Process of charge prevention with low bulk density

M V Sevostyanov¹, T N Il’inà² and I G Martakov¹

¹Department of Technological Complexes Machines and Mechanisms, Belgorod State Technological University of V.G. Shukhov, Kostyukov St., 46, Belgorod, 308012, Russia
²Department of Heat Supply and Ventilation, Belgorod State Technological University of V.G. Shukhov, Kostyukov St., 46, Belgorod, 308012, Russia

E-mail: msev31@mail. ru

Abstract. The processes of agglomeration of dispersed materials, the relevance of their use in the utilization of man-made powdered materials. Shows the need for prehardening of the granulated charge when they are balling with balling. This is especially true for man-made materials with low bulk density, which is an obligatory stage for the formation of micro-granules, the subsequent growth and compaction of which occurs under the action of centrifugal forces. Analytical expressions for calculation of rotation frequency of the forming rolls providing necessary conditions for realization of processes of filtration of gaseous and liquid phases of a composite mix, and also for reception of microgranules of the set density at a vibro-roll method of preliminary compaction are presented. The obtained dependences are the basis for the development of a vibration-centrifugal granulator for the step-by-step process of forming technogenic dispersed materials with low bulk density.

Keywords: Granulation, technogenic materials, compacting rolls, filtration of liquid and gaseous phases, vibration centrifugal granulator.

1. Introduction

In the processing technologies of dispersed materials in many industries to obtain molded products of a given quality, as a rule, use agglomeration processes carried out by extrusion, briquetting, pelleting, etc. The choice of molding method depends on the physicochemical properties of powdered materials, their dispersion, requirements for physical-mechanical parameters of the finished product and other factors [1]. The ever-increasing volume of powdered and dust-like wastes in the production of building materials and products necessitates the utilization of them by compaction [2–5]. However, some man-made materials have low bulk density (less than 200 kg / m³), high dispersion. To obtain a granulated product from such charges, a stepwise molding process is necessary with the obligatory stage of preliminary compaction and the formation of granules centers [6–8]. Such materials include powdered waste from the production of expanded perlite, vermiculite, lime, etc. The study of the characteristic features of the molding process of man-made materials, as well as obtaining analytical dependencies of the filtration processes of the gaseous and liquid phases with the development of recommendations for choosing a method and apparatus for prehardening of a three-phase disperse system is the purpose of this work.
2. Materials and Methods
There are various technological methods of removing the gaseous phase during the formation of powder mixtures: vibrocompaction, vacuum, mechanical action using centrifugal forces, rolling - rolled, screw prehardening, etc. Each of these technological methods has its advantages and disadvantages [9-13].

In our opinion, the most effective way to remove the gaseous phase (deaeration) during compaction of powdered materials is a combination of vibration and mechanical action. This can provide not only a rational method of preparation of the mixture being compacted for granulation with minimal energy consumption, but also allows combining two technological methods: removal of the gaseous phase and obtaining micrograins (microgranulate), which are the centers of granulation.

The technical solution of this technological method can be the vibro-roller method of prehardening of the charge (figure 1).

The process of prehardening of the charge is greatly influenced by its physical-mechanical parameters: the flow ability of the material, depending on the particle size distribution, moisture content of the material and the shape of its particles; coefficients of internal and external friction; the rate of removal of the gaseous phase and others [14].

The main factors determining the flow ability of powdered materials are friction and adhesion of particles between themselves, making it difficult for them to move.

When the charge layer moves from top to bottom and is mechanically compacted in the rolls, the gaseous phase (air) is filtered through a layer of material between the cylindrical surfaces of the rolls and the sidewalls of the loading device. The air coming out through the layer of material rises up, worsening the material flow ability and the conditions for its supply to the roll deformation zone.

