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Efficiency of activation of mineral binders in vortex-layer devices

Эффективность активации минеральных вяжущих в аппаратах вихревого слоя

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Ключевые слова: аппарат; вихревой слой; активация; удар; энергия

Abstract. Improving the efficiency of construction composites is a relevant problem for modern-day material science. One of the ways to solve the problem consists in activating the binders by means of vortex-layer devices. Mathematical transformations produced a formula for calculating the dependency of the number of ferromagnetic-particle collision on the number and velocity of such particles, as well as on the device chamber fill factor. The results obtained by applying the proposed formula differ from D.D. Logvinenko's model by 10 % at max. We calculated the impact force, the impulse of the grinding body in the vortex-layer device, as well as the amount of applied energy per unit of mass of the ground material. It was found out that the impact force and the impulse of force were maximized in the test device. At the same time, energy applied over the grinding time necessary to even out the binder dispersion in the vortex-layer device was 2 to 4.8 times greater compared to conventional devices.

Аннотация. Повышение эффективности строительных композитов является одной из актуальных задач современного материаловедения. Одним из решений данной проблемы является активация вяжущих в аппаратах вихревого слоя. С помощью математических преобразований получена формула зависимости количества соударений ферромагнитных частиц от количества и скорости их движения, коэффициента заполнения рабочей камеры аппарата. Расхождение в результатах, полученных по предлагаемой формуле, с моделью, предложенной Д.Д. Логвиненко, составляет не более 10 %. Определена сила удара, импульс силы мелющего тела в аппарате вихревого слоя, а также количество подведенной энергии на единицу массы измельчаемого материала. Установлено, что наибольшая сила удара и импульс силы происходит в исследуемом аппарате. При этом количество подведенной энергии за время измельчения, необходимое до достижения одинаковой дисперсности вяжущего в аппарате вихревого слоя в 2–4.8 раза выше, по сравнению с традиционными аппаратами.

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1. Introduction

The production of construction materials can be made more efficient by implementing new devices with low specific energy and material consumption while featuring a high degree of impact on the processed material. Such developments are based on novel engineering solutions, theoretical and experimental studies of physico-chemical processes occurring in treated media when exposed to intensive impulses [1–6].

As of today, one of the most promising methods for process intensification and improving the efficiency of physical impact consists in, as recognized, using various physico-chemical effects that exploit internal and external sources of energy [7–12].

Analysis of physico-chemical effects occurring when material is exposed to acoustic, mechanical, electric, magnetic, thermal, radiation, and chemical effects showed that these effects resulted in the dispersion or coagulation of dispersed particles, homogenized the medium, altered the concentration and the spatial distribution of defects, changed the degree of crystallinity and state of aggregation (full or partial), and thus affected the structure-related physico-chemical properties of the material [13–19].

Paper [20] states that treating Portland cement in vortex-layer devices (VLD) considerably increases the rate and strength of heavy-weight concretes. This is due to the mechanical and thermal effects of ferromagnetic bodies altering the structural parameters of Portland-cement particles and the related physico-chemical properties. The degree to which such properties alter naturally depends on the impact frequency and the duration of treatment.

For construction composites the structure of which is formed by the chemical and physical processes of transforming the component (e.g. the mineral binders), strength is the integral indicator that characterizes the quality of the composite structure at a fixed time. The intensity of the structuring process for such composites naturally depends on the physico-chemical properties of the material (treatment that improves such properties can also be referred to as activation). For construction composites, the activation effect can be evaluated on the basis of its strength at a fixed time.

Although there are numerous VLD designs [21–23] for various applications, they are generally flow-through cylindrical tubes of non-magnetic materials, with induction coils mounted on the outer surface in a sealed housing. Ferromagnetic grinding bodies of a specific geometric shape are placed in the tube and are moved by the rotating electromagnetic field generated by the inductor windings, see Figure 1.

