for an 11 cm column of substrate would be equivalent to the midpoint (0.55 kPa) in that column (Figure 1a). However, since the container was actually an inverted, truncated cone, AES$_{cc}$ was determined as 0.715 kPa, using container capacity (CC) predictions from the ECV model for 12.5 cm tall azalea containers filled with 11 cm of substrate used in the irrigation study (Figure 1b). CC was equivalent to a volumetric water content at container capacity (Θ_{cc}). Substituting Θ_{cc} for Q in equation [1], suction (h) at Θ_{cc} was calculated. The AES$_{cc}$ was then converted to an effective, largest water-filled pore-size diameter using equation [2].

2.5. Pore fractions

In this study, macropores were selected as pore sizes > 416 m. Pore sizes within the macropore range cannot hold water under tension induced by gravity when allowed to drain after saturation. This is equivalent to pores that drain between 0 and 0.715 kPa. Mesopores (from Luxmoore, 1981) were selected as being in the pore size range of ≤ 416 to ≥ 10 m. Richards et al., (1964) suggested that container suctions during commercial plant production do not normally exceed 30 kPa (effective pore diameter of 10 μ) between irrigations. Karlovich, et al. (1986) and Milks, et al. (1989b) confirmed that available water content at tensions > 30 kPa is very small in peat-, bark-, and soil-based substrates. This range is equivalent to pores that drain between 0.715 and 30 kPa.

Micropores were categorized into the pore-size range of 0.2 to 10 m. This would be equivalent to volumes of water held between 30 kPa and 1.5 MPa. Pores ≤ 10 m would remain filled with water under normal production conditions where plants were irrigated at suctions ≤ 30 kPa. If plants were allowed to dry between 30 kPa and 1.5 MPa, the micropores would drain. These pores could be considered to house the water reserve for substrates.

Water held at suctions > 1.5 MPa would be found in pores with effective pore diameters < 0.2 m. However, water held in this range would include that absorbed into very small interaggregate and intraggregate pores and that adsorbed onto particle surfaces by hydrogen bonding (Bunt, 1988; Hillel, 1982; Handreck and Black, 1984).This water would be considered unavailable to plants. The range of effective pore diameters < 0.2 m was labeled as ultramicropores (from Bouma, 1981). The ultramicropore fraction would be equivalent to the unavailable water (UW) volumes in Table 1.

3. Results

3.1. Substrate Moisture Retention.

Large differences existed in the moisture retention curves (Figure 2). The peat mix had the greatest amount of water released (232 ml) between 0 kPa and 1.5 MPa followed by the soil mix (180 ml) and bark mix (172 ml) respectively. Moisture retention curves for the bark and soil mixes have lower water contents than the peat mix as tension increases. Moisture content has been described as a growth regulating variable (Johnson et al., 1981; Karlovich, 1986; Lieth and Burger, 1989; Spomer and Langhans, 1975). Less water was available for plant growth (Table 1) in the bark and soil mixes.

3.2. Water and Air Capacity Characterization.

The air and water capacities measured for the three mixes and predicted for a 12.5 cm container are listed in Table 1. The peat and bark mixes had the greatest total porosity (TP), followed by the soil mix. Container capacity (CC) and available water (AW) were greatest in the peat mix, followed by the soil and bark mixes, respectively. The unavailable water (UW) for the peat and bark mixes were similar but were much greater than in the soil mix. Air space (AS) in the soil mix was less than both the peat and bark mixes.

3.3. Particle Size.

Table 2 contains the particle-size distributions for the three substrates. These show the peat mix as consisting mainly of medium sized particles (between 0.5 and 2.0 mm) which retain large amounts of water (Bunt, 1988) and contributed to the large values of total porosity (TP), container capacity (CC), air space (AS), and available water (AW) (Table 1). This combination of particle sizes and low bulk density (BD) created a substrate with a high water holding capacity (Table 1).

The bark mix had the coarsest texture but had proportions of finer sized particles (< 0.5 mm) similar to the soil mix (Table 2). The smaller particles apparently nested into the larger pore spaces reducing TP, CC, and AS (Table 1). This nesting has been suggested by many researchers (Beardsell, 1979; Bilderback et al., 1982; Erwiyono et al., 1990; and Wallach et al., 1992a).

