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ARTIFICIAL SOIL (SUBSTRATE) SELECTION FOR HIGHER PLANT CULTIVATION IN SPACE: GROUND-BASED TESTS FOR ASSESSMENT OF SOME SUBSTRATE PHYSICAL PROPERTIES

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Abstract

The proposed study presents an approach for early assessment of substrate properties. This includes a course of measurements for preliminary evaluation of part of the substrate's physical and hydro-dynamical characteristics. Two sets of measurements were carried out using standard methods to analyze the substrate's agro-physical properties. In the first set, three different substrate trademarks (Balkanine, Turface and Ekolin) with similar particle sizes (1-2 mm) were tested. The bulk density (BD) of substrate layers of three different thicknesses was measured to study the possibility to achieve repetitive density for the needs of mathematical modelling. In the second set, the physical and hydro-dynamic properties of four particle sizes of Balkanine fractions (PSD) were tested. BD, capillary water capacity, water-holding capacity and saturated water capacity for the four PSDs were determined and discussed. The data show that the 1.5-2 mm fraction is most suitable for earth and space applications because of its low BD (high total porosity) with low StDev values which suggest a repetitive BD when packing the substrate in a real root module and more favourable proportion between air and water content.

Introduction

Continuous improvement of the root-zone media is an important research area motivated by the need to provide suitable root environment for higher plant cultivation in microgravity. Systems for controlling root environment are required to provide steady substrate moistening, non-stop and balanced transfer of nutrients to plant roots and good gas exchange. A range of conflicting and inadequate requirements has raised problems in the development of root modules for space application. Mass, volume and power constraints have been caused by the requirement to get maximum yield from minimum area (or volume) and power. This imposes hard power and space restrictions on the equipment and reduces the root module volume what leads to higher density of the root area components. The problems of water containment and liquid and gas phase separation in microgravity are of great importance for providing adequate air-water balance in small volume root environment. The separate-phase systems based on porous solids to separate air and water have been adopted for space utilization in most plant growth facilities. Substrates of solid particles are considered to be the most appropriate medium for plant growth in long-term space experiments because of their longevity, repeated use and repeated crops in the same substrate. Particulate substrates that have been used in ground-based and flight tests include peat-vermiculite mixes, arcillite, isolite, Profile and Turface (porous ceramic aggregates with Osmocote pellets used as slow-release fertilizer), Balkanine (natural nutrient saturated zeolite) etc.

Microgravity affects heat transfer, mass exchange processes, fluid behaviour, nutritive concentration gradients in the substrates, and capillary properties of artificial soils. The “free” movement of small substrate particles between the larger ones in the root medium container volume changes the aerating – water-carrying pore ratio and geometry and disturbs the medium homogeneity and density. Furthermore, the substrate particle shrinkage and swelling caused by changes in their water content and the vigorously developing root systems in a small root module volume also leads to variable pore geometry and changes in water retention.

There is still little information available about the nature of problems that might occur in small volumes in microgravity. The current understanding of the nature of water and air transport in porous media in microgravity is not sufficiently well developed to allow clear interpretation of microgravity experimental results. Therefore, upon completing the *Mir* Orbital Station (OS) experiments, scientists from different countries that have experience in various areas of fluid and soil physics, plant physiology, hardware development, and flight experiments met to identify and discuss critical issues of water and air flow through porous media in microgravity [1]. The specific objective of this meeting was to examine the control of air, water, and solutes in a root zone containing solid substrates. Possible mechanisms affecting water and air transport in microgravity that lead to accentuated hysteresis, reduced hydraulic conductivity, and altered soil-water characteristic curve were discussed. The published studies [2], [3] etc. determine the physical and hydraulic properties of baked ceramic aggregates that have been used as a root medium in ground-based and space experiments. The published information provides to summarize a set of requirements for the substrates – possible candidates for plant growth experiments. The substrate media selected for plant growth research purposes should have definite physical characteristics:

- Substrates for space application should have low specific weight and small packing volume, so as to require minimum launch power.
- Particle size has been a debatable parameter and it should be determined by compromise. The relatively large particle size range (1-5 mm), chosen for aeration reasons for the early *Svet* Space Greenhouse (SG) flight experiment (1990) resulted in water movement problems. On the other hand, the smaller particles (less than 1 mm) impede aeration and such substrate has more pronounced hysteresis of the water retention curve which causes moisture control problems.
- Substrates are required to have uniform particle size distribution, i.e. flatter plateau of the water release curve which means more stringent control of water transport and aeration.
- The parameters mentioned above allow achieving low and repeatable bulk density when filled up in a fixed volume and levelled without compression. The substrate bulk density can be additionally increased using standard compacting methods [2]. Compacting is used to reduce the changes in pore geometry due to overloads during launch, particle rearrangement under microgravity and other factors which lead to changes in substrate–water–air relations.
- Substrates should have long-term spatial and time parameter stability, so as to provide relatively unchangeable particle and pore geometry. This means that no degradation and no swelling of particles in time and space are allowed.

