Experience with Selected Physical Methods to Characterize the Suitability of Growing Media for Plant Growth

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Keywords: bulk density, total pore space, structural stability, root resistance, water retention, rewetting, hydrophobicity, water transport, oxygen transport

Abstract

The variety of materials and mixes of materials used in horticulture as growing media is large. Peat products, wood products, composts, mineral fibres, mineral particles, synthetic foams, synthetic fibres and organic fibres; all these products are more or less suitable growing media.

Selected physical aspects related to plant growth requirements, are used to discuss the suitability of growing media for plant growth. Aspects mentioned include bulk density, total pore volume, structural stability, root resistance, water retention, rewetting, hydrophobicity, water transport, and oxygen transport. Methods to measure these aspects and experience with the results are also discussed in this review.

In conclusion, the physical properties used to assess the suitability of substrates for growth share a large dependence on pore architecture. This made it possible to relate the formulas for water retention, hydraulic conductivity and diffusivity to each other. It seems possible to extend this unification to resistance to rooting and re-wetting. Bulk density, total pore space and structural stability exercise their influence on plant growth mainly through the key characteristics for growth assessment: resistance to rooting, water retention, rewetting and water and oxygen transport. Better definitions and possibly new methods to characterise rewetting, hydrophobicity and refreshment rate are advocated. When assessing the influence of water and oxygen transport, individual layers and gradients towards the roots are of importance because of the very fast transport rate changes with water or air filled pore space.

INTRODUCTION

The variety of materials and mixes of materials used in horticulture as growing media is large. Peat products, wood products, composts, mineral fibres, mineral particles, synthetic foams, synthetic fibres and organic fibres; all these products are more or less suitable as growing media (Table 1).

The aim of this review is to discuss those physical characteristics of different growing media which are important for plant growth. The choice of the physical parameters to be discussed is inspired by some of the basic functions of the roots, anchorage, the uptake of water and the uptake of mineral nutrients (Kramer and Boyer, 1995).

Anchorage in itself is provided by all rooting media. But there are distinct differences in root growth between various rooting media. These are thought to be represented by *root resistance*, *bulk density* and *total pore space*. These properties are not always stable in time. Therefore *structural stability* is included in the review. The uptake of water is related to the force with which the rooting medium holds the water, the *water retention*. The uptake of water is also determined by the dynamic water transport towards the roots. To accurately describe water transport in rooting media it is necessary to consider some changes in water retention in time caused by either hysteresis or hydrophobicity. These changes are thought to be characterised by *rewetting* and *hydrophobicity* measurements. The uptake of minerals is - questionably – not regarded as a physical aspect of rooting media. The passive transport of nutrients to the roots is quite similar to the dynamics of *oxygen transport* towards the roots, and oxygen transport is definitively considered a physical aspect of rooting media. Oxygen is necessary for proper root growth and the uptake of some nutrients.

This choice of physical aspects is of course limited. Furthermore the aspects are interrelated. A low water tension may facilitate growth by promoting transport of water and nutrients, but at very low water tensions the amount of air-filled pores will become too low for sufficient oxygen transport. Higher water tensions may be used by growers e.g., to create denser pot plants. Imperfect *rewetting* capacity of a substrate will amplify any unevenness in crop water supply and uptake. In practice growers will use more frequent irrigation cycles on this type of medium.

These physical parameters can be described by means of various methods. Some of these methods are long in use and have been proven satisfactorily, while others may show clear disadvantages especially for some materials. Many of the methods are derived from soil science (Klute et al., 1986), while new methods are still developing and need to be tested (Raviv et al., 1999; Blok and Cassamassimo, 2001; Wever et al., 2004; Naasz et al., 2005).

CURRENT METHODS FOR SELECTED PHYSICAL ASPECTS

Sample Preparation

Measurements of physical aspects are usually markedly influenced by both, the selection and exact preparation of bulk samples, and the consequent sub sampling into individual samples. It is therefore important to apply strict rules for sampling and sub-sampling (EN 12579, 1999; EN 13040, 1999). Furthermore, different groups of rooting media require different sampling and preparation methods, as do different storage systems like heaps, production batches or bags. For example small coherent materials like pre-shaped plugs for rooting will be used as such albeit after bulk sampling from different production batches. Larger coherent units like poly urethane slabs are cut after bulk sampling from different production batches. Loose soft materials like peat and compost are easily compressed by their own weight and moisture content. They may first have to be bulk sampled from various places and at standard depths from heaps. Then they will be brought to a standard moisture level, entered in a controlled way into sample holders and subjected to a standard pressure.

