THE MECHANISM OF ADHESION OF MOIST POWDERS TO SOLID SURFACES IN THE PRESENCE OF A TEMPERATURE FIELD

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An examination is made of the basic factors which influence the creation of forces causing powders to adhere to solid surfaces in the presence of a temperature field. An experimental investigation has been conducted on an apatite concentrate.

The adhesion of powders to solid surfaces is a phenomenon that is both widely encountered and little studied. In a number of cases it creates considerable difficulties in solving certain technical problems.

Investigations conducted with the object of studying conditions of occurrence and development of adhesion of apatite concentrate, a powdered material with mean particle diameter $D_m = 58 \cdot 10^{-6}$ m, to the walls of a special wagon, have shown that the concentrate, when loaded, has a humidity not exceeding 1.5%, and a temperature of 323–333° K, while the walls of the wagon have a temperature up to 243° K in winter time.

According to contemporary ideas of the theory of mass transfer [1], the formation of a temperature field causes displacement of the moisture under the influence of the temperature gradient, which in turn causes a redistribution of the moisture within the material.

As may be seen from Fig. 1a, a noticeable change in moisture content is observed only near the wagon walls, in a comparatively thin layer. Similar results were also obtained in laboratory conditions during investigation of a column of apatite (Fig. 1b). In practice the humidity of the layer at the wall may vary in the range 3 to 12%.

Moistening of the boundary layer due to displacement of moisture under the influence of the temperature gradient creates conditions for the generation of capillary forces, the result of the action of which is also adhesion of the material to the solid surface.

For wettable powdered materials, for which the contact angle may be assumed to be zero, the curvature of the meniscus formed in a capillary is negative. The amount of moisture concentrated in the boundary layer is not enough for the liquid to rise in the capillary to the limiting height. As a result, the capillary forces causing the adhesion effect, which may be called a "suction" phenomenon, will be expressed by the relation

$$p_c = \rho g h_{cap} - \rho g h = \rho g (h_{cap} - h). \qquad (1)$$

In the given case h_{cap} is the limiting height of capillary rise in the powders examined; h is the actual height of capillary rise (in the case where the solid surface is horizontal, h is the height of the capillary rim above the solid surface).

Since the amount of moisture concentrated close to the surface is sufficient to saturate only a layer of small height, while the height h_{cap} may be of the order of several meters, the quantity h in this case may be neglected, and then formula (1) takes the form

$$p_c = \rho g h_{cap}. \qquad (2)$$

Since

$$h_{cap} = 2\sigma / r,$$

where σ is the surface tension, and r is the radius of the system consisting of cylindrical capillaries of a single radius, equivalent as regards capillary rise to the disperse medium examined, then

$$p_c = 2\sigma / r. \qquad (3)$$

The action of these forces also causes "suction" of the skeleton of the disperse material to the solid surface.

The phenomenon of "suction" in conditions of distribution of moisture similar to those which arise in condensation and thermal transfer of moisture in wagons, was first observed by us under laboratory conditions in a special instrument. On the solid surface was set up a ring, into which was poured an

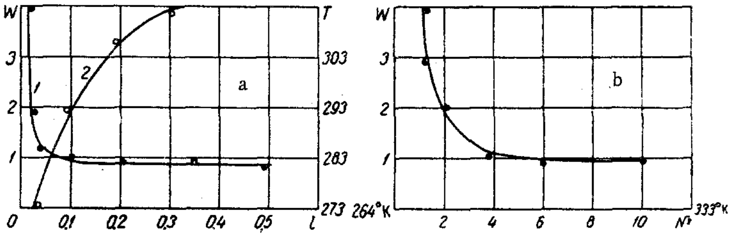

Fig. 1. Variation of a) humidity W, % (1) and of temperature, T, ° K (2) in the special wagon, and b) of the humidity in a column with apatite (l is the length, No. is the ring number).

Experimental Values of the Force Required to Displace the Specimens

Material	Displacing force, N	Friction coefficient	Normal force N_e, N
Glass (smooth)	17.6	0.74	22.8
Plastic	13.7	0.60	22.8
Steel sheet (rolled)	14.2	0.62	23.0
Epoxy resin ED-5	13.2	0.70	18.9
Laminated plastic	12.2	0.62	19.7
Polyvinylchloride TU4040	17.1	0.81	21.2
Low-pressure polyethylene	11.8	0.76	15.5
Textolite	13.2	0.71	18.6
Concrete	14.2	0.9	15.7
Nickel steel	12.2	0.66	21.8

acetylene concentrate saturated with water, this being in a fluid state. The top was filled up with dry apatite, and then a specimen was formed with the aid of a press. Then the force necessary to displace the specimen was determined (see table). The mass humidity of the boundary layer, measured after displacement of the specimen, was 9–12%.