Both particle size and density determine porosity and thus, water retention properties of the material. To achieve high water retention, substrates are required to have good hydraulic characteristics:

- High water holding capacity of the substrate material is needed to achieve high volumetric water content (wettable porosity) for the matric potential control range. For the purpose, the substrate material should have low bulk density and high porosity.

- Substrate material with low hysteresis is preferable for use [1]. Hysteresis occurs in the range of water potential control where small changes in water content produce significant matric potential changes. This range depends strongly on particle size. Dani Or [1] notes that Turface has turned to be harder to control compared to isolite and zeolite because of its high hysteresis.
- Substrate material is required to have high hydraulic conductivity which depends on the pore size. Saturated hydraulic conductivity is greater for the larger particle size fractions. Unsaturated hydraulic conductivity also depends strongly on volumetric water content.

A possible way to overcome the complexity and uncertainty of using particulate media would be to engineer a material specifically designed for space application. Such a material would have fixed pore geometry and optimized pore shape and size in order to achieve better control of the water and air flow through the root medium.

The process of selection of substrate capable to support suitable root environment in small volume containers on earth and in space involves a lot of long, hard and expensive analysis in specialized laboratories. The purpose of this investigation is to suggest a way for preliminary selection of substrates – candidates for space utilization. This includes a course of measurements for early evaluation of part of the substrate's physical and hydro-dynamical characteristics. In case some parameter goes beyond the specified limits, the substrate is not subject to further accurate study in specialized laboratories.

The study proposed is part of a research of the *Svet-3* SG project targeted at development of algorithm for automatic control of plant growth environment to maintain optimal conditions in the chosen substrate during different plant development stages.

Materials and Methods

Substrate materials of three trademarks with the same particle size distribution (1-2 mm) were tested:

1. Balkanine™ (Stoilov, G., I. Petkov, D. Dimitrov, (1979, Bulgarian Patent No 40343), Bulgaria;
2. Turface® (Profile Products LLC, Buffalo Grove, IL, USA);
3. Ekolin® (NIPRORUDA JSCo, Bulgaria).

The first two substrates were used in all space experiments carried out onboard the *Mir* OS in the *Svet* SG in 1990-2000. The third substrate was proposed by specialists from NIPRORUDA to be subject to test. Below is described the test program used for our research. It could be applied to test all sorts of substrates for evaluation of their physical properties.

A. *Assessment of bulk density (BD) for the three trademark substrates*

Air-dry substrates stored under definite environmental conditions have been commonly used for laboratory plant experiments. The object of the proposed set of measurements is to test the possibilities for early evaluation of the physical properties of air-dry substrates without using compaction techniques. These measurements aim to check if the height and the area of the root modules used for plant experiments influence bulk density when filled up and without additional compacting.

Three vessels of different heights (5.5, 11 and 40 cm) and volumes (1009.5, 1045.6 and 675.1 cm^3, respectively) were filled up with each kind of substrate and levelled using a laboratory spatula. Sample mass (air-dry basis) was measured to calculate bulk density as $BD_{ad} = m_{ad}/V_b$ where BD_{ad} and m_{ad} are the bulk density and mass of air-dry substrate and V_b is the bulk volume. Each test was replicated 50 times. Hygroscopic moistures (θ_h) of 100 g substrate samples after drying for 48 hours at 105ºC were calculated: $\theta_h = m_h/m_s$, where m_h is the mass of the hygroscopic substrate and m_s is the mass of absolutely dry substrate. The bulk densities thus determined (air-dry basis) were re-calculated on oven dried basis using $BD = BD_{ad}/(1+\theta_h)$. The results, processed statistically, provide an idea of the lowest bulk density value for each substrate which is possible to achieve before compacting in the experimental root module volume.

