HORTSCIENCE 31(7):1177–1179. 1996.

Characteristics of Internal Porosity of Cork Container Media

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Additional index words. particle density, total porosity, effective porosity, ash content

***Abstract.* The structure of cork (*Quercus suber* L.) bark presents a series of characteristics, suggesting that internal porosity is partly occluded. This study determined the porosity in the waste cork industry (C) and when such waste product had been composted during 4 (CC-4), 7 (CC-7), and 10.5 months (CC-10.5). The particle density of the intact and finely ground material differed significantly in all particle size ranges larger than 0.5 mm. The porosity of the cork substrates ranged from 80% to 94% of the total volume, according to granulometry and the degree of decomposition. However, large particles and less decomposed material with a high porosity had up to 10% of the total volume as occluded pores. The material's effective porosity varied slightly between the various particle sizes and degrees of decomposition, which ranged between 80% and 89%, having an average value of 85%. The ash content was highly correlated with the particle density of the finely ground material. Nevertheless, and due to occluded porosity, we cannot estimate the "effective porosity" from the ashes; therefore, we must resort to techniques that involve the displacement of a fluid, such as liquids or gas pycnometry or submersion.**

Most media substrates are porous materials with many of intragranular hollows. These internal pores may be connected to the intergranular pores or they may be occluded. Such occluded porosity does not contribute to the water and gas exchange between the growing medium and the plant and, therefore, it should not be included when the "effective porosity" (EP) of the material is determined.

The fraction of total space occupied by pores, "total porous space (TP)" is calculated from the bulk density (ρ_a) and the particle density (ρ_r), as TP = $(1 - \rho_a/\rho_r)$. When the particle density is determined by techniques that measure the displacement of a fluid, such as pycnometric methods or submersion, the volume of occluded pores is included as a part of the particle's volume, and the previous equation calculates the EP. The particle density obtained through these methods has been named "pseudoreal" (Gras, 1987) to distinguish it from the "real particle density," which would be determined after the destruction of all of the occluded pores by means of fine grinding.

For organic substrates, particle density is often estimated as a function of the substrate ash content. Equations either establish a linear relationship between these two characteristics (Puustjarvi and Robertson, 1975), or else they are the result of presuming that the solid matrix is made up of a mixture of mineral (the ashes) and organic material. So ρ_r is calculated by:

$$\rho_r = \frac{100}{\dfrac{c}{2.65} + \dfrac{100 - c}{\rho_o}}$$

where c is the percentage of ash based on dry weight and ρ_o is the density of organic material. Authors differed on the value selected for ρ_o (De Boot et al., 1974; Gabriëls and Verdonck, 1991; Gras, 1987), whereas density of mineral material was always 2.65 $g{\cdot}cm^{-3}$. When calculating TP with the estimated particle density as a function of the ash content, the occluded porosity is included within the total porous space, which leads to overestimating the "air capacity" of the substrate.

Cork is a tissue that is made up by hollow dead cells, with average sizes that range from 30 to 40 µm. The average thickness of its walls is 1 µm and they are arranged without interstices between them. These walls are formed by five layers: a central, lignified layer; two thick suberized layers that combine fine wax and suberin sheets; and, finally, two outer cellulosic layers. The plasmodesmata canals of these cellular walls are occluded. The above mentioned characteristics make cork a tissue with a very low density (120 to 160 $kg{\cdot}m^{-3}$); it also is compressible, elastic, waterproof, a strong thermal and acoustic isolator, and highly resistant to decomposition. As a result of these properties, cork is used in many industrial applications (Vieira, 1991).

Joined with suberized cells are impurities present in the cork bark: sclerenchyma cells with extremely thick lignified walls; cells rich in tannins and resinous substances; other nonsuberized cells, such as the inclusions of the liber and the phelloderm tissues, as well as the "raspa" (outer part of the bark, which is made up by the cells from the phelloderm and the cortex that have dried up and died during the process of separating the bark from the tree and that are impregnated with cellular fluids and other substances). Such impurities, and the pieces of cork to which they are linked, constitute the waste cork industry that is used as container media.