Bulk Density, Total Pore Space, Root Resistance and Structural Stability

Bulk density ($kg.m^{-3}$) is defined as the ratio of mass of dry solids to the bulk volume of the soil (Blake and Hartge, 1986) (Table 1). Bulk density is measured by weighing a known volume of rooting medium after heating to 105°C. Non-rigid materials like e.g., peat and composts need to be weighed under carefully defined pressure and filling circumstances. Transport vibrations may alter bulk density considerably. Various norms have been put down (EN 12579, 1998).

The total pore space (%v/v, TPS), is usually calculated from the total volume minus the volume occupied by the solids. To accurately assess suitability for plant growth, the total pore space may have to be corrected for the amount of non connected pores. There is no fixed method to measure the amount of non connected pores but a fair estimate is usually found by grinding the material to a powder and measuring its density thereafter.

The resistance to rooting (kPa) can be measured with a cone penetrometer. The cone penetrometer is supposed to represent a root growing through the medium. The force needed to insert the cone in the medium is measured. Ideally, the penetrometer reading is then correlated to measured pressures of growing roots, but more often it is used on itself. Before the reading becomes stable, some compression of the medium takes place. A larger cone angle and a larger cone diameter increase the distance over which compression takes place before a stable reading is found (Bullens, 2001).

Structural stability is defined as the behaviour of bulk density over time. A poor structural stability leads to a loss of substrate volume, a decreased total pore space and sometimes an increase of small particles in the bottom layer. Structural stability may be influenced by oxidation, mechanical disturbance and chemical breakdown. The structural stability is often measured by the difference in bulk density and TPS before and after crop growth. Other methods assess the risk of structure loss of a given material by exposure to a standard destructive environment (OxiTop® method after Veeken et al., 2003). The OxiTop® method uses a standardised time of oxidation of a water-dispersed organic rooting medium at standard time, temperature and pH and with prevention of nitrification. A standard test for pH degradation of mineral fibres does not yet exist.

Water Retention

The waterholding capacity is a function of the total pore space and a suction force applied (either in cm water pressure or kPa). The more suction is applied, the drier the rooting medium gets (main drainage curve in Klute, 1986). For rooting media with suctions up to 10–20 kPa suction tables are in common use. The suction is usually applied by placing the samples on a bed of very fine sand or clay in a water tight container connected to an adjustable overflow. Various variants exist, e.g., by using air pressure, especially as, at higher suctions, air will enter the sand bed of the suction table. Strict procedures for sample preparation, saturation and measuring time have to be observed.

The rewetting curve (main wetting curve in Klute, 1986) shows the ability of a rooting medium to take up water against gravity from a well defined point of dryness. The rewetting curve is measured on the same type of apparatus and in the same units as described for measuring the waterholding capacity (EN 13040, 1999).

Hydrophobicity is the irreversible loss of water retention upon drying. One of the main causes is the deposition of hydrophobic molecules on pore walls. It can be measured as a decrease in water contact angle or water drop penetration time (Michel et al., 2001). The measurement requires many microscopic observations and is laborious.

Water Transport

A simple formula after Darcy characterizes water transport; $Q=Kh*dH/dx$. With Q being the flux in m, Kh the unsaturated hydraulic conductivity in $m.s^{-1}$, dH the head difference in m and dx being the distance in m. Thus one can calculate or model water transport rates for any head difference over any distance in a given rooting medium. The real difficulty is in finding Kh. Kh may be found with a series of formulas of the form; $Kh = Ksat * (WFP/TPS)^m$. Ksat being the hydraulic conductivity at saturation, WFP the water filled pore fraction v/v and TPS the total pore space v/v, m being a constant. The only real variable now is the water filled pore space. The influence of WFP on Kh is very large as represented by the exponent. The relation WFP over TPS is though to represent the tortuosity of the transport path (Allaire et al., 1996). The measurement of either Ksat or Kh requires careful pre-treatment of the samples and the apparatus used (da Silva et al., 1995; Wever et al., 2004).