The soil mix had the most uniform particle-size distribution (Table 2). The percentage of coarser particles (> 2.0 mm) was similar to the peat mix and the percentage of finer particles similar to the bark mix, but with higher bulk density.

3.4. Pore Fraction Analysis.

Macropores. The peat mix contained the largest fraction of pores (11%) in this range (Fig 3). The fraction of total pore space consisting of macropores in the bark mix (7%) was less than the peat mix, with the soil mix having the lowest macropore percentage (3%). This indicated that the peat mix had the greatest air space after drainage, followed by bark and soil mixes, respectively. This agreed with the air space data in Table 1.

Mesopores. The largest portions of pore space for the soil (37%), bark (36%), and peat mixes (47%) were in this mesopore range (Fig 3). Water storage capabilities may be most influenced by the mesopore range. This middle range of pores shifts from being water-filled at CC to containing more air and less water as tensions rise. Mesopores are continuously being filled, drained, and refilled during plant production.

Micropores. The peat and soil mixes had 9% and 6% of their total volumes occupied by micropores, respectively (Fig 3). The percentage of water remaining in the bark mix in the micropores was ≤ 1% of the container volume, as evident by the extremely small amounts of water available at suctions > 30 kPa (Figure 2). Wilting and tissue death may occur more rapidly under moisture stress in the bark mix. Water-filled micropores may provide some protection against plant moisture stress under conditions of extreme suctions in substrates during crop production. The water in these pores may be viewed as a type of water stress “buffer” not used under normal irrigations but extracted by plant roots when suctions exceed 30 kPa.

Ultramicropores. Since these values were derived from the water held at tensions ≥ 1.5 Mpa, they were the same as the values for unavailable water (Table 1).

When comparing the fraction distributions of the three substrates in figure 3, several items stand out. First, the soil-based substrate had a large volume of solids compared to the soilless substrates. Second, the micropore fraction in the bark substrate is very small, indicating almost no water reserve available to the plant. Third, the volume of each substrate available for holding and disseminating water for production (mesopores) is less than the volume fraction generally associated with water holding capacity. These observations are consistent with those drawn using water retention and particle size data.

4. Discussion

Because these pore fractions are based on intended use, the range of pores within a given pore fraction can vary. For example, AES$_{cc}$ will change with the height of the substrate and container geometry. Therefore, as AES$_{cc}$ increases, the percentage of macropores increases. The mesopore fraction also changes with AES$_{cc}$, but the micropore percentage remains unchanged as long as normal irrigation began at 30 kPa. Also, other methods for determining total porosity, container capacity, moisture retention at various tensions, and unavailble water can be used to determine pore size distributions.

Based on the results of this study, micropore percentages appear to be dependent on substrate properties and irrigation parameters, while macropores and mesopores are dependent on substrate properties, irrigation parameters, and container geometry.

As irrigation systems become more sophisticated, substrates need to become more efficient at capturing, holding and transporting water to the root system. Pore fraction analysis may prove a useful tool in altering substrates, by providing a method of refining these structures for specific irrigation and container production situations. Manipulation of pore fractions within the substrate could be used to match substrate structure with irrigation and plant growth needs. Expanding the analysis of substrate physical properties to include container and irrigation options may aid in the development of irrigation methods tailored to the water transport capabilities of individual substrates.

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Table 1. Percent volume of substrate attributed to total porosity (TP) and unavailable water (UW). Dry bulk density (BD) of three container substrates. ECV model predictions of percent volume water attributed to container capacity (CC), air space (AS), and available water (AW) of 11 cm height substrate in a 12.5 cm height azalea container.

Substrate [z]	Tp[y]	UW	CC	AS	AW	BD
		(% of Total Volume)				(g·cm^{-3})
Peat-based	87.2a[x]	21.6a	74.4	12.8	52.8	0.15a
Bark-based	70.6b	28.7a	60.2	10.4	31.5	0.50b
Soil-based	56.5c	12.5b	51.3	5.2	38.8	1.10c

[z] Peat substrate contained 1 sphagnum peat moss (<6mm): 1 horticultural grade vermiculite no. 2 (v/v).

Bark substrate contained 3 aged bark (<13mm): 1 sphagnum peatmoss (<6mm): 1 concrete grade sand (v/v/v).