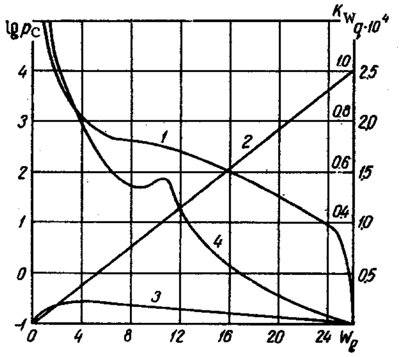

Fig. 2. Dependence of p_c (1), k_w (2), q'_σ (3), and q_Σ (4) on W_g.

As may be seen from the table, the adhesion force in a given case is practically independent of the nature of the material of the solid surface. We examined the mechanism of this phenomenon in [2].

We will now examine the possibility of obtaining the quantities mentioned by calculation. The "suction" force of the disperse material to the solid surface per unit area is

$$q_\sigma = p_c k_w. \qquad (4)$$

The dependence of the variation of capillary pressure on the humidity of the powder for apatite concentrate was obtained experimentally in [3] and is shown in Fig. 2, curve 1.

If we assume that the law of variation of quantity of moisture in the section of the boundary layer under examination is identical to the law of variation of quantity of moisture in the volume, then the dependence of the variation of the area occupied by the moisture on the backing upon the weight humidity of the powdered material may be represented by a coefficient of water saturation:

$$k_w = V_w/V_{pore} = W_g \gamma_m / 100 \varepsilon \gamma_w. \qquad (5)$$

The quantity k_w (Fig. 2, line 2) may vary in the range 0 to 1.

Having $p_c(W_g)$ and $k_w(W_g)$ available from the graphs, we obtain the dependence $q_\sigma(W_g)$.

In determining the total force of adhesion of the powders to the backing, we should take into account, in addition to the component due to capillary pressure, the component due to surface tension σ applied to the perimeter of the wetted area χ.

When the powder makes contact with the backing, there may exist simultaneously in the boundary layer regions of continuous coverage, together with isolated area. Therefore, simultaneously with the increase of perimeter of an individual area, there will occur a decrease of the total perimeter of the wetted area, as the individual areas fuse together. From these considerations, we obtain an expression for the component of specific adhesion force due to the action of surface tension,

$$q'_\sigma = \frac{\sigma}{R} \frac{\pi}{2} c(1 - k_w), \qquad (6)$$

where $c = \mathrm{tg}\,\frac{\theta}{2}\left(2 - \mathrm{tg}\,\frac{\theta}{2}\right)$ is a trigonometric function depending on the humidity, and obtained for the case of contact of a spherical particle with a plane.

The dependence $q'_\sigma(W_g)$ is shown in Fig. 2 by curve 3, obtained by calculation, using a spherical particle model [4]. The packing was assumed to be cubic, since the porosity of the model (n_m = 47%) is close to that of apatite (n_a = 45%). The particle radius is $R = D_m/2 = 29 \cdot 10^{-6}$ m.

Thus, the total specific adhesion force may be represented in the form

$$q_\Sigma = q_\sigma + q'_\sigma = p_c k_w + \frac{\sigma}{R} \frac{\pi}{2} c(1 - k_w). \qquad (7)$$

The dependence $q_\Sigma(W_g)$ is shown in Fig. 2 by curve 4. Having the dependence $q_\Sigma(W_g)$ available graphically, we may calculate the total adhesive force acting on the area of contact ω_c of the powder with the backing:

$$N = q_\Sigma \omega_c. \qquad (8)$$

We will calculate the total adhesive force according to (8) for the case when W_g = 11% and $\omega_c = 20 \cdot 10^{-4}$ m^2 (the area of the specimen).

From the graph of Fig. 2 we determine $q_\Sigma = 1.22 \cdot 10^4$ N/m^2. Substituting the values of q_Σ and ω_c in (8), we obtain

$$N = 1.22 \cdot 10^4 \cdot 20 \cdot 10^{-4} = 24.4 \text{ N}.$$

According to the data of the table, the adhesive force is $N_e = 22.8$ N for the case of contact of apatite with glass, a value very close to that calculated.

NOTATION

p_c is the capillary pressure; ρ is the density of fluid; g is the acceleration due to gravity; h_{cap}, h are the limiting and actual height of capillary rise; σ is the surface tension; r is the radius of equivalent capillary; q_σ is the specific "suction" force; k_w is the water saturation coefficient; V_w is the volume of water in pores; V_{pore} is the volume of pores; W_g is the humidity by weight; R is the particle radius; Θ is the polar angle; ω_c is the area of contact; N is the total adhesive force; γ_m, γ_w are the specific weight of powder and water.

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