METHOD OF OPTIMUM COMPACTING OF CONTROL MATERIAL IN MOISTURE SENSORS

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A theoretical analysis of the methods of packing loose medium in humidity sensors is given and their experimental investigations are presented. Power packing is recommended for continuous moisture sensors, while inertial-power packing is recommended for discrete sensors.

One of the main problems to be solved in moisture measurement of loose materials is to minimize the interfering factors in the sensor [1]. Among these interfering factors is the variability of the granulometric composition Γ and the density P of the controlled sample. For a number of materials, whose granulometric composition varies within small limits, the effect of Γ and P can be eliminated or stabilized by compacting in the sensor [1, 2]. Some authors [3-5] consider that vibrational packing permits to stabilize the factors Γ and P better than power packing and thereby obtain better reproducibility and smaller error of measurements. Others [2, 6], on the other hand, take the power packing as the optimum method. This contradiction in the present problem depends primarily on the different nature of the physico-mechanical characteristics of the investigated materials; secondly, it is accounted for by the fact that in many articles on moisture measurement there are no comparative investigations of the two methods of packing.

In the present article an attempt is made to provide a validation of the optimum method of packing for the products of mining enriching industry for the purpose of developing rational moisture sensors.

Primary converters of the two constructions were prepared for the investigations. One is similar to the version presented in [2]; it is a capacitive moisture sensor with power packing and has plane ring electrodes. The second similar to the version given in [3]. Here packing is produced as a result of vibration of the sensor. The tests were conducted in identical climatic situations with the same material (apatite concentrate) and the same measuring instrument (F-meter type moisture meter).

The collected statistical sets of results and the chosen estimate criteria, for which the correlation coefficient r and the root mean square S_W in measuring the moisture were used, showed that the sensor with power packing gives better metrological characteristics. The values of S_W and r for the sensor with power packing are 0.121 and 0.965% absolute in the range of 0-1.6% moisture; in the case of the vibrosensor the corresponding values were 0.254 and 0.92% abs. Considering the identical nature of the conditions of the experiment (except the method of packing) the larger error in the second case should be attributed only to the method of packing.

During the experiments the effect of separation of the loose medium into classes differing in coarseness and specific weight could be detected in the vibrosensors. Henceforth we shall call this the vibrosegregation effect. The negative influence of vibrosegregation on the metrological characteristics of the moisture sensors is determined by two basic factors:

A. The intrinsic structure of the medium is layered during the vibrations and hence its parameters such as the coefficients of porosity, form of the moisture inclusions, dimensions of the particles in local zones of the sensor, dielectric constant of the material etc. change.

B. The chemical composition of the loose material changes in local zones of the sensor, for example, in the near-electrode zone.

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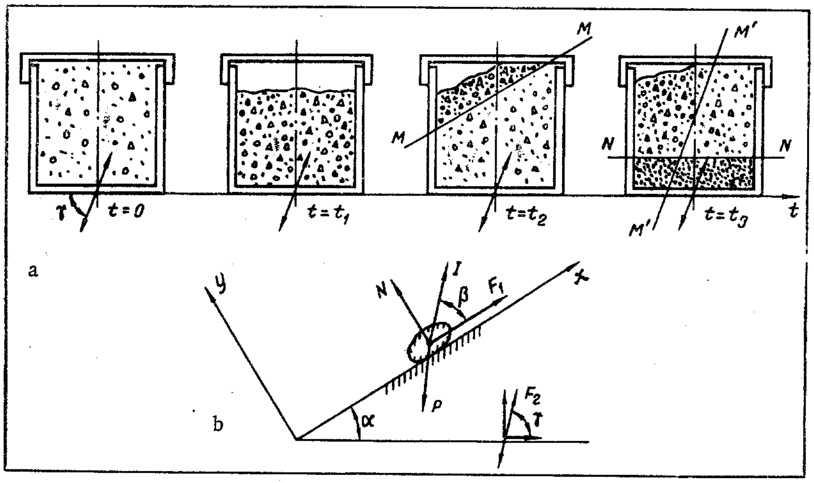

Fig. 1. Dynamics of the process of separation of a loose medium in the vibrosensor of moisture (a) and the group of forces acting on a particle in the process of vibrosegregation (b).

