Healthy Substrates Need Physicals Too!

Ted E. Bilderback[1], Stuart L. Warren[1], James S. Owen, Jr.[2], and Joseph P. Albano[3]

ADDITIONAL INDEX WORDS. **container media, pine bark, sphagnum peat moss, sand, arcillite, physical properties**

SUMMARY. Many research studies have evaluated potential organic and mineral container substrate components for use in commercial potting substrates. Most studies report results of plant growth over a single production season and only a few include physical properties of the substrates tested. Furthermore, substrates containing predominantly organic components decompose during crop production cycles producing changes in air and water ratios. In the commercial nursery industry, crops frequently remain in containers for longer periods than one growing season (18 to 24 months). Changes in air and water retention characteristics over extended periods can have significant effect on the health and vigor of crops held in containers for 1 year or more. Decomposition of organic components can create an overabundance of small particles that hold excessive amounts of water, thus creating limited air porosity. Mineral aggregates such as perlite, pumice, coarse sand, and calcined clays do not decompose, or breakdown slowly, when used in potting substrates. Blending aggregates with organic components can decrease changes in physical properties over time by dilution of organic components and preserving large pore spaces, thus helping to maintain structural integrity. Research is needed to evaluate changes in container substrates from initial physical properties to changes in air and water characteristics after a production cycle.

Technical assistance of Mary Lorscheider and William Reece is gratefully acknowledged. Research was supported in part by USDA-ARS Floriculture and Nursery Initiatives grants (SCA #58-6618-2-2027).

[1]Professors.

[2]Graduate Research Assistant.

[3]Research Horticulturist, USDA-ARS, U.S. Horticulture Research Laboratory, Ft. Pierce, Fla.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
100	bar	kPa	0.01
3.7854	gal	L	0.2642
2.5400	inch(es)	cm	0.3937
25.4000	inch(es)	mm	0.0394
0.0160	lb/ft^3	g·cm^{-3}	62.4274
0.5933	lb/yard^3	kg·m^{-3}	1.6856
28.3495	oz	g	0.0353
0.7646	yard^3	m^3	1.3080

Like people, horticultural substrates are unique and exhibit variable physical and biological changes as they age. Container substrates used in production of horticultural crops are predominantly organic components such as peat moss or bark blended with other organic or mineral components. The objective of this paper is to discuss physical properties of container substrates, changes in air and water characteristics during growth cycles, and management strategies that can be implemented to reduce negative effects on growth of crops.

There are no distinct universally accepted standards for the physical properties of container substrates. However, suggested ranges for easiest management of most potting substrates utilized in commercial production of horticultural crops are within the following ranges: total porosity (TP) (50% to 85%), air space (AS) (10% to 30%), container capacity (CC) (45% to 65%), available water (AW) (25% to 35%), unavailable water (UAW) (25% to 35%) and bulk density (D_b) (0.19 to 0.7 g.cm^{-3} dry weight) (Yeager et al., 1997) (Table 1). If potting substrates are within these suggested physical property ranges, irrigation and nutrient programs may require less intense management. Initial physical properties of potting mixes can be engineered for optimal characteristics. Moisture retention characteristics of components blended into a container substrate are an average of the individual components. However, even when the same components are blended in identical ratios, physical properties vary due to differences in particle size. Pine bark can vary from one shipment to the next. For example, two pine bark samples were hammermilled to pass through a 1.5-inch screen on separate dates by a commercial nursery pine bark supplier. Particle size distribution for the two samples was compared in the N.C. State Horticulture Substrates Laboratory. Particle size distribution was obtained by screening four 100-g air dried samples of each for 5 min at 160 shakes/min with a Ro-Tap shaker (W.S. Tyler, Inc., Mentor, Ohio) and U.S. standard sieves. The finest particles that passed through a sieve opening of 0.5 mm and four smaller sieves before being collected in the receiver pan were compared. Results revealed that 21.9% (by weight) of fine particles were collected from the first sample while 34.3% fine particles (by weight) were collected for the second sample. One explanation for the differences was moisture content of the pine bark at the time of processing. Several rain events preceded processing of the second sample. The moist sample remained in the hammermill longer than a dry sample; thus more grinding occurred before the bark passed through the 1.5-inch screen. Pokorny and Henny (1984) also noted that substrates with the same components and ratio of components were assumed to be the same, but in their studies physical properties were not identical. Differences in physical properties in their study were due to

