DECREASE OF ELASTIC PROPERTIES OF OLEAGINOUS FLAX RESIDUES BY DECORTICATION
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ЗНИЖЕННЯ ПРУЖНИХ ВЛАСТИВОСТЕЙ ЗАЛИШКІВ ЛЬОНУ ОЛІЙНОГО ЗА РАХУНОК ДЕКОРТИКАЦІЇ

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ABSTRACT
Harvesting of oleaginous flax seeds creates a biomass of stem residues that needs to be processed or utilized. Many methods of processing this biomass into various products (fiber, fuel, composites, etc.) have been offered. The first step in processing oleaginous flax residue is spinning it into rolls. However, oleaginous flax stems have highly elasticity properties and quick recovering abilities which make residue processing difficult. This paper suggests methods of decreasing the elasticity properties of oleaginous flax residue by destroying the higher layer of stem – decortication. Elasticity properties are influenced by layer thickness, humidity, and the amount of flax breakage as it passes through the roller pairs of a roller machine (decorticator). An increase in humidity and in the number of passes through the decorticator makes elasticity properties decrease. It allows making rolls that will keep their shape for a long period without any additional influences. In the future, these rolls can be used as a fuel or for a longer processing. The research results show a correlation with the rational number of machine roller pairs which can be used to develop new engineering designs for oleaginous flax harvesting.

РЕЗЮМЕ
Після збирання врожаю насіння льону олійного залишається біомаса стеблових відходів, яка потребує переробки або утилізації. На сьогодні запропоновано багато способів подальшої переробки такої біомаси в продукцію різного функціонального призначення (волокно, паливо, композити і т.д.). Всі вони на першому етапі передбачають скручування зібраної біомаси у рулони. Проте стебло льону олійного має великі пружні властивості та здатне швидко відновлюватись. Це ускладнює процеси переробки біомаси стебел льону олійного. У даній статті автори пропонують зменшувати пружні властивості за допомогою руйнування верхнього шару стебла - декортикації. Досліджено та встановлено, що на зменшення пружних властивостей біомаси стебел льону олійного впливають: товщина шару, вологість та кількість проминань (пар вальців у пристосуванні для руйнування стебел біомаси). Збільшення вологості та кількості проминань призводить до зменшення пружних властивостей. А це в свою чергу дозволяє скрутити рулони достатньої густини, які будуть тривалий час утримувати свою форму без впливу додаткових засобів. Такі рулони у подальшому можна використовувати в якості палива, або для подальшої переробки.

INTRODUCTION
Oleaginous flax seeds can be used for food industry, cosmetology, medicine, etc. Therefore, popularity of oleaginous flax continues to grow among agricultural producers. However, a large amount of plant residues remains in the field after oleaginous flax harvesting. This problem can be solved by providing industrial usage of all plant parts – seed and stems. The oleaginous flax stem residues can be utilized to obtain fiber and to produce hard fuel. It was proved that usage of small-sized fuel rolls obtained from oleaginous flax residues is effective and ecofriendly (*Yaheliuk, S. et al., 2020*). The main conditions to form pellets out of flax shive and stem residues have also been identified (*Yahelyuk, S. et al. 2018*). It was determined (*Onuikh Yu. M., 2019*) that there is a possibility to obtain a quality fiber out of oleaginous flax stems on the territory of Western Ukraine.

The similar research has been conducted for France territory conditions. *(Ouagne P. et al., 2017).* It was specified by *Dudarev Igor* what crop harvesting technologies should be applied to obtain a quality fiber (*Dudarev, I., Say, V., 2020*). It is determined that in different geographical areas oleaginous flax has different qualities – the length, stem thickness, bast content. It should be mentioned that oleaginous flax is harvested under differing environmental conditions and differing ripeness. The technologies to obtain and to use oleaginous flax residues depending on its properties (ripeness level, height, fiber content) have been offered by *Yaheliuk S. and others* (*Yaheliuk, S., Didukh, V., Boyko, G., 2020*). Spinning to rolls is also needed for a quick and comfortable transportation. However flax stems have significant elasticity properties and an ability to recover when loading effect is removed (*Hajlis, G. 2004*). These properties can be explained thanks to the flax stem structure. Various parts of flax stem or various phases of ripeness can have various elasticity properties (*Goudenhooft C. et al., 2018*). Also, the environmental conditions influence formation of stem's and fiber's elasticity properties (*Stamboulis A., Baillie C.A., Peijs T., 2001*). Oleaginous flax stems' elasticity properties cause expanding of inside layers of a spinning formed roll. In that case, the unspinning of the roll can happen. So, for each variant of usage of oleaginous flax stem residues (fiber or solid fuel materials) it is needed to decrease elasticity properties of the stem. To achieve integrated oleaginous flax biomass processing, it is required to consider stem characteristics directly at the time of harvesting.