B. *Assessment of bulk density for four particle size distributions of Balkanine*

Balkanine was successfully used in the space plant experiments carried out in the *Svet* SG onboard the *Mir* OS in 1990, 1995 and 1996. For the 1997-2000 *Svet-2* SG experiments, this substrate was substituted by Turface which is wide-used and well studied by our American colleagues.

Analyses of the porous substrate water relations [5] observed in the space experiments show that an optimal wettable – air-filled porosity relation in microgravity can not be achieved by using a wide PSD range (for example 1-3 mm). Small particles fallen into the large particle pore space could not be tightly compacted irrespective of the compaction techniques used when preparing the root module on Earth. In microgravity, this causes dynamic changes in the contact pressure and contact surface between particles which influences drastically the unsaturated hydraulic conductivity of the substrate. This calls for study of the physical and hydro-dynamic properties of narrower PSDs for experimental substrates.

Balkanine was sieved to retain four particle size fractions – (0.05-0.9); (1.0-1.5); (1.5-2.0); (2.0-3.0) mm using standard sieves. Bulk density of the four PSDs was determined. For the purpose, the following procedure comprising two sets of measurements was used: (a) an aluminum cylinder 6 cm high and 6.5 cm in diameter (volume 200 cm^3) was filled up with air-dry substrate of each fraction without compacting. Substrate material was levelled, sample mass was measured and BD was calculated, and (b) the cylinder was filled in 2-cm layers and each layer was tamped manually using a cylindrical tool with a tabular front surface of about 5 cm^2. After compaction sample mass (m_c) was measured and bulk density (BD_c) was calculated. Each measurement was replicated 10 times. During the measurements the hygroscopic moisture of the tested PSDs was determined by oven drying at 105°C for 48 hours. The absolutely-dry sample masses were determined and the BDs were calculated as described above. The results were statistically processed and the compaction coefficient (K_c) was calculated as: $K_c = BD_c/BD$.

C. *Assessment of capillary water capacity, water holding capacity and saturated water capacity for the four Balkanine PSDs*

Capillary water capacity, water holding capacity and saturated water capacity for PSDs – (0.05-0.9); (1.0-1.5); (1.5-2.0); (2.0-3.0) mm were determined. Cylindrical plastic vessels 6 cm high, 6.5 cm in diameter (volume 200 cm^3) and with an about 90º contact angle of wetting were used for these measurements.

The vessels used to measure saturated water capacity had a valve inlet in the bottom end allowing saturation from below – water table rising to or above the surface. The saturation process took about 3 hours. Air bubbles captured in the substrate volume were not been removed. The saturated sample weight was measured. The absolutely-dry substrate weight and the net water weight were calculated using coefficient (K_w) for re-calculation of the hygroscopic moisture (θ_h) of air-dry substrate: $K_w = 1+\theta_h$.

Saturated water content was calculated as θ_{sat} (m) = m_w/m_s (weight basis) or θ_{sat} (v) = V_w/V_b (volume basis).

The vessels used to measure capillary water capacity and water holding capacity had a number of holes on the bottom allowing free water movement inwards and outwards when capillary suction and water draining after saturation respectively occurs. Capillary water capacity was determined after the sample's weight had reached a constant value (the process lasted several days). After measuring the weight of the sample with capillary retained water the vessel was dipped slowly into another vessel with water and stayed there to full saturation. About two hours later the vessel with the sample was pulled out, it was covered with a plastic lid preventing from evaporation and water was allowed to drain freely. After completing the drainage process the sample weight was measured and the retained water content was calculated.

Capillary water capacity (θ_{CWC}) was calculated as θ_{CWC} (m) = m_{CW}/m_s (weight basis) or θ_{CWC} (v) = V_{CW}/V_b (volume basis) and water holding capacity (θ_{WHC}) as θ_{WHC} (m) = m_{WH}/m_s (weight basis) or θ_{WHC} (v) = V_{WH}/V_b (volume basis) where m_s was the sample mass for oven dry substrate. The measurements were replicated three times.

Results

The results from measurements of sample mass and volume used to calculate BDs for the three tested kinds of substrate were statistically processed and presented in Tables 1, 2 and 3.