Oxygen Transport

A simple formula characterizes oxygen transport trough air; $Q=Dh*dC/dx$. Dh is the unsaturated oxygen diffusivity in $m^2.s^{-1}$. Thus one can calculate or model oxygen transport rates Q in $g.m^{-2}$, for any concentration difference, dC in $g.m^{-3}$, over any distance, dx in m, in a given rooting medium. The real difficulty is in finding Dh. Dh may be found with a series of formulas of the form; $Dh = Do * (AFP^a*TPS^b)$. Do being the oxygen diffusivity in air. AFP are the air filled pores v/v, TPS the total pore space in v/v and a and b are constants. The only real variable is the air filled pore space. The influence of AFP on Dh is extremely large as represented by the exponent (Wever et al., 2001). The measurement of either Dh or Do requires careful pre-treatment of the samples and the apparatus used (Klute, 1986). A variant including realistic plant oxygen use is the construction of an air tight container around the rooting material of a growing plant. In such systems an oxygen gradient from top to bottom will arise and data may be used as input for improving models (Blok and Cassamassimo, 2001). The measurement of oxygen in air or water has become much easier with the introduction of fibre optic methods (Blok and Gérard, 2001). The introduction of the sensors in the material still requires great care and a control procedure to be sure the measurement is reliable i.e., no air leakage is introduced by the measurement. Another approach is the installation of air chambers with local contact to the atmosphere in the rooting media under study (Wever et al., 2001). The oxygen content in the air chambers can be measured either by entering the sensor through a suitable septum or by using an air tight syringe to take a sample to a gas chromatograph.

EXPERIENCE WITH SELECTED PHYSICAL ASPECTS

Bulk Density, Total Pore Space, Root Resistance and Structural Stability

1. Bulk Density. The bulk densities for most growing media are 3–20 times lower than 1500 kg.m^{-3} which is often found in soils (Table 1). For a given material an increase in bulk density will decrease the total pore space and affect growth mainly through the effects of reduced free pore space and increased rooting resistance. More than one figure for bulk density is necessary to describe rooting media with a density profile e.g., in some peats, layers e.g., in some rockwools (Bullens, 2001) or crusts e.g., on some polyphenols.

2. Total Pore Space. Total pore space for most growing media is 1.5–3.0 times higher than 35% found in common soils (Table 1). An increase in total pore space will decrease the water retention, increase oxygen transport and increase root penetration. Materials like synthetic foams as poly urethanes and polyfenols, volcanic materials like tuffs and expanded minerals like perlites may contain 10–20% of non connected pores. When non connected pores are subtracted from the Total Pore Space, the resulting Free Pore Space is the correct figure to use in calculations for water retention, water and oxygen transport (Baas et al., 2001).

3. Resistance to Rooting. The ease of rooting is determined by the material density and the way the particles are connected. Typical penetrometer values for rooting media are 2–20 times lower than a common 1200 kPa found in soil. Root and shoot development react to differences in rooting resistance over the whole range of values found (Bullens, 2001) (Fig. 1). Fibrous materials like rockwool and coarse peat may be compacted over several centimeters before a stable reading is found unless an adapted cone is used with a maximum diameter of 2 mm and a cone angle of 30 degrees. Rigid materials like Rockwool should be measured in three directions as the fibers may be deposited preferably in some directions and roots will prefer those directions. Rigid materials like Rockwool and pressed peat/soil plugs and cubes may also show a marked compaction profile.

4. Structural Stability. When the structure is affected, total pore volume decreases, water retention increases, oxygen transport becomes slower and rooting resistance increases. An increase in small particles in the bottom layer will do the same locally in the bottom layer. Especially organic rooting media are deteriorating because the material is oxidised, partly by micro biological activity. All rooting media are affected by rooting and mechanical causes. Some mineral rooting materials may be affected chemically by incidental low pHs (Table 2). The development of standardized destructive environment tests, or ageing tests for rooting media may benefit from the experience of compost and organic waste technology (Veeken et al., 2003).

Water Retention

1. Water Retention. Water retention measurements are time consuming, but the results are indicative of the ease of the uptake of water - and nutrition - by plants as well as the wetness in various growing systems. Water retention forces in rooting materials are usually 10–100 times lower than the common values for soil growing of 10–100 kPa. At low water retention forces the growth is highest but very low water retention forces are sometimes avoided e.g., when the amount of air filled pores becomes too low for proper oxygen transport. Water retention forces high enough to decrease the fresh weight growth may be desirable e.g., to create denser, i.e., better quality pot plants (Fig. 2).