One of the ways to decrease oleaginous flax stem elasticity properties is decortication. The process of decortication according to *Wade Chute, Heny, Rolheiser (Wade Chute, Heny, Rolheiser, 2010)* consists of successive chopping, screening, disc refining, crude bast, crude core, clean bast, bast fiber recovery, clean core. Those procedures are used to receive fiber out of bast crops. Decortication has certain advantages. It does not require a very complicated machinery, allows to produce fiber at reasonable prices, provides a high productivity of bast fibers (*Munder F., Hempel H., 2004*). It was researched, following hemp example, that decortication process is substantially impacted by the plant diameter thus it is essential to select efficient parameters for machinery work (*Boyko G., Tikhosova H., Ternova T., 2020*). *A. N. Assanova* with a group of researchers have defined the role of decortication in bast fibers processing and have determined how decortication process impacts the purity of fiber (*Assanova, A. N. et al., 2020*). However, the researches (*Zimniewska, M. et al. 2017*) have defined that decortication process unfortunately negatively impacts the quality of flax fiber. It is also important to say that the cutting force for textile flax exceeds the cutting force for oleaginous flax by 3-4 times. The value distinction of cutting force increases for the group of stems. The effort of cutting is also influenced by stems humidity (*Yaheliuk S., et al., 2021*).

In summary, it follows that decortication suits the decreasing of oleaginous flax stem elasticity properties best of all. However, nowadays decortication is applied only for fiber crops fiber separation, mainly for hemp. While the decreasing of oleaginous flax stem elasticity properties is not adequately explored. The usage of oleaginous flax stems as a biomass to spin into small-sized rolls does not demand the chopping. It is sufficient just to break the oleaginous flax residues. It is important to define how the elasticity properties of oleaginous flax stems alter under the mechanical effect of pairs of tailored shape rollers (decortication). The article is intended to tackle these issues.

MATERIALS AND METHODS

The research has been conducted with the purpose of determining efficient number of roller pairs of a roller machine (decorticator) used for decortication, which are required to decrease elasticity properties of oleaginous flax residues. The research results are aimed at developing new equipment to improve the current technologies of oleaginous flax harvesting and processing to obtain products of various functional purposes (seeds, fiber, fuel).

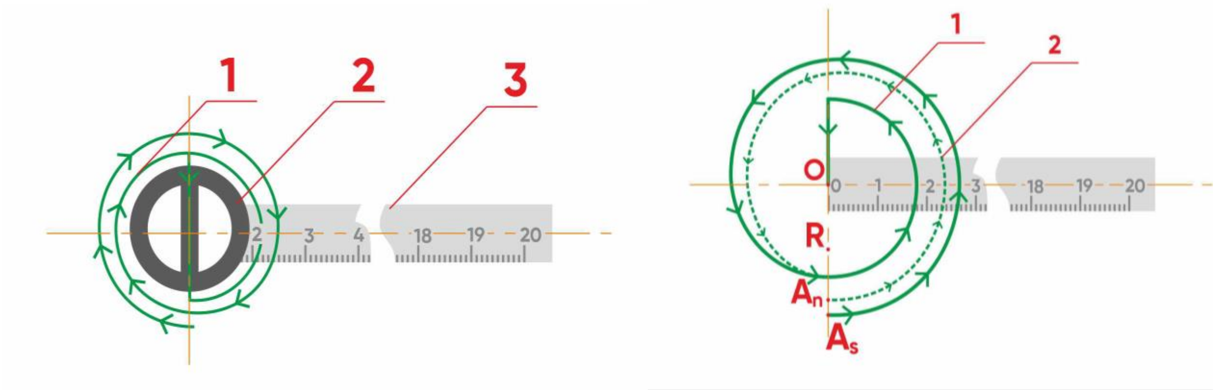
To determine the elasticity properties of oleaginous flax stem residues, the methodology that was described by *V. Didukh (Didukh V., Albota D., 2021)* for a single stem can be used. The undamaged stem was reeled on a 20 mm diameter bushing with a groove (fig. 1, a). The elasticity for such stem was assumed as 100%. It was held for *60 s*. Then it was released. The stem recovered and came untwisted. There, where the top of a stem stopped the mark *A* was done (fig. 1, b). When stabilization was reached a radius *R* was measured. The intact stem was as a basic model. The range OA for it was assumed as a 100%. The oleaginous flax stem elasticity coefficient *k* (recovery) was determined via radius change, that was fixed by the range from the center of bushing (mark O), and the point where the top of a stem stopped (mark A)

$$K = 1 - \left(\frac{OA_s - OA_n}{OA_s}\right), \tag{1}$$

where:

OA_s – the radius of stem untwisting, assumed as a reference, mm;

OA_n – the radius of stem untwisting followed after *n* number of stem breakings, mm.



a b

Fig. 1 - Determination of oleaginous flax stem elasticity properties

a - the twisting of stems onto the bushing; b - the diagram of stem (recovery):
1 - stem; 2 - ruler; 3 - bushing with a groove.

Coefficient *K* describes the decrease of stem elasticity properties. An increase of its value is the evidence of elasticity properties decrease. It depends on stem properties and number of mechanical actions that cause the damage (destruction) of stem's surface. We assume, that elasticity of a bunch of oleaginous flax stems prior to breaking is also 100% and any mechanical effect enables decreasing stem elasticity properties.

It's important to determine the rational parameters of oleaginous flax stems and the quantity of breakings for optimum decreasing of stem residues elasticity properties. To achieve that, the experiment planning mathematical method was applied *(Box G.E.P., Behnken D. W., 1960; Aziz R. A., Aziz S. A., 2018).* Due to this method, it is determined how oleaginous flax residues' elasticity properties decrease depending on number of flax breakings (number of roller pairs) and on the properties of oleaginous flax residues (humidity and layer thickness).

Experimental equipment – a real model of decorticator of a drum type (fig. 2), was produced to decrease oleaginous flax stem elasticity properties.

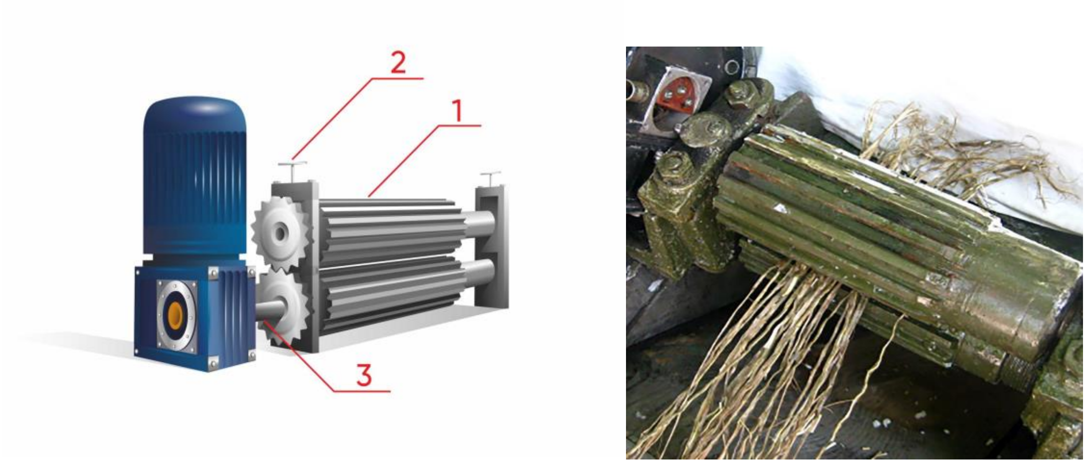


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Fig. 2 - Equipment (model of decorticator) to decrease oleaginous flax stem elasticity properties

a - the diagrammatic view of used equipment; b – the oleaginous flax residues breaking;
1 - the pair of breaking rollers; 2 – the controller of pressing force; 3 - the drive

The decrease of flax stem elasticity properties originates from running of flax stems through the pairs of tailored shape rollers *1* with *65* mm diameter with projections and notches of trapezoidal overcut. Dimensions of the projections at the base of trapezoid are *8* mm and at the top of it *5* mm, the height of projections is *4* mm. The rollers contain *13* projections each.