Table 1. Mean bulk density (BD), standard deviation (StDev), and coefficient of deviation (CD) for 50 samples of uncompacted 1-2 mm Balkanine and 3 pot heights

Bulk density for uncompacted Balkanine 1-2 mm			
Pot height	h = 5.5 cm	h = 11 cm	h = 40 cm
Number of samples	50	50	50
Mean BD [g/cm^3]	0.7867	0.7767	0.7586
StDev [g/cm^3]	0.0024	0.0025	0.0028
CD [%]	0.30	0.33	0.37

Table 2. Mean bulk density (BD), standard deviation (StDev), and coefficient of deviation (CD) for 50 samples of uncompacted 1-2 mm Turface and 3 pot heights

Bulk density for uncompacted Turface 1-2 mm			
Pot height	h = 5.5 cm	h = 11 cm	h = 40 cm
Number of samples	50	50	50
Mean [g/cm^3]	0.5571	0.5461	0.5433
StDev [g/cm^3]	0.0030	0.0019	0.0029
CD [%]	0.54	0.35	0.54

Table 3. Mean bulk density (BD), standard deviation (StDev), and coefficient of deviation (CD) for 50 samples of uncompacted 1-2 mm Ekolin and 3 pot heights

Bulk density for uncompacted Ekolin 1-2 mm			
Pot height	h = 5.5 cm	h = 11 cm	h = 40 cm
Number of samples	50	50	50
Mean [g/cm^3]	0.4460	0.3858	0.4566
StDev [g/cm^3]	0.0273	0.0244	0.0334
CD [%]	6.11	6.32	7.31

After oven-drying of about 100 g substrate samples the hygroscopic substrate moisture at 40% relative air humidity was fixed at: 2.35% for Turface, 5.60% for Balkanine and 5.37% for Ekolin. BD of the three kinds of substrate was calculated using a coefficient of re-calculation of the air-dry mass into absolutely dry mass which was 1.0235 for Turface, 1.0560 for Balkanine and 1.0537 for Ekolin.

The results show considerable differences in BDs for the three kinds of substrate. Great deviation coefficient is observed for Ekolin. Fig. 1 shows the frequency polygons for the three kinds of substrate and provides to evaluate visually the measurement data's statistical distribution.

Measurement data for Ekolin do not show normal distribution. An additional study discussed below provided to find the reason for this result.

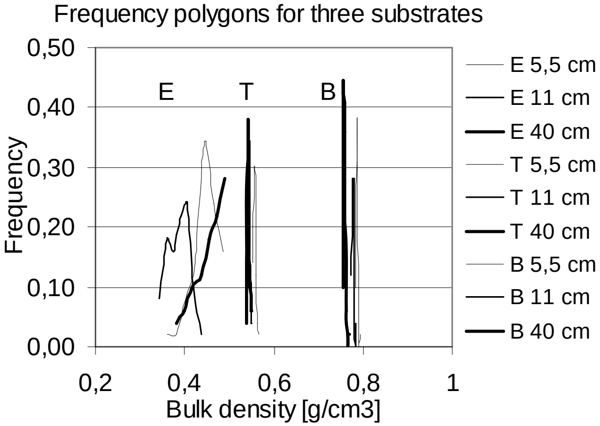

Fig. 1. Comparative illustration of 7-interval frequency polygons for the three tested kinds of substrate – E – Ekolin, T – Turface, and B – Balkanine

Figure 2 allows visual observation of the substrate surface for the three tested kinds of substrate after applying a compaction procedure. A study of BD and hydro-dynamic changes in the substrates after treatment show additionally the processes of particle composition demix for Ekolin (the right pot on the picture).

Fig. 2. A view of Turface, Balkanine, and Ekolin substrate surfaces after compaction procedures – water saturation and 50 Hz vibrations (10 min)

The results from some physical measurements of Ekolin properties show high heterogeneity, quite differing particles and low mixing capability. Such properties do not match the requirements for the substrates used in microgravity experiments. Turface has been well studied and characterized in details by American scientists. For this reason, we chose Balkanine as an experimental substrate and subjected it to our proposed test procedure to evaluate the substrate's physical properties.

As mentioned above, characteristics of narrower PSD should be used for microgravity experiments. For this reason, four PSD fractions for Balkanine were sieved and tested.

After oven-drying of about 100 g substrate samples the hygroscopic substrate moisture at 60% relative air humidity was fixed at 7.1%. A coefficient of re-calculation of the air-dry mass into absolutely dry mass of 1.071 was used.

Bulk density data for compacted and uncompacted substrate samples of each PSD were determined and presented on Table 4.

