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[illegible] During the period of industrial development of society, an intensive development of synthesized materials and products for mankind, the development of innovative technologies and technical means for the complex processing of man-made materials with various physical and mechanical characteristics (density, dispersion, water demand, ductility, etc.) becomes increasingly important [1, 2].

At that in industrialized countries, a great attention is paid to the development of promising resource-saving technologies for compacting technogenic polydisperse materials in various ways: by pressing, briquetting, extruding, vibrating, and vibration-centrifugal or pneumatic-mechanical granulation, etc. [3 - 7].

The establishment of general and specific regularities of compaction processes and the structural-deformation interaction of particles predetermines the directions of constructive and technological perfection of machines and units, as well as energy conservation in many ways.

This is of particular importance during the complex processing and utilization of man-made powdered materials - MMPM (the dusting of drying and burning aggregates, the waste of chemical and woodworking, pulp and paper, agricultural-industrial complex and other industries) [8 - 12].

The specific features of MMPM: low bulk density, increased dispersion and moisture capacity, structure anisotropy, poor flow ability and increased adhesion, etc., largely determine the conditions for the compaction of materials, the energy consumption for molded body production, and the metal capacity of the equipment.

[illegible] To study the process of viscous-plastic material movement through the channel of a

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spinneret with a variable cross-section and to establish the general tendency of material compaction process in the entire range of molding pressures (before the final production of molded bodies).

[illegible] the construction of compression and kinetic curves of compaction. Thus the dynamics of material compaction process is set along the entire length of the spinneret channel.

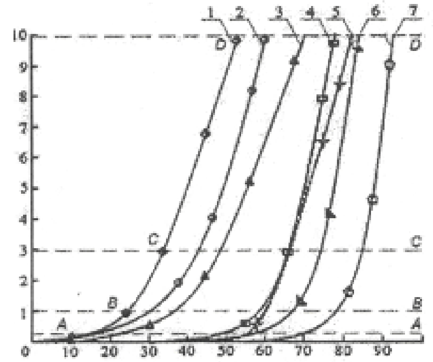
[illegible]: The basic equations are obtained characterizing the process of the viscous-plastic material movement through a spinneret channel with a variable cross-section: the equation of the axial pressure change along the length of a conical and a cylindrical part of the spinneret, respectively; The pressing equation that takes into account the physical-mechanical characteristics of the molded material. The analysis of the equations made it possible to establish a general character of material compaction process in the entire range of molding pressures (before the final production of the formed bodies). Based on theoretical and experimental studies, they developed patent-protected resource-saving aggregates for the processing and utilization of technogenic materials with various physical and mechanical properties. The units have advanced technological capabilities. They provide the improvement of product quality and productivity.

Significance of the study: Theoretical and experimental studies, as well as design and technological developments, allowed creating resource-saving units for technogenic material compacting with a number of technological advantages. The materials of the article can be useful for the students engaged in scientific work at the level of diploma writing, namely: for bachelors, undergraduates, experts, young scientists - graduate students and doctoral students engaged in a similar scientific topic within the field of viscous-plastic material molding.

[illegible] resource-saving aggregates, molding channel, spinnerets, extrusion force, granules, variable cross-section.

[illegible]

The analysis of sealing curves of various technogenic materials formed in a cylindrical press matrix indicates the presence of a sufficient long first stage of compaction with an intensive packing of particles (the removal of the gaseous phase) with minimal energy costs (Figure 1). [6, 7]



Compression curves of material compaction:

1 - expanded perlite sand, (W = 50%); 2 - dust of rotary kilns for cement production, (W = 12%); 3 - dust removal device of rotary kilns for lime production,

(W = 18%); 4 - dust removal device of rotary kilns for claydite production, (W = 17%);

5 - shredded waste of woodworking production with an oil slime binder, $C_{св}$ = 40%; 6 - wood-polymer composite mixture;

7 - fine pulp and paper waste, (W = 10%).

A similar picture of compaction is observed during two-sided pressing of materials in a press matrix with an arcuate profile of punch forming surface (Figure 2), which is characteristic of the geometric profile of cells in the forming elements of roller briquette presses.