Table 1. Physical properties of selected substrates.[z]

Substrate[y]	Total porosity (% vol)	Air space (% vol)[y]	Container capacity (% vol)	Available water (% vol)	Unavailable water (% vol)	Bulk density (g·cm^{-3})[x]
Screened aged pine bark (1/4 inch)	81	11	70	37	33	0.19
Screened aged pine bark (1/2 inch)	84	19	65	33	32	0.19
Screened aged pine bark (1/2 inch) + builders sand (80:20)	77	11	66	41	25	0.45
Screened aged pine bark (1/2 inch) + sphagnum peat moss (90:10)	79	11	68	36	32	0.19
Screened aged pine bark (1/2 inch) pertlite (70:30)	85	29	56	23	33	0.21
Screened aged pine bark (1/2 inch) + perlite + peat moss (70:15:15)	85	14	71	43	28	0.18
Screened aged pine bark (1/2 inch) + perlite + peat moss (63:22:15)	84	11	73	46	27	0.19
Screened aged pine bark (1/2 inch) + PermaTill aggregate[w] (70:30)	75	25	50	23	27	0.40
Pine bark (3/8 inch) + mushroom compost + peat moss (65:20:15)	83	24	60	34	26	0.18
Pine bark:soil (9:1)	74	15	59	33	26	0.31
Pine bark:peat moss:rice hulls (3:2:2)	88	19	69	34	35	0.19
Pine bark + rice hulls + peat moss +cardboard biosolids + hardwood fines (42:42:7:4.5)	85	15	70	48	22	0.29
Fir bark:peat moss:pumice (1:1:1)	84	12	72	47	25	0.29
Fir bark:peat moss:pumice (50:30:20)	85	23	62	37	25	0.25
Fir bark:pumice:peat moss (75:15:10)	84	21	63	37	26	0.25
Normal ranges	50–85	10–30	45–65	23–35	23–35	0.19–0.70

[z]All analyses performed using standard soil sampling cylinders [3 inches (7.6 cm) i.d., 3 inches high] at the North Carolina State University Horticultural Substrates Lab, Raleigh.

[y]1 inch = 2.54 cm. Air space and container capacity affected by height of container. Air space calculated as total porosity-container capacity. Container capacity predicted as percent volume at drainage. Available water calculated as container capacity-unavailable water. Unavailable water determined as percent volume at 1500 kPa (15.0 bar).

[x]1 g·cm^{-3} = 62.4274 lb/ft^3.

[w]PermaTill aggregate (Carolina Statlite Co., Salisbury, N.C.)

shrinkage and particle size differences of the components blended. Variation of identical components occurs if dry components are blended compared to blending moist components. Dry components when mixed tend to fit together tightly and increase D_b of the substrate compared to when moist components are blended. Consequently, air space is reduced when dry components are mixed and water may even pool on the substrate surface. Airhart et al. (1978a) reported that an air dry peat-vermiculite substrate required 5 d to reach 70% to 78% of moisture saturation while milled pine bark required 48 d to achieve 58% to 70% saturation.

Composts for potting substrates have been widely tested using a variety of materials, including municipal wastes such as yard waste, garbage wastes, and biosolids/sludge; agricultural wastes such as rice hulls, cotton gin trash, peanut hulls; and animal and industrial wastes such as kitchen wastes, fly ash, and animal processing plant wastes. Many of these organic composts in addition to hypnum or reed-sedge peats, and sphagnum peat moss hold moisture within the particles similar to a sponge. Furthermore, composted materials often lack the coarse, large particles necessary for adequate aeration and therefore are not used in amounts greater than 50% of the volume for most container substrates (Bilderback and Jones, 2001). In contrast, bark, sand, and most aggregates hold moisture between particles, therefore air and water retention characteristics are largely dependent upon how components "blend together" initially. However, due to aging, decomposition, and softening of particles under production conditions, most bark components can also hold considerable moisture within particles as well (Airhart et al., 1978b).

