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Use of DEM to characterize damage of delicate fruit on feeders with reciprocating drive

Wykorzystanie DEM do opisu uszkodzeń owoców delikatnych na podajniku z napędem posuwisto-zwrotnym

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Abstrakt

W artykule opisano modelowanie technologią DEM uszkodzeń borówki wysokiej, podczas transportu na podajniku z napędem posuwisto-zwrotnym. Określono modelowe wartości sił normalnych oraz stycznych w punktach kontaktu borówki. Przeprowadzono symulacje uwzględniające wpływ zmiany wydatku masowego transportowanych owoców na wartości sił normalnych i stycznych. Wykazano, że zmiana wydatku masowego borówki nie powoduje przekroczenia dopuszczalnych sił stycznych i normalnych, oddziałujących pomiędzy owocami.

Abstract

This article describes the modeling by DEM technology of damage to highbush blueberries, during transport on a reciprocating feeder. The modeled values of normal and tangential forces at the blueberry contact points were determined, and the effect of changing the mass output of the transported fruit on the values of normal and tangential forces was studied. It has been shown that the change in the mass output of blueberries does not exceed the permissible tangential and normal forces, interacting between the fruits.

Słowa kluczowe: borówka wysoka, podajnik, siły styczne/normalne, DEM

Keywords: blueberry, feeder, tangential/normal forces, DEM

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1. Introduction

The main purpose of the article is to familiarize the the reader with a description of the computational method for the movement of fragile fruit on a trough conveyor with reciprocating drive, so as to minimize the the number of damages to the transported raw material.

Soft fruits damages during transport is one of the most important problems to be solved in the food industry. Damage mechanisms are complex and interrelated. A significant part of technological operations requires the transportation of raw material using vibrating conveyors. Dynamic interactions of transport equipment and the interaction of fruits with each other cause deterioration of the physical and chemical properties of the raw material. During the transportation of food raw materials (fruits), unfavorable phenomena occur that reduce the quality of the raw material, leading to the loss of weight of the raw material, which can be subjected to further technological processes. It is assumed that transporting food is a mobile variety of storage, therefore, the transformations occurring in transported products are affected by the same factors that interact during its storage. The rate of these transformations depends on temperature, ambient humidity and oxygen and carbon dioxide content [1].

Soft fruits tend to behave like viscoelastic materials when subjected to stresses and strains [2-5]. The resulting mechanical behavior of an assembly of viscoelastic particles (fruits), is a complex, integrated effect defined by the geometry of the particles, their shape and roughness of the surface bounding the structure, and the number and strength of the objects' interaction points (contact points). They are a consequence of the shape, size, roughness and strength of the fruit, as well as any other external forces. The movement of stressed particles causes shear stresses that lead to a break in the continuity of the fruit surface. Experimental studies of the effect of external forces occurring during fruit transport have not led to reliable results on the behavior of individual particles/fruit in the studied crop [6-7].

Promising results are provided by the use of the DEM modeling method. During numerous simulations, it has been shown to be a numerical method suitable for modeling the behavior of discontinuous media with different physical properties. Therefore, it should be considered that DEM is a suitable tool in modeling bulk systems of soft and deformable particles.

The dynamic behavior of granular materials such as rocks, powders and agglomerates has been studied using DEM. However, its application to agricultural and food particles has been more limited [8].

The most common geometric shapes that have been used to represent particles in DEM modeling are circular disks or spheres [9]. This is because most available point-of-contact theories assume this shape, leading to a reduction in the initial model parameters and making calculations very simple. Other non-circular and non-spherical primitive shapes, as well as irregularly shaped particles, have been used to approximate more like real particles, which are usually irregularly shaped [10]. In DE modeling, during loading, the deformation of the particles is usually treated as a "virtual" deformation, meaning that the particles can overlap rather than deform due to the contact force. The particles then separate under the assumption that the original shape of each particle has been preserved. The advantages of preserving the shape of the particles are related to the method of calculating contact forces and the subsequent translation and rotation of the particles. Virtual boundaries are left in the DEM modeling, hence a particle that has moved beyond the boundary of the computational area on one side is returned to the system to preserve the total number of particles in the system [11].