Fig. 2 demonstrates compression curves: $\eta_i = f\left(\overline{P}_i\right)$, $\rho_i = f\left(\overline{P}_i\right)$, $H_i = f\left(\overline{P}_i\right)$, where η_i is the material compaction degree, the ratio of the current density value of the compacted material ρ_i the limit value of density γ_w, kg/m^3; H_i – the current value of compacted material layer height, m; $\overline{P}_i$ – the current value of the pressing pressure, MPa.

The value of angles $\varphi_{упл1}$, $\varphi_{упл2}$, $\varphi_{упл3}$ characterizes the rate of material compaction and deformation $v_{упл}$ at a given stage of the compaction curve.

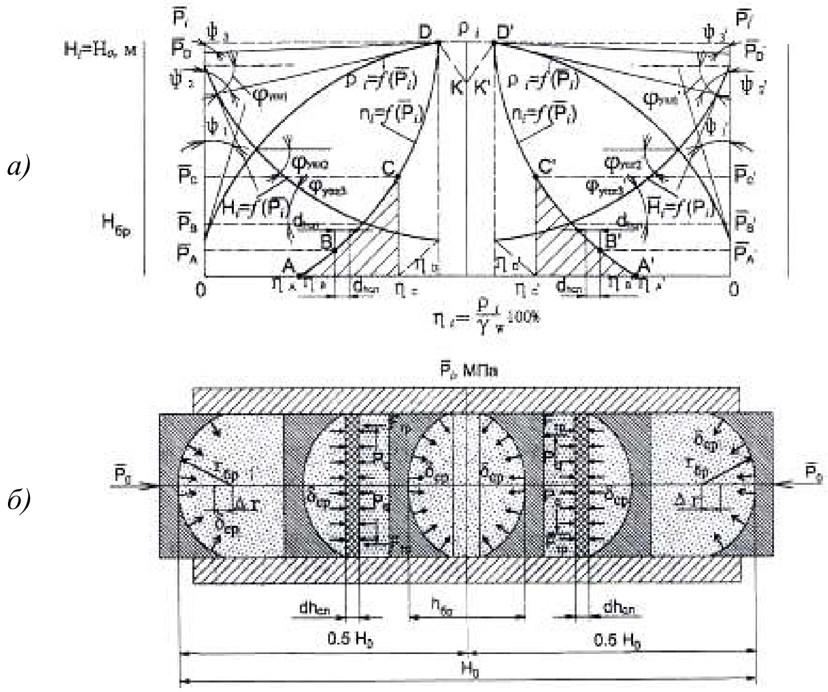


Fig. 2. Kinetic curves of charge compaction process in a press matrix with an arc-shaped profile of punch forming surface:

a) - Compression curves: $\eta_i = f\left(\overline{P}_i\right)$, $\rho_i = f\left(\overline{P}_i\right)$, $H_i = f\left(\overline{P}_i\right)$;

б) – the scheme for charge bilateral pressing calculation in a press matrix.

The dynamics of material compaction process is characterized by the intensity of the volume mass change ρ_i in time t, i.e. by first derivative:

$$\rho'_{упл\,i} = \frac{d\rho_{упл}}{dt} = \rho_0 H_0 \frac{d}{dt}\left(\frac{1}{H_i}\right) = -\rho_0 H_0 \frac{dH_i/dt}{H_i^2}. \tag{1}$$

Since

$$v_{упл\,i} = \frac{dH_i}{dt}; \quad \rho_{упл\,i} = \rho_0 \frac{H_0}{H_i}, \tag{2}$$

then

$$\frac{d\rho_{упл\,i}}{dt} = -\rho_{упл\,i} \frac{v_{упл\,i}}{H_i}, \tag{3}$$

i.e. the intensity of the compacted material volumetric mass change is directly proportional to the product of the current bulk mass $\rho_{упл\,i}$ by the rate of compaction and deformation $v_{упл\,i}$ and is inversely proportional to the current value of the layer height H_i for a compacted material.

