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Nota

EXPERIMENTAL METHOD TO DETERMINE SOME PHYSICAL PROPERTIES IN PHYSICS CLASSES

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ABSTRACT

Particle density, gravimetric and volumetric water contents and porosity are important basic concepts to characterize porous systems such as soils. This paper presents a proposal of an experimental method to measure these physical properties, applicable in experimental physics classes, in porous media samples consisting of spheres with the same diameter (monodisperse medium) and with different diameters (polydisperse medium). Soil samples are not used given the difficulty of working with this porous medium in laboratories dedicated to teaching basic experimental physics. The paper describes the method to be followed and results of two case studies, one in monodisperse medium and the other in polydisperse medium. The particle density results were very close to theoretical values for lead spheres, whose relative deviation (RD) was -2.9 % and +0.1 % RD for the iron spheres. The RD of porosity was also low: -3.6 % for lead spheres and -1.2 % for iron spheres, in the comparison of procedures – using particle and porous medium densities and saturated volumetric water content – and monodisperse and polydisperse media.

Keywords: particle density, porous medium density, gravimetric water content, volumetric water content.

RESUMO: *PROPOSTA DE MÉTODO EXPERIMENTAL PARA DETERMINAR ALGUNS ATRIBUTOS FÍSICOS EM AULAS DE FÍSICA*

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Densidade de partículas, umidades gravimétrica e volumétrica e porosidade são conceitos básicos importantes para caracterizar sistemas porosos, como é o caso do solo. Neste estudo, apresentou-se uma proposta de método experimental para a medida dessas grandezas físicas, em aulas de física experimental, em amostras de meios porosos compostos de esferas de diâmetros iguais (meio monodisperso) e diâmetros diferentes (meio polidisperso). A não utilização de amostras de solo é em razão da dificuldade de trabalhar com amostras desse meio poroso em laboratórios dedicados ao ensino de física experimental básica. O artigo apresenta o método a ser seguido e os resultados para dois estudos de caso, um meio monodisperso e outro polidisperso. Os resultados de densidade de partículas apresentados foram bastante próximos dos valores teóricos para as esferas de chumbo, cujo desvio relativo (DR) foi de -2,9 %, e para as esferas de ferro, de +0,1 %. A porosidade também evidenciou baixos DR, -3,6 %, para esferas de chumbo, e -1,2 %, para esferas de ferro, na comparação dos procedimentos, utilizando as densidades de partículas e do meio poroso e a umidade volumétrica de saturação, e dos meios monodisperso e polidisperso.

Palavras-chave: densidade de partículas, densidade do meio poroso, umidade gravimétrica, umidade volumétrica.

INTRODUCTION

Porosity (ϕ) is an important property of porous media. In physics, ϕ is defined as the ratio of the pore volume of the porous medium by the respective total volume. Porosity is inversely related to the medium density, that is, increases in density lead to a reduction in ϕ (Hillel, 1998; Libardi, 2004).

The density of porous systems is defined in two ways: particle density and porous medium density (Reichardt and Timm, 2004; Prevedello and Armindo, 2015). When the porous medium soil is considered, which consists of three phases (solid, liquid and gaseous), particle density is also called solid density (d_s) and porous medium density is known as soil bulk density (d). In conceptual terms, the former is defined as:

$$d_s = \frac{m_s}{V_s} \qquad \text{Eq. 1}$$

and the latter as:

$$d = \frac{m_s}{V} \qquad \text{Eq. 2}$$

where m_s (Mg), V_s (m^3) and V (m^3) represent the solid mass, solid volume and soil volume. For an average mineral soil, d_s has a value around 2.65 Mg m^{-3}, but varies from 1.30 to 1.50 Mg m^{-3} for organic soils (Hillel, 1998; Libardi, 2004). The d value also varies between soil types, for example, sandy soils have values between 1.30 and 1.80 Mg m^{-3} and clayey soils between 1.00 and 1.40 Mg m^{-3} (Libardi, 2004). Details about the d_s and d measurement methods were provided by Flint and Flint (2002a) and Grossman and Reinsch (2002).

From the d_s and d values, it is possible to determine ϕ, as expressed in the following equation:

$$\phi = \frac{V_p}{V} = \frac{V - V_s}{V} = \left(1 - \frac{V_s}{V}\right) = \left(1 - \frac{m_s}{d_s}.\frac{d}{m_s}\right) = \left(1 - \frac{d}{d_s}\right) \qquad \text{Eq. 3}$$

where V_p (m^3) represents pore volume.

