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The geometric shape of the transported material batches in the vertical branch of a belt conveyor

Leopold Hrabovský[1*] and *Jan* Blata[1]

[1]Faculty of Mechanical Engineering, Department of Machine and Industrial Design, VSB - Technical University of Ostrava, 17. listopadu 2172/15, 708 00 Ostrava - Poruba, Czech Republic

Abstract. Transport above the limit angle of transport inclination provided using belt conveyors can be done in several ways. If we omit the methods based on an increase in the contact force of the transported material in relation to the surface of the conveyors belt and increase in the coefficient of friction, we will focus only on the method based on the principle of preventing the movement of the transported grains on the surface of the conveyors belt. This principle uses transverse cleats that prevent the movement (sliding or rotation) of material grains along the entire length of the conveyor belt, which is inclined at a high angle to the horizontal plane. Material grains are transported on the surface of a conveyor with cleats, distributed with a regular spacing along the entire length of the endless loop of the conveyor belt. To prevent material grains from falling of such a belt, corrugated sidewalls are fitted on both edges of the conveyor belt. This paper describes two variants that take into account the mutual position of the cleats in relation to the corrugated sidewalls. For each of the variant, the relationship is given with which it is possible to analytically quantify the volume of the bulk loose material batch that is spread over the area of the cleat in the vertical section of this conveyor belt design. The results of the measured values concerning the height of the loose material pile that were taken using laboratory instruments are listed in the tables and compared with the theoretically calculated values. Key data that must be known to calculate the pile height, and the volume of the transported material batch represent the exact value of the angle of repose for the loose material. The angle of repose of a particular loose material does not acquire a constant size, as it changes from its maximum (static angle of repose) depending on the shaking, flattening or absorbing liquid to its minimum (surcharge angle). The paper presents geometric shapes of batches for the transported material used for both limit values of the angle of repose.

1 Introduction

Loose materials, whether natural or artificial, must be handled in various areas of industry both in the horizontal and vertical planes. The requirement to transport the necessary volume or weight of material quantity to a specific offtake point places demands on the optimal selection, perfect design and precise implementation of the transport equipment. Of the whole

* Corresponding author: leopold.hrabovsky@vsb.cz

range of continuously operating transport equipment, belt conveyors are the most widely used type for the transport of loose materials in practice. Despite a number of advantages, belt conveyors also have some shortcomings, among which a limited inclination angle for transport can be included, if a conveyor of standard construction is used as a load-bearing element.

In the article [1] are given the relationships to calculate the parameter *p [m]* and height h_{max} *[m]* of the parabola, which is the envelope of the surface for filling the transversal belt. Using these relationships, it is possible to analytically quantify the specific height h_{max} of the parabola, if the surcharge angle Θ *[deg]* for the transported material is known and loading width *b [m]* (for a flat loading profile) or a clear loading width b_1 *[m]* (for the trough loading profile) of the conveyor belt.

The distance z_x *[m]* over which the transported material is spread and carried on the surface of the straight conveyor belt before the cleat of height *H [m]* is described in [2].

It is similar to an inclined belt conveyor that uses a conveyor belt with cleats, and which is supported by flat [2] or trough [1] roller idler frames, as for a vertical belt conveyor of the Flexowell type [3], see Fig. 1, it is necessary to feed the transported material (on a conveyor belt into the space between two adjacent cleats spaced apart by a value of L_c *[m]*) in batches of a precisely defined volume size.

The belt conveyor of the Flexowell type [3], designed by Scholtz company, is based on an atypical design of drawing and load-bearing elements, which is formed by the traditional structure of a conveyor belt to which cleats and rubber corrugated sidewalls are vulcanized, or mechanically attached in the case of larger structures.