The consideration of the elementary layer equilibrium of the mixture compacted in a cell under the influence of two-sided stresses $\sigma_{ср}$ and $\sigma_{ср} + d\sigma_{ср}$ at its infinite small thickness $dh_{сл}$:

$$\sigma_{ср} \cdot S_{пр.м} - \left(\sigma_{ср} + d\sigma_{ср}\right) \cdot S_{пр.м} - \sigma_{ср} \cdot f_0 \cdot \xi \cdot U \cdot dh_{сл} = 0\,; \tag{4}$$

where $S_{пр.м}$ – press matrix section area, m^2;

$d\sigma_{ср}$ – elementary increment of voltage at force action on a condensed layer, N/m^2;

U – press matrix perimeter, m;

f_0, ξ – the coefficients of external friction and lateral expansion respectively.

After the appropriate transformations we obtain an analytical expression to calculate the pressing force of powdered charge:

$$P_0 = \sigma_{ср} \cdot S_{пр.м} \cdot \left[e^{\left(1-\frac{\eta_0}{\eta_{бр}}\right) \cdot H_0 \cdot \frac{U \cdot f_0 \cdot \xi}{S_{пр.м}}} - 1 \right]. \tag{5}$$

The analysis of the obtained expression shows that the pressing force depends on the average stress in a layer $\sigma_{ср}$, the geometric parameters of a press matrix $S_{пр.м}$, U, the initial height of a layer – H_0, and on the physical-mechanical characteristics of the material being pressed: η_0, $\eta_{бр}$, f_0, ξ.

The values of a pressed mixture density degree in the initial $\eta_0 = \frac{\rho_0}{\gamma_w} \cdot 100\%$ and compacted $\eta_{бр} = \frac{\rho_{бр}}{\gamma_w} \cdot 100\%$ states are determined at the corresponding values of the density ρ_0 and $\rho_{бр}$, as well as by the maximum possible value of a pressed body density γ_W taking into account the presence of a liquid phase in it:

$$\gamma_W = \frac{100 \cdot \gamma_{тв} \cdot \gamma_{ж}}{\left(100 - W\right) \cdot \gamma_{ж} + W \cdot \gamma_{тв}}\,; \tag{6}$$

where $\gamma_{тв}$ – is the true density of a mixture solid phase, kg/m^3;

γ_W – the true density of the mixture liquid phase, kg/m^3;

W – the content of a liquid phase in the mixture, %.

The value of the average normal stress in a layer can be determined by the following formula:

$$\sigma_{ср}=\frac{(1+\mu)\cdot\left(2\cdot P_{пр.\max}-\tau_{сц}\cdot\sin\varphi_i\right)}{3\cdot(1+\sin\varphi_i)};\tag{7}$$

where μ – the coefficient of transverse deformation (Poisson's ratio);

$\tau_{сц}$ – the parameter that takes into account the adhesion of the pressed particles at the nominal pressing pressure, MPa;

φ_i – internal friction angle, φ_i = arctg f_i;

f_i – internal friction ratio;

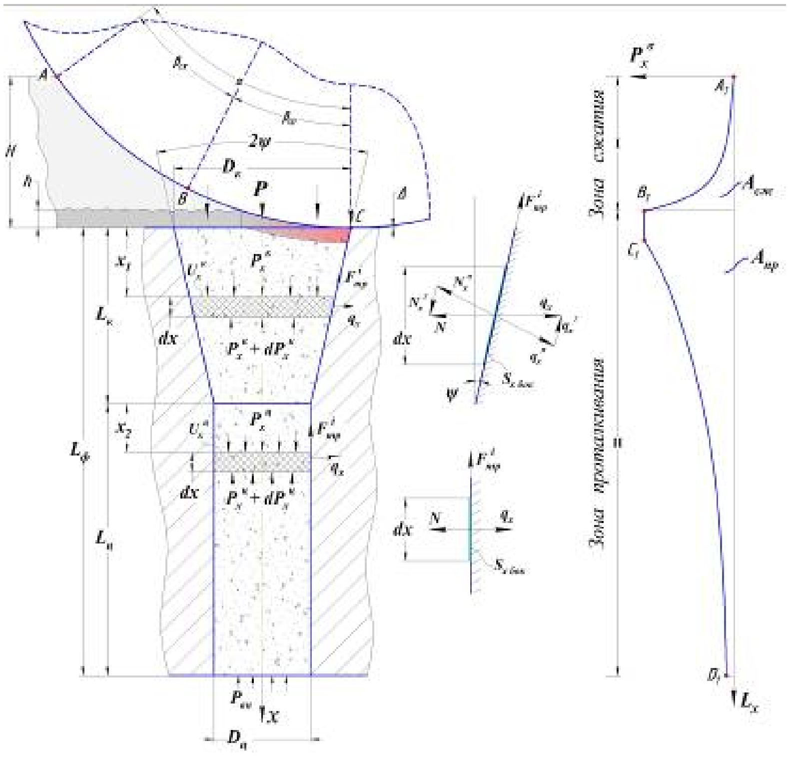
$P_{пр.\max}$ – the maximum pressing pressure corresponding to γ_W value, MPa.