The filtration rate of the gaseous phase passing through the cross-sectional area of $H_0$ thickness and width $B$ can be determined by the formula:

$$\vartheta_{gas} = \frac{Q_{gas} \cdot \rho_{gas}}{H_0 \cdot B (\rho_{gr} - \rho_0)}$$  \hspace{1cm} (1)

where $Q_{gas}$ – gas phase consumption, m$^3$ / s; $\rho_{gr}$ – density of formed microgranules, kg / m$^3$; $\rho_0$ – initial density (bulk density) of the material, kg / m$^3$.

The stage of preliminary compaction of the charge and its microgranulation is followed by the stage of final molding of the granules with the application of dynamic action. In this regard, it is advisable to know the range of variation of the compaction rate of the material in the study of the granulation of materials with different physical and mechanical characteristics: from materials with high
bulk density (iron ore production waste $\rho_0 > 4 \cdot 10^3$ kg / m$^3$), carbonate-clay materials ($\rho = (2...4) \cdot 10^3$ kg / m$^3$); as well as man-made materials with a bulk mass of $\rho_0 = 800 - 2000$ kg / m$^3$ and materials with a low initial bulk mass, $\rho_0 < 800$ kg / m$^3$ and less (exfoliated vermiculite, perlite, captured dust of rotary kilns of cement, lime and other industries).

The minimum pre-compaction rate of the charge is determined on the basis of conditions that exclude the free passage of powdered materials through the roll gap, which determines the diameter $d_{gr}$ of the microgranulate particles or the height of the microgranules $h_{gr}$ (due to their irregular geometric shape). In this case, the flow ability of compacted material $q$ should be taken into account, which determines the free passage of material through the roll gap $h_0$ (figure 1).

The maximum speed of microgranulation $\vartheta_{gr}$ is limited by the rate of filtration of the gaseous phase, moving towards the compacted layer of powdered material and making it difficult to deliver to the sealing zone between the rollers.

The critical filtration rate of the gaseous phase through a layer of powdered material limits the value $\vartheta_{gr}$ and is determined by the value of the Reynolds criterion [15]:

$$ Re = \frac{Ar^{0.68} \cdot H_{ch}}{600} \left[ \frac{H_{ch}}{h_{gr} + (R_1 + R_2)(1 - \cos \alpha_{hr})} \right]. $$

(2)

where $H_{ch}$ – thickness of compacted charge in the area of its seal, m; $R_1, R_2$ – forming rollers radius, m; $h_{gr}$ – size of microgranules, m (figure 1).

Assuming that the volumetric flow rate of the gaseous phase through the upper section of the thickening zone $h_0 = h_{gr} + (R_1 + R_2)(1 - \cos \alpha_{hr})$ is $Q_{gas} = BH_0 \vartheta_{gas}$ determine the critical filtration rate of the gaseous phase:

$$ \vartheta_{gas} = \vartheta_{max} \left( \frac{\rho_{gr}}{\rho_0} - 1 \right) \frac{h_{gr}}{h_{gr} + (R_1 + R_2)(1 - \cos \alpha_{hr})}. $$

(3)

According to

$$ Re = \frac{\vartheta_{cr} \cdot d_{sz}}{\vartheta}, $$

where $d_{sz}$ – suspended size of forming charge particles, m; $\vartheta$ – kinematic viscosity of the gaseous phase, m$^2$/s.

As well as expressions (2) and (3), we obtain the maximum pre-compaction rate of the charge:

$$ \vartheta_{max} = \frac{Ar^{0.68} \cdot H_0 \cdot \vartheta \cdot \rho_0}{600 \cdot h_{gr} \cdot (\rho_{gr} - \rho_0) \cdot d_{sz}}. $$

(4)

Thus, in the development of design-technological parameters of the roller-type device for the implementation of the process of microgranulation of powder particles, the condition:

$$ \vartheta_{min} \leq \vartheta_{for} \leq \vartheta_{max}: $$

$$ \pi D_1 n_v = \frac{Ar^{0.68} \cdot H_0 \cdot \vartheta \cdot \rho_0}{600 \cdot h_{gr} \cdot (\rho_{gr} - \rho_0) \cdot d_{sz}}. $$

