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A STUDY OF THE POROSITY OF GAS FILTRATION CAKES

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Abstract - The purpose of this work was to determine the porosity of gas filtration cakes composed of powdery organic and inorganic materials, employing a technique whereby an optical microscope generates images of the powdery layer deposited on the surface of the filtering medium. To this end, experimental cake filtration porosity data were obtained as a function of the surface filtration velocity. The images generated by the optical microscope were analyzed by using an image analyzing program that supplied the cake porosity values. The results revealed that porosity decreases as surface filtration velocity increases. The average porosity of corn starch was higher than that of tapioca powder and phosphate concentrate, possibly due to the shape of the particles, differences in the physicochemical characteristics of the materials, and grain distribution. Based on the relation of the experimental average porosity data and the filtration velocity, an empirical correlation was found that better fit these parameters.

Keywords: Cake filtration; Fabric filters; Gas cleaning; Gas filtration; Particle removal; Porosity.

INTRODUCTION

The steady growth of industrialization and urbanization has led to indices of pollution that are increasingly serious and threatening to human health. Because air pollution affects the quality of life, attacking nature and the environment, increasingly stringent laws restricting the emission of polluting agents into the atmosphere began to be passed from the 1970s on.

Many possible measures are available to reduce the amount of harmful agents in the atmosphere, e.g., careful planning of industrial facilities, purification of industrial gases, and removal of fine particles from the air. Among the various processes employed to eliminate particulate matter from the atmosphere, filtration is an important operation utilized in the separation of gases from solids. Fabric filters are one of the most widely used means for filtering, since they are inexpensive, easy to handle and highly efficient in removing fine particles. To optimize and improve the filtration process, a more detailed understanding is required of some of the structural characteristics of the cake filtration, one of which is its porosity. This is a very important structural property, since a drop in the filter's pressure during the filtration operation and the force needed to remove the powder layer depend on this parameter. However, due to its great fragility, its experimental measurement is extremely difficult.

Owing to this difficulty, Coury (1983) developed a method whereby the porosity of cake filtration can be estimated based on equations found in the literature, which describe the resistance of a porous

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*To whom correspondence should be addressed medium to the outflow of a fluid, considering measures of pressure drops in the particle layer for a given outflow of gas and knowing the cake's total mass. This method was dubbed the indirect method.

Other researchers have developed methodologies to determine porosity through direct measurement techniques involving the use of scanning electron microscopy (Schmidt and Loffler, 1991; Aguiar and Coury, 1996) and laser equipment (Tsai and Cheng, 1998).

Aguiar and Coury (1995) adapted the method proposed by Schmidt and Loffler (1991), proposing an experimental method to estimate the porosity of cake filtration, which they dubbed the direct method. By this method, porosity is determined based on images representing the transversal section of cake filtration obtained by SEM (scanning electron microscopy) and then analyzed by image analysis programs.

Tsai and Cheng (1998) estimated cake porosity based on Equation (1), whereby the cake's thickness (L) was measured with a laser sensor device:

$$\varepsilon = 1 - \frac{W}{\rho_p L} \tag{1}$$

where W is the mass of powder deposited on the filtering medium per unit of area. In the aforementioned study, the authors also investigated the influence of the superficial filtering velocity on the porosity, using superficial filtering velocities (V_f) of 1 to 9 cm/s and three different powdery materials, and finding an empirical equation that relates the superficial filtering velocity with a cake's average porosity, Equation 2, where A and B are empirical constants:

$$\varepsilon = 1 - A\ V_f^{B} \tag{2}$$

Negrini et al. (1999), using as a powdery material phosphate rock, whose particle density (ρ_p) is 2940 kg/m^3 and which has an average particle diameter of 18 μm, observed that, at gas superficial filtration velocities (V_f) of 5.4; 6.8; 8.1 and 8.9 cm/s, the porosity at the cake-fabric interface was lower than at the air-cake interface, decreasing at all the velocities investigated as the cake's thickness increased. Using dolomitic limestone as a powdery material, Aguiar and Coury (1996) came up with similar results. They also found that porosity decreased with increasing velocity, and that Equation (2) also best fit their experimental data.