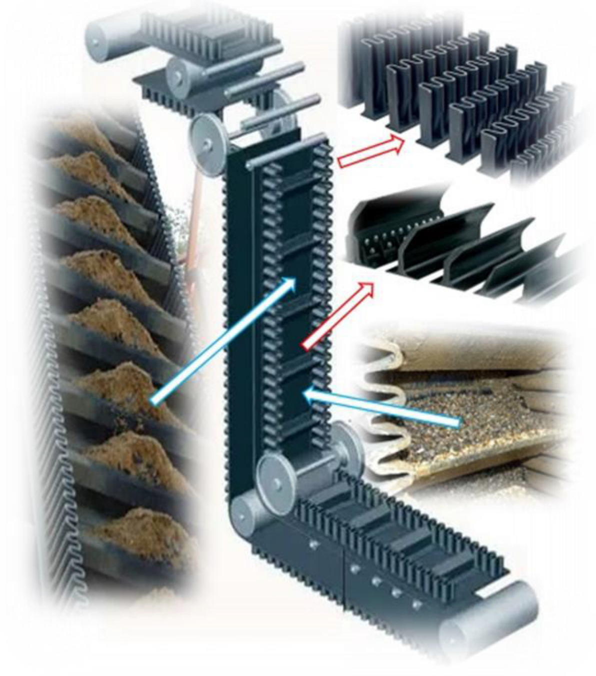

Fig. 1. Vertical conveyor with a conveyor belt equipped with cleats and corrugated sidewalls

Conveyed material of a specific surcharge angle Θ is in case of the Flexowell conveyor [4], [5] fed onto the conveyor belt in the horizontal section, and only exceptionally in the vertical one. Grains of the transported loose material are fed (by transferring from the previous conveyor or discharged from the outlet of a hopper) in the horizontal section to the load-bearing element (conveyor belt with cleats and corrugated sidewalls) and they are rearranged in the transfer section of the Flexowell conveyor. When transported in the vertical section of the conveyor, they are supported by cleats of a height H_c *[m]*.

To prevent the conveyor belt of width *B [m]* to pull away from the conveyor rollers in the load-bearing branch (the flat loading profile of the conveyor belt), pressure rollers (Fig. 2) of width B_1 *[m]* are applied in the transfer section of the conveyor.

The falling of material grains over the side edges of the cleats is prevented by using the corrugated sidewalls of height H_s *[m]* and width B_2 *[m]*.

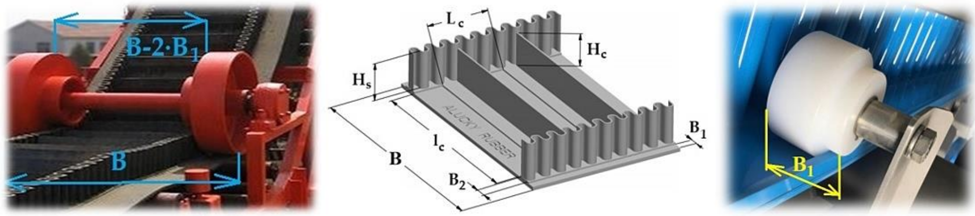

Fig. 2. Conveyor belt pressure drum with cleats and corrugated sidewalls.

The length of the cleat l_c *[m]* is the same as the loading width of the conveyor belt *b* [6], [7]. The length of cleat l_c can be described according to Fig. 2 using the relationship (1).

$$l_c = B - 2\cdot\left(B_1 - B_2\right)\ [m] \tag{1}$$

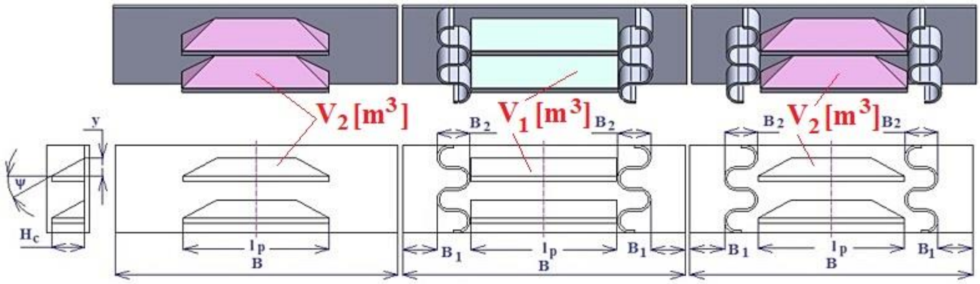

Fig. 3. The volume of material batch spread over the cleat.