Finally, taking into account the values of (7), the expression (5) has the following form:

$$P_0=\frac{(1+\mu)\cdot\left(2\cdot P_{пр.\max}-\tau_{сц}\cdot\sin\varphi_i\right)}{3\cdot(1+\sin\varphi_i)}\cdot S_{пр.м}\cdot\left[e^{\left(1-\frac{\eta_0}{\eta_{бр}}\right)\cdot H_0\cdot\frac{U\cdot f_0\cdot\xi}{S_{пр.м}}}-1\right].\tag{8}$$

The study of the conditions for viscous-plastic material extrusion through the die plates of a flat or an annular press matrix of press roller extruders is equally important for theory and practice [9 ± 13].

Let's consider the conditions of material compaction in a cylindrical die with a conical lead (Figure 3).



а) б) в)

Fig. 3 The scheme for a material extrusion force calculation through a spinneret with a variable cross-section:

a) - the equilibrium condition for an elementary layer of a material; b) - the scheme of forces; c) - the graph of the extrusion pressure change

Let us compose equilibrium equations of an elementary isolated layer in a conical and a cylindrical part, respectively:

$$P_xS_x-\left(P_x+dP_x\right)S_x-f_i\cdot q_x\cdot U_x^{\kappa}\cdot\cos\psi\cdot dx- \\ -q_x\cdot U_x^{\kappa}\cdot\sin\psi\cdot dx+q_x\cdot U_x^{\kappa}\cdot\mathrm{tg}\,\psi\cdot\cos\psi\cdot dx=0\,; \tag{9}$$

$$P_xS_x-\left(P_x+dP_x\right)S_x-f_i\cdot\left(\xi\cdot P_x+q_0\right)\cdot U_x^{ц}\cdot dx=0\,; \tag{10}$$

where P_x – the axial pressure, Pa;

S_x – the cross-sectional area of a channel at the depth x, m^2;

f_i – internal friction ratio;

q_x – the value of lateral pressure, Pa;

U_x – the perimeter of the cross-section channel at the depth x, m;

ψ – inclination angle of the channel walls to its axis, deg.

At that we have the following

conical part	cylindric part

$$q_x = \xi \cdot P_x + q_0\,; \tag{11}$$

$$S_{x\,бок} = \frac{U_x^{к} \cdot dx}{\cos\psi}\,; \qquad\qquad S_{x\,бок} = U_x^{ц} \cdot dx\,; \tag{12}$$

$$N^{\sigma} = q_x^{\sigma} \cdot S_{x\,бок} = q_x \cdot U_x^{к} \cdot dx\,;$$

$$N^{\tau} = q_x^{\tau} \cdot S_{x\,бок} = q_x \cdot U_x^{к} \cdot \operatorname{tg}\psi \cdot dx\,; \qquad\qquad N = q_x \cdot S_{x\,бок} = \left(\xi \cdot P_x + q_0\right) \cdot U_x^{ц} \cdot dx\,; \tag{13}$$

$$F_{тр}^{i} = f_i \cdot N^{\sigma} = q_x \cdot U_x^{к} \cdot dx\,; \qquad\qquad F_{тр}^{i} = f_i \cdot N = f_i \cdot \left(\xi \cdot P_x + q_0\right) \cdot U_x^{ц} \cdot dx\,; \tag{14}$$

where q_0 – the residual lateral pressure, Pa;
ξ – lateral expansion ratio, $\xi = q_x / P_x$;
$S_{бок}$ – the area of an elementary layer lateral surface, m^2;
q_x^{σ}, – normal and tangential component of the lateral extension q_x^{τ}, Pa;
N^{σ}, – normal and tangential components of the wall N^{τ} reaction of the spinneret channel N, H.