The deformation of particles and their potential damage are important to the quality of the final product. In addition, the behavior of most soft, deformable particles is far from purely elastic, which is the most common assumption about particle behavior in DE simulations. In contrast, most agricultural and food materials exhibit viscoelastic behavior. Therefore, the feature of standard DE models that assumes "hard" particles tends to underestimate bulk density when applied to systems of "soft" particles (viscoelastic), which deform significantly and thus reduce pore volume before failure [12].

In most DEM simulations, the behavior of many thousands of particles is modeled. However, these are always 4 to 8 orders of magnitude smaller than the actual values. Computational simplicity often results in the selection of larger particles with visible grain boundaries compared to the real system, in order to maintain acceptable computational analysis execution time within the assumed system boundaries and facilitate subsequent image analysis. The scaling effect, in which the number of particles represents only a very small, perhaps even insignificant, portion of the total spatial domain, is another problem to be addressed in DEM simulation [13-17].

Therefore, the purpose of this article is to present an innovative computational-simulation method using Rocky DEM software to describe the behavior of particles during their movement on the feeder. The adoption in the model of the deformability and viscoelasticity of spherical particles, corresponding to the shapes of highbush blueberries (*Vaccinium corymbosum*), makes it possible to overcome the limitations that have previously existed when using DEM.

To understand the causes and mechanisms of fruit interactions and impact damage, it is necessary to study the practical aspects of these interactions [18,19]. Impact analysis should take into account the individual interactions between fruits and the interactions of fruits on the feeder walls. In addition, the strength characteristics of the feeder and the fruit being transported should be taken into account. The mathematical description should take into account the damping properties of the raw material leading to load relaxation, friction between the fruit and between the fruit and the feeder trough. Finally, the computational model must take into account the susceptibility of the fruit to damage, determined as a function of its maturity, the temperature at which transport occurs, etc. [20]

2. Materials and Methodology

2.1. Computational model

Simulation calculations, using RockyDEM software, were carried out defining the following research objectives, which included:

1) multi-criteria simulation of the movement on a conveyor of highbush blueberries (*Vaccinium corymbosum*), commonly known as American blueberries,

2) calculation of normal forces and tangential interactions between the blueberry fruit and the walls of the conveying device,

3) calculation of energy restitution coefficients taking into account the physical and chemical properties of blueberry fruit.

The mathematical model used to analyze the interaction of tender fruit during transport involved determining the forces acting on individual particles due to their mass, and calculating interactions with walls and other particles. The highbush blueberry model shown in Figure 1 was used for the simulations.

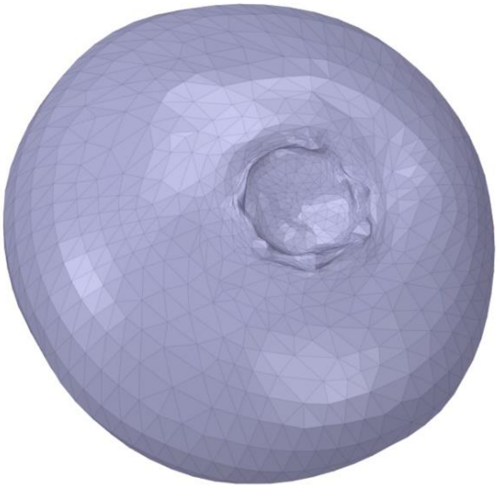

Fig. 1. Graphic model of the blueberry fruit

For the correctness of the simulation, the material constants (Table 1) of the transported raw material were assumed and the process conditions for which the simulation was carried out were determined. A constant mass flow of blueberry fruit equal to 0.1 kg/s was assumed. The following diameter distribution was assumed for the analysis: 80% of blueberries with a characteristic diameter of 12 mm and 20% with a diameter of 15 mm.

Tab. 1. Summary of selected physical properties of blueberry fruits used in the model.

Variable	Value
Blueberry-wall static friction coefficient	0.6
Coefficient of dynamic friction blueberry-walls	0.6
Static friction coefficient between blueberries	0.7
Blueberry-blueberry dynamic friction coefficient	0.7
Bulk density of blueberry fruit, kg/m^3	640
Young's modulus, MPa	0.6092

A coefficient of restitution of 0.7 was assumed for initial calculations, while in further calculation steps a parametric analysis was carried out to study the effect of the coefficient on the values of forces acting on the fruit.