Very little data have been published on changes in organic container substrates as they decompose over time. In a study conducted by Harrelson et al. (2004), physical properties of fresh pine bark and aged pine bark (aged for 1 year in an unprotected location) were compared at initial potting and after 1 year in production (Table 2). Total porosity of both fresh and aged pine bark sources were similar at potting; however, AS, CC, AW, UAW, and D_b were very different. The aged pine bark had 25.2% AS compared to 39.3% AS for fresh pine bark. The suggested range for pine bark as a single component is 20% to 30% air space (by volume); therefore, the 39.3% AS for fresh pine bark had few micropores to hold moisture (Bilderback and Jones, 2001). This observation was supported by the difference in CC as the fresh pine bark had only 49.0% CC compared to 61.1% CC for aged pine bark. Available water content in fresh pine bark was 9.8% compared to 26.3% for aged pine bark. Aged pine bark as a single component substrate initially possessed the physical properties that met all the required criteria for vigorous crop growth under typical nutrient and irrigation programs. In contrast, fresh pine bark had very low AW and excessive AS. These physical properties would demand a change in traditional irrigation management.

Harrelson et al. (2004) compared physical properties after 56 and 336 d of fresh and aged pine bark sources blended with coarse builders sand (8 pine bark : 1 sand, 11% sand by volume). These substrates were also used in a 160-d plant growth study. Total dry weight of skogholm cotoneaster (*Cotoneaster dammeri* 'Skogholm') grown in the aged 8 pine bark : 1 sand was 12% larger than cotoneaster grown in fresh 8 pine bark : 1 sand substrate. Additional N did not increase growth in the fresh pine bark–sand substrate; therefore, the authors speculated that the growth differences were due to differences in physical properties (Table 2). Container capacity and AW in the aged pine bark–sand substrate were significantly greater than fresh pine bark 56 and 336 d after treatment initiation (DAI) (Table 2). This was also reflected in the volume of irrigation required to maintain a 0.2 leaching fraction in each substrate. Aged pine bark with a higher AW capacity required a greater volume of water. This supports a conclusion that it was difficult to maintain adequate water in the fresh pine bark–sand substrate and growth was limited by AW content. The authors concluded that fresh pine bark–sand substrate would require frequent irrigation with small quantities of water due to limited AW content. Of additional interest is the change in AW and AS from 56 to 336 DAI in the fresh 8 pine bark:1 sand substrate (Table 2). Available water increased from 15.8% to 22.3% while AS decreased from 36.3% to 24.9%. These changes demonstrate dramatic improvements in the physical properties with time. Conversely, the aged pine bark–sand substrate became marginally acceptable with a decrease in AS from 25.9% to 17.0%. Consequently, both fresh and aged pine bark can present challenges to the grower.

Spomer (1975) stated that drainage in organic substrates could be improved either by increasing container depth or by amending the medium with coarse components. Aggregates such as perlite, PermaTill (concrete block particles; Carolina Statlite Co., Salisbury, N.C.), pea gravel, pumice, sand, screened fly ash, granite shavings, and calcined clay can be used as coarse components for potting substrates. Ag-

Table 2. Effect of age of pine bark on physical properties.[z]

Pine bark	Total porosity (% vol)[y]	Air space (% vol)	Container capacity (% vol)	Available water (% vol)	Unavailable water (% vol)	Bulk density ($g \cdot cm^{-3}$)[x]
Prior to treatment initiation (pine bark substrate)						
Aged	87.3 a[w]	25.2 b	61.1 a	26.3 a	35.8 b	0.19 a
Fresh	88.3 a	39.3 a	49.0 b	9.8 b	39.2 a	0.17 b
56 d after treatment initiation (8 pine bark:1 sand substrate)						
Aged	82.8 b	25.9 b	56.9 a	22.7 a	34.3 a	0.32 a
Fresh	85.4 a	36.3 a	49.1 b	15.8 b	33.3 a	0.32 a
336 d after treatment initiation (8 pine bark:1 sand substrate)						
Aged	74.9 b	17.0 b	57.9 a	30.0 a	27.9 b	0.35 a
Fresh	80.1 a	24.9 a	55.2 b	22.3 b	32.6 a	0.35 a