Let's transform and integrate the expressions (9) and (10):

conical part	cylindrical part

$$\int_{P}^{P_1} \frac{dP_x}{\xi \cdot P_x + q_0} = -\int_{0}^{x_1} \frac{4 f_i \cdot \cos\psi}{D_к - 2x_1 \cdot \operatorname{tg}\psi}\, dx\,; \qquad\qquad \int_{P_1}^{P_2} \frac{dP_x}{q_0 + \xi \cdot P_x} = -\int_{0}^{x_2} f_i \cdot \frac{U_x^{ц}}{S_x} \cdot dx\,. \tag{15}$$

After the corresponding transformations, we obtain the equations for axial pressure variation along the length of the spinneret conical and cylindrical part, respectively:

$$P_x^{к} = \left(P + \frac{q_0}{\xi}\right) \cdot \left(\frac{D_к - 2x_1 \cdot \operatorname{tg}\psi}{D_к}\right)^{\frac{2 f_i \cdot \cos\psi}{\operatorname{tg}\psi} \cdot \xi} - \frac{q_0}{\xi}\,; \tag{16}$$

$$P_x^{ц} = \left(P_1 + \frac{q_0}{\xi}\right) \cdot e^{-\xi \cdot f_i \cdot \frac{4}{D_ц} \cdot x_2} - \frac{q_0}{\xi}\,; \tag{17}$$

where $D_к$ – the entrance section diameter of the conical part of the channel, m;
P – the normal pressure component on the side of the forming roll, Pa.
P_1 – the pressure at the inlet to the cylindrical part, Pa.

Solving the equation (16) with respect to P at $x_1 = L_к$ and $P_x = P_{вн}$ (since there is the resistance from the cylindrical part) we obtain the expression to determine the resistance of the spinneret conical part:

$$P_к = \left(P_{вн} + \frac{q_0}{\xi}\right)\cdot\left(\frac{D_к}{D_ц}\right)^{\frac{2 f_i \cdot \cos\psi}{\mathrm{tg}\psi}\cdot\xi} - \frac{q_0}{\xi}; \tag{18}$$

where $P_{вн}$ – the pressure at the exit from the conical part of the spinneret, Pa;

$D_ц$ – the diameter of the spinneret cylindrical part, m.

Similarly, we determine the resistance of the spinneret cylindrical part at $x_2 = L_ц$ and $P_x = 0$ (since there is no back pressure at the spinneret outlet):

$$P_ц = \frac{q_0}{\xi}\left[e^{\xi\cdot f_i\cdot\frac{4}{D_ц}\cdot L_ц} - 1\right]. \tag{19}$$

Then the full resistance of the spinneret is obtained by substituting the right-hand side of the expression (19) instead of $P_{вн}$ in (18). After the corresponding transformations, we have the following:

$$P_ф = \frac{q_0}{\xi}\cdot\left[e^{4\cdot\xi\cdot f_i\cdot\frac{L_ф - L_к}{D_ц}\cdot}\cdot\left(\frac{D_к}{D_ц}\right)^{\frac{2 f_i\cdot\cos\psi}{\mathrm{tg}\psi}\cdot\xi} - 1\right]; \tag{20}$$

where $L_ф$ – the spinneret length, m.

The equation of pressing, which takes into account the physical-mechanical characteristics of the molded material, can be represented in a general form [8, 9, 11, 12]:

$$P = C\cdot\left(e^{a\cdot(\rho_i - \rho_0)} - 1\right); \tag{21}$$

where C – constant parameter, Pa;

a – an empirical parameter characterizing the properties of a material, m^3/kg;

ρ_0, ρ_i – the initial bulk density of the pressed material and its density in the molded state, kg/m^3.