The analysis was conducted for a shaking conveyor, for which there is product movement in a plane parallel to the plane of the trough. In addition, the transported material slides in the trough under the influence of inertia forces. Figure 2. shows the CAD model of the conveyor.

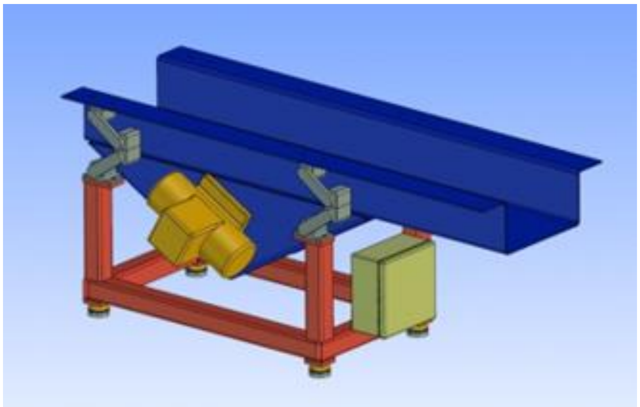

Fig. 2. CAD model of the conveyor

A linear spring hysteresis model was used to determine the normal forces [21]. This model describes elastic collision with energy dispersion due to the deformation of the particle. The model used is described by equation (1). Analyses were conducted in a non-stationary (time-varying) mode this equation was made time-dependent. The normal force at a given time step F_n^t is, according to the DEM Technical Manual [21]:

$$F_n^t = \begin{cases} min\left(K_{nl}s_n^t, F_n^{t-\Delta t} + K_{nu}\Delta s_n\right) if\ \Delta s_n \geq 0 \\ max\left(F_n^{t-\Delta t} + K_{nu}\Delta s_n, \lambda K_{nl}s_n^t\right) if\ \Delta s_n < 0 \end{cases} \tag{1}$$

where:

F_n^t and $F_n^{t-\Delta t}$ normal forces at design step t and t-Δt,

$\Delta\ s_n$ is the change in the distance of the particles in the normal direction (Fig.10), the value is positive when the particles approach and negative when the particles separate. K_{nl} and K_{nu} are the stiffness values of the particle in the normal direction with increasing and decreasing load.

The values of the particle stiffn K_{nl} i K_{nu} are dependent on the particle parameters, namely the particle's Young's modulus E, the coefficient of restitution ε and the particle size L. The material data associated with the particle are entered by the user. For contact between two particles or a particle and a wall, the stiffnesse K_{nl} i K_{nu} are described by equations (2) and (3):

$$\frac{1}{K_{nl}} = \begin{cases} \dfrac{1}{K_{nl,p1}} + \dfrac{1}{K_{nl,p2}} \\ \dfrac{1}{K_{nl,p}} + \dfrac{1}{K_{nl,b}} \end{cases} \tag{2}$$

$$K_{nu} = \frac{K_{nl}}{\varepsilon^2} \tag{3}$$

Where the subscr *p1* oraz *p2* efer to particle 1 and particle 2, respectively. The individual values of the stiffness of the particle $K_{nl,p}$ and the wall $K_{nl,b}$ are calculated according to the following formulas:

$$K_{nl,p} = E_p L \tag{4}$$

$$K_{nl,b} = E_b L \tag{5}$$

where:

- E_p is the value of Young's modulus or elasticity of the particle material, which the user enters in the Rocky DEM editing panel,
- E_b is the Young's modulus or elasticity value of the wall material, which the user enters in the Rocky DEM editing panel,
- L is the size of the particle.

The tangential forces resulting from contact between the borings were determined using an elastic Coulomb model. In this case, the collision is treated completely elastically. In the ideal case (excluding frictional forces), it could be described by equation (6):

$$F_{\tau,e}^{t} = F_{\tau}^{t-\Delta t} - K_{\tau}\Delta s_{\tau} \tag{6}$$

where:

$F_{\tau}^{t-\Delta t}$ is the value of the tangential force at time t-Δt,

Δs_{τ} S is the change in particle distance in the tangential direction,

K_{τ} is the value of the stiffness of the particle in the tangential direction defined as the fraction of the normal stiffness K_{nl} from equation (1).