By positioning the cleats conveniently on the working surface of a conveyor belt in relation to the corrugated sidewalls (Fig. 3), the volume of the batch for the transported material carried by the cleat in the vertical branch of the conveyor can be increased. If the corrugated sidewalls are placed in relation to the cleat as in Fig. 3b, and if the angle ψ *[deg]* is the static (natural) angle of repose for the material [8], the volume V_1 *[m³]* of the material batch can be expressed according to Eq. (2).

$$V_1 = \int_{-l_c/2}^{l_c/2} S_{yz}\cdot dx = 2\cdot\int_0^{l_c/2} \frac{1}{2}\cdot H_c\cdot y\cdot dx = 2\cdot\int_0^{l_c/2} \frac{1}{2}\cdot H_c^2\cdot tan(\psi)\cdot dx\ [m^3] \tag{2}$$

Fig. 4a can be expressed if we know the static angle of repose ψ for the transported material, height *y [m]* Eq. (3) and surface S_{yz} *[m²]* Eq. (4) for one batch of the transported material in plane *yz*.

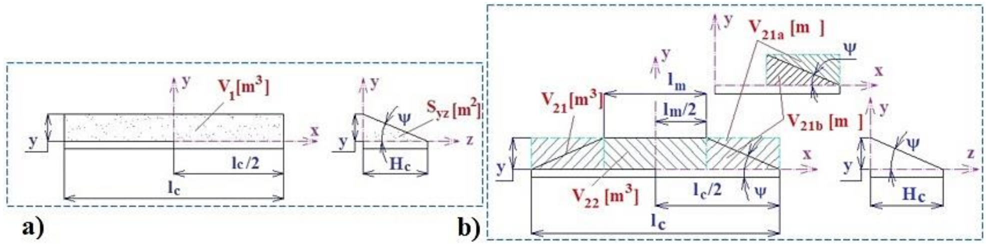

Fig. 4. The geometric shape of the material batch static angle of repose ψ transported by the cleat concerning the position of the corrugated sidewalls.

$$y = H_C \cdot tan(\psi) \ [m] \tag{3}$$

$$S_{yz} = \frac{1}{2} \cdot H_C \cdot y = \frac{1}{2} \cdot H_C^2 \cdot tan(\psi) \ [m] \tag{4}$$

If the corrugated sidewalls in relation to the cleats are placed according to Fig. 3c, or if the conveyor belt is not fitted with corrugated sidewalls (Fig. 3a), the volume $V_2 \ [m^3]$ of the material batch (Fig. 3 and Fig. 4b) can be expressed using the following relationship (5). Material volume $V_{22} \ [m^3]$ on the length of the section $l_m \ [m]$, see Fig. 4b, can be expressed by the relationship (6).

$$V_2 = 2 \cdot V_{21b} + V_{22} \ [m^3] \tag{5}$$

$$V_{22} = \int_{-l_m/2}^{l_m/2} S_{yz} \cdot dx = 2 \cdot \int_{0}^{l_m/2} \frac{1}{2} \cdot H_C \cdot y \cdot dx = 2 \cdot \int_{0}^{l_m/2} \frac{1}{2} \cdot H_C^2 \cdot tan(\psi) \cdot dx \ [m^3] \tag{6}$$

Volume $V_{21} \ [m^3]$ (Fig. 4b) of the transported material carried in both end parts of the cleat can be expressed using the relationship (7). The volume size of transported material $V_{21} \ [m^3]$ (Fig. 5a) can be divided into two volumes $V_{21a} \ [m^3]$ and $V_{21b} \ [m^3]$ see the relationship (8).

$$V_{21} = \frac{V_1 - V_{22}}{2} = \int_{l_m/2}^{l_c/2} \left(\frac{1}{2} \cdot H_C \cdot y \right) \cdot dx \ [m^3] \tag{7}$$

$$V_{21b} = \int_{0}^{H_C} S_{yz}(x) \cdot dx = \int_{0}^{H_C} \frac{1}{2} \cdot (H_C - x)^2 \cdot tan(\psi) \cdot dx \ [m^3] \tag{8}$$