Table 4. Bulk densities and standard deviations for four tested PSD of uncompacted (BD) and compacted (BD_c) Balkanine

Bulk density data for four Balkanine PSD				
PSD	BD [g/cm^3]	±StDev	BD_c [g/cm^3]	±$StDev_c$
0.05-1.0 mm	0.8517	0.009	0.9791	0.009
1.0-1.5 mm	0.7365	0.005	0.8422	0.005
1.5-2.0 mm	0.7268	0.001	0.8325	0.003
2.0-3.0 mm	0.7374	0.001	0.8576	0.003

Data shows that the compaction coefficients are 1.150, 1.143, 1.145 and 1.163. As may be seen from the comparative chart in Fig. 3, the 1-2 mm fractions have lowest BD and highest total porosity, respectively. The low StDev values for the two cases suggest a repetitive BD when packing the substrate in a real root module.

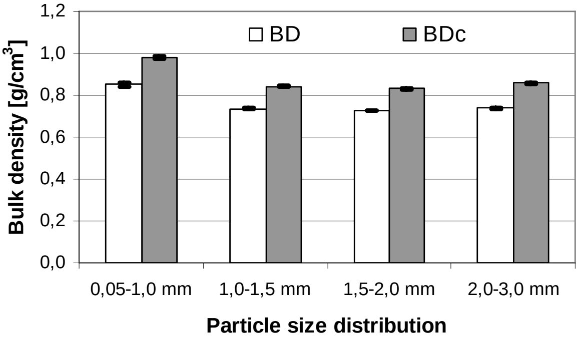

Fig. 3. A comparative chart of the bulk densities and standard deviations for the four tested PSDs of uncompacted (BD) and compacted (BD_c) Balkanine samples

The most important parameters reflecting the relations air-water-substrate are shown on Table 5.

Table 5. Total porosity (calculated) (TP), saturated water content (SWC), water holding capacity (WHC), capillary water capacity (CWC) and maximum hygroscopicity (MH) for the four tested Balkanine PSDs

	Substrate water relations, (volume basis)			
PSD	0.05-1.0 mm	1.0-1.5 mm	1.5-2.0 mm	2.0-3.0 mm
TP	0.59	0.64	0.65	0.64
SWC	0.54	0.57	0.55	0.55
WHC	0.52	0.49	0.40	0.37
CWC	0.49	0.38	0.36	0.34
MH	0.17	0.14	0.14	0.15

Total porosity (TP) was calculated as TP = (1-BD/PD), where PD = 2.37 g/cm^3 is the particle density for Balkanine measured by Zakharov [5]. The maximum hygroscopicity MH = 17% (weight basis) has been measured by Zakharov, too. This parameter is the maximum quantity of water molecules adhered to the particle surface at 99% relative air humidity. This water quantity is not available for plant use.

The chart in Fig. 4 presenting tabled data shows that in normal laboratory experimental conditions, when no measures are taken to expel the air bubbles captured in the substrate volume, the saturated water content is a bit lower than the total porosity for all PSDs.

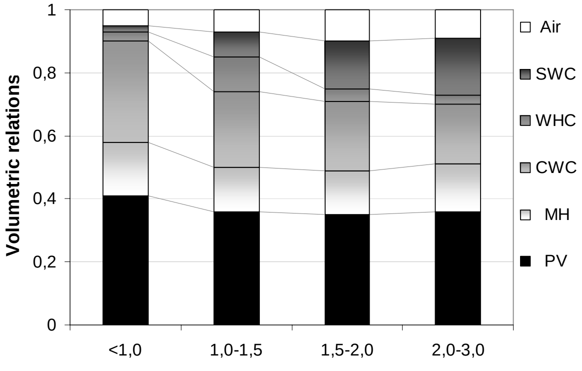

Fig. 4. Volumetric relations of the total porosity (TP), saturated water capacity (SWC), water holding capacity (WHC), capillary water capacity (CWC) and maximum hygroscopicity (MH) for the four Balkanine PSDs

It can be seen that the three water capacity parameters for the smallest substrate fractions are too close which results in small air filled porosity for aeration. For the 1.0-1.5 mm PSD the water holding capacity is close to the saturated water content which leads to higher hysteresis.

Discussions

The greatest part of the time and funds spent to prepare a space plant experiment is allocated to ground-based task development. The choice of suitable substrate, particle size distributions and mixes, aerating and watering regimes and technologies, techniques for repeated seed sowing and plant growth in a root module, development of algorithms to control the actuating mechanisms as well as the accurate assessment of the phenomena observed in the root media during experiments are continuously developed and improved.

