INVESTIGATION OF DENSITY CHANGE OF AGRICULTURAL MATERIALS

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The operation of mechanisms of agricultural machines is connected with action of power forces on the worked out material, which results in their deformation. In its turn, depending on the properties of the materials, the load on tools varies widely and affects the qualitative parameters of the fulfillment of the technological process. Hence, when designing agricultural machines, information about deformation resistance properties of the used materials is necessary.

Most agricultural materials, under the made assumptions, can be considered to be a quick medium, in which binding forces between particles are available. The material can be in limited volume under the action of tools or other factors, which leads to their density change. Well-known research in this field can be divided into two trends according to the adopted model.

In the first case the material is examined as a collection of descrete particles, that have the form of absolutely hard disks or balls of the same size. This trend of research is reflected in works [1, 2, 6, 11]. This model enables to establish the relationship between stresses by acting on the material with the tested binding forces. But in many cases the assumptions of absolute hardness and equal size of particles of agricultural materials are not adequate.

The second trend is connected with results of research shown in works [3, 4, 5, 10, 12]. Here the used materials are examined as a solid medium, the model enables to establish mathematical dependencies, which include the experimentally determined physico-mechanical properties of the material. But they are often examined elsewhere as a completely quick one, or the achieved investigation results can be used only in the narrow limits of a specific machine structure.

RELATIONSHIP BETWEEN OPERATING AND SIDE STRESSES

Due to the power forces of agricultural machines' tools acting on the worked out material, stresses appear in it. In this case material compression deformation takes place and some of its elements slide over the confining surface. Stresses that appear parallel to the direction of the acting forces caused by the tool are the operating ones. And stresses extending in the direction perpendicular to the operating ones, are side ones. For establishing a relationship between them we will conduct theoretical research under the following assumptions:

- consider the material to be solid medium,
- material is in limiting stressed state,
- values of material friction coefficients over confining surface are constant.

Under the above listed assumptionslet's consider the element of quick binding material (QBM, Fig. 1), that directly bears against the surface it slides over.

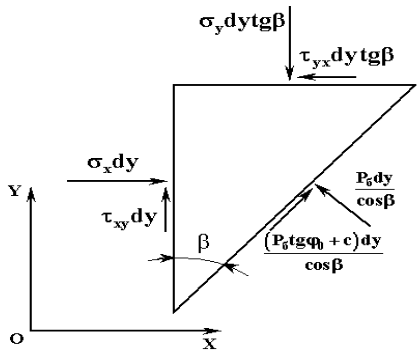

Fig. 1. Diagram for determining relationship between stresses

It is acted by:

$\sigma_y dy\text{tg}\beta$, $\sigma_x dy$ – normal forces, caused by stresses, acting accordingly along axes OY and OX;

$\tau_{yx} dy\text{tg}\beta$, $\tau_{xy} dy$ – tangential forces, caused by correspondingly tangential stress τ_{yx} and τ_{xy};

$\dfrac{P_б dy}{\cos\beta}$ – normal force of slide surface reaction;

$\dfrac{\left(P_б \text{tg}\varphi_0 + c\right) dy}{\cos\beta}$ – friction force.

Equilibrium condition of material examined:

$$\begin{cases} \sum_{i=1}^{n} F_{ix} = 0 \Rightarrow \sigma_x dy - \tau_{yx} dy\text{tg}\beta - P_б dy + \left(P_б \text{tg}\varphi_0 + c\right) dy\text{tg}\beta = 0 \\ \sum_{i=1}^{n} F_{iy} = 0 \Rightarrow \tau_{xy} dy - \sigma_y dy\text{tg}\beta + P_б dy\text{tg}\beta + \left(P_б \text{tg}\varphi_0 + c\right) dy = 0 \end{cases} \tag{1}$$

For completely quick material which is in limiting stressed state the following relation is true [8]:

$$\frac{\sigma_2'}{\sigma_1'} = \frac{1-\sin\varphi_0}{1+\sin\varphi_0} \tag{2}$$

where:

σ_1' and σ_2' – correspondingly maximum and minimal principal stress.