[z]All analyses performed using standard soil sampling cylinders [3 inches (7.6 cm) i.d., 3 inches high] at the North Carolina State University Horticultural Substrates Lab, Raleigh.
[y]Air space and container capacity affected by height of container. Air space calculated as total porosity-container capacity. Container capacity predicted as percent volume at drainage. Available water calculated as container capacity-unavailable water. Unavailable water determined as percent volume at 1500 kPa (15.0 bar).
[x]$1 g \cdot cm^{-3} = 62.4274 lb/ft^3$.
[w]Means within columns and weeks after treatment initiation followed by the same letter are not significantly different as determined by Fisher's protected least significant difference, $P = 0.05$.

gregates that are used in the nursery industry tend to be local products. Some products, such as pea gravel, coarse sand, and concrete block particles, can drastically increase wear on mixing equipment and, in the case of fly ash, raise pH and alter chemical properties of potting substrates. Aggregates can also grind organic components, reducing particle size if mixed for too long in mechanical blending equipment. Addition of sand to bark is a common practice throughout the U.S. Nurseries add sand to bark to increase the weight of containers to prevent blow-over and to slow infiltration rate of irrigation water as it moves through the container profile, particularly in fresh bark. The slower infiltration rate promotes more thorough wetting of the substrate, compared with straight coarse bark particles, through which water can channel rapidly to the bottom of the container (Bilderback and Jones, 2001). Growers use sources of sand that are available locally due to costs related to hauling. Mortar sand used in laying brick must be used cautiously in potting mixes since it has very fine particles and readily fills pores between larger bark particles, reducing AS. Most growers use washed builder's sand (particle size distribution is approximately 56% of particles between 2.0 to 0.5 mm with ≤10% particles <0.2 mm). Builders sand usually has a wet weight of 120 lb/ft^3, approximately 9% AS and 36% TP (Bilderback, 1982). In some localities, well point gravel that has a large particle size [approximately 56% particles ≥2.0 mm; 40% particles between 2.0 mm to 0.25 mm; and 5.0% ≤0.5 mm (small particles)] is used by nurseries. When potting materials have greatly different particle sizes, such as pine bark and fine sand, the final volume is not additive if they are mixed together (e.g., 1 $yard^3$ plus 1 $yard^3$ results in less than 2 $yard^3$, perhaps 1.5 to 1.75 $yard^3$). In this situation, a great increase in the D_b of the substrate would be expected. An increase in bulk density results in lower TP and decreased AS. Even coarse builder's sand is much smaller in particle size than large pine bark particles; therefore, adding sand usually increases moisture retention and AW content but reduces AS and TP when added to bark.

Arcillite is a calcined montmorillite and illite clay. When used as a substrate amendment, arcillite improved growth of container-grown nursery crops (Warren and Bilderback, 1992; Wildon and O'Rourke, 1964). Determining optimal rates for components used in potting substrates requires experimentation. Testing should include evaluation of physical and chemical characteristics as well as growth studies of promising combinations of components. In a study conducted by Warren and Bilderback (1992), arcillite was incorporated into milled, screened pine bark in incremental rates of 0, 45, 90, 112, or 136 $lb/yard^3$. Container capacity, AW, and D_b increased with increasing arcillite rate, whereas TP and UAW were unaffected (Table 3). Air space decreased with increasing arcillite rate from 29.2% for pine bark alone to 20.8 % at the 136 $lb/yard^3$ arcillite rate. Sunglow azalea (*Rhododendron* 'Sunglow') growth increased curvilinearly with increasing arcillite rate with the maximum dry weight of 39.5 g occurring at 112 $lb/yard^3$. Shoot dry weight of skogholm cotoneaster also increased curvilinearly with increasing arcillite rate. The maximum dry weight of 132.0 g also occurred with 112 $lb/yard^3$.