As a result of the special properties of this bark, the structure of cork residues differs from that of other barks that have been used as substrates and have been studied by several authors (Airhart et al., 1978; Pokorny and Wetzstein, 1984). Also, *Q. suber* bark internal porosity may be mostly occluded. The high content of tannins, waxes, and suberins makes it difficult to decompose, and, quite probably, it contains some undamaged suberized cells, particularly among the bigger particles, even following composting. If this is so, and because of occluded porosity, it would be incorrect to determine the air capacity of that substrate as a function of its ash content, which is the commonly used method.

In the present study, we determined the value of occluded porosity in cork substrates that had undergone various processes, and we relate this value to granulometry and particle structure.

Materials and Methods

Waste cork industry materials were composted for zero (C), 4 (CC-4), 7 (CC-7), or 10.5 months (CC-10.5). Once air-dried, the material was sieved with standard sieves with openings of 2, 1, 0.5, 0.25, and 0.125 mm.

Bulk density was determined according to De Boot et al. (1974). The particle density of the finely ground material was measured in a water pycnometer; that of the intact material was determined through the submersion method for particles >0.25 mm, while the density of particles <0.5 mm was measured in a water pycnometer (Blake and Hartge, 1986). In both methods, water reached the boiling point to ensure that all the air had been removed. The ash content was determined through calcination in an oven at 550 °C for 5 h on samples that had been previously oven-dried at 105 °C.

Total porosity (TP) was calculated from bulk density (BD) and particle density for the finely ground material (PD), as TP = (1 – BD/PD). Effective porosity (EP) was calculated from BD and particle density for the intact material (SPD), as EP = (1 – BD/SPD). The volume of the cork particles occupied by occluded pores (OP) was calculated from SPD and PD, as OP = (1 – SPD/PD).

The number of replications varied depending on the standard error of the results obtained (up to 20 replications in some determinations); at least three replications were used for each determination that was made on PD and four for the remaining determinations. Data

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Received for publication 10 Jan. 1996. Accepted for publication 2 July 1996. This work was financed by the CICYT as part of the AGF94-0941 Project. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

were analyzed by regression analysis and analysis of variance and means were separated by Tukey's test.

Table 1. Particle density (g•cm^{-3}) for the intact material (SPD) and for the finely ground material (PD) in cork container media.

Medium[z]		Particle size (mm) 4–2	2–1	1–0.5	0.5–0.25	0.25– 0.125	<0.125
C	SPD	0.623	1.015	1.407	1.528	1.674	1.762
	PD	1.395	1.455	1.557	1.626	1.643	1.785
		**	**	**	**	NS	NS
CC-4	SPD	0.716	1.123	1.463	1.618	1.730	1.843
	PD	1.465	1.485	1.575	1.659	1.744	1.886
		**	**	**	**	NS	NS
CC-7	SPD	0.712	1.284	1.518	1.644	1.735	1.843
	PD	1.489	1.499	1.612	1.648	1.780	1.819
		**	**	**	NS	NS	NS
CC-10.5	SPD	0.873	1.381	1.553	1.639	1.747	1.783
	PD	1.548	1.553	1.682	1.715	1.779	1.801
		**	**	**	**	NS	NS

[z] C: cork; CC-4, CC-7, CC-10.5: cork composted for 4, 7, or 10.5 months, respectively.

[NS, **] Nonsignificant or significant at $P \leq 0.01$, respectively, by Student's *t* test.

Table 2. Percentage of the volume of the cork particles occupied by occluded pores.

Particle size (mm)	Substrate[z] C	CC-4	CC-7	CC-10.5
4–2	55.4	51.1	52.2	43.7
2–1	30.3	24.4	14.3	11.0
1–0.5	9.6	7.1	5.9	7.9
0.5–0.25	5.7	2.5	0.5	4.4
<0.25	0.0	1.0	0.2	1.5
Significance				
Linear	**	**	**	**
Quadratic	**	**	**	**
Means	20.3 a[y]	17.3 b	14.6 c	13.8 c

[z] C: cork; CC-4, CC-7, CC-10.5: cork composted for 4, 7, or 10.5 months, respectively.