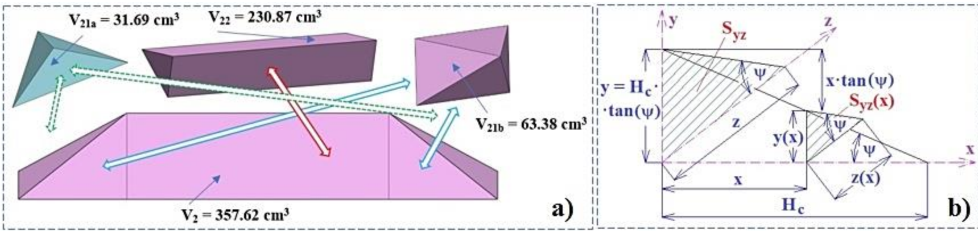

Fig. 5. Volume V_i *[m³]* of a sub-part of the geometric shape in the material batch carried by the cleat without the influence of corrugated sidewalls a) by SolidWorks software, b) computational sketch.

Height *y(x) [m]* and length *z(x) [m]* of the transported material pile depending on the distance *x [m]* (according to Fig. 5b, it follows that $x = 0 \div H_c$ *[m]*) in plane *xy* can be expressed by relationship (9). The surface size $S_{yz}(x)$ *[m²]* according to Fig. 5b can be expressed using relationship (10).

$$y(x) = y - x \cdot tan(\psi) = H_c \cdot tan(\psi) - x \cdot tan(\psi) = \left(H_C - x\right) \cdot tan(\psi) \; [m]$$
$$z(x) = \frac{y(x)}{tan(\psi)} = H_C - x \; [m] \tag{9}$$

$$S_{yz}(x) = \frac{1}{2} \cdot y(x) \cdot z(x) = \frac{1}{2} \cdot y(x) \cdot \frac{y(x)}{tan(\psi)} = \frac{1}{2} \cdot (H_c - x)^2 \cdot tan(\psi) \; [m^2] \tag{10}$$

If the corrugated sidewalls are placed in relationship to the cleat as shown in Fig. 3b, and the angle *Θ* is a surcharge angle of the transported material, the volume V_3 *[m³]* of the material batch (for the case when the corrugated sidewalls prevent grains from falling over the end parts of the cleats) can be expressed using the relationship (11).

$$V_3 = \int_{-\frac{l_C}{2}}^{\frac{l_C}{2}} S_{yz}(x) \cdot dx = 2 \cdot \int_0^{\frac{l_C}{2}} \left(h_{max} - \frac{z^2}{2 \cdot p} \right) \cdot dx = \int_0^{l_C} \left(h_{max} - \frac{z^2}{2 \cdot p} \right) \cdot dx \; [m^3] \tag{11}$$

where *z [m]* is the horizontal distance of the parabola vertex from the parabola point in plane *zy* of the coordinate system (of which the axis is parallel to the *y*-axis), see Fig. 6b.

According to Fig. 6, if we know the value of surcharge angle *Θ* for the transported material, we can express the height of the pile cross-section for the belt filling *y(z) [m]* (i.e., the vertical distance of the parabola point from the *z*-axis) using the relationship (12) and surface $S_{yz}(x)$ *[m²]* by relationship (13) for one batch of the material transported in the plane *yz*. In the relationship (12) expression *p [m]* (14) represents the parabola parameter and expression h_{max} *[m]* (14) the height of the parabola.