The method is derived from soil science and the application for rooting media creates some small interpretation problems. One drawback is the sample height of 5 cm, which is treated as a point sample. For smaller suction forces applied (from 0–15 cm suction force i.e., 0–1.5 kPa), the sample height influences the reading. Another drawback is that the sample is initially wetted up to halve its height, while rooting media characteristically drain at the bottom.

2. Rewetting. Rooting media are very different in their ability to rewet e.g., coir dust is known to rewet excellently (Wever et al., 1997). Unfortunately it is still difficult to characterize rewetting ability experimentally because standard methods from soil science require too large pressure heads before rewetting for some rooting media. The problem is in choosing the point of defined dryness. The point of dryness has to be related to dry but practical circumstances which are different for different materials. The actual situation during growing is even more complicated as many drying and rewetting cycles are following one another, ending and starting from different points of dryness (Raviv et al., 1999). Plants do not react directly to differences in rewetting ability but imperfect rewetting will amplify any unevenness in crop water use of a given area. In practice this will force growers to use more frequent irrigation cycles.

3. Hydrophobicity. It is still difficult to discern between uncomplete rewetting caused by air entrapment and pore diameter changes at the one hand (the classic causes of hysteresis i.e., the difference between a drainage curve and the subsequent wetting curve) and pore wall hydrophobicity on the other hand. The difference is of practical importance as drying peat and rooting media in which roots and algae are present display varying grades of hydrophobicity which may affect growth. Wetting agents are sometimes used to facilitate rewetting of hydrophobic rooting media. When using wetting agents the initial maximum water content reached is lower than after a few rewetting cycles because of the reduced surface tension of the water (Fig. 3).

Water Transport

The application of standard measurement devices from soil science for the measurement of unsaturated hydraulic conductance in rooting media proved difficult as the hydraulic conductivities at higher water contents were 100–1500 times faster than the 1–100 cm.d^{-1} found for soils (Fig. 4). Several apparatuses have been proposed over the last decade (Da Silva et al., 1995; Wever et al., 2004; Naasz et al., 2005). Consequent validation by other groups has not yet been reported for all of these and many rooting media have not yet been measured. Despite the very high initial hydraulic conductivities, water transport rates may be growth limiting because the transport rate drops so very rapidly with water content itself, and because water uptake by horticultural crops is very high, and because the rooting volume is usually small (Raviv et al., 1999). Growth may also be hindered by low water content and transport rates around the roots while the overall water content is still acceptable (Caron and Nkongolo, 1999; Caron et al., 2002).

When rooting media have been properly characterised for Kh, or the relation Kh-Ksat, further work may be based upon model calculations for specific rooting media dimensions and specific cultivation and supply techniques.

Even in top down irrigation systems, such as drip irrigation, a lot of water is redistributed from bottom to the top of the rooting medium. The dry parts of the rooting medium can accumulate a load of salt or patches with EC values several times the desired value. No methods are available to assess the refreshment rate correctly.

Oxygen Transport, Oxygen Diffusion

Actual measurements of diffusivity against air filled pores are not abundant (Wever et al., 2001). Calculations based on water content measurements prevail (Caron and Nkongolo, 2004). The curves show an exponential decrease in Dh with AFP (Fig. 5). The inevitable effect is that rooting media tend to have a profile of decreasing oxygen and increasing carbon dioxide content (Fig. 6). Important consequences of the exponential decrease of Dh with AFP are; oxygen diffusion rates in all substrates with interrelated pores may, for lower air filled porosities i.e., under 40%v, be simplified to one relation with air filled porosity. Based on flux calculations for diffusion only, and with dimensions width x height < 20 x 20 cm, oxygen levels in horticultural substrate systems may detectably drop in layers with less than 30% air filled pores. Anoxia may be expected in layers in horticultural substrate systems with less than 10% air filled pores. The exception in Fig. 5 is perlite which had to be corrected for the amount of closed not interrelated pores before it fitted the common line.

In rooting media oxygen is supplied through the irrigation water and used by roots and micro-organisms alike. It is argued that the roots use many times the amount of oxygen supplied in irrigation water. The plant use may be as high as 0.2 mg $O_2.g^{-1}.h^{-1}$ FW-roots (Blok and Gérard, 2001). With 1 kilogram of roots per square meter this is 0.2 $g.h^{-1}.m^{-2}$. The supply is 1 $L.h^{-1}.m^{-2}$ max. At 20 degrees this 1 L contains 8 mg O_2 which is clearly 25 times too low. Oxygenation of supply water is perhaps helpful in reducing the amount of nitrite formed in the supply but does not in itself supply the plant in any way with enough oxygen.