Silva et al. (2000) conducted a study of the effect of operational variables on the formation of filtration cake in fabric filters, finding that the filtration velocity was the variable that most strongly affected the cake's porosity and specific resistance. The interaction between the mass flow-rate of the powder and the filtration velocity was also substantial in these variables. The authors also observed that the porosity first decreased and then increased with the increase in filtration velocity and in the mass flow-rate of the powder, while the specific resistance of the cake increased and decreased under the same experimental conditions.

Lucas (2000) attempted to apply the method proposed by Aguiar and Coury (1996) to determine the porosity of cakes composed of a powdery organic material derived from cassava (tapioca), but did not obtain satisfactory results, since the SEM images of the transversal section of tapioca did not provide sufficient contrast to be analyzed because both the tapioca and the resin used for fixing it were organic materials.

To find the porosity of gas filtration cake composed of powdery organic materials, Ito et al. (2001) adapted the method proposed by Aguiar and Coury (1995). Using an optical microscope, they generated images of the filtration cake and compared them with SEM images, finding that the microphotographs showed a similar quality. They also estimated average porosity values by the two methods, producing very similar results with 10% deviations.

In view of the above, this study aimed to determine the porosity of filtration cake composed of powdery organic and inorganic materials and to analyze the influence of the superficial filtration velocity on the average porosity. To this end, the technique developed by Ito et al. (2001) was employed, using an optical microscope to generate images of the structure of the powder layer deposited on the surface of the filtration medium.

MATERIALS AND METHODS

Materials

Three particulate materials were used in this study: tapioca, corn starch (organic materials) and phosphate concentrate (an inorganic material). The density values of the powders were measured using a MICROMETRICS helium pycnometer, while particle diameters were measured using a HORIBA particle characterization device. The average values found are listed in Table 1. A polyester felt fabric, supplied by the company Gino Cacciari and weighing 534 g/m^2, was used as a filter.

Figure 1 shows the grain distribution of the tapioca, corn starch and phosphate concentrate powders.

Equipment

The Figure 2 shows a diagram of the device used for the filtrations tests.

Experimental Procedures

Filtration

During filtration, the powder feeder dispersed the powdery material to be filtered into the air at a constant mass flow-rate of the powder. The “dirty” air was sucked (by a Venturi suction pump) into the filtration box, where it passed through the filter placed horizontally and perpendicular to the gas (air) outflow. The particles were deposited onto the fabric filter, where they adhered, forming the filtration cake. The flow of “clean” air exiting the filter was measured using a plate with a hole coupled to a digital manometer and then released into the atmosphere. The superficial filtration velocity was kept constant throughout the formation of the cake for the three types of powder used in this study, at 5; 7.5; 10; 12.5 and 15 cm/s. The total filtration time was set at 800 seconds. Filtration was concluded when this predetermined time was over, which corresponded to different filtration cake thicknesses. The mass flow-rate of the powder was 0.03 g/s for tapioca, 0.02 g/s for corn starch, and 0.04 g/s for phosphate concentrate.

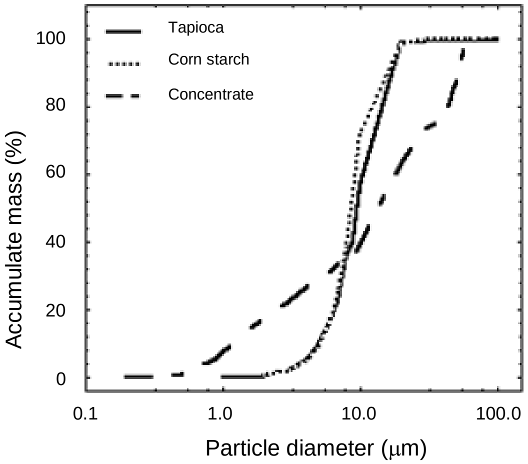

Figure 1: Grain distribution of the powders obtained with the help of the HORIBA device.