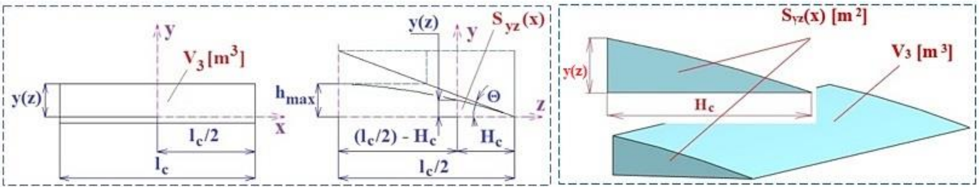

Fig. 6. The geometric shape of the material batch surcharge angle *Θ* carried by the cleat.

$$y(z) = h_{max} - \frac{z^2}{2 \cdot p} = \frac{l_c \cdot tan(\Theta)}{4} - \frac{z^2 \cdot tan(\Theta)}{l_c} = \left(\frac{l_c}{4} - \frac{z^2}{l_c}\right) \cdot tan(\Theta)\ [m] \quad (12)$$

$$S_{yz}(x) = \int_{\frac{l_c}{2} - H_c}^{\frac{l_c}{2}} y(z) \cdot dz = \int_{\frac{l_c}{2} - H_c}^{\frac{l_c}{2}} \left(h_{max} - \frac{z^2}{2 \cdot p}\right) \cdot dz\ [m^3] \quad (13)$$

$$p = \frac{l_c}{2 \cdot tan(\Theta)}\ [m],\ h_{max} = \frac{l_c \cdot tan(\Theta)}{4}\ [m] \quad (14)$$

2 The experimental device, measurement methodology

In the R&D laboratory of the Department of Machine and Industrial Design, Faculty of Mechanical Engineering, VSB-Technical University Ostrava, experimental measurements were carried out to determine the height y_m *[m]* for the transported material batch spread out on a cleat of length l_c *[m]* and height H_c *[m]*, fixed in a vertical section in relation to a conveyor belt fitted with corrugated sidewalls.

The experimental site consists of three mutually separable parts, see Fig. 7. The basic part is a straight chute 1, which includes a frontal 1a and side 1b board. Sliding (in the *x*-axis direction), the side board 2 along the width of the trough 1 simulates, together with the side board 1b, the corrugated sidewalls of the Flexowell type conveyor belt. On the frontal board 1a using bolts 4, there is a slider mounted 3 (movable in *z*-axis), simulating a cleat.

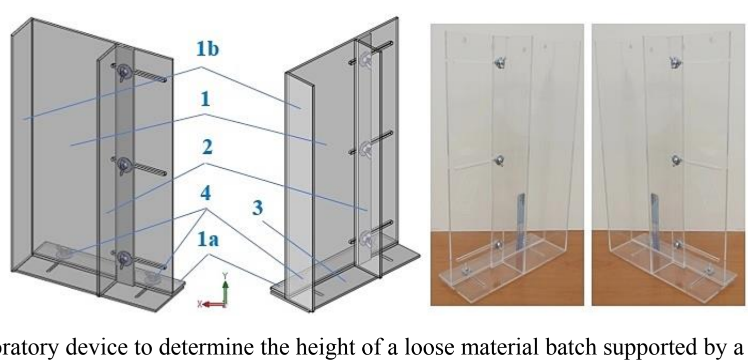

Fig. 7. Laboratory device to determine the height of a loose material batch supported by a cleat of height H_c and length l_c.

Loose material [9] was gradually evenly spread along the entire length l_c of the cleat (slider 3) with known height H_c, parallel to the horizontal plane. Maximum height *y* (3), or *y(z)* (12), for the option displayed in Fig. 3b, of the material layered on the cleat (in contact with the vertical wall of the trough 1) was read using a ruler attached to the back of the trough 1. and the data were entered into Table 1-2.

For the variant displayed in Fig. 3a or Fig. 3c, the sliding side board was removed from measuring device 2. Using a ruler, the height *y(x)* (9) of material spread on the cleat was measured and the data were entered into Table 3-4.

3 Values measured in the laboratory

For versions with cleats placed against surcharge angles on a conveyor belt of the Flexowell type (as in Fig. 3b) using the laboratory device, the height y_m of the loose material was measured depending on the height H_c by moving slider 3, by which the layer of the loose material is supported. The measured values of the height y_m for the loose material (chickpeas $\psi = 27$ *deg*, $\Theta = 16$ *deg*, hulled grains $\psi = 29$ *deg*, $\Theta = 19$ *deg*) on the trough, see Fig. 7, which simulates the vertical section of the Flexowell type conveyor belt, were compared with theoretically calculated height *y* (3), see Table 1 or Table 2.