Crops in small containers may overcome decomposition problems in early periods of production if roots become distributed throughout the potting substrate quickly. The greatest disadvantage is that AS may be reduced too much over production periods, requiring careful irrigation management to avoid waterlogging and anoxia of roots (Bilderback and Jones, 2001). Waterlogged substrates are also a problem in large containers when crops are held for as long as 2 years during a production cycle. Under long production cycles, substrate in large containers becomes spongy. Very little data or documentation of the effects of organic component decomposition have been published due to the difficulty of measuring physical property changes over time. Laboratory analyses of initial physical properties at potting can be compared to end of the production cycle physical properties. However, comparisons are usually not conducted under laboratory conditions since changes in D_b of the substrate that occurred over time are difficult to reproduce by packing sample cores for porometer laboratory analyses (Bilderback et al., 1982; Fonteno, 1996; Niemiera et al., 1994). Rather than packing cores in the lab, there are two procedures that can be used to compare substrate physical characteristics over a period of time. One alternative is to bury sample cores in fallow containers; these containers containing cores are then placed under production conditions. The cores are removed after either 9 weeks or 1 year and physical properties determined (Warren and Bilderback, 1992). This procedure is not frequently done since very few researchers have equipment for physical property analysis and laboratory sample cores are tied up for long periods of time. A second alternative is to conduct initial laboratory analyses by packing cores for porometer analyses; then samples for end of production analysis are created by filling fallow containers with the substrate and placing the fallow containers under nursery production

Table 3. Physical properties of arcillite amended pine bark substrate.[z]

Arcillite rate ($lb/yard^3$)[y]	Total porosity[x] (% vol)	Air space (% vol)	Container capacity (% vol)	Available water (% vol)	Unavailable water (% vol)	Bulk density ($g\cdot cm^{-3}$)[w]
0	79.9	29.2	50.7	20.4	30.3	0.19
45	76.4	24.2	52.2	23.6	28.6	0.22
90	80.4	25.1	55.3	24.9	30.4	0.24
112	78.2	23.4	54.8	24.6	30.2	0.25
136	74.0	20.8	53.2	24.1	29.1	0.27
Significance						
Linear	NS	**	*	*	NS	**
Quadratic	NS	NS	*	*	NS	NS

[z]All analyses performed using standard soil sampling cylinders [3 inches (7.6 cm) i.d., 3 inches high] at the North Carolina State University Horticultural Substrates Lab, Raleigh.

[y]1 $lb/yard^3$ = 0.5933 $kg\cdot m^{-3}$.

[x]Air space and container capacity affected by height of container. Air space calculated as total porosity-container capacity. Container capacity predicted as percent volume at drainage. Available water calculated as container capacity-unavailable water. Unavailable water determined as percent volume at 1500 kPa (15.0 bar).

[w]1 $g\cdot cm^{-3}$ = 62.4274 lb/ft^3.

[NS, *, **]Nonsignificant or significant at $P \leq 0.05$ or $P < 0.01$, respectively.

conditions for a determined length of time. Core samples can then be collected from fallow containers by driving a sharpened beveled ring attached to a sampling core into the substrate and extracting the sample for porometer analysis. It can be difficult to obtain intact samples using this procedure if large particles such as coarse pine bark are a component in the substrate.

Several volume displacement methods have been reported that provide approximate values for TP, AS, CC and D_b (Bilderback, 1982; Gessert, 1976; Spomer, 1975; Whitcomb, 1979). Most of these procedures begin with determining the volume of the container. This procedure frequently includes covering drain holes of selected containers and measuring the volume of the container by filling the container with water or substrate. The next step measures the amount of water required to saturate the substrate, followed by uncovering the drain holes and measuring the volume of water drained from the container. There are similar procedures that substitute wet weight of substrates after drainage, and oven dry weight of substrates (Fonteno, 1996). Other procedures suggest inserting plastic bags in containers to determine air and water characteristics (Cooke et al., 2004).

Although conducting "home remedy" analyses of physical property results will not be as precise as laboratory analyses, these procedures can be used to investigate changes between initial and end of production physical properties of container substrates (Cooke et al., 2004). Simply weighing fallow substrate-filled containers after potting and comparing them to end of production container weight could be useful in understanding changes in physical properties over time. To obtain useful data, overfill 10 containers with potting substrate, tap the bottom of the containers three times on a surface to settle the substrate, then level the substrate with the top of the container. Containers are then irrigated, drained for 2 h, and wet weight recorded. At the end of the production cycle containers are irrigated, drained for 2 h and weighed. The shrinkage of the substrate from the top of the container could be measured to determine an approximate final volume and wet D_b. by dividing the final weight of the container by the adjusted volume of the container. Changes in wet D_b can then be compared between initial and final samples. Pokorny (1993) recommended that growers determine D_b of potting substrates, as many quarantine requirements for interstate shipping require pesticide application based on D_b of potting substrates. Bulk density is usually expressed as the dry weight per given volume of container substrate either as pounds per cubic foot or grams per cubic centimeter. To determine a dry bulk density, contents of the container would need to be placed in an oven and dried until they no longer lose weight. This generally can be accomplished by placing a 1-gal container in an oven at 145 °F for 48 h.