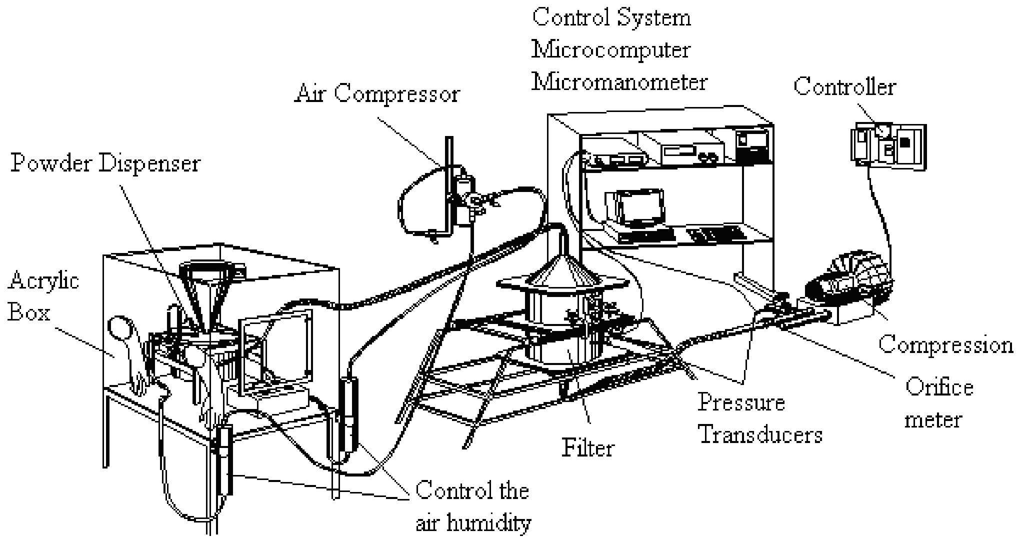

Figure 2: Overall view of the filtration device.

Estimated Porosity

Images Obtained by Optical Microscopy

The method consisted, initially, of passing the vapor from an instant adhesive (Loctite-416), dragged by the damp airflow, through the filtration medium containing the filtration cake. The flow of compressed air dragging the instant adhesive vapor was constant and well below the superficial filtration velocity (0.5 cm/s) to avoid any alteration of the cake's structure. After "pre-hardening", the filtration medium together with the powder cake were set in a fixing resin (Loctite PMS-10), and then placed in a furnace at 60°C for about 48 hours to cure the resin. After the cake was completely hardened, it was cut into small squares of approximately 1 cm^2. These pieces were then set, with the transversal section of the cake facing the surface, in cylindrical PVC molds, using a thermally rigid resin, Fiberglass – 10249. The specimens were then sandpapered and polished to remove every scratch left by the sandpaper, allowing for perfect observation and imaging by optical microscopy.

The samples were well polished to leave the surface as devoid of roughness and as smooth as possible. This step was important because any waviness or scratch on the sample's surface makes it very difficult to observe and acquire images through the optical microscope, generating distorted and fuzzy images and leading to incorrect results.

Image Analysis

The images generated by the optical microscope were analyzed using an image analyzing program, Image Pro Plus. This program has a function that renders the image real with only two levels of color – light points (white) and dark points (black), which we call "binarization", that allows light and dark areas to be counted, thus determining the porous spaces. In the images obtained for the powdery organic materials, the dark points represented the particles and the light points the pores.

Determining the Porosity

The porosity of a porous solid system is defined as the ratio of the volume of empty spaces to the total volume. Assuming that the porous medium is homogeneous, the quantification of this parameter can be used to characterize the system's structure.

Thus, the samples were sectioned randomly and then, by analogy with the volumetric porosity calculated from flat areas, the superficial porosity, defined as the ratio of empty area to the total area, was determined. The porosity was therefore determined using digitalized images, based on the percentage of black points (pixels) and white points (porous spaces) in the total number of black and white points (particles and pores). The value obtained to represent the porosity depends on the "binarization" and the contrast, which must be perfect. This binarization was done by the Image Pro Plus program, which renders binarized photographs as real and similar as possible to the original image. The operator must therefore be very careful at this stage, because it is he who defines whether the binarized photograph is a true copy of the one taken directly from the optical microscope.