Table 1. Height y_m, $y_m(z)$ of material batch - chickpeas, $\psi = 27$ *deg*, $\Theta = 16$ *deg*.

H_c, y, y(z) [mm]	y_m [mm]	$y_m(z)$ [mm]	H_c, y, y(z) [mm]	y_m [mm]	$y_m(z)$ [mm]	H_c, y, y(z) [mm]	y_m [mm]	$y_m(z)$ [mm]
20, 10.2, 5.4	7 [1]	4	50, 20.4, 10.0	14	8	70, 35.7, 15.5	30	15
	8	5		15 [2]	9		29	14
	7	4		15	9		29 [3]	14
Σy_m, $\Sigma y_m(z)$	22	13		44	26		88	43
$\Sigma y_m/n$, $\Sigma y_m(z)/n$	7.3	4.3		14.7	8.7		29.3	14.3
y_m	7.3 ± 1.7			14.7 ± 1.7			29.3 ± 1.7	
$y_m(z)$	4.3 ± 1.7			8.7 ± 1.7			14.3 ± 1.7	

[1] see Fig. 8a, [2] see Fig. 8b, [3] see Fig. 8c.

For the measurements taken, placing the cleats against the corrugates sidewalls as in Fig. 3a or Fig. 3c, the laboratory equipment was modified. This modification consisted in removing sliding side board 2 (that simulated the corrugated sidewalls mounted on a real conveyor belt of the Flexowell type [10]), which did not prevent a batch of loose material supported by slider 3 (simulating a cleat of height H_c) to slide over the right edge of slider 3.

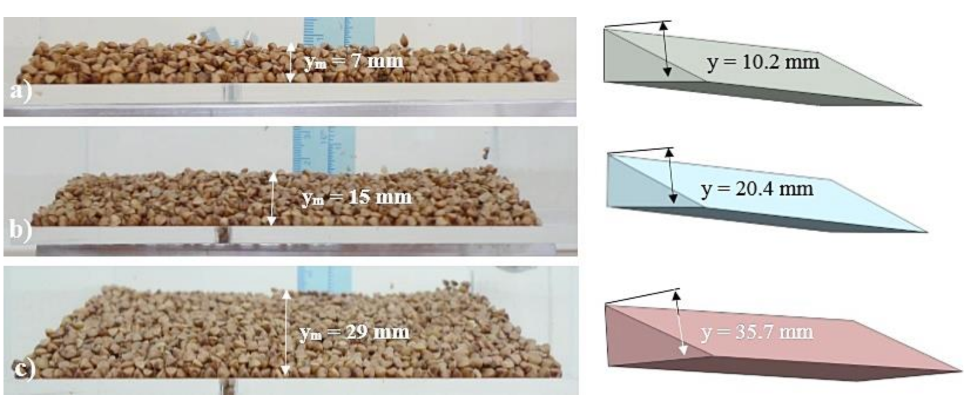

Fig. 8. Theoretically and experimentally determined height *y* and y_m and *y(z)* and $y_m(z)$ for the loose material batch.

Table 2. Height y_m, $y_m(z)$ of the material batch - hulled grains, $\psi = 29$ *deg*, $\Theta = 19$ *deg*.

H_c, y, y(z) *[mm]*	y_m *[mm]*	$y_m(z)$ *[mm]*	H_c, y, y(z) *[mm]*	y_m *[mm]*	$y_m(z)$ *[mm]*	H_c, y, y(z) *[mm]*	y_m *[mm]*	$y_m(z)$ *[mm]*
20, 11.1, 6.4	8	5 [4]	50, 22.2, 12.0	16	10	70, 38.8, 18.7	32	18
	9	5		15	10 [5]		31	19
	9	5		16	9		31	18 [6]
Σy_m, $\Sigma y_m(z)$	26	15		47	29		94	55
$\Sigma y_m/n$, $\Sigma y_m(z)/n$	8.7	5.0		15.7	9.7		31.3	18.3
y_m	8.7 ± 1.7			15.7 ± 1.7			31.3 ± 1.7	
$y_m(z)$	5.0 ± 0.0			9.7 ± 1.7			18.3 ± 1.7	

[4] see Fig. 9a, [5] see Fig. 9b, [6] see Fig. 9c.