The last statement is valid for products of inorganic origin, for example, clay, construction sand, products of mining enriching industry, etc., because in the process of size reduction of such materials into different classes of coarseness, particles of different minerological (chemical) composition separate out, whose electrophysical characteristics are intrinsically in sharp contrast.

The basic theoretical premises justifying the separation of a loose medium under the action of vibration [1, 7] can be reduced to the following:

1. Predominance of the drag force acting on the particle in the medium in the positive direction (downward) over the force in the negative direction (upward)

$$F_+ > F_-.$$

2. The presence of particles in the volume of the loose medium, that are heavier than the medium, i.e.

$$\Delta = \frac{m}{m_0} > 1,$$

where m is the mass of the particle, m_0 is the average mass of the material (medium) in the volume equal to the volume of the particle, and Δ is the index of the presence of particles heavier than the medium.

3. The presence of certain vibration conditions, i.e.

$$A\omega^2 > \frac{F_- m_0 (\Delta - 1) g}{m_0 (\Delta - 1)},$$

where g is the acceleration of free fall, A, ω are the amplitude and frequency of vibration for which "floating" (to the surface of the medium) of the heavier particles is observed.

4. The presence of nonsymmetric oscillations of the loose medium during symmetric oscillations of the container

$$U'(\tau + \pi) \neq U'(\tau),$$

where U' is the acceleration of external perturbations acting on the medium. For this case the rate of relative displacement of the particles in the medium, when its effective weight P* is equal to zero, is given by the known formula [7, 1]

$$v = \frac{1}{2} \frac{m_0}{m} (\Delta - 1) \omega [U'(0) + U'(\pi)], \tag{1}$$

where

$$P^* = m_0 (\Delta - 1) g - \frac{1}{2} (F_+ - F_-). \tag{2}$$

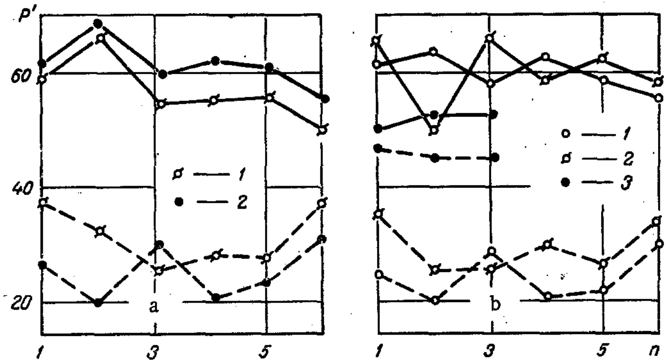

Fig. 2. Graph showing the presence of class + 0.42 mm in opposite sections of the regions of the sensor as a function of the moisture of the loose material (a): 1) W = 1.4%, 2) 0.4% and on the vibration acceleration (b): 1) a = 12 g, 2) 5 g, 3) 1 g. Continuous curves – 1st segment; dashes — 2nd. P in %.

Hence during nonsymmetric oscillations of the medium $v \neq 0$ and therefore the effect of vibrosegregation will be clearly seen. The first and fourth conditions may radically change the effect of the second and third conditions. This is accounted for, for example, by the floating of the heavy particles.

The theoretical premises for the effect of vibrosegregation [1, 7] were obtained for an idealized loose medium, i.e. a medium with particles of strictly spherical shape in the absence of any type of surface forces at the points of contact of the particles with each other.

It was necessary to verify conditions 3 and 4 experimentally for real loose materials. Furthermore, it was necessary to determine the effect of moisture and the state of the surface of the particles on the rate and degree of manifestation of vibrosegregation effect. The answers to these questions were provided by the experiments, whose results are presented below.

Ground bitumenous coal and tin concentrate, whose physico-mechanical properties differ sharply, were chosen as the investigated materials. The granulometric composition of these materials is almost identical (0-3) mm; the specific weight has different values: for coal γ = 1.5 g/cm^3, while for tin concentrate lies in the range 3.1-7 g/cm^3. The state of the surface of the particles is also different: whereas carbon is a strong adsorbent, tin concentrate does not have these properties. The experimental equipment consisted of a vibration bench, the moisture sensor, a capacitive moisture meter, and an acceleration meter with piezoelectric sensor. The vibration bench consisted of a vibration platform and equipment for regulating the frequency in the range 10-1000 Hz and acceleration in the range 0-13 g.