RESULTS AND DISCUSSION

Filtration tests

Figure 3 illustrates the filtration curves for the three types of powdery material, for a superficial filtration velocity of 10 cm/s.

As can be seen in Figure 3, as the filtration time increases, the pressure drop becomes much greater for the phosphate concentrate than it is in the case of tapioca and corn starch. This difference is related to the physicochemical properties of these powdery materials and, particularly, the density of phosphate concentrate, which is twice that of tapioca and corn starch.

The filtration curves for the phosphate concentrate, which displayed the sharpest drop, i.e., almost 6.5 KPa, showed a different behavior. After the first layers of powder had been deposited on the cloth filter, all the curves displayed a linear behavior up to approximately 4.5 KPa, after which they deviated. This behavior was also observed in the study of Silva et al. (2000). According to Dennis and Klemm (1982), who showed various types of filtration curves, including one similar to that depicted in Figure 3, this phenomenon may have to do with the collapse of the pores (a break in the structure of the filtration cake), leading to a consistent reduction in the pressure drop and a substantial increase in powder penetration. Possibly there are other explanations for this behavior, such as the cake's compressibility (Aguiar and Coury, 1996; Schmidt, 1991 and 1993), compressibility of the gas, deformation of the filtering cloth at high pressure drop values. However, no unequivocal explanation is available so far.

Figure 4 shows in greater detail the behavior of the filtration curves of the two organic powders, at a superficial filtration velocity of 10 cm/s.

The drag curve as a function of the powder mass deposited per unit of area can be divided into two regions. In the first, the particles become deposited on the fibers of the cloth, forming an initial powder layer. In this initial phase, there is an interaction between the particles and the cloth's fibers, and the collection mechanisms are important. In the second region, the drag increases linearly with the mass of powder per unit area, forming the filtration cake. As can be seen in Figure 4, the first region was clearer for tapioca, which reached slightly higher drag values than corn starch for the same superficial filtration velocity of 10 cm/s. This behavior was also displayed at the other filtration velocities investigated in this study. It was found that, during the filtering operation, the tapioca compacted more than the corn starch. This meant that the tapioca powder better filled the groove on the revolving plate of the powder feeder, so that the mass flow-rate of the powder on the filter was greater with tapioca (0.03 g/s) than for corn starch (0.02 g/s). This undoubtedly caused it to reach a higher pressure drop.

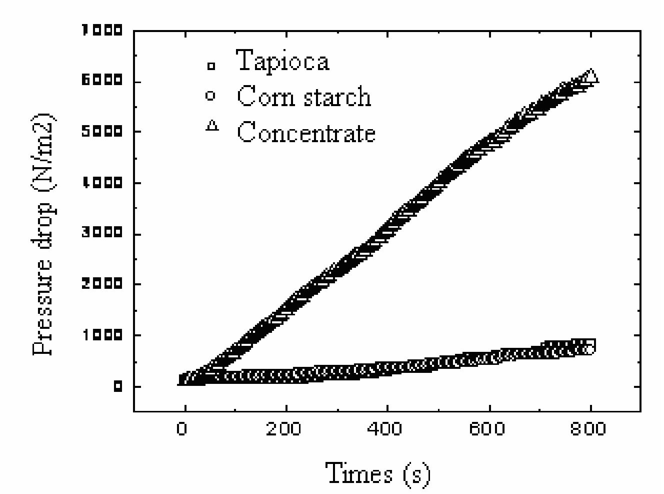

Figure 3: Pressure drop versus filtration time for the three types of powdery material.