(5)

So the rotational speed of the forming roll:
\[ n_v = \frac{Ar^{0.68} \cdot H_0 \cdot \theta \cdot \rho_0}{1884 \cdot D_1 \cdot (\rho_{gr} - \rho_0) \cdot d_{sz}} \]  

(6)

If the process of prehardening of a moldable powder mixture is not accompanied by significant energy consumption, then the process of deformation of a compacted moisture-saturated mixture is accompanied by both structural and mechanical changes of the formed samples (reorientation and packaging of polydisperse particles, their adhesion-autohesion interaction, etc.), and the migration of the liquid phase from the zones greatest stress.

The liquid phase, which fills the pores between the particles, due to its incompressibility, provides, together with the solid phase of the structural system, elastic resistance to external stresses, and when the yield strength of the material is exceeded, it moves to reduced pressure zones.

When studying the process of migration of the liquid phase in a powdery mixture and using Darcy's law [16], an analytical expression was obtained to determine the necessary time for filtering a liquid through a granular layer of a moldable mixture:

\[ \tau_f = 0.5\eta_g \cdot r_0 \cdot X_0 \cdot \frac{\theta_g^2}{S^2} \cdot \frac{\Delta P}{\Delta P} \]  

(7)

where \( \theta_g \) – volume of filtered liquid, m³; \( \tau_f \) – time of filtration, s; \( S \) – surface of filtration, m²; \( \Delta P \) – pressure difference, N·m⁻²; \( \eta_g \) – viscosity of the filtered liquid, Pa·s; \( R_{res} \) – resistance of the granular medium, m⁻¹;

\[ R_{res} = r_0 \cdot X_0 \cdot \frac{\theta_g}{S} \]

where \( r_0X_0 \) – resistivity and reduced thickness of the granular medium, respectively, m⁻¹.

The obtained analytical expression is of great importance for the practice of forming moisture-saturated powder mixtures and obtaining high-quality granules from them.

Regardless of the method of force (pressing, centrifugal molding, vibration, etc.) in the molding of granules and the design of the unit for granulating materials, it is necessary to observe the filtration conditions of the gaseous and liquid phase, defined by expressions (6) and (7), respectively.

**Figure 2.** Kinematic scheme (a), general view of the vibration-centrifugal granulator (b): 1 - main drive motor; 2 - V-belt transmission; 3 - gear pair; 4 - eccentric shaft; 5 - counterweights; 6 - electric device for warning and microgranulation of the material; 7 - elastic microgranulation compaction roller; 8 - vibration gutter; 9,10,11 - material granulation drums; 12 - toroidal chambers; 13 - movable frame; 14 - crawlers; 15 - rack guide; 16 - intermediate shaft
3. Results
Our studies of the filtration conditions of the gaseous and liquid phases during the compaction of powdered materials, the obtained analytical expressions for calculating the time of air filtration and the migration of the liquid phase in the moldable mixture at the stage of its preliminary compaction, were used in the design and creation of highly efficient process equipment for the step-by-step granulation process - vibration - centrifugal granulator [17, 18] (figure 2).

Studies [19] have shown that to ensure an effective process of microgranulation of moisture-saturated mixtures and filtration of the liquid phase, it is necessary to observe the condition:

$$n_f \leq \frac{2\sqrt{F(1 - \mu^2)} \cdot S^2 \cdot \Delta \rho}{0.5 \pi \cdot \eta \cdot r_0 \cdot \rho_0 \cdot \theta^2 \cdot \sqrt{\pi \cdot E_f \cdot R_f}}$$

(8)

where $\mu$ - Poisson's ratio, for an elastic material, such as rubber $\mu = 0.4...0.5$; $E_f$ - modulus of elasticity of the forming surface of the roll, for rubber $E_f = (10...100) \times 10^5$ N/m$^2$; $F$ - compressive force, N/m.