[y] Mean separation by Tukey's test, $P \leq 0.05$.

[**] Linear or quadratic at $P \leq 0.01$.

Table 3. Total porosity (TP) and effective porosity (EP) for cork substrates.

Substrate[z]	Particle size (mm)	TP (% vol)	±SE	EP (% vol)	±SE
C	4–2	93.4	0.29	85.1	0.65
	2–1	90.1	0.27	85.7	0.37
	1–0.5	86.0	0.49	84.5	0.55
	0.5–0.25	83.6	0.28	82.8	0.35
	<0.25	84.9	0.68	84.8	0.68
CC-4	4–2	92.1	0.44	83.8	0.90
	2–1	90.7	0.28	87.7	0.37
	1–0.5	87.2	0.80	86.3	0.85
	0.5–0.25	85.2	0.57	84.8	0.59
	<0.25	84.3	0.60	84.0	0.60
CC-7	4–2	91.9	0.25	83.1	0.53
	2–1	88.5	0.31	86.5	0.36
	1–0.5	85.5	0.40	84.6	0.42
	0.5–0.25	84.0	0.51	83.9	0.51
	<0.25	83.7	1.67	83.6	1.65
CC-10.5	4–2	91.8	0.32	85.4	0.57
	2–1	88.0	0.46	86.5	0.52
	1–0.5	86.3	0.44	85.2	0.48
	0.5–0.25	86.3	0.47	85.7	0.49
	<0.25	84.6	0.81	84.3	0.82

[z] C: cork; CC-4, CC-7, CC-10.5: cork composted for 4, 7, or 10.5 months, respectively.

Results and Discussion

SPD and PD differed significantly for all the particles >0.5 mm (Table 1). For particles <0.25 mm, PD and SPD were similar, indicating that there were no occluded pores on these fractions. The differences between these two densities were greater when the particles were larger and when the material was less decomposed.

Determining particle density of organic materials is more difficult than for mineral soils (Fonteno, 1993); thus, various measuring methods have been suggested (Terés et al., 1993), the results of which vary with the fluid used (water, gas, polar or nonpolar organic fluids, etc.). The eventual alterations on the walls caused by the measurement method (use of boiling water) may lead to underestimation of the volume of occluded pores, which might be higher than the calculated value.

In a huge piece of cork, more than 85% of the volume is made up of cellular cavities that are not connected to the outside (Fortes and Rosa, 1988; Vieira, 1991). In the industrial residues used as a substrate, such values are much lower because there are nonsuberized cells and other cells with fractured walls. As the particles are smaller, the chance for the cellular walls to be exposed to rupture are higher and, therefore, OP rapidly decreased as the size of the particles decreased (Table 2). However, the slow decrease of OP during composting would be a reflection of the slow attack of microorganisms on these suberized walls and would be in harmony with the nondetection of typically lignolytic microorganisms in the composting pile (Avilés et al., 1995).

TP and EP were higher when particles were bigger (Table 3). However, larger particles and less decomposed material, which had a higher porosity, might have up to 10% of their total volume occupied by occluded pores. As a result, EP varied slightly between the different particle sizes and degrees of decomposition and varied between 80% and 89%, showing an average value of 85%.

Cork residues have a polyhedral form that resembles that of sand particles. Thus, we may assume that the volume of pores between the cork particles will be similar to that measured between sand particles, with a similar distribution of the sizes. The volume of the pores found in sand was similar for various fractions of a range of particle sizes and ranged from 42% to 50% with a mean of 44% (data not shown). We may deduce that the volume of internal pores of cork that open outwardly is ≈40%. These values are similar to those found for other barks (Pokorny and Wetzstein, 1984; Spomer, 1975).