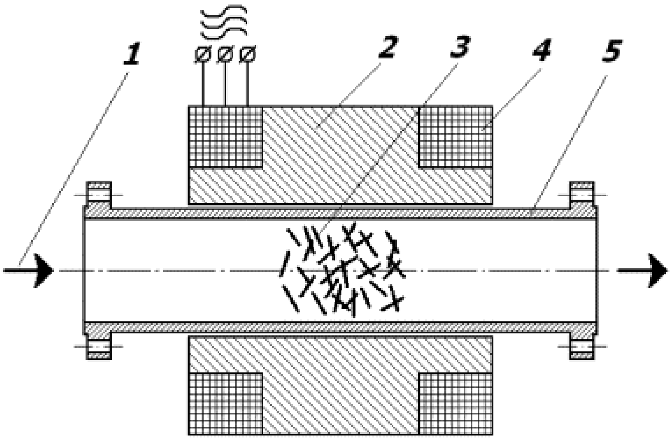

Figure 1. Schematic diagram of a vortex-layer device:
1 is the flow of the treated material (substance); 2 is the inductor core; 3 are ferromagnetic grinding bodies; 4 is the inductor winding; 5 is the non-magnetic housing

2. Research methods

To evaluate the motion of ferromagnetic particles in the VLD chamber, we assumed a model where ferromagnetic bodies, each having a volum V, move in the enclosed volume VLD, see Figure 2.

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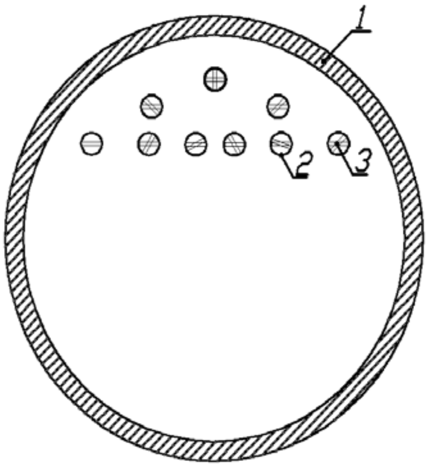

Figure 2. Idealized ferromagnetic-body motion model: 1 is the chamber; 2 is the volume occupied by a rotating ferromagnetic body; 3 is the ferromagnetic body

When calculating the number of collisions between ferromagnetic particles, we varied the number of such particles from 0 to 200.

For this research, we used a Model 297 vortex-layer device by Regionmettrans LLC.

3. Results and Discussion

In VLD, a ferromagnetic grinding body placed in a rotating magnetic field is exposed to a number of forces and moments of force: the torque caused by the rotating magnetic field; the force and the moment of force affecting the body when colliding with another such body; the force and the moment of friction between the grinding bodies or a body and the housing wall; the resistance force and the damping moment caused by an external force affecting the moving body; as well as the gravity force, the centrifugal force of inertia, and the Coriolis force.

When grinding, ferromagnetic bodies perform complicated translational motion in three-dimensional space while also making circular motions in different planes. Thus, the motion of a ferromagnetic body has six degrees of freedom. D.D. Logvinenko proposed the following mathematical model of VLD mixing:

$$\left.\begin{aligned} & m\left(\ddot{r}-r\varphi^{2}\right)=F_{r\text{óä}}+F_{r\text{òð}}+F_{r\text{ä}} \\ & \frac{m}{r}\frac{d}{dt}\left(r^{2}\varphi\right)=F_{1}+F_{2}+F_{3} \\ & \ddot{\varphi}=\frac{1}{I}\left(M_{0}+M_{1}+M_{2}+M_{3}\right) \end{aligned}\right\} \qquad (1)$$

where φ is the angle between the particle magnetic-moment vector (coincides with its greatest axis) and the magnetic-field intensity vector; *I* is the particle moment of inertia relative to the rotation axis; M_0 is the torque caused by the effect of the uniformly rotating magnetic field on the particle; F_1, M_1 is the force and moment a particle is exposed to when colliding with another particle; F_2, M_2 *is* the force and moment of friction between particles or between a particle and the wall; F_3, M_3 is the force and the damping moment caused by the effect of external medium on a moving particle; *r* is the distance between the particle and the rotation axis.