The first set of measurements of Balkanine, Turface and Ekolin had as its objective to assess the ability of these loose materials for keeping their minimal BD while filling up the volume of dishes of various shapes. The effect of the measuring dish height, dish sectional area related to the substrate particle diameter and material compaction while levelling on BD was determined. As may be seen from Tables 1-3 and Fig. 1, BD increases in the sequence Ekolin, Turface, Balkanine and Ekolin shows a minimal BD of about 0.4 g/cm^3. The tendency for substrate compacting when filling up a dish 5.5 cm in height and levelling is pronounced for Balkanine and Turface. The substrate column with height of 40 cm and 4.6 cm in diameter involves self-compacting but the relatively small dish diameter limits the particle number in one layer and reduces the levelling effect on BD. So, the difference between BDs in the dishes of 5.5 cm and 40 cm in height for Balkanine is 0.0281 g/cм^3, which exceeds StDev 10 times. These results show that it is also necessary to assess the actual BD of substrates when filling up small-dimension dishes (few dm^3) with complicated interior (water and aeration pipes, wick and compaction fabrics and others).

Statistical distribution for Ecolin’s BD requires to determine the substrate structure. The manufacturer provides information about the use of “natural clinoptilolite, expanded perlite, vermiculite, water-soluble polymers, saturated with biogenic elements” in the substrate mixture production. The Stoke’s law was applied in an experiment to separate the substrate component particles (Fig. 5).

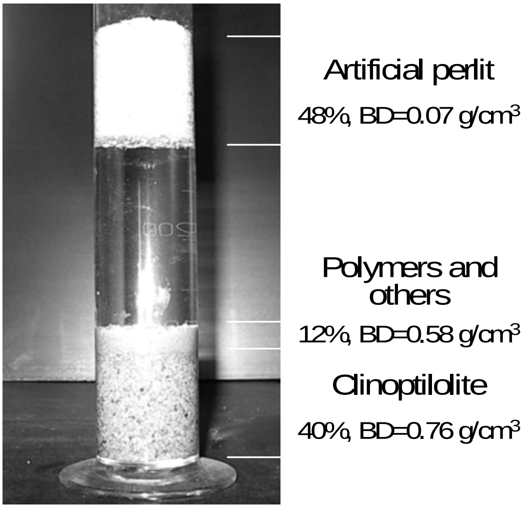

Fig. 5. Ekolin after particle separation

Down below 40% of the volume was occupied by particles with BD = 0.76 g/cm^3 (clinoptilolite), following by 12% particles with BD = 0.58 g/cm^3 above, and 48% was the artificial perlite with BD = 0.07 g/cm^3 keeping afloat. The great disparity between the particle BDs and dimensions allows easier demix when filling up the dish. It was found that the artificial perlite granules did not have the desired hardness and stability (they swell). The results from measurements showed that the requirements for the physical properties of substrates for space application are considerably higher and the further study of Ekolin was abandoned.

Turface has a low BD value (about 0.55 g/cm^3), the total porosity reaches 78% at 2.5 g/cm^3 particle density. The slightly higher CD (0.35-0.54%) compared to Balkanine's CD (0.30-0.37%) can be accounted for the particle shape of both materials. Turface has a slaty particle shape which provides to achieve close contact between particles, respectively greater unsaturated water flow. Fig. 6 shows the three substrates after they have been compacted under saturation with water and 50 Hz vibrations for 10 minutes. After water draining Turface surface becomes smooth, the Balkanine particles keep their outlines and the Ekolin particles demix and a part of them swell.

As mentioned above, Turface has been studied in details by American scientists and used in space plant growing. This is one of the reasons to continue studying Balkanine which is currently used in our work. Balkanine's accessibility, the available data from ground-based and space experiments, the data about its properties obtained in Russia, USA and Bulgaria, the mathematical modelling and the accumulated experience are additional reasons for testing this material with different laboratory practices and equipment.

Balkanine is natural zeolite charged with chemical elements which provide nutrients for plant growth during several vegetation cycles (over 5). Ivanova [6], [7] provides detailed information about the agrochemical characteristics and use of Balkanine in space experiments. Petrov [7] provides the results from phase analysis performed on a DRON 3M powder X-ray diffraction apparatus using a CoKα radiation source.