Equation (6) describes the ideal case. However, in the simulation cases analyzed, it was necessary to additionally take into account the force limit as well, by determining the Coulomb limit:

$$F_{\tau}^{t} = min\left(\left|F_{\tau,e}^{t}\right|, \mu F_{n}^{t}\right)\frac{F_{\tau,e}^{t}}{\left|F_{\tau,e}^{t}\right|} \tag{7}$$

Where μ is the coefficient of friction defined for a given contact pair. If the force determined from equation (5) exceeds the limit value described by the μF_{n}^{t} component, the force takes the value of this component and the sign determined for equation (5).

Simulation of blueberry transport was carried out on a trough conveyor, which was designed in CAD. The digital model of the structure was then imported in STL format for simulation calculations. A reciprocating motion implemented along the feeder trough with deflections of 6 mm was assigned for the conveyor geometry. The return movement of the trough was faster than the forward movement and the time for each was 0.01 s and 0.03 s, respectively.

3. Results of simulation

3.1. Simulation of normal forces

Figure 3 provides a screen view of the Rocky DEM during the transport of blueberries on a smooth trough. The figure includes the distribution of normal forces acting on the blueberries in the conveyor trough.

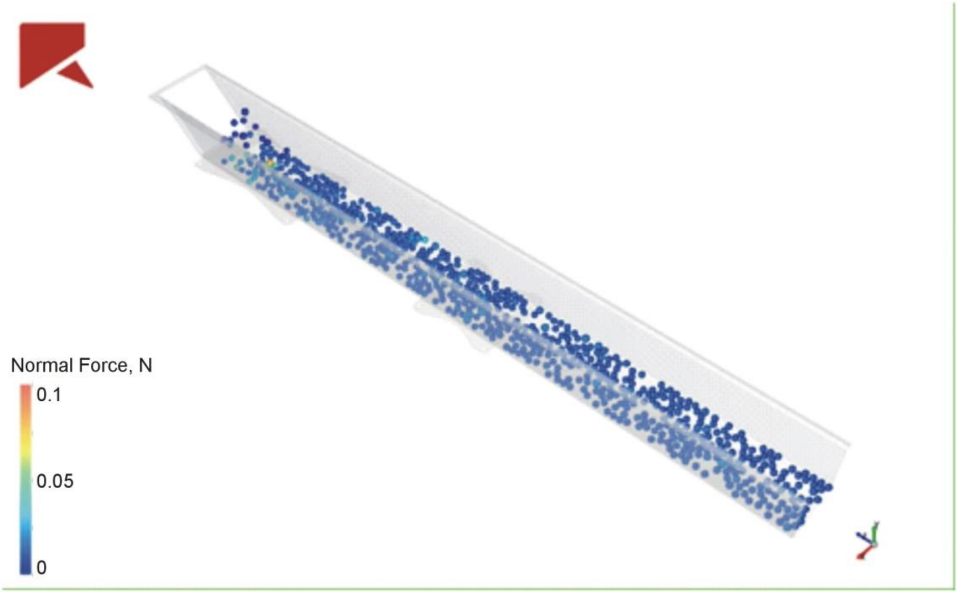

Fig. 3. Summary of normal forces acting on the blueberry

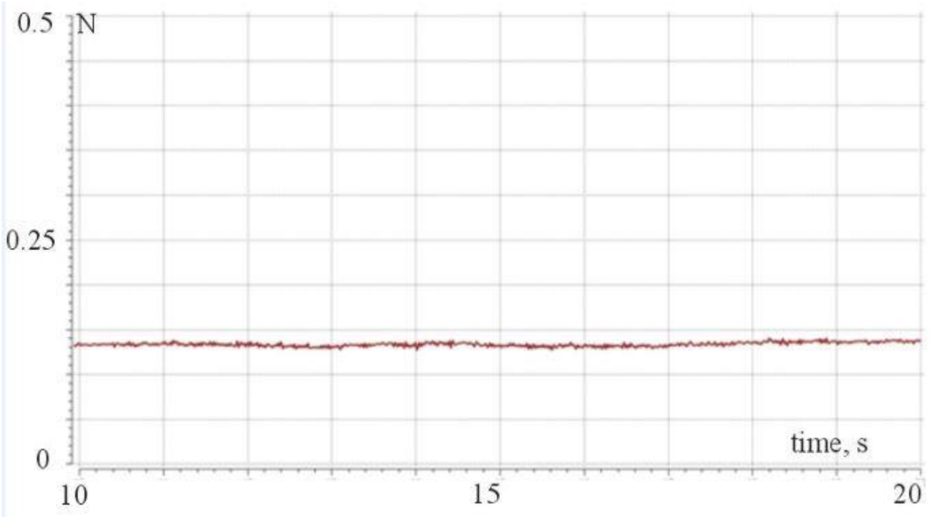