Solution of the equation system (1) presented in [24–27] revealed the pulsed nature of the effects that the potential fields of hydrodynamic and electromagnetic forces have on the processed medium in VLD. However, this system (1) contains multiple unknown variables finding which is difficult. This is why this paper proposes and approach that can considerably reduce the number of unkowns and evaluate the efficiency of treating a material in an VLD device.

Assume that the volume occupied by a rotating ferromagnetic body equals:

$$V = \frac{4}{3}\pi R^3 = \frac{\pi l^3}{6} \tag{2}$$

where R is the radius of the ferromagnetic body equal to half its length l (for cylinder-shaped ferromagnetic bodies).

Force of the resistance to the motion of the ferromagnetic body in a dispersed medium can be written as:

$$F_R = \rho \frac{v^2}{2} k \tag{3}$$

where ρ is the density of the processed dispersed phase, v is the average velocity of ferromagnetic bodies, k is the coefficient that depends on the processed medium.

Assume that the magnetic field influences the ferromagnetic body with a force proportional to its volume V:

$$F_M = fV \tag{4}$$

where f is the coefficient that depends on the magnetic-field induction.

From Newton's third law, it follows that $F_R = F_M$, thus the ferromagnetic body should have the following velocity:

$$v = \sqrt{\frac{f\pi l^3}{3\rho k}} \tag{5}$$

The activation effect depends on the number Z of collisions between ferromagnetic bodies and the dispersed-phase particles. Given that at $N = 0$ (where N is the number of ferromagnetic bodies and dispersed-phase particles) it must be that $Z = 0$, whereas at a greater N (a more critical ferromagnetic-body saturation factor of the chamber) there must be less collision, the dependence of Z on N can be written as:

$$Z = K\frac{v}{1+\alpha v^2}\beta \tag{6}$$

where α is the VLD parameter; β is the coefficient directly proportional to the number of ferromagnetic bodies; K is the ferromagnetic-body saturation factor of the chamber that equals the ratio of ferromagnetic-bodies volume to the enclosed volume VLD.

To build the dependency of the collision number on the number of ferromagnetic bodies, we have to define the parameter α.

To that end, assume that the activation effect W is directly proportional to Z, then:

$$W = CK\frac{v}{1+\alpha v^2}\beta \tag{7}$$

To find the parameter α, one has to use the results of two experiments with different v, K and N. To that end, it is enough to consider two values of the activation effect W for which the duration of treatment, the speed of treatment, and the ferromagnetic-body diameter-to-length ratio is specified, for instance, in [8]. Thus, at $K_1 = 0.04$ and $K_2 = 0.1$, $N_1 = 60$ units and $N_2 = 150$ units, $v_1 = 4.56$ m/s and $v_2 = 8.41$ m/s. For these values, $\alpha = 0.051$.

Figure 3 shows the dependency of the collision number Z on the number of ferromagnetic bodies N_T.

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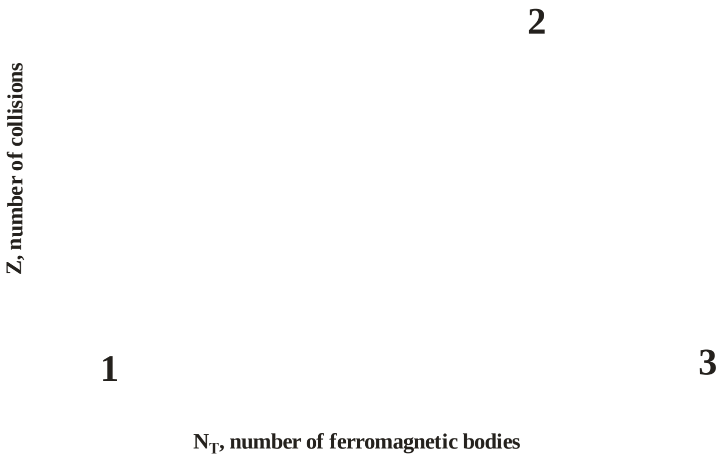