Examining a graphic representation of the given phenomenon with additional axis τ (fig. 2) we can write the following dependence:

$$\sin\varphi_0 = \frac{BC}{AC} = \frac{(\sigma_1 + c\cdot\operatorname{ctg}\varphi_0) - (\sigma_2 + c\cdot\operatorname{ctg}\varphi_0)}{(\sigma_1 + c\cdot\operatorname{ctg}\varphi_0) + (\sigma_2 + c\cdot\operatorname{ctg}\varphi_0)} = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2 + 2c\cdot\operatorname{ctg}\varphi_0} \tag{3}$$

Or:

$$\frac{\sigma_2 + c\cdot\operatorname{ctg}\varphi_0}{\sigma_1 + c\cdot\operatorname{ctg}\varphi_0} = \frac{1-\sin\varphi_0}{1-\sin\varphi_0} \tag{4}$$

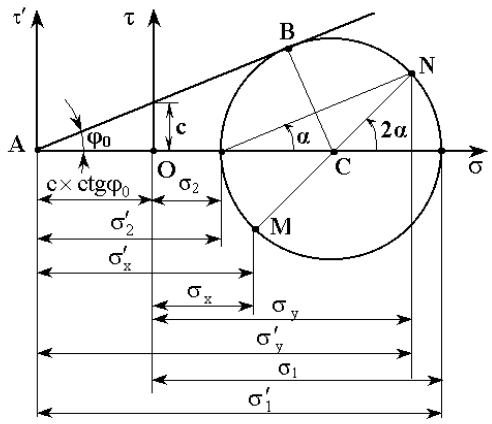

Fig. 2. Diagram of limiting stressed state of quick material

The dependence corresponds to limiting stressed state for QBM, but at the time satisfies the case with completely quick material as $\sigma_1' = \sigma_1 + c\cdot\operatorname{ctg}\varphi_0$ and $\sigma_2' = \sigma_2 + c\cdot\operatorname{ctg}\varphi_0$.

Let's introduce a notation:

$$\xi_{\min} = \frac{\sigma_2 + c\cdot\operatorname{ctg}\varphi_0}{\sigma_1 + c\cdot\operatorname{ctg}\varphi_0} = \frac{1-\sin\varphi_0}{1-\sin\varphi_0} \tag{5}$$

where:

$\xi_{\min}$ – minimal value of side pressure coefficient, when the stress σ_1' is the largest.

In general case operating $\sigma_y^{'}$ and side $\sigma_x^{'}$, stresses acting on the considered element are not the principal ones. Hence the value of side pressure coefficient will be different from $\xi_{\min}$ and will depend on an angle a between platforms of their action. So, for a general case on the basis of Fig. 2 we can write:

$$\sigma_{в}' = \frac{\sigma_1' + \sigma_2'}{2} + \frac{\sigma_1' - \sigma_2'}{2}\cos 2\alpha = \sigma_1' \cos^2\alpha + \sigma_2' \sin^2\alpha \qquad (6)$$

$$\sigma_{г}' = \frac{\sigma_1' + \sigma_2'}{2} - \frac{\sigma_1' - \sigma_2'}{2}\cos 2\alpha = \sigma_1' \sin^2\alpha + \sigma_2' \cos^2\alpha \qquad (7)$$

Having divided (6) into (7) and taking into account (5), we shall get:

$$\frac{\sigma_x'}{\sigma_y'} = \frac{\mathrm{tg}^2\alpha + \xi_{\min}}{\xi_{\min}\mathrm{tg}^2\alpha + 1} \qquad (8)$$

From (8), analogous to (5), we'll write:

$$\xi = \frac{\left(\sigma_x + c \times \mathrm{ctg}\varphi_0\right)}{\left(\sigma_y + c \times \mathrm{ctg}\varphi_0\right)} = \frac{\mathrm{tg}^2\alpha + \xi_{\min}}{\xi_{\min}\mathrm{tg}^2\alpha + 1} \qquad (9)$$