The zeolite used for Balkanine production has double porosity - inner-particle and inter-particle. Zakharov [5] and Jones [4, 8] measure the basic hydro-physical characteristics and report that the sharp drop in the matric potential at 22% water content due to full macro-pore water draining leads to drastic decrease of water conductivity (Fig 6).

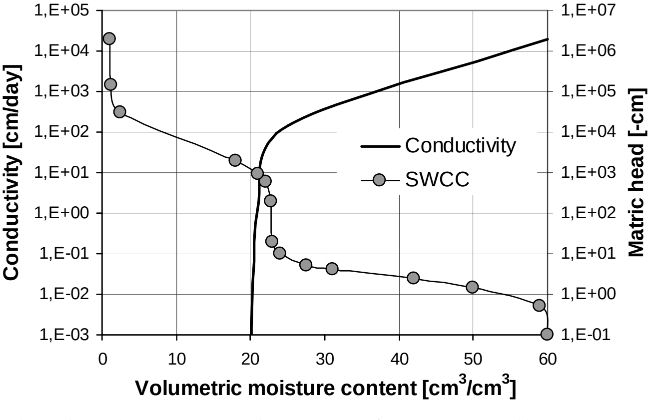

Fig. 6. Matric head and water conductivity of 1-2 mm Balkanine versus volumetric moisture content. (Jones and Or, [13])

Some disadvantages of Balkanine are: (a) appearance of a small fraction (below 0.2 mm) after shocks and vibrations imitating the mechanical effects during equipment launch; (b) comparatively large BD (about 0.84 g/cм^3); and (c) inner-aggregate porosity concentrated in the range below 10 μm which reduces unsaturated water conductivity and limits water flow at substrate water content below 0.22 cm^3/cm^3.

The results from BD calculation for the four PSDs (Table 4) show that BD and compaction coefficient (about 14.4%) are lowest for the 1.0-1.5 and 1.5-2.0 mm fractions. Standard deviations for the compacted 1.5-2.0 and 2.0-3.0 mm fractions are higher than the ones for uncompacted fractions, a fact which reflects the substrate material's sensitivity to the compaction procedure method and duration. This is especially important in the cases when substrate is packed in a root module together with additional accessories and soft materials.

The air-water-substrate volumetric relations (Table 5 and Fig. 4) provide information about the total water capacity of the four PSDs, the plant available water part and aeration porosity. Fonteno [9] notes that for soilless substrates that do not contain fine particles, the root module height has a significant effect on the air-water proportions. Our data show that for sample vessel height of 6 cm the water holding capacity is too close to saturation for fractions smaller than 1.0 mm and 1.0-1.5 mm and the capillary water capacity is about 1.5 times higher than the gravitational water for 1.0-1.5 mm fractions and draw level with it for 2.0-3.0 mm fractions. The water contained in the substrate at maximum hygroscopicity (MH, about 14-17% volumetric) is absolutely unavailable for the plant's roots. This conclusion is corroborated by Shaydorov [10] who has determined volumetric water content of 15% at wilting point for salad crops grown in 1-3 mm Balkanine.

The following conclusions could be drawn based on the measurements conducted and discussed above:

- 0.05-0.9 mm PSD has highest BD (about 1 g/cm^3); 7% aeration porosity; 35% Plant Available Water (PAW), 2% difference between saturation and water holding capacity; operation mode close to saturation and blocking of about 5% air bubbles.
- 1.0-1.5 mm PSD has BD = 0.84 g/cm^3; 15% aeration porosity; 35% PAW; 8% difference between saturation and water holding capacity; operation mode with blocking of about 7% air bubbles.
- 1.5-2.0 mm PSD has BD = 0.83 g/cm^3; 25% aeration porosity; 26% PAW; 15% difference between saturation and water holding capacity; operation mode with balance between air and water content; blocking of about 10% air bubbles.
- 2.0-3.0 mm PSD has BD = 0.86 g/cm^3; 27% aeration porosity; 22% PAW; 18% difference between saturation and water holding capacity;

operation mode with predominant aeration volume; blocking of about 9% air bubbles.

Water distribution in substrate pores can be determined using the pore size distribution curve. Drzal [11] presents an analysis of pore size distribution ranges for container substrates. The effective diameter of the biggest water filled pore for every characteristic value of the water head can be calculated using the *Jurin* equation:

(1) $d_p = 4.\sigma/\rho_w.g.h$

where d_p is pore diameter, σ is water surface tension (72.75 J/m^2), ρ_w is water density (1 Mg/m^3), g is gravitational acceleration (9.81 m/s^2), and h is matric head (m).