CONCLUSION

A limited set of physical properties characterizes a large number of different growing media. Pore architecture interrelates most of the properties such as bulk density, total pore space, resistance to rooting, structural stability, water retention, rewetting, hydraulic conductivity and diffusivity. Hydrophobicity is probably not depending on pore architecture and refreshment rate probably is. The importance of pore architecture made it possible to relate the formulas for water retention, hydraulic conductivity and diffusivity to each other. It seems possible to extend the formulas at least to resistance to rooting and rewetting.

Bulk density, total pore space and structural stability exercise their influence on plant growth mainly through resistance to rooting, water retention, rewetting and water and oxygen transport rates. This makes bulk density, total pore space and structural stability replaceable as estimators of suitability of a rooting medium for plant growth. Resistance to rooting, water retention, rewetting and water and oxygen transport parameters are at present the key characteristics for growth assessment.

Rewetting, hydrophobicity and possibly refreshment rate are not yet univocally defined. There is a need for better definitions and possibly for new methods to characterise rewetting, hydrophobicity and refreshment rate.

Individual layers should be considered when assessing the influence of water and oxygen transport. This is because of their very fast changes with water or air filled pore space. The same is true for gradients towards the roots. If a plant wants to adapt to an increase in the transpiration – a daily reality – it must create a larger pressure head to increase the flux to its roots. At the same time this will decrease the number of water filled pores around the root and thus decrease the hydraulic conductivity. To avoid over simple models, theoretical work should thus include real water or oxygen uptake patterns in time, realistic rooting medium dimensions and a time step procedure. Validations have been improved by electronic water content measurements and are starting to benefit from the fibre optic oxygen and carbon dioxide measurements.

Although outside the scope of this article, the same goes for the uptake of nutrients which is closely related to transpiration (passive uptake) and water filled pore space (for diffusion). Joining water and nutrient transport and uptake models may therefore be worthwhile.

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Tables

Table 1. Bulk density and volumes occupied by solids, water and air and Total Pore Space in some examples of growing media (volume%).

	Bulk Density ($kg.m^{-3}$)	Solids (Volume%)	Water (Volume%)	Air (Volume%)	Total Pore Space (Volume%)
Glasswool	-	2	59	39	98
Rockwool	49	3	69	28	97
Perlite	105	4	35	61	96
Polyurethane	78	5	18	77	95
Peat	113	9	54	37	91
Pumice	431	17	32	51	83
Clay granules	489	24	21	55	76
Pouzzolane	-	47	20	33	53

Source: Kipp et al., 1999.

Table 2. Change in bulk density and water retention and rewetting characteristics as related to the chemical breakdown of rockwool fibres caused by pH values of 3.5–4.5 around roots of a rose crop.

Sample	Bulk Density ($kg.m^{-3}$)	Water (v/v%)					
		Pressure head (cm)					
		-7.5	-12.5	-25	-100	-12.5	-7.5
New	81	94	76	12	1	1	3
next to block	112	95	90	33	5	7	32
under block	162	93	94	43	17	19	42

Source: Kipp and Wever, not published.