Fig. 4. Average forces in time acting on blueberry fruit in the normal direction

For a better interpretation of the results, Figure 4 shows the values of the average forces acting on the fruit in the direction normal to its surface. And Figure 5 shows the values of the standard deviation of the average force acting on the fruit in the direction normal to its contact surface.

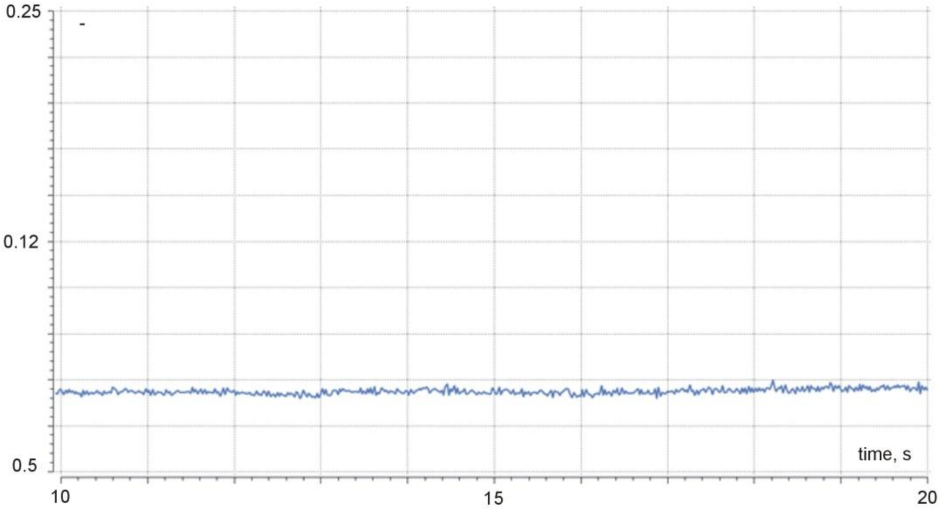

Fig. 5. Mean standard deviation (SD) of normal forces acting on blueberry fruit

3.2. Simulation of tangential forces

During the simulation, collision statistics of tangential forces acting on blueberries between fruits, as well as due to collisions with conveyor walls, were collected. Tangential forces, like normal forces, are an indicator of the quality of the transport as they are responsible for the damage caused on their surface, which indirectly affects the internal structure of the fruit. The results presented here are for the last 10 seconds of fruit movement on the feeder, while the simulation time was 20 seconds. This allowed the steady state operation of the feeders to be obtained and the simulation model to provide average values for a sufficiently long period of operation of the equipment. Figure 6 shows the results of the simulations obtained for tangential forces, while Figure 7 shows the changes in the standard deviation of the average force acting on the fruit in the tangential direction.