For the research, freshly picked (humidity (W) 48.5%) and lightly dried (W=30% and W=11.5 %) oleaginous flax stem residues, Sonechny variety, were used. The thickness of oleaginous flax stem layer (H) was altering from *2* mm to 153 mm. The stems were run through the rollers (Fig. 2) from one to five times. Every experiment finished with determination of elasticity properties decrease of the flax stem biomass in accordance to the described methodology.

The following factors impact on the decrease of flax stem elasticity properties: stems layer thickness (X_1), humidity (X_2), as well as number of flax breakings thus running through the pairs of breaking rollers (X_3). A symmetric non-positional Box-Behnken Experimental Design (*Aziz A.R.A., Aziz S.A., 2018*) was applied to plan this experiment. In order to implement a three-factor experiment up to this plan, it is necessary to conduct 15 experiments.

With a purpose of compiling the factors and levels of variation table (Table 1) the information available from written sources and the results of previous studies were taken into account. The Box-Behnken plan is designed to use three levels for each factor: upper (+1), main (0), and lower (-1).

Table 1

Variables and Their Levels in Box-Behnken Design

Levels of variation	X_1 – stem layer thickness H, mm	X_2 - material humidity W, %	X_3 – number of flax breakings *n*
Upper (+1)	153.0	48.5	5
Main (0)	75.5	30.0	3
Lower (-1)	2.0	11.5	1
Range of variation	77.5	18.5	2

The experiment planning matrix is represented in Table 2 in a coded form. The experiments order was established using a table of random numbers. The response function (elasticity properties decrease of oleaginous flax stem residues biomass, in percentage) in the area of factor, space is presented as a nonlinear regression equation (2):

$$Y_i = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1X_2 + b_{13} X_1X_3 + b_{23} X_2X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 \quad (2)$$

Table 2

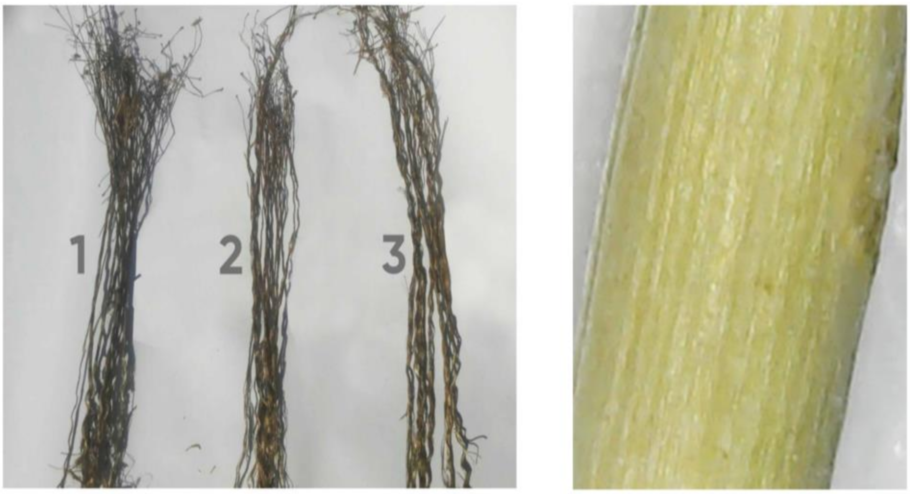
Design of experiment

Run	Stem layer thickness H, mm	Material humidity W, %	Number of flax breakings n
1	-1	-1	0
2	-1	1	0
3	1	-1	0
4	1	1	0
5	-1	0	-1
6	-1	0	1
7	1	0	-1
8	1	0	1
9	0	-1	-1
10	0	-1	1
11	0	1	-1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

Achieved experimental data has been processed in Mathcad-2015. The experiment permitted to create a mathematical model, that describes a process of change for oleaginous flax residues elasticity properties due to decortication depending on set parameters: the layer’s thickness, the humidity of oleaginous flax stem residues biomass and the number of repeated flax breakings (number of roller pairs of the roller machine).

During the research the samples of oleaginous flax stem residues biomass having various level of elasticity properties decrease (Fig. 3, a) were obtained.

The external traces of stem destruction was researched by means of electronic digital microscope with USB and the software. The microscope was utilized to study 30% humidity stem surface. Fig. 3 (b) represents oleaginous flax stem surface under the microscope before it was broken.



a) b)

Fig. 3 – Oleaginous flax stem residues biomass

a - stems processed by decorticator; b - stem surface prior to research commencement;
1 - single breaking; 2 - three-time breaking; 3 - five-time breaking.