Figures

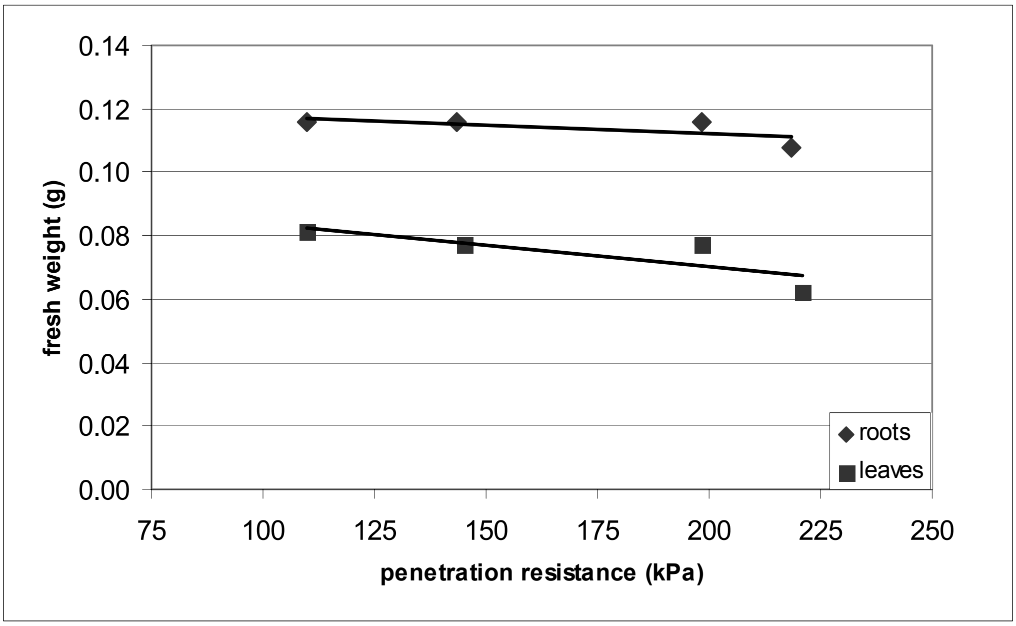

Fig. 1. Decreasing growth with increasing penetration resistance on peat. Source: Bullens, 2001.

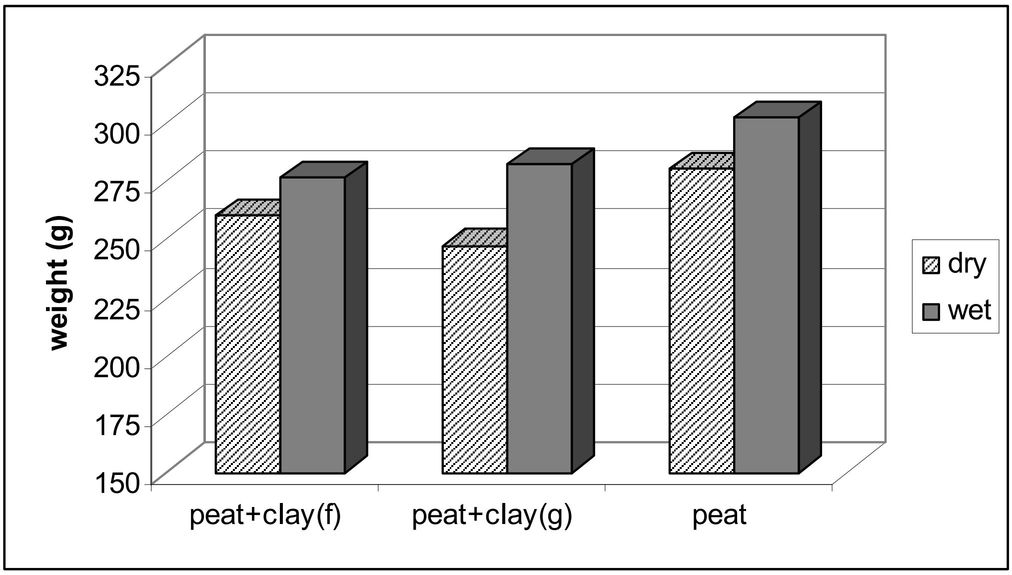

Fig. 2. Total weight of begonia plants at the end of the cultivation period with a dry or wet watering regime. f=fine clay, g=granulated clay. Despite the lower fresh weight yield, growers preferred the denser plants produced on the dry peat/clay mixtures (Wever et al., 2004b).