Knowing initial and end of production cycle physical property values would allow growers to determine a critical "sell or shift" schedule. Physical properties affect all the resources in the container, including water and air space, and nutrient availability. Excessive water held in containers limits root growth and the overall vigor of the crop. Plants growing in waterlogged containers begin to decline, resulting in application of crop protection chemicals and minor element supplements, such as chelated iron, to maintain a healthy appearance in plants that no longer have actively growing roots.

Literature cited

Airhart, D.L., N.J. Natarella, and F.A. Pokorny. 1978a. Influence of initial moisture content on the wettability of a milled pine bark medium. HortScience 13:432–434.

Airhart, D.L., N.J. Natarella, and F.A. Pokorny. 1978b. The structure of processed pine bark. J. Amer. Soc. Hort. Sci. 103:404–408.

Bilderback, T.E. 1982. Container soils and soilless media, p. 1–12. In: V. Bonaminio (ed.). North Carolina nursery crops production manual. Bul. NCPM 9, N.C. Agr. Ext. Serv., Raleigh.

Bilderback, T.E., W.C. Fonteno, and D.R. Johnson. 1982. Physical properties of media composed of peanut hulls, pine bark and peatmoss and their effects on azalea growth. J. Amer. Soc. Hort. Sci. 107: 522–525.

Bilderback, T.E. and R.K. Jones. 2001. Horticultural practices for reducing disease development, p. 387–400. In: R.K. Jones and D.M. Benson (eds.). Diseases of woody ornamentals and trees in nurseries. APS Press, St. Paul, Minn.

Cooke, A., T.E. Bilderback, and M. Lorscheider. 2004. Physical properties measurements in container substrates: A field quantification strategy. Proc. Southern Nursery Assn. Annu. Conf.. 49th Annu. Rpt. p. 102–104.

Fonteno, W.C. 1996. Growing media: Types and physical/chemical properties, p. 93–122. In D.W. Reed (ed.). Water, media and nutrition for greenhouse crops. Ball Publ., Batavia, Ill.

Gessert, G. 1976. Measuring air space and water holding capacity. Ornamentals Northwest 3:59–60.

Harrelson, T., S.L. Warren, and T.E. Bilderback. 2004. How do you manage aged versus fresh pine bark?. Proc. Southern Nursery Assn. Annu. Conf. 49th Annu. Rpt. p. 63–65.

Niemiera, A.X., T.E. Bilderback, and C.E. Leda. 1994. Pine bark physical characteristics influence pour-through nitrogen concentrations. HortScience 29:789–791.

Pokorny, F.A. and B.K. Henny. 1984. Construction of a milled pine bark and sand potting medium from component particles: II. Medium synthesis. J. Amer. Soc. Hort. Sci. 109:774–776.

Pokorny, F.A. 1993. Bulk density in container plant production. Georgia Green Ind. Assn. Nswl. March. p. 28.

Spomer, A.L. 1975. Small soil containers as experimental tools: Soil water relations. Commun. Soil Sci. Plant Anal. 6:21–26.

Warren, S.L. and T.E. Bilderback. 1992. Arcillite: Effect on chemical and physical properties of pine bark substrate and plant growth. J. Environ. Hort. 10:63–69.

Whitcomb, C.E. 1979. Plants, pots and drainage. Ornamentals South 1(4):16–19.

Wildon, C.E. and F.L.S. O'Rourke. 1964. The effect of arcillite in media for pot plants. Mich. State Univ. Res. Rpt. 16.

Yeager, T., C. Gilliam, T.E. Bilderback, D. Fare, A. Niemiera, and K. Tilt. 1997. Best management practices, guide for producing container-grown plants. Southern Nursery Assn., Atlanta.