Another way of measuring ϕ is from the saturated volumetric water content, θ_s (m^3 m^{-3}), which represents the water volume contained in saturated sample by the sample volume, and is defined using the saturated gravimetric water content, U_s (kg kg^{-1}):

$$U_s = \frac{m_{H_2O}}{m_s} = \frac{d_{H_2O}V_{H_2O}}{dV} \therefore \theta_s = \frac{d}{d_{H_2O}}U_s \qquad \text{Eq. 4}$$

where V_{H2O} (m^3), m_{H2O} (Mg) and d_{H2O} (Mg m^{-3}) represent water volume and water mass contained in the saturated sample and water density. However, it is worth remembering that the method expressed by equation 4 is not usually recommended due to the inherent difficulties in soil saturation process (Dane and Hopmans, 2002).

Similarly to d, ϕ is also affected by the soil textural class, with values from 0.62 to 0.53 m^3 m^{-3} in clayey and 0.47 to 0.32 m^3 m^{-3} in sandy soils (Libardi, 2004). Details on the different experimental methods to measure ϕ can be found in Flint and Flint (2002b).

Although the determination of ϕ is very common in any soil physics laboratory, this concept is only practiced with students, in most cases, on specific subjects in the soil area. In most of the agronomy and/or technical courses (farming, land surveying) soil physics is not a specific compulsory subject. For this reason, students may only have contact with the measurement of the soil basic physical properties in graduate courses.

Since the laboratories dedicated to teaching of experimental physics are usually used exclusively for experiments in the area of basic physics and shared by different professors, working with soil samples is almost impossible in these spaces. For this reason, one alternative is to simulate porous media and obtain its physical properties, such as: particle density, porous medium density, gravimetric and volumetric water contents, and porosity.

This study proposes an experimental method to determine the basic physical properties of porous media, which can be extended to soils, for courses of experimental physics of students of agronomy or technical courses in the agriculture area. More specifically, the proposed experiments are related to the subject Experimental Physics with the module "Hydrostatic and Hydrodynamics", of the agronomy graduation course at the State University of Ponta Grossa.

MATERIAL AND METHODS

Instead of volumetric flaks, pycnometers without calibration lids with volumes between 15 and 30 mL (Figure 1b) were used, although the former could also have been used. These pycnometers were used to guarantee they were completely filled with spheres, that is, up to the brim. In this way, instead of using the pycnometer reference volumes, the mass of pycnometers filled with water was measured and their volume determined from the water density at room temperature. In the case of using volumetric balloons, the procedure would be the same. It is important to highlight that although pycnometers with larger volumes can be used, the porous medium saturation process becomes more critical, and pycnometers with volumes smaller than 15 mL may hamper the filling with different-sized spheres and the saturation procedure of the porous medium.

As porous medium, lead and iron spheres with the same diameter (Figure 1a) and with different diameters (not shown in the figures) were chosen. However, spheres of different metals could have been used, depending on the availability of material used in the laboratory of experimental physics classes. Homogeneous porous media were built with these spheres, consisting of metallic spheres with the same diameter (monodisperse) or heterogenous media, with spheres of different sizes (polydisperse). Thus, to simulate both situations and verify the efficacy of the experimental method proposed, two experiments were carried out: Experiment 1 – monodisperse medium and Experiment 2 —- polydisperse medium.

Since ϕ can either be determined by equation 3 or 4, the procedures applied in this study when using one or the other, both for Experiment I and Experiment II, are presented below, for a comparison of the two experiments as well.

If equation 3 is chosen, measurements of d_s and d are necessary, following the steps:

a. Determination of the pycnometer internal volume (V_{pic}). In this case, the procedure initially involved the measurement of the pycnometer mass ($m_{pic} = m_1$), clean and dry (Figure 1b) and, later on, the mass of the water contained in the pycnometer ($m_{pic + H_2O} = m_2$) (Figure 1c). In this way, after knowing the room temperature and the water density, V_{pic} was determined as follows:

$$V_{pic} = \frac{m_2 - m_1}{d_{H_2O}} \qquad \text{Eq. 5}$$

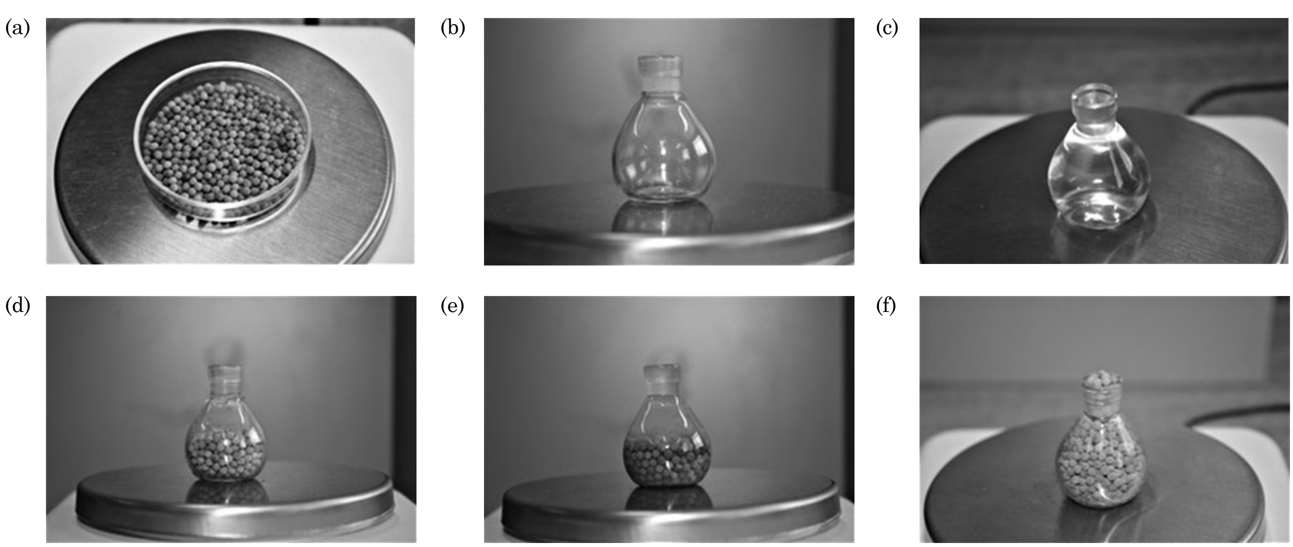

Figure 1. Lead spheres (a); pycnometer without lid (b); pycnometer without lid full of water (c); pycnometer without lid with lead spheres to measure particle density (d); pycnometer without lid with lead spheres full of water (e); pycnometer without lid with lead spheres to measure the porous medium density, gravimetric and volumetric water contents and porosity (f).

b. Determination of particle density. After V_{pic} determination, it was necessary to measure d_s by determining the mass of the metal spheres in the half-filled pycnometer ($m_{pic+sph} = m_3$) (Figure 1d), and the pycnometer filled with metal spheres and water mass ($m_{pic+sph+H2O} = m_4$) (Figure 1e). Thereafter, water mass was determined, which in the case of the pycnometer with spheres is given by the difference between the two measurements previously carried out in this step ($m_4 - m_3 = m_5$) and the sphere mass, given by the difference between the first measurement of this step and the first measurement of the previous step ($m_3 - m_1 = m_{sph}$). Therefore, d_s was calculated using the following relation:

$$d_s = \frac{m_3 - m_1}{V_{pic} - \left(m_5 / d_{H_2O} \right)} \quad \text{Eq. 6}$$

c. Porous medium density determination. To determine d, it was necessary to fill the pycnometer completely to its maximum volume with the metal spheres and then determine the mass denominated $m_{3'}$ (Figure 1f). Thus, d was calculated by the following expression:

$$d = \frac{m_{3'} - m_1}{V_{pic}} \quad \text{Eq. 7}$$

If the second method is used, that is, equation (4), it is necessary to obtain U_s measurements and then θ_s, for which the following steps were taken:

a. Determination of the pycnometer mass. In this experiment, the following measurements were carried out: clean and dry pycnometer mass (m_1) (Figure 1b), pycnometer completely filled with metal spheres to its maximum volume mass ($m_{3'}$) (Figure 1f) and pycnometer totally filled with metal spheres and water ($m_{4'}$); next, the water mass inside the pycnometer was determined by the difference between the last two measurements carried out in this step ($m_{5'} = m_{4'} - m_{3'}$).

b. Determination of the gravimetric water content of the porous medium. With the determinations of the previous step, U_s was calculated by the expression:

$$U_s = \frac{m_{5'}}{m_{3'} - m_1} \quad \text{Eq. 8}$$

c. Determination of the saturated volumetric water content. Once the U_s value was obtained through equation 8 and the previous step, and d was given by equation 7, step 3 in the first option, θ_s was determined by the expression:

$$\theta_s = \left(\frac{m_{5'}}{m_{3'} - m_1} \right) \left(\frac{d}{d_{H_2O}} \right) \quad \text{Eq. 9}$$

After ϕ was determined by employing equations 3 and 4, the efficacy of both procedures was compared in Experiments I and II, considering the relative deviation (RD) between them:

$$RD(\%) = \left(\frac{\phi_2 - \phi_1}{\phi_1} \right) \cdot 100 \quad \text{Eq. 10}$$

where index 1 refers to the procedure using equation 3 and index 2 is related to the procedure using equation 4.