Soil substrate contained 1 Sandy clay loam (<6mm): 1 sphagnum peatmoss (<6mm): 1 concrete grade sand (v/v/v).

[y] TP = Total water dained + (wet weight - dry weight)
CC = (wet weight - dry weight)
AS = TP - CC
UW = Water volume remaining after pressure of 1.5 MPa was applied.
AW = CC - UW
BD = Weight of solids / Total Volume

[x] Mean separation by columns by LSD, $\alpha = 0.05$.

Table 2. Particle Size Distribution of Three Container Substrates[z]

Particle Size (mm)	Peat Mix Mean	Bark Mix Mean	Soil Mix[y] Mean	Particle Size Range[x]
	(% of Dry Weight)			
> 6.3	0.85	2.51	1.04	
6.3 - 4.0	1.48	4.87	1.22	
4.0 - 2.8	2.72	4.80	3.12	*Coarse*
2.8 - 2.0	4.00	6.14	4.74	
2.0 - 1.4	7.63	7.91	9.02	
1.4 - 1.0	17.32	11.21	13.32	
1.0 - 0.71	26.54	16.46	18.58	*Medium*
0.71 - 0.50	17.32	16.48	17.88	
0.50 - 0.355	9.23	12.65	13.07	
0.355 - 0.250	5.22	8.40	8.55	
0.250 - 0.180	2.99	4.76	4.73	*Fine*
0.180 - 0.106	2.53	2.56	2.77	
< 0.106	2.17	1.25	1.96	

[z] Peat substrate contained 1 sphagnum peat moss (<6mm): 1 horticultural grade vermiculite no. 2 (v/v).
Bark substrate contained 3 aged bark (<13mm): 1 sphagnum peat moss (<6mm): 1 concrete grade sand (v/v/v).
Soil substrate contained 1 Sandy clay loam (<6mm): 1 sphagnum peat moss (<6mm): 1 concrete grade sand (v/v/v).

[y] Soil is Sandy Loam (73.72% Sand, 21.95% Silt, 4.34% Clay)

xParticle size range: Coarse = > 2.0 mm, Medium = 0.50 - 2.0 mm, Fine = < 0.50 mm