Solving the equation (9) relatively σ_x, we'll get:

$$\sigma_x = \frac{\sigma_y(\mathrm{tg}^2\alpha + \xi_{\min})}{\xi_{\min}\mathrm{tg}^2\alpha + 1} - \frac{2c \times \cos\varphi_0 \times (1 - \mathrm{tg}^2\alpha)}{(1 + \sin\varphi_0)(\xi_{\min}\mathrm{tg}^2\alpha + 1)} \qquad (10)$$

Thus, side stress for QBM is equal to side stress for completely quick material reduced to some value $C_\Sigma = \dfrac{2c \times \cos\varphi_0 \times (1 - \mathrm{tg}^2\alpha)}{(1 + \sin\varphi_0)(\xi_{\min}\mathrm{tg}^2\alpha + 1)}$, caused by binding forces of material.

Thus:

$$\sigma_x = \sigma_y \xi - C_\Sigma \qquad (11)$$

where:

ξ – side pressure coefficient for completely quick material.

For establishing the dependence of confining surface normal pressure from vertical stresses let's solve the system (1):

$$\sigma_x dy - \tau_{yx} dy\mathrm{tg}\beta - P_б dy + \left(P_б \mathrm{tg}\varphi_0 + c\right)\mathrm{tg}\beta dy - \sigma_y dy\mathrm{tg}^2\beta + \\ + \tau_{xy}\mathrm{tg}\beta dy + P_б dy\mathrm{tg}^2\beta + \left(P_б \mathrm{tg}\varphi_0 + c\right)\mathrm{tg}\beta dy = 0$$

Having taken into account (11) and the law of tangential stresses twoness, we will write:

$$\sigma_y\xi - C_\Sigma - P_б + P_б \text{tg}\varphi_0 \text{tg}\beta + c\times\text{tg}\beta - \sigma_y \text{tg}^2\beta + \\ + P_б \text{tg}^2\beta + P_б \text{tg}\varphi_0 \text{tg}\beta + c\times\text{tg}\beta = 0 .$$

Whence after transformations:

$$P_б = \frac{\sigma_y(\xi - \text{tg}^2\beta) + 2c\cdot\text{tg}\beta - C_\Sigma}{1 - 2\text{tg}\varphi_0\text{tg}\beta - \text{tg}^2\beta} \tag{12}$$

For determining angle α between the platform of operating stress and the platform of maximum principal stress let's consider the diagram shown in fig. 3 and write down the equilibrium condition of the element:

$$\begin{cases} \sum_{i=1}^{n} F_{xi} = 0 \Rightarrow \sigma_2' AC - \sqrt{P_f^2 + P_N^2}\cos(90^0 - (\Theta - \varphi_0)) = 0 \\ \sum_{i=1}^{n} F_{yi} = 0 \Rightarrow \sigma_1' AB - \sqrt{P_f^2 + P_N^2}\sin(90^0 - (\Theta - \varphi_0)) = 0 \end{cases} \tag{13}$$

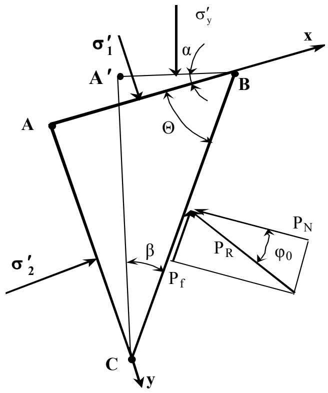

Fig. 3. Diagram for determining angle α between the platform of vertical stress and the platform of maximum principal stress

After transformations from system (13) we have:

$$\frac{\sigma_2'}{\sigma_1'}\text{tg}\Theta = \text{tg}(\Theta - \varphi_0) \tag{14}$$