To ensure the specified performance of the granulator, in addition, it is necessary to take into account its throughput in obtaining quality products, which should also take into account the obtained values $n_f$.

The granulation (formation of compacted embryos), which further stabilizes the quality characteristics of the granules (their geometrical dimensions and shape, density distribution by volume, etc.), is important for the structure formation of granules during their stepwise formation. Prehardening obtained the following expression:

$$n_f \leq \frac{1}{2P} \sqrt{\frac{K_{mn} - \sigma_f (1 + K_{\varphi}) \zeta}{K_{hr} \cdot \rho_0 \cdot r_{0gr}(r_0 + r_{0gr})(1 + K_{\varphi})}}$$

(9)

where $K_{mn}$ - coefficient taking into account inter-contact interaction of particles during their compaction; $K_{\varphi}$ - coefficient taking into account the internal friction of the particles.

Values $K_{mn}$ and $K_{\varphi}$ related by ratios, $K_{mn} = 2K_{sc} \cos \varphi$, $K_{\varphi} = \sin \varphi$, where $K_{sc}$ - the coefficient of adhesion of the particles to the moldable mixture; $\varphi$ - angle of internal friction of particles in the mixture.

The coefficient of internal friction $f$ is related to the angle of internal friction $\varphi$ by dependence $f = \tan \varphi$ or $\varphi = \arctan f$.

Using the values $K_{mn} = 2K_{sc} \cos \varphi$, and $K_{\varphi} = \sin \varphi$, finally we get

$$n_f \leq \frac{1}{2P} \sqrt{\frac{2K_{sc} \cos \varphi - \sigma_f (1 + K_{\varphi}) \zeta}{K_{hr} \cdot \rho_0 \cdot r_{0gr}(r_0 + r_{0gr})(1 + \sin \varphi)}}$$

(10)

where

$$\zeta = \frac{2K_{\varphi}}{1 + K_{\varphi}} = \frac{2 \sin \varphi}{1 + \sin \varphi}$$

4. Discussion
The analytical expressions obtained by us characterizing the general conditions of the process of microgranulation of particles by the method of their volume compression allow us to establish not only the speed parameter of the dynamic effect on compacted particles for a given technical solution (sealing rolls), but also allow to determine the effect of other physicomechanical characteristics and tech-
nological parameters on microgranulation process. This, in turn, allows the use of various physical and chemical methods developed by us to improve the process of granulometry.

Analytical expressions (7, 9, 11) were used to calculate the frequency of rotation of the sealing rolls of the pilot-industrial vibratory-centrifugal granulator developed by us (figure 2). For materials with low bulk density, for example, pearlite-containing mixtures, \( \rho_{\text{bulk}} = 150 \text{ kg/m}^3 \), \( \rho_{\text{gr}} = 1000 \text{ kg/m}^3 \) with the parameters of the sealing device \( l = 0,041 \text{ m}, \Delta l = 0,002 \text{ m}, (l, \Delta l \text{ - length and width the gap between the rolls, respectively}), D_h = 0,25 \text{ m}, \) the rotational speed of the forming roll should not exceed values of \( n_f \leq 2,7 \text{ s}^{-1} \).

To ensure the conditions for the removal of the gaseous phase and the compaction of the charge, the rotational speed of the forming rolls (7) is \( n_f \leq 0,04 \text{ s}^{-1} \), i.e. the removal of the gaseous phase occurs at low speeds of the rolls.

According to the experimentally obtained data for perlite mixtures, we take: \( K_{\text{sc}} = 0,93 \cdot 10^6 \text{ Pa}, \sigma_f = 2,0 \cdot 106 \text{ Pa}, r_0 = 0,05 \cdot 10^{-3} \text{ m}, r_{\text{gr}} = 2 \cdot 10^{-3} \text{ m}. \) The frequency of rotation of the sealing rolls, calculated by equation 10, is \( n \leq 2,8 \text{ s}^{-1} \).