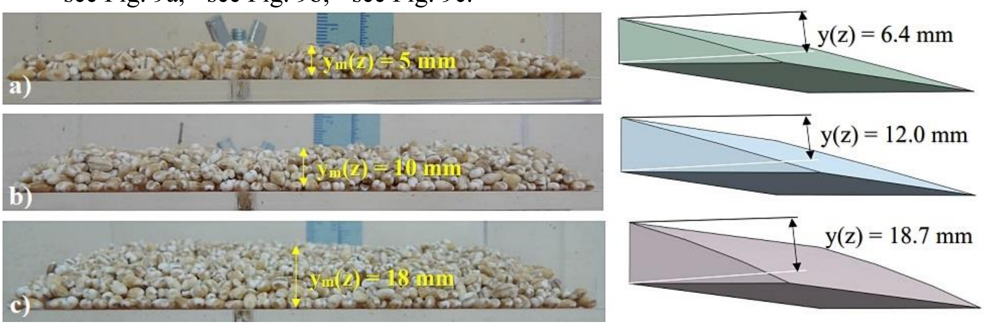

Fig. 9. Theoretically and experimentally determined height *y(z)* and $y_m(z)$ of the loose material batch.

Using laboratory instruments, the heights y_m and lengths x_m *[m]* ($x = H_c \cdot tan(\psi)$, see Fig. 10) were measured for various loose materials, depending on the height H_c, i.e. extending slider 3, by which the layer of loose material is supported. Measured values for height y_m and length x_m *[m]* of the loose material batch represented by hulled grains taken by laboratory equipment are shown in Table 3.

Fig. 11 illustrates two geometric shapes for the batch of the transported material volume V_1 (2) and V_2 (5) in the vertical branch of the Flexowell type of the conveyor belt depending on the mutual position of the cleat and corrugated sidewalls.

Table 3. Height y_m and length x_m of the material batch - hulled grains, $\psi = 29$ *deg*.

H_c, y, x [mm]	y_m [mm]	x_m [mm]	H_c, y, x [mm]	y_m [mm]	x_m [mm]	H_c, y, x [mm]	y_m [mm]	x_m [mm]
20, 11.1, 36.1	7 [7]	21 [7]	50, 22.2, 72.2	19 [8]	56 [8]	70, 38.8, 126.3	31 [9]	111 [9]
	8	20		18	60		31	115
	8	22		18	58		32	112
Σy_m, Σx_m	23	21		55	174		94	338
$\Sigma y_m/n$, $\Sigma y_m/n$	7.7	7.0		18.3	58.0		31.3	112.7
Σy_m	7.7 ± 1.7			18.3 ± 1.7			31.3 ± 1.7	
Σx_m	21.0 ± 2.5			58.0 ± 5.1			117.7 ± 5.9	

[7] see Fig. 10a, [8] see Fig. 10b, [9] see Fig. 10c.

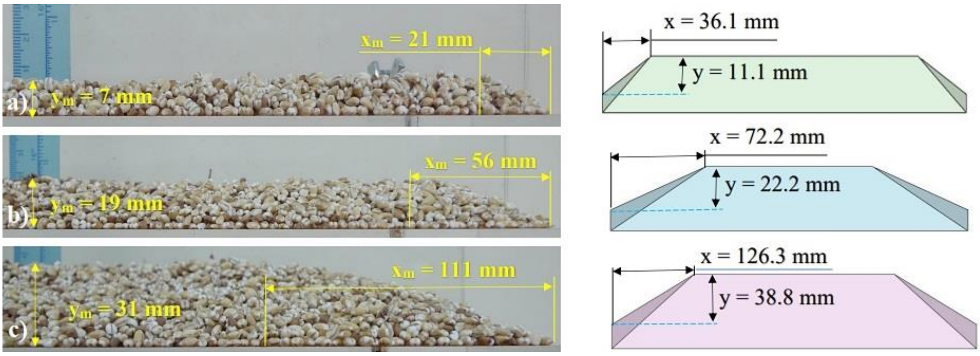

Fig. 10. Theoretically and experimentally determined height y_m and length x_m of the loose material batch.