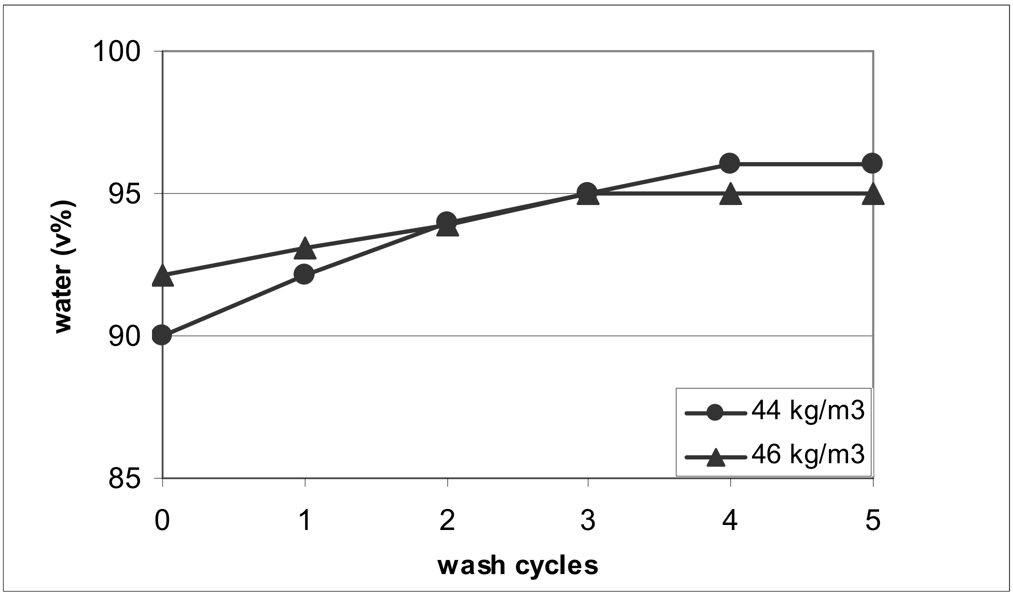

Fig. 3. Volume of water at leak out situation after repeatedly 'washing' 2 types of stonewool treated with a wetting agent before testing. Source: Kipp and Wever, not published.

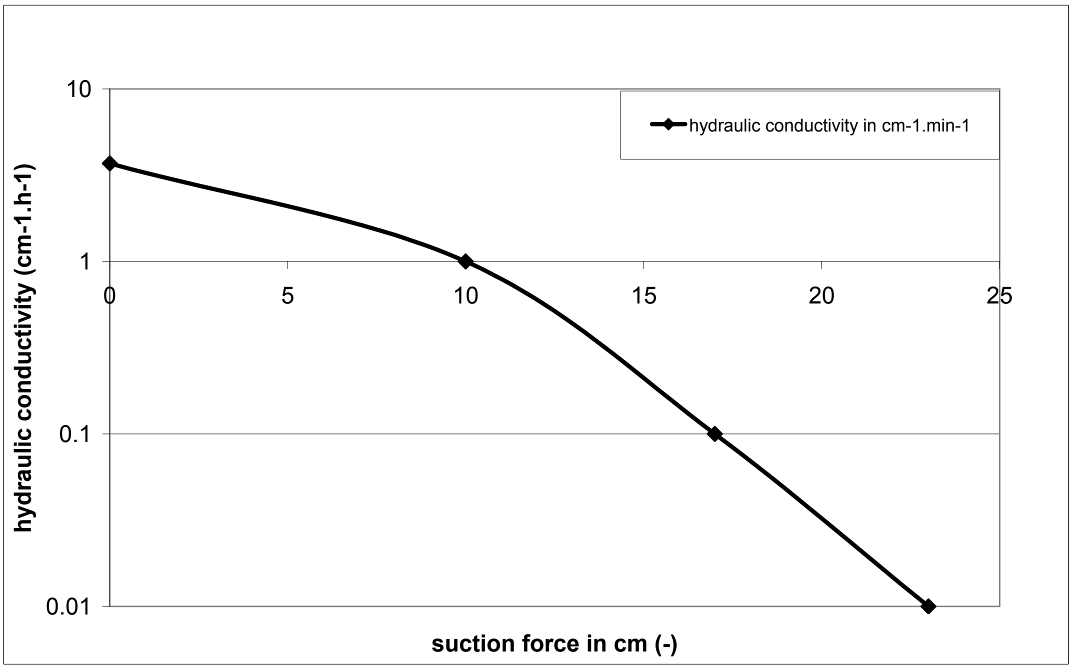

Fig. 4. Unsaturated hydraulic conductivity in relation to suction force applied. After Da Silva et al., 1995.