Having taken into account (5), we will write:

$$\xi_{\min}\text{tg}\Theta = \frac{\text{tg}\Theta - \text{tg}\varphi_0}{1 + \text{tg}\Theta\text{tg}\varphi_0} \tag{15}$$

On the basis of expression (15) we get the following equation:

$$\xi_{\min}\mathrm{tg}\varphi_0\mathrm{tg}^2\Theta-(1-\xi_{\min})\mathrm{tg}\Theta+\mathrm{tg}\varphi_0=0 \qquad (16)$$

Since:

$$\left[\frac{(1+\sin\varphi_0)-(1-\sin\varphi_0)}{1+\sin\varphi_0}\right]^2-\frac{4\mathrm{tg}^2\varphi_0(1-\sin\varphi_0)}{(1+\sin\varphi_0)}=0,$$

then the solution of equation (16) will look like:

$$\mathrm{tg}\Theta=\frac{1-\xi_{\min}}{2\xi_{\min}tg\varphi_0} \qquad (17)$$

Angle Θ determines the position of the platform, on which the maximum principal stress is acting, and the angle between this platform and platform of action σ_y will be:

$$\alpha=90^0-\beta-\Theta=90^0-\beta-arctg\left(\frac{1-\xi_{\min}}{2\xi_{\min}tg\varphi_0}\right) \qquad (18)$$

The received dependencies for determining the relationship between operating and side stresses (11), normal pressure of confining surface (12) and the angle that determines the position of principal platforms (18) enable to solve a number of specific tasks, related to the determination of distribution of stresses in a limited volume of agricultural materials.

INVESTIGATION OF QBM TRAVEL MECHANISM IN RESERVOIR

The most typical task, considered for QBM, is its travel in limited volume. Let's examine the travel of material under the action of gravitation forces in a reservoir with cross-sections of a corresponding form (Fig. 4 a, b). Under t = const from QBM flow we shall separate elementary layer with thickness dy. Since reservoirs are symmetric, suppose the forces and stresses, acting along axes OX and OZ are equal to the modulus. In this case the given layer is acted (Fig. 4, b):

– from below, at a distance y – vertical stress $\sigma_в$;

– from above, at a distance y + – respectively stresses $\sigma_в+d\sigma_в$, where $d\sigma_в$ – stress increase in section dy;

– from sides – normal pressure of confining surface $P_б$ and tangential pressure from friction force $P_{F_{тр}}$;

– in the centre of mass of an element the force of weight G is applied.

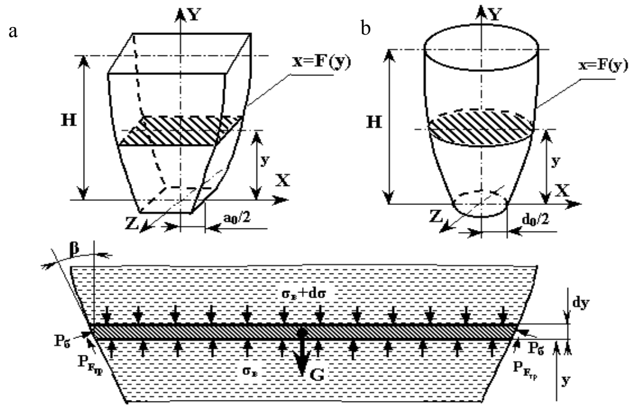

Fig. 4. Diagram of forces action on elementary layer in hopper

In this case the differential equation of the centre of mass of an element motion, projected on axis OY will look like this:

$$\sigma_в S_1 - S_2(\sigma_в + d\sigma_в) + P_{F_{тр}} S_б \cos\beta + P_б S_б \sin\beta - G = ma \qquad (19)$$

where:

S_1 – cross-section area of material flow at a distance y from the origin of coordinates,
S_2 – cross-section area of material flow at a distance $y + dy$,
$S_б$ – side surface area of the element examined,
β – slope of generator's side surface of material flow at a distance y.