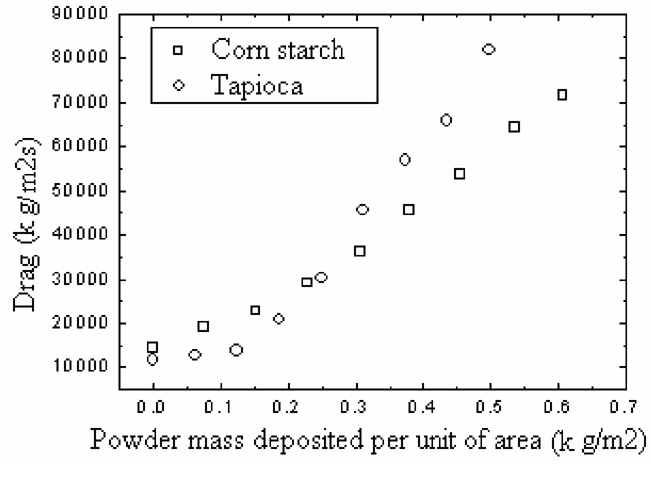

Figure 4: Drag curve as a function of the powder mass deposited per unit area for the organic powders.

Experimental Determination of the Specific Resistance of the Cake (K_2)

The experimental value of K_2 can be calculated from the increase in pressure drop (ΔP) in the filter and mass gain (M) caused by the accumulation of powder on the filtering medium (Leith and Allen, 1986), as expressed by Equation (3):

$$K_{2,\exp} = \frac{(\Delta P / V_f)}{(M/A)} = \frac{S}{W} \tag{3}$$

where A is the free area for filtration, V_f is the superficial filtration velocity, S is the drag and W is the mass of powder deposited per unit of area. Therefore, K_2 was estimated from Equation (3) and from experimental filtration curves such as those shown in Figure 4. The values of K_2 thus obtained for the three powdery materials are listed in Tables 2 to 4.

Tables 2 to 4 indicate that K_2 increased as the superficial filtration velocity increased for the three powdery materials. A comparison of the two organic powders reveals that tapioca showed higher K_2 values, which is congruent with the curves shown in Figure 4.

Determining the Average Porosity

Direct Method

The average porosity was determined as described in the materials and methods section, based on the images of the transversal sections of the filtration cake, using the image analyzing program Image Pro Plus.

The average porosity values of the filtration cake of the organic materials, tapioca and corn starch, are listed in Tables 2 and 3, respectively. These tables indicate that the average porosity values varied from 0.54 to 0.48 in the case of tapioca and from 0.66 to 0.59 for corn starch with the increase in superficial filtration velocity (V_f) from 5.0 to 15.0 cm/s.

Comparing the average porosity (ε) of the cake filtration of the organic powders given in Tables 2 and 3, one finds that tapioca's ε values were lower than those of corn starch. This may have been due to the powder's physicochemical properties, particularly particle shape, since the particle density values for these two powders were similar, as can be seen in Table 1. Moreover, they presented practically the same grain distribution, as Figure 1 demonstrates. The tapioca underwent greater powder compaction during filtration, increasing its packing, for which reason it showed higher drag (Figure 2) and K_2 values and, hence, lower porosity values.

Table 4 lists the average porosity values of the filtration cake for the inorganic powder, phosphate concentrate. It can be noted that the average porosity values varied from 0.63 to 0.59 as the filtration velocity rose from 5 to 15 cm/s. Although it showed higher K_2 values than the organic powders, its average porosity values were close to those of corn starch.

Porosity as a Function of Superficial Filtration Velocity

Having found the experimental values of average porosity for the three types of powders, see Tables 2 to 4, an equation was fit that better related the average porosity data of filtration cake and the superficial filtration velocity.

The empirical equation that best fit the experimental data for the three powders was Equation (2), which was also obtained by Tsai and Cheng (1998).

Equation (4) was the one that best represented the experimental data for tapioca, for filtration velocities varying from 5 to 15 cm/s, with a correlation coefficient (R^2) equal to 0.98.

$$\varepsilon = 1 - 0.38\ V_f^{0.11} \tag{4}$$

Equation (5), for corn starch, showed a correlation coefficient (R^2) equal to 0.99 for the same range of velocities.

$$\varepsilon = 1 - 0.26\ V_f^{0.17} \tag{5}$$

Lastly, Equation (6), for phosphate concentrate, showed a correlation coefficient (R^2) equal to 0.98, also for the same range of filtration velocities.

$$\varepsilon = 1 - 0.32\ V_f^{0.09} \tag{6}$$

The filtration cakes of the organic and inorganic powders were formed under the same experimental conditions.