RESULTS

Experiment I – monodisperse medium – was carried out with lead spheres (diameter ~ 2.50×10^{-3} m) to simulate a homogeneous porous medium. Experiment II – polydisperse medium – was carried out with iron spheres (diameter 4.78×10^{-3} m and 6.36×10^{-3} m), to simulate a heterogeneous porous mzedium. The sphere diameter was measured with a 0.02 mm precision steel caliper. It was necessary to determine d_s using equations 5 and 6 in Experiments I and II. The data used to determine particle density are shown in table 1 and, since the temperature in the laboratory was 21.5 °C, the d_{H_2O} value used in all calculations was 0.9978 Mg m^{-3}.

From the data in table 1, the following results were obtained for d_s: 10.87 Mg m^{-3} (lead) and 7.81 Mg m^{-3} (iron). Considering the theoretical values of the sphere density: 11.20 Mg m^{-3} (lead) and 7.80 Mg m^{-3} (iron), the relative deviation values were: -2.9 % and +0.1 %, respectively, showing the reliability of the method used to determine d_s.

The procedure had to be carried out carefully, to ensure that all spaces between the spheres were efficiently saturated with water. Otherwise the d_s values would be underestimated.

Determining d by equation 7 was necessary for Experiment I and II; the data used to determine d are shown in tables 1 and 2.

Table 2 also presents data needed for Experiment II, that is, U_s and θ_s measurements with equations 8 and 9, respectively.

From the data in tables 1 and 2, it was possible to obtain the following values for d, U_s, θ_s and

Table 1. Data used to measure particle density of the porous medium

Sphere	Mass(1)				
	m_1	m_2	m_3	m_4	m_5
	Mg × 10^{-6}				
Lead	8.96	19.36	50.91	57.46	6.55
Iron	8.90	26.31	43.67	56.64	12.97

(1) Weighing precision 1×10^{-8} Mg.

Table 2. Data used in the measurement of porous medium density, saturated gravimetric and volumetric water contents and porosity

Sphere	Mass[(1)]		
	$m_{3'}$	$m_{4'}$	$m_{5'}$
	Mg × 10^{-6}		
Lead	114.46	121.08	6.62
Iron	82.79	90.69	7.90

(1) Weighing precision 1 × 10^{-8} Mg.

ϕ: 6.34 Mg m^{-3}; 0.063 Mg Mg^{-1}; 0.402 m^3 m^{-3}; 0.417 m^3 m^{-3} – equation 3 and 0.402 m^3 m^{-3} – equation 4 for the pycnometer with lead spheres – Experiment I; 4.23 Mg m^{-3}; 0.107 kg kg^{-1}; 0.453 m^3 m^{-3}; 0.458 m^3 m^{-3} – equation 3 and 0.453 m^3 m^{-3} – equation 4 for the pycnometer with iron spheres – Experiment II. The relative deviations calculated through equation 10 between the two procedures to determine ϕ with lead and iron spheres, Experiments I and II were -3.6 % and -1.2 %, respectively. The highest RD observed for lead spheres was associated to the difficult saturation of this porous medium, due to the smaller diameter of the spheres when compared to the iron spheres. The sphere saturation process in the second procedure was critical and required special care to guarantee that the porous medium would be completely saturated. A thin stick (2.00 × 10^{-3} m diameter) was used to stir the porous medium within the pycnometer without lid for the saturation process. Also, if the volume of the porous medium presents decreases slightly in this procedure, it is necessary to add more spheres to fill the medium completely and also take their mass into account in the equations 7 at 9.

Figure 2 shows the results for ϕ and RD. The ϕ values for both procedures in Experiments I and II (Figure 2a) and the respective RD obtained by equation (10) (Figure 2b) were compared.

In figure 2b, the RD of the ϕ measured using the determined d_s value (Equation 6) and the theoretical d_s value (tables) are presented. If in the experimental procedure, the spheres are known to be made of pure substance, there is no need to determine d_s with the procedures indicated by equation 6. However, in this study this fact applies to the iron but not to the lead spheres. Due to the high RD of the lead spheres, it was presumed they were not pure.