For conditions \( E_f = 1 \cdot 106 \text{ Pa}, \mu = 0,5 \text{ (for rubber)}, l = 0,041 \text{ m}, F = 0,22 \cdot 106 \text{ n / m} \) (for pearl-containing mixtures), the rotational speed of the forming rolls calculated by equation (9) is \( n_f \cdot v \leq 2,0 \text{ s}^{-1} \).

Thus, to ensure the conditions for removal of the gaseous phase, filtration of the liquid, compaction of the charge with the formation of microgranules for pearlite-containing mixtures at the VCG productivity \( Q = 50-100 \text{ kg/h} \), the rotational speed of the forming roll should be \( n_f = 1,1 - 2,0 \text{ s}^{-1} \).

Comprehensive studies of dispersed materials with different physicochemical properties allowed us to develop a classification of dispersed materials with recommendations on the organization of the processes of their agglomeration [20].

5. Conclusion

The obtained analytical expressions describing the processes of removing the gaseous phase, the movement of the liquid phase in the moldable mixture have found their application in the development of the roller device for pre-compaction of the mixture of the vibratory-centrifugal granulator.

This device allows to realize the stage of preliminary compaction of a moldable mixture with a bulk density of less than 200 kg/m³ with the formation of microgranules, the subsequent growth and compaction of which is carried out in a forming unit consisting of three drums.

Acknowledgments

The work was performed within the framework of the implementation of the Development University program based on the BSTU named after V.G. Shukhov using equipment based on the Center of High Technologies BSTU named after V.G. Shukhov.

References
[1] Il’ina T N 2009 Processy’ aglomeracji v texnologyiakh pererabotki dispersny’x materialov [The agglomeration processes in the processing technologies of dispersed materials] (Belgorod: BGTU im. V.G.Shukhova) [In Russian]
[2] Glagolev S N, Sevostyanov V S, Il’ina T N and Uralsky V I 2010 Texnologicheskie moduli dlya kompleksnoj pererabotki texnogenny’x materialov [Technological modules for complex processing of technogenic materials] Himicheskoe i neftegazovoe mashinostroenie 9 pp 43-5 [In Russian]
[3] Sevostyanov M V, Il’ina T N, Uvarov, V A and Shinkarev L I 2015 Sposoby’ kompaktirovaniya texnogenny’x materialov i texnicheskie sredstva dlya ix realizacii [Ways of compacting man-made materials and technical means for their implementation] Vestnik BGTU im. V.G.Shukova 2 pp 107-11 [In Russian]
[4] Sevostyanov M V and Il’ina T N 2014 Klassifikacionny’j analiz texnicheskih sredstv dlya kompaktirovaniya texnogenny’x materialov [Classification analysis of technical means for
the compaction of man-made materials] Naukoemkie texnologii i innovacii: sb. dokladov Yubileinoj Mezdunar. nauch.-prakt. konf., posvyashennoj 60-letiyu BGTU im. V.G. Shuxova (Belgorod: BGTU im. V.G.Shukhova) 4 pp 121-6 [In Russian]

[5] Sevostyanov M V, Il’ina T N, Shkarpetkin E A, Koshchukov A V and Emelyanov D A 2013 Utilizatsiya poroshkooobrazny’x otxodov promy’shlennoj promy’shlyennoj predpriyatiy [Utilization of powdered industrial waste] Sb. nauchn. tr. Mezd. Nauchno-prakticheskoy konf. «Aktual’ny’e problemy’ razvitiya nauki i obrazovaniya» (Moscow: «AR-Konsalt») pp 12-3 [In Russian]