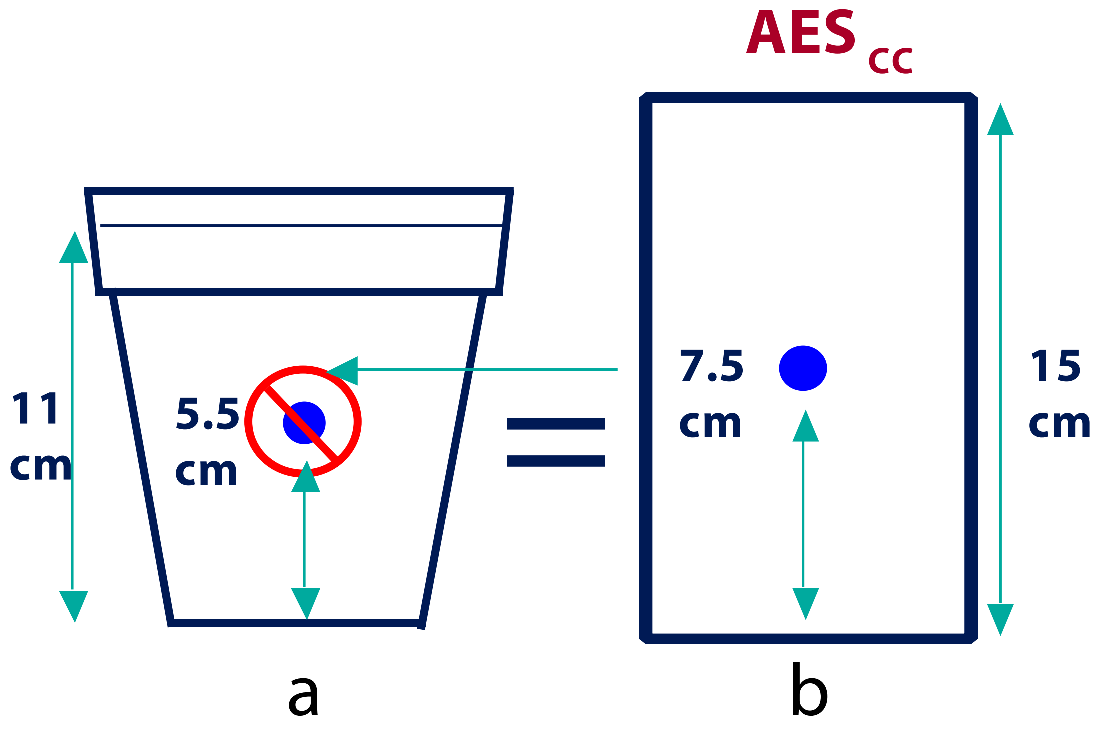

Figure 1 - Average Effective Suction @ Container Capacity

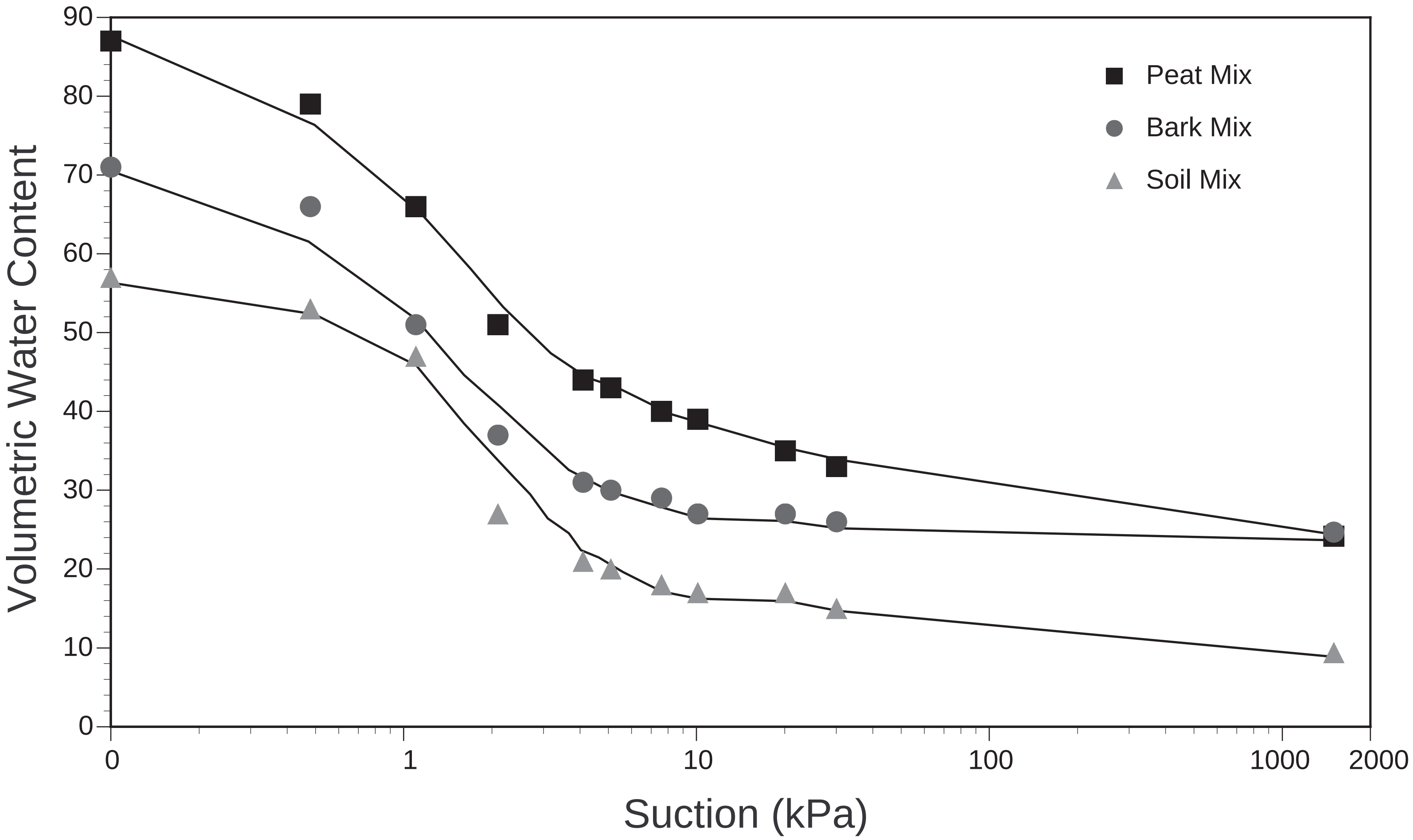