RESULTS AND DISCUSSION

As a result of the research (Table 3) the data has been received defining elasticity properties decrease, *K, %,* that depends on the humidity, *W, %,* the oleaginous flax stem biomass layer thickness, *H, mm,* and the number of flax breakings, *n.*

Table 3

Box-Behnken design scheme and elasticity decrease response values

Run	Stem layer thickness, H, [*mm*]	Material humidity, W, [%]	Number of flax breakings, n	Elasticity decrease, K, [%]
1	2.0	11.5	3	36.1
2	2.0	48.5	3	48.5
3	153.0	11.5	3	49.9
4	153.0	48.5	3	62.4
5	2.0	30.0	1	32.6
6	2.0	30.0	5	47.1
7	153.0	30.0	1	46.5
8	153.0	30.0	5	61.0
9	75.5	11.5	1	51.8
10	75.5	11.5	5	66.3
11	75.5	48.5	1	64.3
12	75.5	48.5	5	78.8
13	75.5	30.0	3	61.7
14	75.5	30.0	3	61.7
15	75.5	30.0	3	61.7

Then, the regression equation to determine change for oleaginous flax residues elasticity properties is as follows (3):

$$Y(H,W,n) = 27.15 + 0.048\text{H} + 0.19\text{W} + 3{,}62\text{n} + 0.003H^2 + 0.009W^2 \quad (3)$$

where H - stem biomass layer thickness, W - stem biomass humidity, n - number of flax breakings.

The response surfaces (Fig. 4, a) and their contour plots (Fig. 4, b) are constructed using the regression equation (3). At the same time with experiment conducting there were single stems picked out of broken oleaginous flax stem biomass and the damaged surface was examined under the microscope. Stem surface state correlated to a number of breakings is reflected in Fig. 4, c.