When looking at the conveyor belt from the side, cleats can be inclined to the longitudinal axis of the conveyor belt by an angle β *[deg]*, which is less than *90 deg*. These cleats are produced with the same angle of inclination β along with its entire height H_c *[m]* model C [11] or as angled i.e., angles of inclination β_1 *[deg]* and β_2 *[deg]* model TC [11]. Cleats of type C and TC can transport a larger volume of loose material batch compared to transverse cleats inclined at an angle of 90 degrees relative to the longitudinal axis of the conveyor belt [12].

Fig. 11. The geometric shape of the transported material batch provided by the conveyor belt of the Flexowell type.

4 Conclusion

The volume amount of material that can be transported by the Flexowell type of belt conveyor per unit of time can be regulated by the speed of the conveyor belt movement, the size of the transported material batches fed into the space between the two cleats and the distances of cleats. The minimum spacing for cleats that can be designed for a specific material transported by a belt conveyor is determined by the maximum height of the material batch layer spread over the cleat. The height of the material batch carried by the cleat is influenced by the cleat height and angle of inclination, and by the angle of repose.

This paper presents relationships that take into account only the perpendicular angle of inclination for a given cleat against the longitudinal axis of the conveyor belt. If the cleat is from the side view (the plane *yz* of the coordinate system) to the belt conveyor inclined at an angle $\beta < 90$ *deg*, the original area of the transported material batch would be increased in plane *yz* by the area in the shape of a right-angled triangle. The size of this triangular area can be calculated from the length (equal to the height of the cleat), the triangle hypotenuse and angle β inclination of the cleat.

Experimentally determined height values y_m and $y_m(z)$ of the two other kinds of material batches that were transported (chickpeas and hulled grains), on laboratory equipment (see Fig. 7) in the case when the height y_m and $y_m(z)$ of the material batch pile is the same along the entire length l_c of the cleat, are listed in Table 1. and Table 2. Experimentally obtained height values y_m and $y_m(z)$ have been verified with theoretically calculated height values y (3) and $y(z)$ (12). The measured values for the height y_m achieved only $69\% \div 84\%$ of the height y value that was theoretically calculated for chickpeas and $72\% \div 82\%$ for hulled grains. This difference between the measured values and theoretical calculations can be explained by the fact that when the conveyor belt passes from the horizontal section to the vertical one, the transported grains of the material are rearranging from the original shape to the shape illustrated in Fig. 8. Rearrangement of material grains in the transfer section of the Flexowell type belt conveyor happens while the conveyor belt is moving, which shakes off the material and causes changes (a decrease by $18\% \div 28\%$) of the angle for the surface lines of the cone formed by the transported material in relation to the horizontal plane, i.e. the static angle of repose.

Experimentally obtained values for height $y_m(z)$ from the geometric shape of the transported material (plane yz) achieved only $74\% \div 97\%$ values of theoretically calculated height $y(z)$ for chickpeas and $75\% \div 96\%$ for hulled grains (Fig. 9). Greater differences between the measured values $y_m(z)$ and theoretically calculated values $y(z)$ were achieved at lower heights of cleat H_c. When moving slider 3 on the laboratory device by 70 mm (which simulated the height of cleat H_c), the difference between the measured values $y_m(z)$ and theoretically calculated values $y(z)$ is completely negligible (reaching only 3%).

For calculating capacity, and for an accurate calculation of transport output described using the volume unit $[m^3/h]$ or weight unit $[kg/h]$ for a belt conveyor of the Flexowell type, it is necessary to substitute as ψ expression $\varphi = (0.7 \div 0.8)\psi\ [m^3/h]$ into the following mathematical relationships (2) and (5) as the value of static angle of repose. For materials normally transported it is valid that $\varphi \simeq \Theta$.

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