As the separated volume is confined to two infinitely close areas, in this case we get:

$$S_б = Ldy \qquad (20)$$

$$S = \mu F^2(y) \qquad (21)$$

where:

L – perimeter of material flow cross-section at a distance y from the origin of coordinates,
$x = F(x)$ – equation of generator's limiting surface,
μ – constant coefficient, depending upon the cross-section form of a reservoir.

Taking into account the experimental dependence of volume weight on density load intensity [7], the weight of material in a layer of thickness dy will be:

$$G = \gamma_0 S(\psi + \lambda\sigma_в)dy \qquad (22)$$

where:

γ_0 – bulk density of material,
ψ and λ – experimental coefficients.

For determining the acceleration of the centre of mass of separated volume of material let's take advantage of the approach suggested by Hyachev L.V. [2]

according to which the volume of material, passing through certain cross-section in a time unit (volume productivity) is determined by the formula:

$$Q_v(t) = V(t)S(t) \tag{23}$$

Accordingly:

$$V(t) = \frac{Q_v(t)}{\mu F^2(y(t))} \tag{24}$$

where:

$y(t)$ – the law of motion of the centre of mass of elementary layer in reservoir.

The law of motion of the centre of mass, generally, depends on the properties of material and method of its subsequent travel. Let's examine the case of difficult outflow of material from a reservoir, in which volume productivity of discharge opening as well as of any cross-section of reservoir is determined by the outlet device productivity, which in its turn tends to constant value with a certain error. Thus, under $Q_v(t) = Q_v =$ const, we get:

$$a = \frac{dV(t)}{dt} = \frac{Q_v}{\mu}\frac{d(F^{-2}(y(t))}{dt} = -\frac{2Q_v F'(y(t))y'(t)}{\mu F^3(y(t))} \tag{25}$$

As $y'(t) = V(t)$ and the element is considered at a fixed value $t =$ const, then finally:

$$a = -\frac{2Q^2{}_v F'(y)}{\mu^2 F^5(y)} \tag{26}$$

After substitution of the expressions (20)-(22), (26) into equation (19) and taking into account the expression (12) we'll write:

$$-\frac{d\sigma_в}{dy} + \frac{L\left(tg\varphi_0 + F'(y)\right)}{S\sqrt{1+\left(F'(y)\right)^2}}\left[\frac{\sigma_в(\xi - \left(F'(y)\right)^2) + 2cF'(y) - C_\Sigma}{1 - 2tg\varphi_0 F'(y) - \left(F'(y)\right)^2}\right] -$$
$$-(\gamma_0\psi + \gamma_0\lambda\sigma_в)\left(1 - \frac{2Q^2{}_v F'(y)}{g\mu^2 F^5(y)}\right) + \frac{cL}{S\sqrt{1+\left(F'(y)\right)^2}} = 0 .$$

For the case examined $S/L = F(y)/2$, so we have a differential equation in the form of:

$$\sigma'_в + \sigma_в P(y) = Q(y) \tag{27}$$

where:

$$P(y) = \gamma_0\lambda\left(1 - \frac{2Q^2{}_v F'(y)}{g\mu^2 F^5(y)}\right) - \frac{2\left(\mathrm{tg}\varphi_0 + F'(y)\right)(\xi - \left(F'(y)\right)^2)}{F(y)\sqrt{1+\left(F'(y)\right)^2}\left(1 - 2\mathrm{tg}\varphi_0 F'(y) - \left(F'(y)\right)^2\right)} \tag{28}$$

$$Q(y)=\frac{\left(4cF'(y)-2C_{\Sigma}\right)\left(\mathrm{tg}\varphi_0+F'(y)\right)}{F(y)\sqrt{1+\left(F'(y)\right)^2}\left(1-2\mathrm{tg}\varphi_0F'(y)-\left(F'(y)\right)^2\right)}-$$
$$-\gamma_0\psi\left(1-\frac{2Q^2{}_vF'(y)}{g\mu^2F^5(y)}\right)+\frac{2c}{F(y)\sqrt{1+\left(F'(y)\right)^2}} \tag{29}$$

For the solution of equation (27) the explicit specification of generator's side surface function $x = F(y)$ is necessary, which is a part of the expressions (28) and (29). Resulting from its solution is the expression characterising the distribution of material stresses over a flow volume.