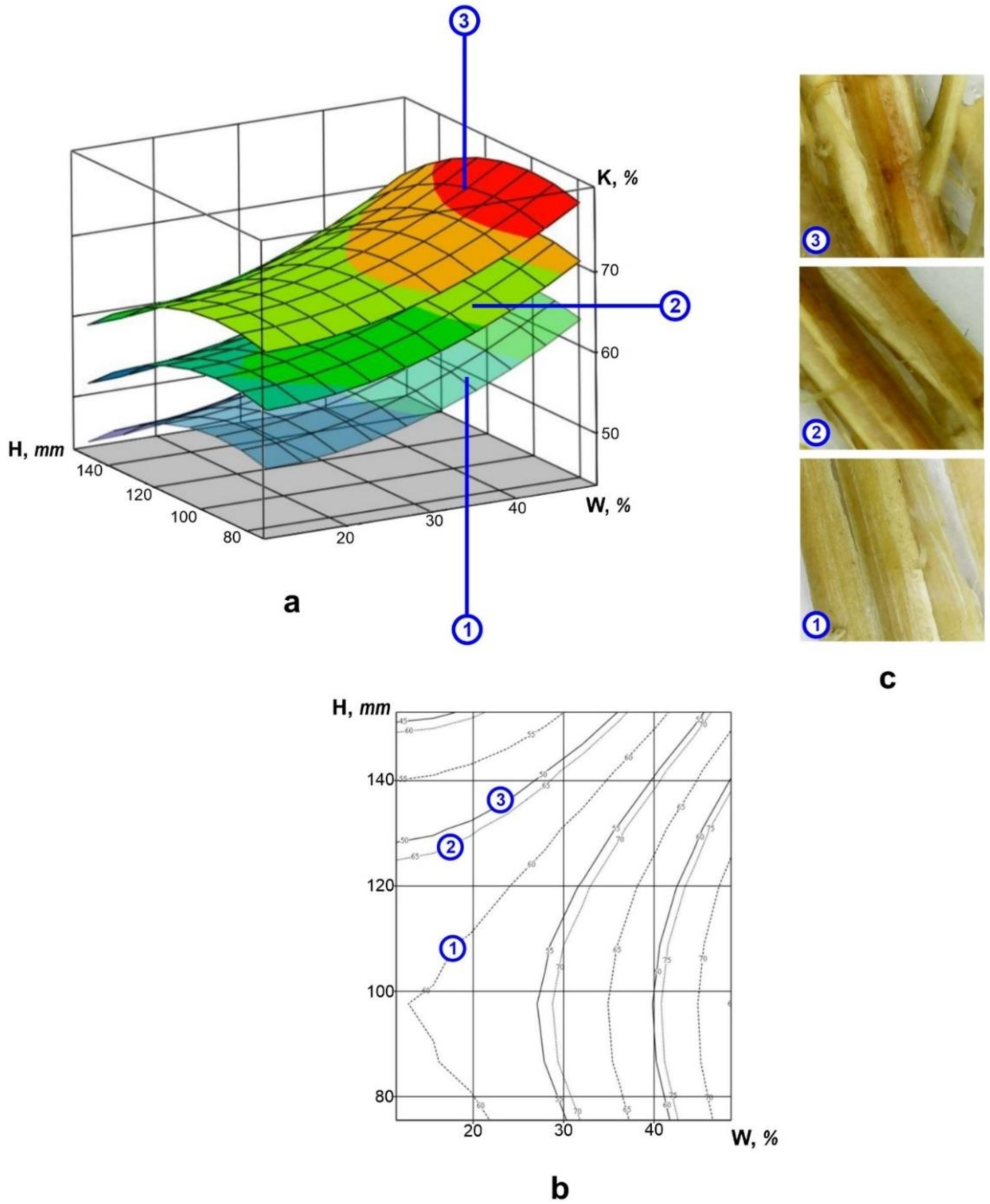


Fig. 4 - Decreasing of oleaginous flax stem residues biomass elasticity depending on humidity and stems layer's thickness

a – response surface; b - contour plots; 1 – single breaking; 2 – three-time breaking; 3 – five-time breaking.

Based on response surfaces and their contour plots it is evident that oleaginous flax residues elasticity properties decrease significantly depends on humidity. With the decrease of humidity, stem biomass elasticity properties increase. This is relevant both for small thickness of flax stem biomass layer (*2* mm) as well as for 153 mm thickness biomass layer. This thickness is equal to the thickness of flax swath on the field during the harvesting. Humidity is the property of oleaginous flax residues that is directly connected to harvesting conditions. It was determined during the research that for 153 mm thickness stem biomass layer and with 48,5% humidity, three-time breaking generates 62% decrease of elasticity properties. At the same time three-time breaking of stems layer of the identical thickness but at 11,5% humidity generates elasticity decrease by 50%. Nevertheless, if stem layer thickness is *2* mm (practically single stem) with humidity of 11,5%, elasticity decreases only 36%.

Considering the above-mentioned it is recommended that initial mechanic processing is conducted in field conditions, directly after harvesting. It is recommended to not permit stems layer humidity drop lower than 30%. The stems layer thickness at the time of flax breaking impacts elasticity properties decreases as well. According to Fig. 3 a, b, the best values for oleaginous flax residues are as follows: 100-120 mm layer thickness, 45-50% humidity. These properties can be achieved if flax biomass is broken directly after harvesting.

The most important factor influencing oleaginous flax stem biomass elasticity properties decrease is the number of flax breakings. Fig 4 b, c shows how the number of breakings impacts the decrease of oleaginous flax residues elasticity properties. Even a single breaking destroys stem integrity (Fig. 4 b, 1). Five-time breaking leads to fiber separation, damage of connections, stem stratification (Fig. 4 b, 3). It was also determined that with five-time breaking of 100-120 mm layer thickness of oleaginous flax residues that has 45-50% humidity, it is possible to decrease elasticity by 75%. Thus, usage of five pairs of a tailored shape breaking rollers is the most effective. However, this number of rollers will significantly complicate decorticator design, will increase metal content and costs.

Therefore, the effective number of flax breaking rollers is three pairs of rollers. When there’s no possibility to install this number onto decorticator or any other harvesting machinery construction then two pairs of breaking rollers will be sufficient.

CONCLUSIONS

The elasticity properties of the oleaginous flax stem are significant. They depend on humidity and stems layer’s thickness. It was determined that for further processing it is needed to noticeably decrease stem residues elasticity properties, regardless of ultimate aim (fiber, briquettes, fuel rolls). It is possible with using a special device - the decorticator, that is equipped with pairs of tailored shape breaking rollers. The results of the conducted experiments proved that even a single breaking decreases stem elasticity by 20-30%. But two-three-time flax breaking (using 2-3 pairs of tailored shape breaking rollers) is considered as the most effective. 5-time breaking does not essentially impact the decrease of elasticity, nevertheless it increases processing time and costs. The results of the conducted research can be used for the development of new machinery designs for oleaginous flax harvesting.

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