At $P = C\cdot(e - 1)$ the density $\rho = \rho_0 + (1/a)$. The value $1/a$ is the increment in the material initial density at the pressure equal to $C\cdot(e - 1)$.

The value of the empirical parameters C and a depend on the structural and mechanical properties of the material (strength, humidity and size of particles) determine the resistance of the material to compression. They are determined experimentally for each material.

Solving jointly the equations (20) and (21) with respect to $L_ф$, we obtain the following:

$$L_{\phi} = \frac{D_{ц}}{(1-n)\cdot 4\cdot f_i\cdot\xi}\ln\left(\left[\frac{C\cdot\xi}{q_0}\cdot\left(e^{a\cdot(\rho_i-\rho_0)}-1\right)+1\right]\cdot\left(\frac{D_{ц}}{D_{к}}\right)^{\frac{2f_i\cdot\cos\psi}{\mathrm{tg}\psi}\cdot\xi}\right). \tag{22}$$

Here, n is the length of the conical part $L_{к}$, expressed in fractions of the spinneret L_{ϕ} total length. For example, n = 0,2 means that the length of the conical part makes 20% of the spinneret total length, at n = 0.35 - 35%, respectively. The value L_{ϕ}, определённая по (22), determined by (22), ensures the obtaining of the given density ρ_i of the developed granules.

The analysis of the equations (5), (8), (18) ... (21) shows the general nature of material compaction process in the entire range of molding pressures (before the final production of molded bodies).

The theoretical and experimental studies presented by us, as well as design and technological developments, made it possible to create resource-saving units for the compaction of technogenic materials with a number of technological advantages, Fig. 4 [13 - 20].

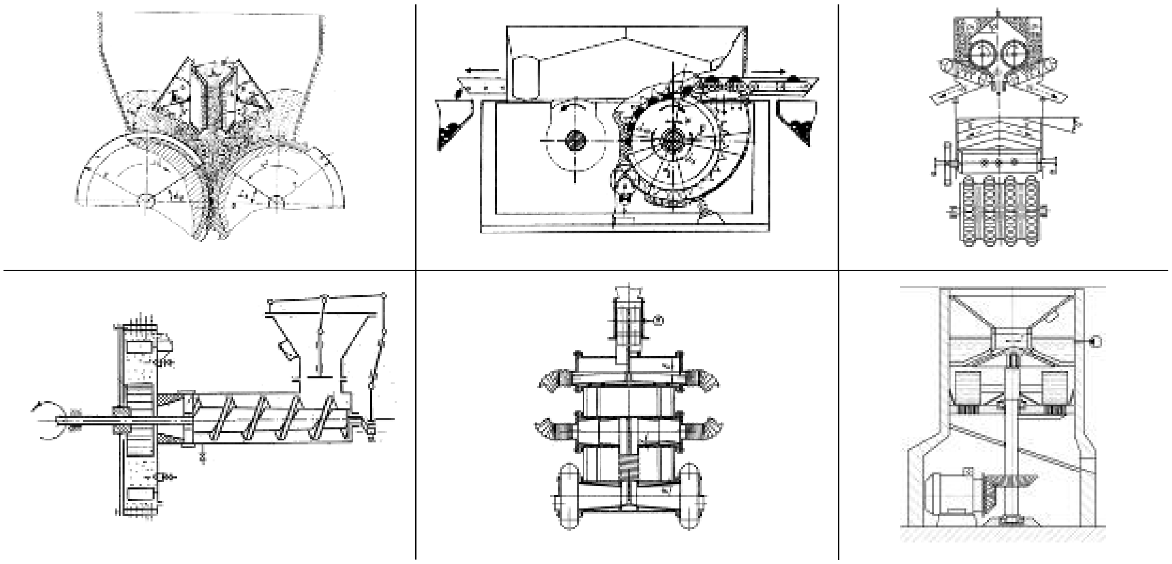


Fig. 4 Patent-protected designs of aggregates for technogenic material compaction.