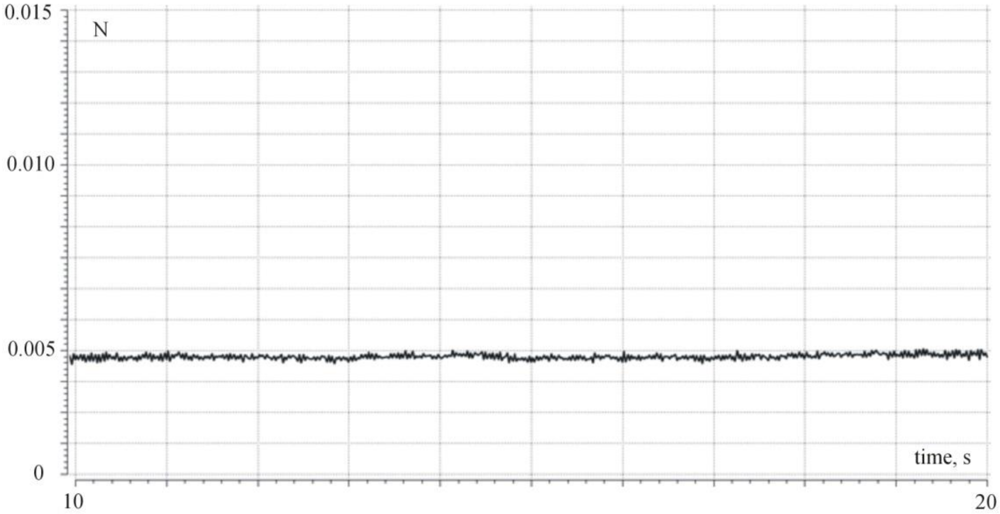

Fig. 6. Average forces acting in time on fruit in the tangential direction

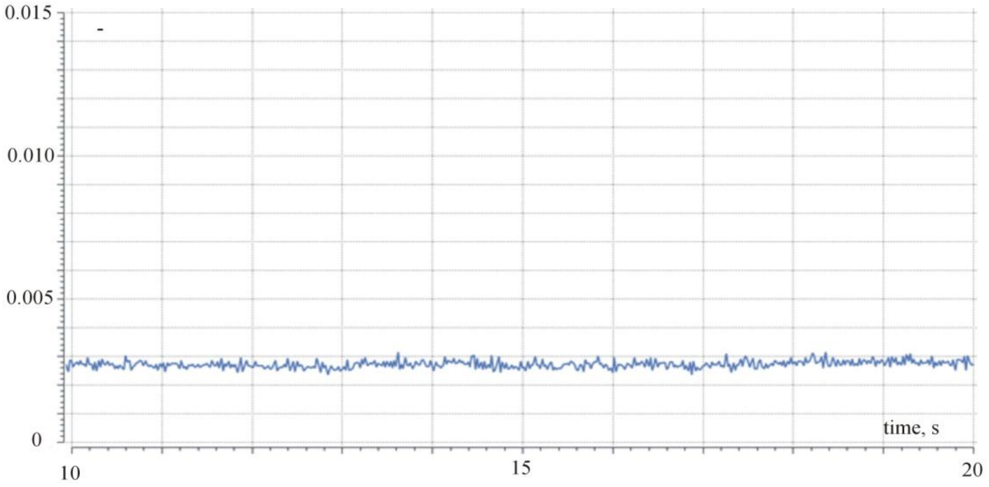

Fig. 7. Standard deviation (SD) of the mean force acting on the fruit in the tangential direction

3.3. Simulation of normal and tangential forces dependent on mass expenditure

In addition to simulating the normal and tangential forces acting on the blueberries, the interactions of the fruit and the transport chute were simulated, making the results dependent on the mass output of the transported fruit on the feeder.