Proposal of alternative configuration of porous medium

A simulation of porous medium as alternative configuration consists of the construction of an acrylic box to hold spheres one on top of the other, in a simple cubic structure (Figure 3) (Hillel, 1998). One advantage of this kind of structure is that ϕ can be calculated theoretically and then

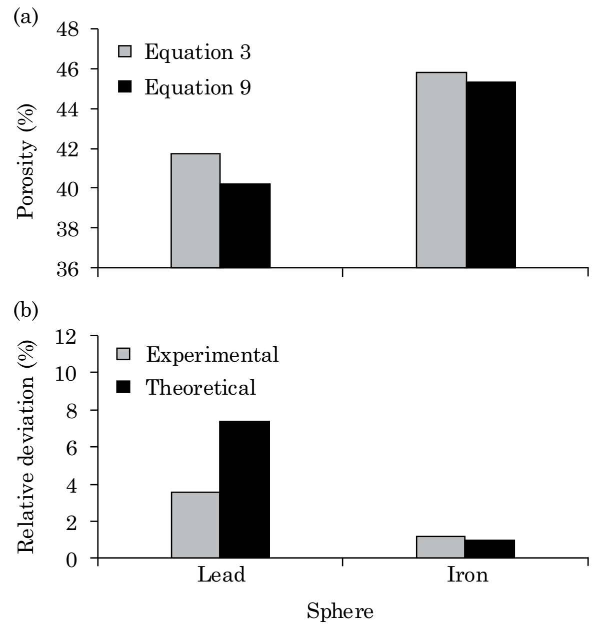

Figure 2. Porosity values (a) and relative deviation (b) for lead and iron spheres used as porous media.

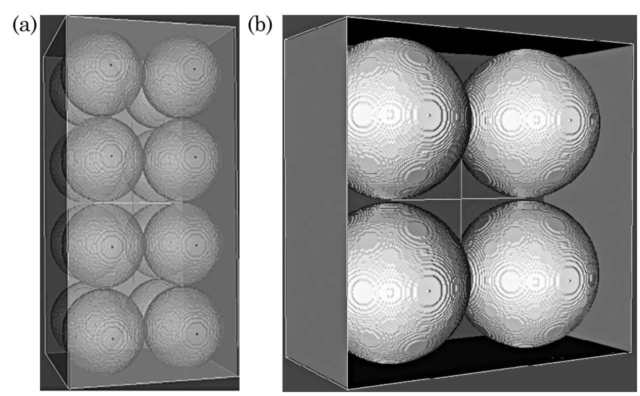

Figure 3. Configuration of a sphere arrangement in a box to simulate a porous medium (a, b). Adapted from Camargo et al. (2012).

measured experimentally, using the processes previously described.

Taking into consideration that each sphere has radius R, the sphere center to center distance is 2R, in the arrangement shown in figure 3. In this case, the sphere occupies a $\frac{4}{3}\pi R^3$ volume and a $16.\frac{4}{3}\pi R^3$ total volume, with the total volume of the porous medium given by $128R^3$ (volume of the rectangular box with the size 8R × 4R × 4R). In this case, the porosity is given by the following equation:

$$\phi = \frac{V - V_s}{V} = \frac{8R^3 - \left(\frac{4}{3}\pi R^3\right)}{8R^3} \cong 0.48 \text{ m}^3 \text{ m}^{-3} \quad \text{Eq. 11}$$

FINAL CONSIDERATIONS

This paper proposes an experimental method in which some basic physics concepts of porous media are discussed for Experimental Physics trials, taught in the module “Hydrostatic and Hydrodynamics” of the Agronomy course of the State University of Ponta Grossa. Also, these procedures might be extended to classes of Experimental Physics taught in technical courses in agriculture, land surveying and related areas.

The proposed experimental method analyzes the concepts particle density, porous medium density, and gravimetric and volumetric water content and porosity. The goal was to demonstrate the potential of further applications of these concepts to measurements of soil samples.

For particle density, the experimental method used was adapted from the traditional volumetric flask method with the use of pycnometer without lid. The porous medium density was measured by traditional methods that use some container to contain the sample.

To demonstrate the validity of the method proposed and its procedures, two distinct porous systems were analyzed, the first with spheres with the same diameter (monodisperse) and the second with spheres of different sizes (polydisperse).

The particle density of both systems determined experimentally presented low deviation (-2.9 % – lead spheres and +0.1 % – iron spheres) compared to the theoretical values. Porosity also showed low deviation (-3.6 % – lead spheres and -1.2 % – iron spheres) when comparing the procedures and monodisperse and polydisperse media using particle density and saturated volumetric water content.

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