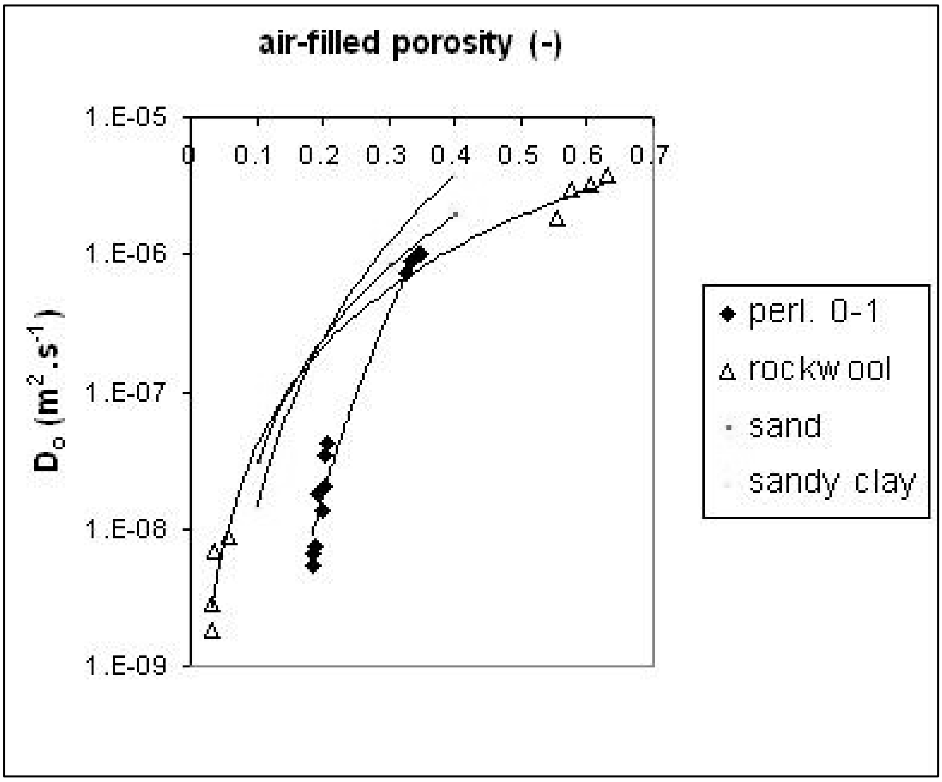

Fig. 5. Measurements of the diffusivity of oxygen in various rooting media against the air filled pore volume in v%. After Wever et al., 2001.

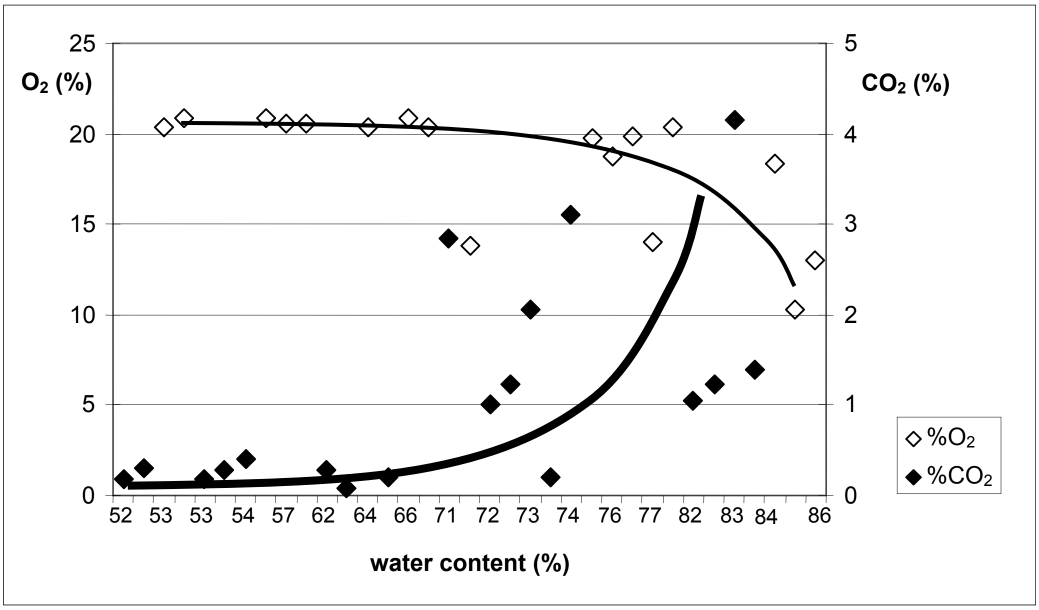

Fig. 6. Very local measurements of oxygen content and carbon dioxide content in the air of pores in rockwool against the local water filled pore volume in v%. After Baas, 2001.