INVESTIGATION OF THE DISTRIBUTION OF MATERIAL STRESSES IN A LIMITED CYLINDRICAL VOLUME

Let's consider the material under the action of uniformly distributed stress q_{max} in a limited volume of radius R (Fig. 5, a). Such material can be plants stalks, formed in a roll.

For conducting theoretical research of stresses distribution we shall add the following to the above made assumptions:

− plants stalks are arranged uniformly over the roll height;

− stalks layers accelerate in a radial direction in the process of volume formation to R = const, close to zero.

By means of two cross-sections, a perpendicular one to cylinder axis and an arranged one from another at a single distance, let's cut the disk in which we shall isolate the element abcd by two areas passing through the disk axis and forming the angle $d\theta$ between them and by two coaxial cylindrical radii surfaces r and $r + dr$ (Fig. 5, a). Normal stresses on an element of cylindrical surface of radius $r + dr$ are denoted by σ_r; stresses on surface of radius r are denoted by $\sigma_r+d\sigma_r$. Normal stresses on surface cb and da are denoted by σ_θ. Consider stresses directions determined on Fig. 5, b to be positive. Tangential stresses on element faces are absent, so normal stresses σ_r and σ_θ will be the principal ones.

The equation of element equilibrium in projection on the axis OX and OY look like:

$$\begin{cases}\sum_{i=1}^{n}F_{ix}=(\sigma_r+d\sigma_r)\cdot r\cdot d\Theta-\sigma_r\cdot(r+dr)\cdot d\Theta+2\cdot\sigma_\Theta\cdot\sin(\frac{d\Theta}{2})\cdot dr=0\\ \sum_{i=1}^{n}F_{iy}=\sigma_\Theta\cdot\cos(\frac{d\Theta}{2})\cdot dr-\sigma_\Theta\cdot\cos(\frac{d\Theta}{2})\cdot dr=0\end{cases} \tag{30}$$

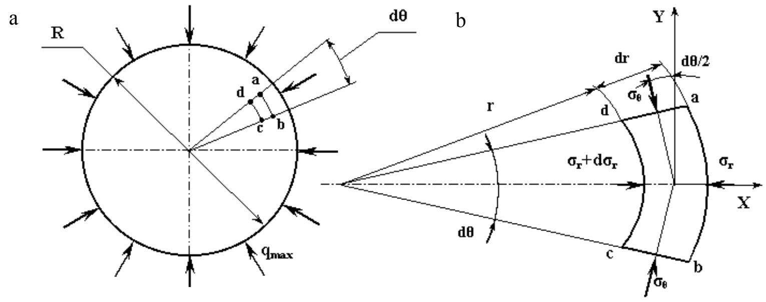

Fig. 5. Diagram of stresses action on plant material roll element

As the second equation of the system (30) is performed identically and $\sin\left(\frac{d\Theta}{2}\right)=\frac{d\Theta}{2}$, since $\frac{d\Theta}{2}\to 0$, we get:

$$\frac{r\cdot d\sigma_r}{dr}-\sigma_r+\sigma_\Theta=0 \tag{31}$$

The analysis of arrangement and properties of material in roll cross-section, under the made assumptions enables to use the theory of quick medium mechanics to determine stresses relationship, acting in the examined cross-section. According to this theory the equilibrium boundary condition written for a polar coordinate system looks like this:

$$\sigma_\Theta=\xi_{\min}\cdot\sigma_r-c\cdot ctg\varphi_0\cdot(1-\xi_{\min}) \tag{32}$$