The completion of the packing and, hence, the completion of the process of vibrosegregation was determined from the time of complete damping of the variations in the capacity of the sensor with the material. The degree and rate of vibrosegregation after the vibration treatment were determined by granulometric analysis of the material from different regions of the inner volume of the sensor. The construction of the sensor made it possible to carry out layer by layer separation of the volume (height of each layer 15 mm, number of layers 4, inner diameter of the chamber 60 mm).

The program of the investigations included several stages: first — determination of the ranges of rates and accelerations of vibration giving rise to the phenomenon of vibrosegregation. The experiments, carried out with carbon at W = 1%, showed that vibrational separation is clearly observed at frequencies of 20-50 Hz in acceleration range a = 1-13 g. The decrease of the acceleration to a < 1 g results in an increase of discreteness and deterioration of the reproducibility of the measurements, since the amplitude of the vibrations is negligibly small. For example, at a = 1 g and f = 50 Hz

$$A = \frac{50a}{2f^2} \simeq 0.1 \text{ мм}. \quad (3)$$

In the construction of vibration moisture sensors used in practice the energy of oscillations with 50 Hz frequency is used, since the use of a frequency other than the supply frequency in electromechanical as

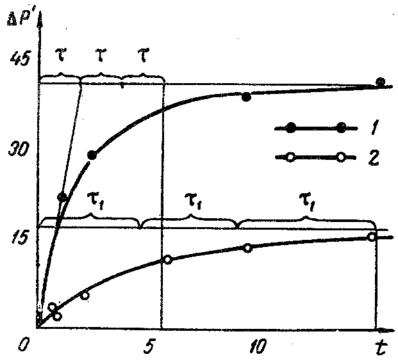

Fig. 3. Characteristics of the process of separation: 1) tin concentrate (W = 0.4%, f = 50 Hz, a = 5 g) and 2) ground carbon (W = 1.2%, f = 50 Hz, a = 5 g), ΔP' in %, t in min.

well as electromagnetic exciters considerably complicates the moisture measuring equipment. Therefore, in the subsequent stages the experiments were carried out at vibration frequency of 50 Hz.

It was found that even on laboratory test benches sometimes it is not possible to produce strictly vertical vibrations. This leads to a unique nature of separation of the loose medium. Let us clarify this statement (Fig. 1).

At the time t = 0 the sensor is completely filled and the structure of the material is identical over the volume. The vibrator is then switched on. The perturbing force (of vibration) F_2 is directed at an angle γ to the horizon. At the time $t = t_1$, the material settles and free space appears in the sensor. Due to the horizontal component of the vibration force the particles get displaced from left to right (see Fig. 1) and then at the time $t = t_2$ they get displaced upward along some inclined surface MM. During the vibrational treatment the angle of inclination α of the plane M'M' (at time $t = t_3$) tends to the angle of the perturbing force vector γ.

The particles of the coarse classes, having a tendency to float, slide downard along the surface M'M', since the force of friction F_1 becomes inadequate for sustaining them on this surface. Therefore such particles occupy the volume to the left of the plane M'M'. The finer particles, which are subjected to capillary adhesion forces to a larger extent, occupy the volume to the right of this surface. A third characteristic region (below the plane NN) can be distinguished, which consists of particles, which belong to the finer classes and are densely packed.

The equations of motion of a particle (Fig. 1b) along the coordinate axes (x the direction along the slip plane M'M' and y the direction perpendicular to x) were derived in [1] and are written in the form

$$\begin{aligned} m\ddot{S}_x &= mA\omega^2\cos\beta\sin\omega t\,(1-K_1) - mg\sin\alpha + F_1, \\ m\ddot{S}_y &= mA\omega^2\sin\beta\sin\omega t\,(1-K_2) - mg\cos\alpha + N, \end{aligned} \quad (4)$$

where $\ddot{S}_x$, $\ddot{S}_y$ are the accelerations of the particles along the axes x and y respectively, β is the angle of the vibration force relative to the plane M'M', K_1 and K_2 are coefficients that depend on the forces of adhesion of the particles to each other, and N is the normal reaction of the inclined plane M'M'.