Figure 3. Dependency of the collision number on the number of ferromagnetic bodies: the solid line is the plot obtained by the formula (6); the dashed line is the plot based on D.D. Logvinenko's data [9]

In Figure 3, one can note the 1-2 section that describes the increase in the collision number at greater numbers of ferromagnetic grinding bodies (until the chamber is saturated), as well as the 2-3 section where one sees less collisions as the number of ferromagnetic grinding bodies exceeds the critical chamber saturation factor, which excess might even result in a full stop.

The proposed formula (6) is in good agreement with the experimental data D.D. Logvinenko obtained [21] by recording the collision numbers using a special barium-titanate transducer. The discrepancy in results is less than 10 %.

Apparently, ceteris paribus (after setting such parameters that only suit the selected VLD device), formulas (6) and (7) are more convenient for evaluating the VLD activation efficiency than the system (1).

When it comes to the exposure to ferromagnetic grinding bodies, the impact force, the impulse of force, and the applied energy are very important parameters. These values are useful for evaluating the efficiency of technological equipment in its corresponding applications.

The grinding-body impact force F is calculated as follows:

$$F = \frac{mv}{t} \qquad (8)$$

where m is the mass of the grinding body; t is the time between the ground-particle and grinding-body impacts.

The impulse of force F_P equals:

$$F_P = Ft_d \qquad (9)$$

where t_d is the duration of grinding until fully homogeneous dispersion is achieved.

The applied energy Y per unit of mass of the ground material depends on the device energy intensity J_g as well as the duration of activation or grinding:

$$Y = J_g t_d \qquad (10)$$

For ABS, J_g can be written as:

$$J_g = CK\frac{v}{1+\alpha v^2}\beta \qquad (11)$$

Table 1 presents a comparison of various devices.

Table 1. F, F_P, and Y values for various devices

Device type	v, m/s	t_d, s	Impact force, F, N	Impulse of force, F_P, N·s	Applied energy Y, J/(kg·s)
Ball mill	0.1	7200	0.128	$7.2 \cdot 10^{2}$	12.4
Planetary mill	6.68	2700	$2.73 \cdot 10^{-5}$	$7.37 \cdot 10^{-2}$	20
Vibrating mill	8.78	600	35.12	$2.11 \cdot 10^{4}$	29
VLD	8.41	300	168.1	$5.04 \cdot 10^{4}$	60

As can be seen from Table 1, VLD features the greatest impact of grinding bodies on the dispersed phase.

Thus, ABS features the greatest impact force and impulse of force. At the same time, energy Y applied over the specified grinding duration is 2 to 4.8 times greater for VLD than for conventional devices.

Note that at a maximum number of collisions, the ferromagnetic-body impact force is maximized as well.

4. Conclusions

The paper presents an idealized model of the motion of ferromagnetic particles in VLD, which models specifies the dependency of the collision number on the size of ferromagnetic grinding bodies, their number and velocity, the density of the ground medium, and the intensity of the electromagnetic field. Comparison of data shows that the results obtained by using this formula differ from D.D. Logvinenko's model by 10 % at max.

The researchers defined the parameter (α) of VLD, equal to 0.051. It was found out that before the device chamber is saturated with ferromagnetic particles, the number of collision rises; after saturated, it falls. With the optimal VLD parameters, the number of collisions is 3700.

There was derived the dependency of the VLD energy intensity on the chamber saturation factor, the ferromagnetic-particle velocity and number.

It was found out that in VLD, the processed material is exposed to the greater force impacts, as it receives 2 to 4.8 times more energy compared to conventional devices.

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