[6] Il’ina T N, Sevostyanov V S, Uralsky V I, Sevostyanov M V and Shkarpetkin E A 2010 Mekhanizm postadipnago granuloobrazovaniya polidispersny’y materialov [The mechanism of stepwise granulation of polydisperse materials] Ximicheskoie i neftegazovoe mashinostroenie 5 pp 11-4 [In Russian]

[7] Sevostyanov M V and Dubinin N N 2003 Konstruktivno-tekhnologicheskoe sovershenstvovanie press-valkovoy’x e’kstrudere [Design and technological improvement of press-roll extruders] Sovremenny’e texnologii v promy’shlennoj stroitel’noj promy’shlyennoj i inistirii: Sb. Mezdunarodny’x kongressa (Belgorod: BGTU im. V.G.Shukhova) 3 pp 31-5 [In Russian]

[8] Sevostyanov M V 2004 Issledovanie usloviy formovaniya materialov v press-valkovom e’kstrudere [Study of materials forming conditions in a press-roll extruder] Mezhvuzovskij sbornik stajte (Belgorod: BGTU im. V.G.Shukhova) pp115-20 [In Russian]

[9] Rieschel H 1971 Über den Verdichtungs vorgang beim Briketieren Aufbereitungs Technik 11 pp 691-8

[10] Ravych B M 1975 Briquetting in non-ferrous and ferrous metallurgy [Briketirovание в цветодной и чernoj metallurgy] (Moscow: Ugledecoizdat) pp 142-76 [In Russian]

[11] Gridchin A M et al. 2006 E’nergosberagencyshchaya tekhnika i texnologiya dlya kompleksnoj pererabotki prirodny’y x i texnogenny’y materialov [Energy-saving equipment and technology for complex processing of natural and man-made materials] Steklo mira 6 [In Russian]

[12] Min’ko N I, Laz’ko E A and Doroganov E A 2009 Effect of finely disperse cullet on glass batch briquetting Glass and Ceramics, Springer US 1 pp305–9

[13] Mulevanov S V, Min’ko N I, Kemenov S A, Osipov A A and Bykov V N 2009 Vibrational spectroscopy analysis of the structure of multicomponent phosphorus-containing silicate glasses Glass and Ceramics, Springer US vol 66 3-4 pp 117-9

[14] Klassen P V, Grishaev I G and Shomin I P 1991 Granulirovanie [Granulation] (Moscow: Khimia) [In Russian]

[15] Il’ina T N 2009 Structural and mechanical properties of pelletized fine materials Chemical and Petroleum Engineering vol 45 3-4 pp 115-8

[16] Zhuzhikov V A 1971 Teoriya i praktika razdeleniya suspenzij [Theory and practice of separation of suspensions] (Moscow: Khimia) pp 26-7 [In Russian]

[17] Il’ina T N, Sevostyanov M V, Shkarpetkin E A and Uralsky V I 2011 Vibracionno-centrobezhljny’y granulyator [Vibration-centrifugal granulator] Patent RF No 2412753 [In Russian]

[18] Il’ina T N, Sevostyanov M V and Shkarpetkin E A 2010 Konstruktivno-tekhnologicheskoe sovershenstvovanie agregatov dlya granuloobrazovaniya poroshkooobrazny’y materialov [Constructive-technological improvement of aggregates for granulating powdered materials] Vestnik BGTU im. V.G.Shukhova 2 pp 100-2 [In Russian]

[19] Sevostyanov V S, Il’ina T N, Sevostyanov M V and Shkarpetkin E A 2011 Issledovanie usloviy processa mikrogranuloobrazovaniya v dispersny’y sistemax [Investigation of the conditions of the process of microgranulation in disperse systems] Vestnik BGTU im. V.G.Shukhova 1 pp 81-6 [In Russian]

[20] Il’ina T N 2013 Klassifikaciya dispersny’y materialov i rekomendacii po processam ix aglomeracii [Classification of dispersed materials and recommendations on the processes of their agglomeration] Ximicheskoie i neftegazovoe mashinostroenie 4 pp 17-9 [In Russian]