PD of cork was highly correlated (r^2 = 0.922, $P < 0.001$) with its ash concentration (Fig. 1) by the linear function PD = 1.434 + 0.012 c, in which c is the percentage of ash based on dry weight. Regression coefficients for slope and intercept were statistically significant ($P < 0.001$). This relationship is very much like the one proposed for peat (Puustjarvi and Robertson, 1975). Both linear functions agreed better with the experimental data than hyperbola arcs calculated by Eq. [1]. This equation underestimated PD when c was high and overestimated PD when c was low because c and ρ_o were not independent variables. Less decomposed and bigger cork particles with an extremely low ash content (Table 4) are made up of a high proportion of suberized cellular walls, the density of which is estimated to range between 1.20 and 1.25 g•cm^{-3} (Fortes and Rosa, 1988; Vieira, 1991), while the smaller and more decomposed particles with a higher ash content also contain a higher proportion of highly transformed organic materials with higher densities. Nevertheless, the estimated PD values for ρ_o = 1.50 g•cm^{-3} (Gabriëls and Verdonck, 1991) were similar to those we obtained experimentally.

The ash content of cork increased with the composting time, due to the decomposition of organic material. However, because of the proliferation of the fungal mycelium that made

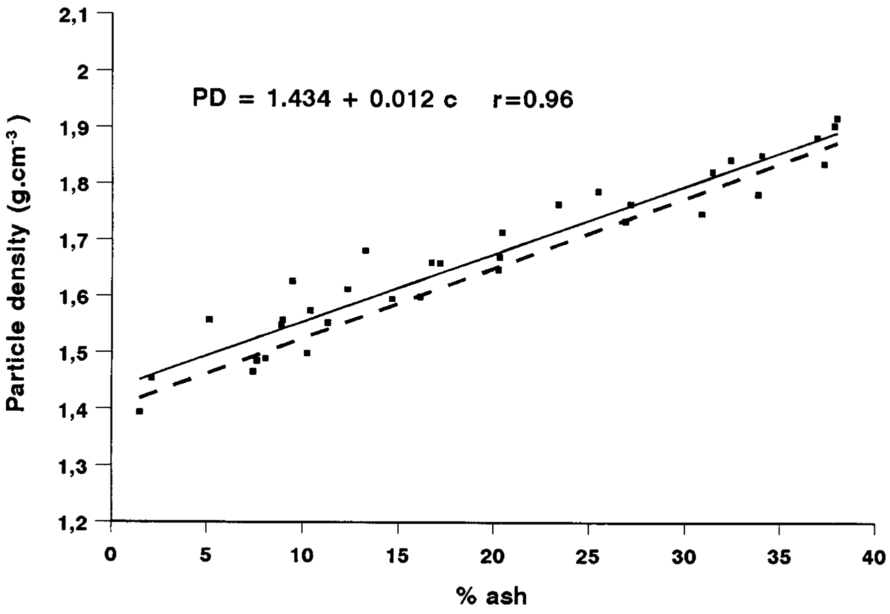

Fig. 1. Relationship between ash concentration (c = percentage of ash, dry weight basis) and particle density (PD) in the finely ground cork. Regression curve (———) and Puustjarvi and Robertson relationship (- - - -). All regression coefficients are statistically significant ($P \leq 0.001$).

Table 4. Ash concentration (dry-weight basis) of the particles of several cork substrates.

Particle size (mm)	Ash concn (%)			
	Substrate^z			
	C	CC-4	CC-7	CC-10.5
4–2	1.5	7.4	8.1	8.9
2–1	2.1	7.6	10.2	11.3
1–0.5	4.6	10.4	12.3	13.3
0.5–0.25	8.3	17.2	20.2	20.5
0.25–0.125	20.3	26.9	30.9	23.4
<0.125	27.2	34.0	37.3	33.8
Significance				
Linear	**	**	**	**
Quadratic	**	**	**	**

^{z}C: cork; CC-4, CC-7, CC-10.5: cork composted for 4, 7, or 10.5 months, respectively.
**Linear or quadratic at $P \leq 0.01$.

up a relevant proportion of the fine fraction of CC-10.5, the ash content of these fine fraction decreased again below the maximum reached after 7 months of composting.

We conclude from our results that the incineration method is a good method to assess the particle density of cork, once its physical organization has been destroyed through grinding, and that this method can be used to calculate TP. However, we must refrain from using this method on cork to estimate the EP, since this material has a high amount of occluded pores and the application of such methodology would lead to overestimation of the air capacity of the substrate.

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