Figure 5 gives a clearer idea of the average porosity variation as a function of superficial filtration velocity for the three powders, with the respective curves estimated from Equations (4), (5) and (6).

Figure 5 indicates that the porosity values of the three powders decreased as the superficial filtration velocity increased. The figure also shows that the porosity of the phosphate concentrate and corn starch was higher than that of tapioca, which was likely due to particle shape.

Table 1: Density and particle diameter values of the three types of material.

Powdered material	ρ_p (g/cm^3)	dp (μm)
Tapioca	1.48	8.67
Corn starch	1.50	9.52
Phosphate concentrate	3.03	14.53

Table 2: Values of specific resistance and average porosity of filtration cake for tapioca.

Test	V_f (cm/s)	ΔP (N/m^2)	K_2 x10^5 (s^{-1})	ε
1	5.0	72.65	0.74	0.54
2	7.5	57.47	1.15	0.53
3	10.0	77.53	1.74	0.51
4	12.5	196.80	2.20	0.50
5	15.0	354.51	2.54	0.48

Table 3: Values of specific resistance and average porosity of filtration cake for corn starch.

Test	V_f (cm/s)	ΔP (N/m^2)	K_2 x10^5 (s^{-1})	ε
1	5.0	16.50	0.16	0.66
2	7.5	29.00	0.54	0.63
3	10.0	73.70	0.88	0.61
4	12.5	65.60	1.28	0.60

Table 4: Values of specific resistance and average porosity of filtration cake for phosphate concentrate.

Test	V_f (cm/s)	ΔP (N/m^2)	K_2 x10^5 (s^{-1})	ε
1	5.0	496.50	2.32	0.63
2	7.5	516.14	5.40	0.61
3	10.0	780.72	5.56	0.60
4	15.0	505.30	11.0	0.59

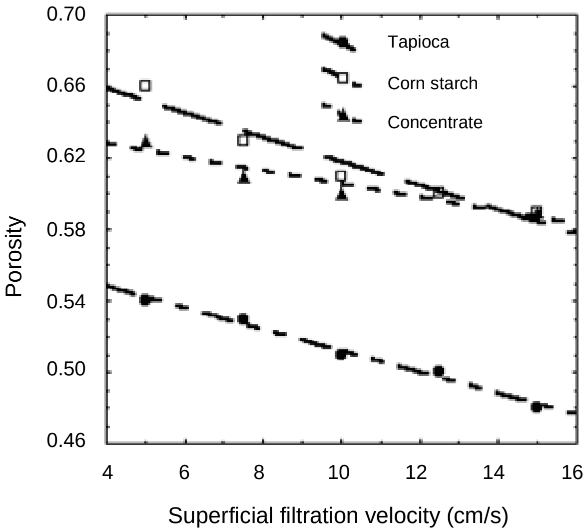

Figure 5: Correlation between porosity and superficial filtration velocity of tapioca, corn starch and phosphate concentrate.

Influence of Particle Shape

A study was made of the particle shapes of the three powders. The image analysis program Image Pro Plus was used to determine the particles' sphericity, based on the value of their average diameter. The sphericity of tapioca was found to be 0.94, corn starch 0.71 and phosphate concentrate 0.60.

Tapioca therefore has approximately spherical particles and a small grain distribution; corn starch particles are more irregularly shaped, but their grain distribution is similar to that of tapioca. Phosphate concentrate, however, shows totally irregular particle shapes and a broad grain distribution, as can be seen in Figures 6, 7 and 8.

Corn starch and tapioca are organic materials possessing practically the same grain distribution and density, and the filtration cakes were formed under the same experimental conditions, with slight variations in the powder feed outflow. Thus, the shape of the particles must have been the determining factor for the reduction in porosity values. The sphericity of tapioca particles is almost 1 (0.94), while corn starch particles are more irregular in shape (sphericity of 0.71) and, according to Tsai and Cheng (1998) and Yu (1997), because spherical particles have the same shape, they fill in interstitial spaces more efficiently, undergoing greater packing and resulting in lower porosity.