On the other hand, matric head (h) and volumetric water content (θ) are related by the substrate-water characteristic curve (SWCC). The fitted SWCC of Balkanine (1-2 mm PSD) shown in Fig. 6 is determined by Jones and Or [12] using the van Genuchten [13] nonlinear model, defined as:

(2) $\theta = \theta_s + (\theta_s - \theta_r)/[1 + (\alpha.|h|)^n]^m$

where θ is the current volumetric water content, θ_s is the saturated volumetric water content, θ_r is the residual volumetric water content at 30 kPa (300 cm), α, n, m are fitting parameters, and h is matric head (cm).

Using the determined water capacities (Table 5) and the corresponding matric heads, as well as eqs. (1) and (2), the pore size distribution ranges were determined (Fig. 7). Easily available water for plant roots in 6 cm high dish filled with Balkanine is kept in about 12-15% of the pores and is concentrated in the range of 5-300 cm matric head.

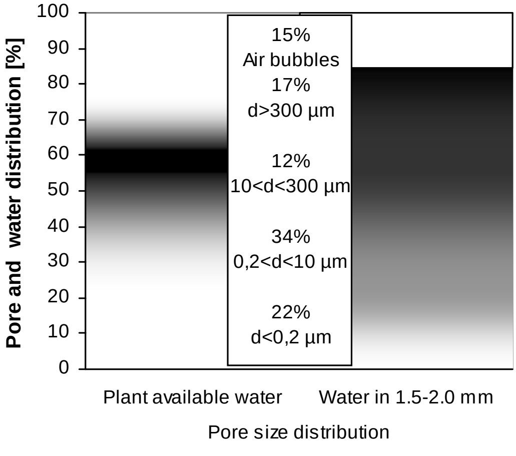

Fig. 7. Plant available water range, pore size distribution, and water distribution in 1.5-2.0 mm fraction

Conclusions

The proposed study presents an approach for preliminary selection of substrates applicable to plant cultivation in microgravity. This includes a course of measurements for early evaluation of part of the substrate's physical and hydro-dynamical characteristics.

Three different trademark substrates (Balkanine, Turface and Ekolin) with similar particle sizes (1-2 mm) were tested. The results of the Ekolin study show high heterogeneity, quite differing particles and low mixing capability. Such properties do not match the requirements for the substrates used in microgravity experiments.

The physical and hydro-dynamic properties of four particle size Balkanine fractions (PSD) were estimated. The data show that the 1.5-2 mm fraction is most suitable for ground-based and space applications because of its lower BD (high total porosity) with low StDev values which suggest repetitive BD when packing the substrate in a real root module and more favourable proportion between air and water content.

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ПОДБОР НА ИЗКУСТВЕНИ ПОЧВИ (СУБСТРАТИ) ЗА ОТГЛЕЖДАНЕ НА РАСТЕНИЯ В КОСМИЧЕСКИ УСЛОВИЯ: НАЗЕМНИ ТЕСТОВЕ ЗА ОПРЕДЕЛЯНЕ НА НЯКОИ ФИЗИЧЕСКИ ХАРАКТЕРИСТИКИ НА СУБСТРАТИТЕ

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Резюме

Предложеното изследване дава един подход за ранна оценка на качествата на субстрата. Той включва серия измервания за предварително определяне на част от физическите и хидродинамичните

характеристики на субстрата. Бяха направени две серии измервания по стандартни методи за анализиране на агрофизическите качества на субстрата. При първата серия измервания бяха подложени на тест три различни търговски марки субстрати (Балканин, Турфейс и Еколин) със сходен размер на частиците (1-2 mm). Беше измерена обемната плътност на три субстратни слоя с различни височини с цел да се изследва възможността за постигане на повторяема плътност за целите на математическото моделиране. При втората серия измервания бяха тествани физическите и хидродинамичните качества на четири фракции субстрат Балканин. Бяха определени и дискутирани обемната плътност, капилярната влагоемност, пълната полева влагоемност и влагоемността при насищане. Данните показват, че фракцията 1.5-2 mm е най-подходяща за наземни и космически експерименти поради по-малката си обемна плътност (по-голяма порестост) и по-малко стандартно отклонение, което говори за повторяема обемна плътност при насипване на субстрата в реален коренов модул, както и поради по-благоприятно съотношение между съдържанието на вода и въздух в обема на субстрата.