Substituting expression (32) in the differential equation (31) we get:

$$\frac{d\sigma_r}{dr}-\sigma_r\cdot\left(\frac{1-\xi_{\min}}{r}\right)=\frac{c}{r}\cdot\mathrm{ctg}\varphi_0\cdot(1-\xi_{\min}) \tag{33}$$

Subsequently:

$$\sigma_r=(-c\cdot r^{(\xi_{\min}-1)}\cdot\mathrm{ctg}\varphi+c_2)\cdot r^{(1-\xi_{\min})} \tag{34}$$

As, under $r=R$ $\sigma_r=q_{\max}$ the integration constant is as follows: $c_2=R^{(\xi_{\min}-1)}\cdot(q_{\max}+c\cdot\mathrm{ctg}\,\varphi)$.

Finally we'll get:

$$\sigma_r=(q_{\max}+c\cdot\mathrm{ctg}\varphi)\cdot\left(\frac{r}{R}\right)^{(1-\xi_{\min})}-c\cdot\mathrm{ctg}\varphi \tag{35}$$

The received dependency (35) enables to establish stresses distribution in plant material from periphery to limited cylindrical volume centre.

LOADS INFLUENCE ON DENSITY OF AGRICULTURAL MATERIALS

Analysis of agricultural materials structure components and their physico-mechanical properties shows that the sort of density change dependence is related to applied load value.

The dependence of volume weight of organic and mineral fertilizers components outflow with broken structure of inner bonds, taking into account, that $P(t) = \sigma_в^0(t)$ where $\sigma_в^0(t)$ – vertical stress in reservoirs on the level of formation of spread material layer, looks like this:

$$\gamma(t) = \gamma_0(\psi + \lambda\sigma_в^0(t)) \tag{36}$$

For practical use of the received expression it is necessary to calculate the value of function $\sigma_в^0(t) = f(t)$ taking into account the quick binding medium (QBM) properties of organic and mineral fertilizers components according to the equation (27).

If the material is formed under the action of external loads, then packing value change depends upon the method of formation. For example, for presses with constant volume of bale chamber only one cycle of external load action can be observed; it is described by the dependence for the principal packing curve [10]:

$$\rho_1 = \frac{\rho_0}{1 - \frac{1}{в}\ln\frac{g + A}{A}} \tag{37}$$

where:

ρ_0 and ρ_1 – correspondingly initial and actual density of material,
$в$ and A – coefficients depending upon material properties,
g – compressive load.

For the press with a variable volume of chamber four cycles of action of external load are typical. The first one lies in a prior packing of material with feeding conveyer. In this case the process is also described by the dependence for the principal packing curve (37). The second cycle corresponds to the process of formation of roll nucleus in initial loop of radius R_{in}, when tension force of belts is close to zero. Hence the discharge of material will take place [10]:

$$\rho = \rho_в + \frac{\ln D}{b_1} \tag{38}$$

where:

ρ_E – material density at the start of discharge,
D and b_1 – coefficients depending upon the material properties.

The third cycle corresponds to the maximum forces attainment moment, when the roll diameter growth starts. In this, due to substantial packing forces the stalks will be compressed according to principal compression curve [10] and the process will be described by the dependence (37). And the initial density will correspond to the one determined by the formula (38).

The fourth cycle corresponds to putting material layers over the roll of radius $R_{in.}$ with further decrease of packing load. Thus, with some assumption, we may consider, that the process of material packing takes place also according to principal compression curve, but the initial density must be considered the density which is equal to flax band density.

Using ideas mentioned above and the received dependency (35) for establishing stresses in a limited volume of plant material, the mechanism of density distribution over the volume of given material can be determined.

CONCLUSIONS

The suggested approach based on the model of solid quick medium enables to get dependencies for determining density change of any agricultural materials under the action of machine tools and other factors.

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SUMMARY

The article presents the method of determining mechanism of stresses distribution in limited volumes of agricultural materials. Based on this mechanism material density change under the action of machine tools and other factors is established.