Figure 2 - Moisture retention curves for three substrates

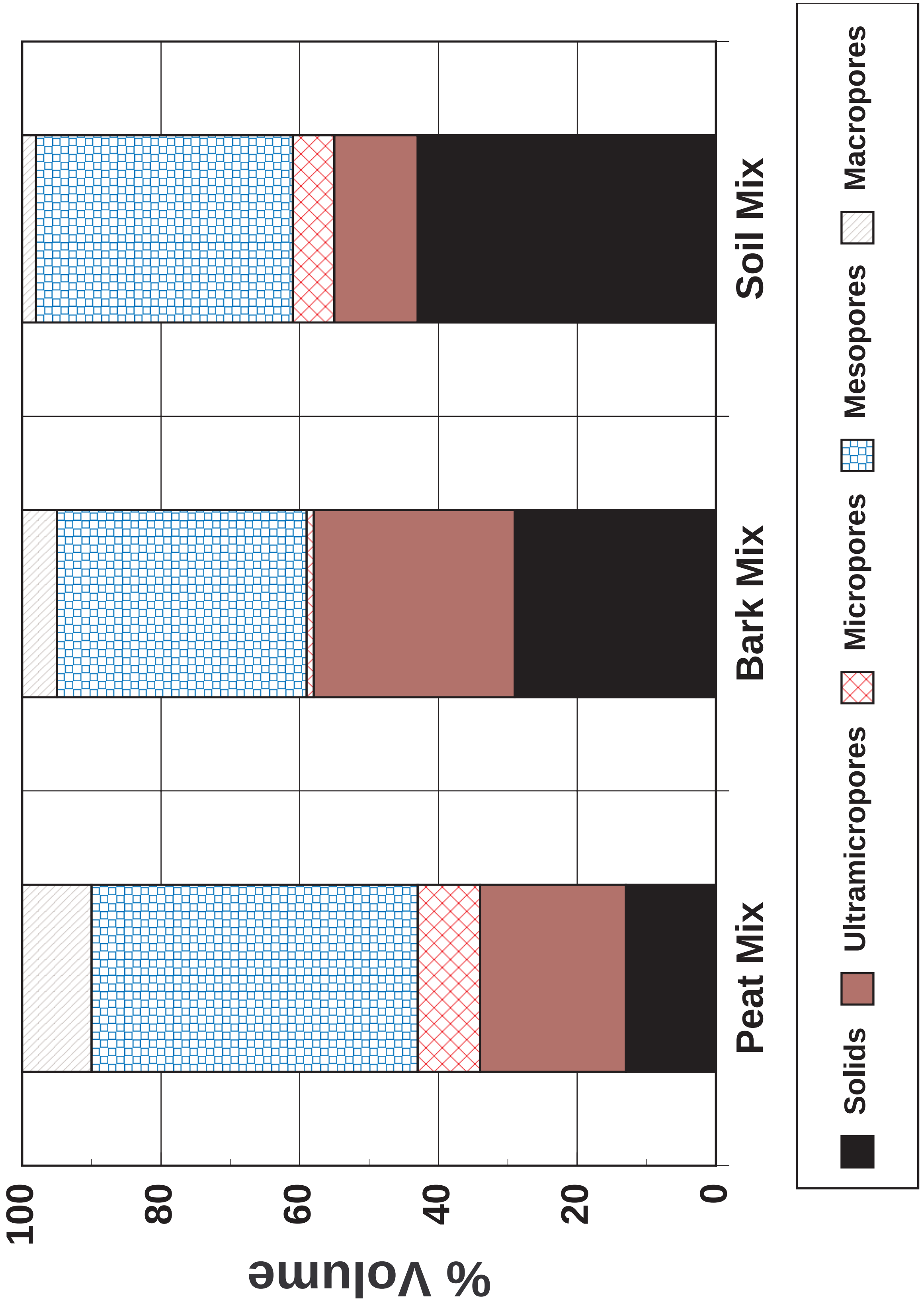

Figure 3 - Pore fraction analysis for three substrates