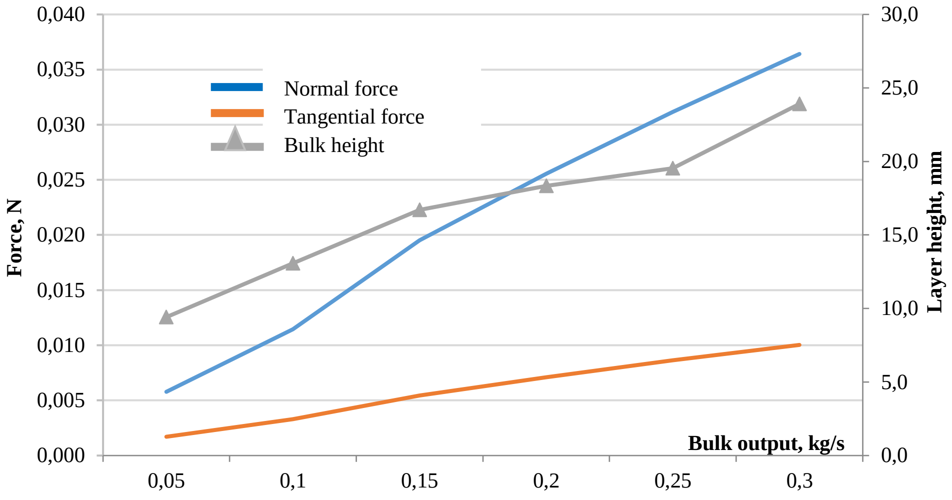

Fig. 8. Average normal and tangential forces acting on the fruit as a function of mass disbursement and layer height

In addition, complementary calculations of changes in the value of the energy restitution coefficient on the values of normal and tangential forces acting on the fruit were carried out. Figure 9 shows the calculated values of normal and tangential forces resulting from the change in the energy restitution coefficient.

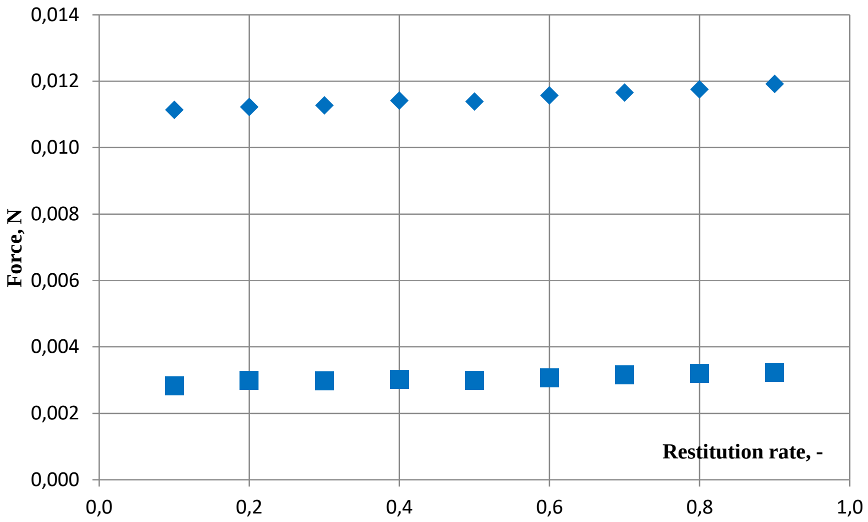

Fig. 9. Average values of forces acting on fruit in the normal and tangential directions depending on the value of the restitution factor; ◆ - normal forces, ■- tangential forces

4. Discussion and conclusions

Based on the simulation results in Figures 3 to 7, it is noticeable that the normal and tangential forces acting on the blueberry fruit are almost unchanged. The normal forces for the tested fruits are about 0.013 N with an SD value of ≅0.0028. Also, the calculated value of tangential forces during the movement of blueberries along the gutter does not show much change and was ~0.0038 N with SD ≅0.0028. Such small values of forces occurring at the fruit contact points ensure the absence of mechanical damage during the movement of fruits on the conveyor transport gutter.

At the same time, a positive correlation was observed between normal and tangential forces during the variation of the mass output of blueberries transported on the conveyor trough. For the smallest simulated mass disbursement of 0.05 kg/s, the normal and tangential forces acting on the blueberry fruit were 0.0218 N and 0.09 N, respectively, with a stabilized blueberry layer height of 11 mm (Fig. 8.). For the highest mass output of 0.3

kg/s, the values of normal and tangential forces were 0.0365 N and 0.014 N, respectively, at a stabilized layer height of 30 mm. At the same time, there was no significant effect of the restitution factor on the value of tangential and normal forces (Fig. 9).

Conducting process simulations clearly indicated the advantages in using a conveyor with reciprocating motion for transporting blueberries and other soft fruits. The very limited number of fruits that can be damaged, during transport, applies to fresh (unfrozen) and frozen fruits. Conducting simulations using RockyDEM software made it possible to determine the forces acting on the transported material along the entire length of the trough conveyor. At the same time, the behavior of the deposit on the conveyor trough was described.

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