The phosphate concentrate has quite irregularly shaped particles (sphericity of 0.61), as does corn starch, but displayed a broader range of grain distributions, which undoubtedly enabled the particles to settle better, leading to a lower porosity.

Lastly, a comparison of tapioca and phosphate concentrate powders confirms that they display differences both in the grain distribution range and in particle shape. According to Endo (2001), monodispersed spherical particles have lower porosity values than polydispersed irregular particles.

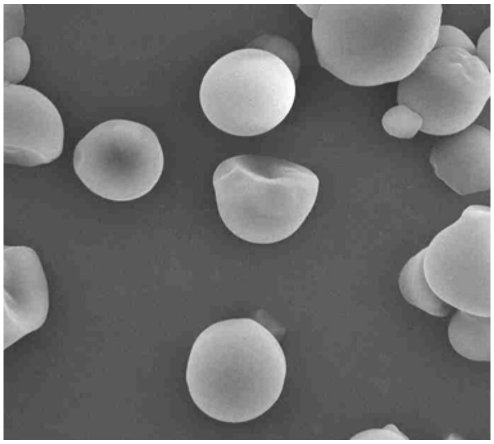

Figure 6: SEM image of tapioca powder magnified 3500 times.

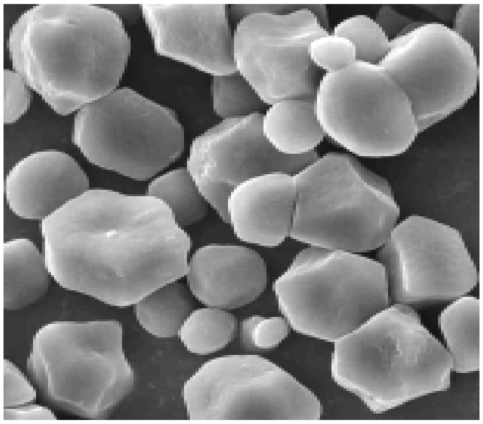

Figure 7: SEM image of corn starch powder magnified 3500 times.

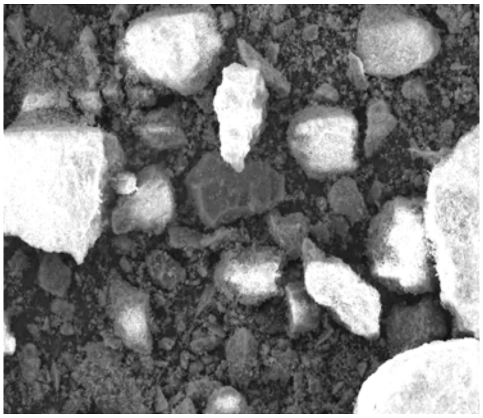

Figure 8: SEM image of phosphate concentrate powder magnified 1000 times.

CONCLUSIONS

- The average experimental porosity values of phosphate concentrate (0.59 to 0.63) and corn starch (0.59 to 0.66) were higher than those of tapioca (0.48 to 0.54).
- The specific resistance of the cake increased as the filtration velocity increased and was the highest in the case of tapioca.
- For the three types of powdery material, the average porosity of the filtration cake decreased as the superficial filtration velocity increased.
- An analysis of the influence of the superficial filtration velocity on the experimental porosity enabled us to obtain an empirical equation relating the filtration velocity with the cake's porosity.
- Particle shape and grain distribution were found to be the most important variables in the formation of filtration cake.

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NOMENCLATURE

A	filtration area	cm^2
d_p	particle diameter	μm
L	cake thickness	cm
K_2	specific resistance of the cake	s^{-1}
M	mass gain	g
Q	mass flow-rate of the powder	$g.s^{-1}$
S	drag	$kg.m^{-2}.s^{-1})$
t	time	s
V_f	superficial filtration velocity	$cm.s^{-1}$
W	mass of powder deposited per unit of area	$g.cm^{-2}$
ΔP	pressure drop	$N.m^{-2}$
ε	porosity	(-)
μ	fluid viscosity	$g.cm^{-1}s^{-1}$
ρ_g	fluid density	$g.cm^{-3}$
ρ_p	particle density	$g.cm^{-3}$

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