The developed units provide the following:

- the possibility of the charge preliminary compaction and the removal of the gaseous phase, which prevents the appearance of microcracks in molded bodies and improves the product quality;
- the variation of pressing pressure range and the expansion of technogenic material use range with different physical and mechanical properties;
- the holding of the pressed mixture under pressure, which reduces the value of elastic deformation after stress removal;

- a charge stream uniform distribution along the width of the working forming elements, which reduces their selective wear;

- the expansion of technological capabilities, the improvement of product quality and aggregate efficiency (the introduction of surface-active additives, the vibration and thermal effects, an internal and external recycling of spillages, etc.).

The developed units are used in innovative resource-saving technologies during the processing and the utilization of technogenic materials with various physical and mechanical properties.

So, for example, the design of press roll aggregates (PRA) with the devices for a charge preliminary compaction [4,16]. Fig. 5 allows to vary the values of compaction coefficients in a sufficiently wide range ($k_{\text{упл}} = 3 \div 7$) and, pressing pressures - $P = (15 \div 60)$ MPa, respectively.

a) б)

Fig. 5. Press rollers for man-made material briquetting:
a) with a jaw retainer; b) with a roller retainer.

They recommend to use the first design of PVA (Fig. 5a) for dust briquetting from drying and calcining aggregates of cement, lime, ceramsite and other industries to solve the problems of polydisperse technogenic material utilization.

The second design of PVA (Figure 5b) can be used for low-flowing technogenic material briquetting with low bulk density, such as the waste of wood processing industries (sawdust) using oil-bearing and other organic binders to obtain solid fuel; the waste during the production of various heat-insulating materials (perlite, vermiculite, isovol, etc.), which are highly effective adsorbents during the purification of liquid media, etc.

In order to improve the efficiency of low-flowing material briquetting with low bulk density ($\rho \leq$ 100-200 kg/m^3) and a high content of gaseous phase, the pressing of which worsens the quality of the pressed products, we developed the PVA with extended zones for charge preliminary compaction [15]. The design of PVA provides an increased capacity of a unit due to two-side compression of the charge from the roll side, its effective deaeration and vibration compression before pressing, the classification of the material - the screening of spill and its return to the molding zone and other advantages.

We developed and theoretically grounded constructive and technological solutions realized during the extrusion of viscous-plastic technogenic materials in a screw extruder [17,18] and a press roller screw extruder with a flat matrix [20].

A screw extruder (Fig. 6a) provides the implementation of various technological operations: a uniform feeding and dosing of man-made charge, the preliminary compaction of man-made materials with low bulk density, the vibration compacting of a mixture with pressing rolls with its holding under pressure for stress relaxation, the possibility of plasticizing additive introduction into a charge forming them and its thermoforming, etc.

The unit can be used during the extrusion of wood-polymer composites, viscous-plastic clay materials, etc.

A press roller extruder with a flat matrix (Fig. 6b), equipped with a device for the preliminary compaction of the charge, should be used for the extrusion of man-made fibrous materials: pulp and paper waste for the production of granular stabilizing additives of crushed-mastic asphalt concrete (GSA CMAC), agricultural-industrial production waste, etc.

Fig. 6. Screw extruder (a) and press roller extruder with a flat matrix (b)

In order to obtain granular (balled) man-made materials, a vibrational-centrifugal aggregate of combined action has been developed (Fig. 7). The unit realizes the following technological operations successively: preliminary consolidation of charge - the formation of embryos, the classification of micro granulated particles (1st chamber, top), particle formation in waterfall cascade mode (2nd chamber), the balling of granules in cascade mode (3rd chamber with cantilevered toroidal nozzles).

[illegible] Vibration-centrifugal aggregate of combined action.

This unit allows you to change the value of the dynamic effect (the frequency of the vibrational-centrifugal action, δ = (300 ÷ 400) kol / min) and its nature (waterfall cascade or cascade regime) depending on the plastic properties of a man-made material.

Thus, the complex of theoretical, design-technological, experimental and pilot-industrial studies carried out by us allowed us to develop a series of patent-protected assemblies designed for the compaction of technogenic materials of various industries in order to solve the problem of resource-saving.

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