The conditions of motion of the particle up the inclined plane can be expressed in the form

$$\begin{aligned} m\ddot{S}_x &> 0, \\ m\ddot{S}_y &> 0. \end{aligned} \quad (5)$$

In the case discussed above condition (5) can not be satisfied for the entire range of particles in the sample.

It should be noted that the limiting angle of inclination of the plane M'M', α, depends on the moisture of the material and the activity of the surface forces at the points of contact of the particles with each other.

The above statement can be accounted for by the unique nature of the distribution of particles in a polydispersive medium in the closed volume of the vibrosensor. Therefore in the next stages of investigation the granulometric analysis was done in sections. Each segment is a cavity to the left or right of the plane, whose trace is shown in the form of the axial line of the sensor (see Fig. 1).

In the second stage of the investigations the effect of the moisture on the degree of vibrosegregation was determined. The results are illustrated in Fig. 2a for experiments with tin concentrate. The cavity of the sensor was divided into two sections each of which separated into coarseness classes; the most coarse and characteristic class + 0.42 mm was taken as an indirect index of vibrosegregation. In Fig. 2a the total weight P of the particles of this class is plotted along the abscissa as the percentage of the total weight of the loose medium of the analyzed section; the serial number of the experiment n is plotted along the ordinate.

On increasing the humidity of the loose medium the vibrosegregation gets less because the number of particles + 0.42 mm in the first (left) section decreases and in the second section increases. For example, the arithmetic mean value (from 6 tests) of the weight difference of particles + 0.42 mm in opposite sections is 35.6% for W = 0.4%, while it is 26.31% for W = 1.4%.

The dependence of the degree of vibrosegregation on the acceleration was determined in the third stage. This dependence is illustrated in Fig. 2b for tin concentrate. At f = 50 Hz the phenomenon of vibrosegregation begins to be seen at $a = 1$ g; it increases considerably on changing the acceleration in the range $a = 1$–5 g but increases insignificantly for $a > 5$ g. The procedure of the experiment in this case is similar to the preceding procedure.

The effect of the surface forces could be estimated by comparing the results obtained for carbon and tin concentrate. The weight moisture of the first was taken as 1.2% and for the second 0.4%, since the specific weights of these materials are 1.5 and 4.5 g/cm respectively. This made it possible to obtain identical volume moisture of the two materials, i.e. to have identical experimental conditions. The results are shown in Fig. 3. As is evident from this figure, the difference in the state of the surface of the particles and the difference of the specific weights of the particles lead to the result that in carbon the rate and degree of vibrosegregation are smaller by a factor of two than for the tin concentrate. For example, $\Delta P'$ for carbon is 16%, while for tin concentrate it is 40.5%; $\Delta P'$ is the difference in the weight of particles of class + 0.42 mm in opposite sections of the sensor. The rate of separation is also smaller by the same factor for carbon ($3\tau_1 \approx 15$ min, $3\tau = 5.5$ min respectively, where τ, τ_1 are time constants of damping of the separation process).

Thus the theoretical premises were confirmed experimentally for the investigated materials; furthermore, an idea of the effect of the moisture and the state of the surface of the particles on the phenomenon of vibrosegregation was also obtained. In the products of mine enriching industry the effect of vibrosegregation is enhanced still more by the fact that the electrophysical properties of particles of different classes differ sharply. For example, the fine class of tin concentrate contains a large part of fluorite mineral, whose specific resistance ρ is $5 \cdot 10^{12}\ \Omega \cdot$cm, whereas the coarse classes contain mainly cassiterite for which ρ is only $8 \cdot 10^{2}\ \Omega \cdot$cm.

Considering this and also the extreme nonreproducibility of the results of the experiment, the power packing method is given preference. It could be possible to consider a combination method, i.e. inertial-power packing method which in certain cases gives better results than those analyzed here. In this case a static load is used to obtain such a density of the medium that the force acting against the vibrosegregation forces become predominant. However, this method is suitable only for discrete measurements in stationary conditions not satisfying the requirements of continuous control, since it is not possible to obtain a continuous flow of the material undergoing vibration and being power-packed at the same time.

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