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Determination of the tension limit forces of a barley malt and a malt crush in correlation with a load size

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Abstract. This article deals with determination of selected parameters of barley malt (whole grain and crushed grain). The barley malt is besides water, hops and brewer's yeast, one of the basic ingredients necessary for the production of traditional Czech pilsner type of beer. The aim of this research is to determine limit force and internal friction angle with depending on the size of the load. The assessed malt crush was produced using a 2-roller malt mill. The 2-roller malt mill is based on the principle of grinding the material in a milling gap between two milling rollers, which is a very commonly used production of the malt crush. By determining the tension limits of the barley malt and the malt crush in correlation with the load, we can obtain very important parameters that inform us of the bulk material behavior, particularly with respect to the storage method (storage shape, height of the stored material layer, and the removal method from the storage, etc.), and to the transport (route gradient, transport speed, etc.). The determination of the tension limits has a direct link with cohesion of the bulk material and thereby contributes to establishing of the basic parameters of the bulk material, such as - the friction angle. The measurement for the angle of internal friction determination were performed on a prototype device. The principle of measurement on a mobile prototype devices is, the upper square chamber slides down the lower square chamber. Barley malt (whole grain and crushed grain) were loaded from 100 g to 5,000 g. The results of measuring were statistically analyzed with software Statistica 12.

Key words: food industry, barley malt, malt crush, bulk material, friction angle.

INTRODUCTION

These basic ingredients are used when manufacturing a traditional Czech pilsener type beer: water, hops, brewer's yeast and barley malt. The light malt is a product made from barley, after four- to five- week ripening in containers. At the beginning of the malt manufacturing technology, there is a phase of pre-cleaning of barley, which is then followed by soaking of barley in special containers so called steeping tanks. A germination of barley was in the past conducted in so called floor malting houses, however nowadays it is being realised by using pneumatic germination drums, or germination boxes, Saladin or Lausmann boxes, or circular germination towers arranged vertically (germination towers), then it is followed by so called kilning which is drying of the green malt in the drying kiln. Such germinated but still green malt is in the first stage pre-dried by dry air at the temperature of 60 °C and then finished at the temperature 80 °C up to 105 °C.

The moisture content definition of the processed materials, respectively of the actual measured sample, was the basic step of the particular experimental measurements. A knowledge of the initial moisture content of the sample (%) is necessary for securing optimal conditions for the additional experiments and possible detection of correlation between measured quantities and entry material.

For ensuring the optimal progress of the next technological steps, the value of moisture content of the processed (stored) materials is the basic requirement. With regard to relevant economical indicators and ingredient quality, the moisture content optimalization is fundamental because higher moisture content causes i.e. a fast development of mould which contributes to a significant deterioration of the ingredient quality. Therefore the moisture content control in individual food companies is not underestimated. The deterioration of ingredients' quality is not the only factor to determine the initial moisture content because losses (especially energetical) are also caused during grinding, as the amount of moisture content affects the amount of energy needed for malt grinding, thus the malt crush production (Dendy & Dobraszczyk, 2001; Kunze, 2010).

The type of the produced malt depends on the temperature of the air used for drying because lower temperatures of the drying air produce light malts and high temperatures produce dark malts. The dried malt is after kilning cleaned from damaged grains, dust and roots and it is further transported to a container where it has to stay for a certain period followed by another processing, the so called air resting. Light malts in Czechia are generally pilsner types (the temperature of drying air up to 85 °C), or Vienna and Dortmund malt type (Kunze, 2010; Chládek et al., 2013).

Before the actual brewing, the malt is mechanically grinded using malt mills (grinders) that work on the principle of grinding between two counter-rotating rollers (the so-called roller mills respectively Malt grist mills), grinding using rotating hammers (so called hammer mills) and grinding between two discs (so called steel disc mills, respectively dispersants). The product of malt grinding is called a malt crush, which is the basic material for the actual beer brewing (Vaculík et al., 2013; Smejtková et al., 2016).

The traditional beer brewing is bringing together subjects from a wide range of fields that include i.e. fermentation chemistry, microbiology, but also subject of grain treatment, transport and storage. These very subjects of grain treatment, the transport, and the storage are demanding a knowledge of the basic parameters of the processed materials, thus the bulk materials. Among basic properties of the bulk materials, where barley malt and the malt crush undoubtedly belong, can be included: density, bulk density, friction angle (Chotěborský & Linda, 2014).

The paper is aimed at determining the tension limits, depending on the load size of the barley malt and the malt crush. In the case of incoherent (ideally) bulk materials, an external friction coefficient is defined, which is characterizing the frictional properties of the mass on the surfaces of containers and mats (external surfaces) and an internal friction coefficient is characterizing the frictional properties of the internal section area

(Afzalinia & Roberge, 2007; Ibrahim, 2008; Boac et al., 2010; Gil et al., 2013, Liu et al., 2015; Zheng et al., 2017).

For cohesive bulk materials, the interactions between particles are also affected by cohesiveness. An ideally loose substance can be mostly compared to a dry matter with particles larger than 0.25 mm (ČSN ISO TS 17892-10). Finer milled substances are showing a cohesiveness. Cohesive forces impact the contact points of the particles. Therefore, the finer is the substance, the greater is the cohesiveness because in the unit of volume there is a greater number of contact points. Cohesion forces are of different physical nature (Jacobson et al., 2004; Afzalinia & Roberge, 2007; Kaliniewicz, 2013; Sologubik et al., 2013; Fürll & Hoffmann, 2015; Kibar, 2016).

The main objective of this paper is a determination of selected mathematical and physical parameters of colored and light malt, i.e. size of the grain, density, bulk density, specific weight of the malt, repose angle and determination of tension limits.

MATERIAL AND METHODS

Before the actual determination of tension limits of the barley malt and the malt crush, depending on the load size, the moisture content of the processed materials was defined.

During grinding of the rated barley malt varieties was used a double roll crusher KVM 130/150 (Fig. 1), manufactured by KVM Uničov, Czech Republic, with a maximum output of 250 kg h^{-1} and two electric motors, each with a power of 2.05 kW. The distance between the grinding rollers, i.e. the gap between the rollers, was set to 0.4 mm.

Determination of the mathematical and physical parameters

Determining the moisture content of the assessed barley malt was implemented using a moisture analyzer OHAUS MB25 (Fig. 2).

Figure 1. The double roll crusher KVM 130/150.

Figure 2. Moisture analyzer OHAUS MB 25.

Firstly, representative samples of malt were taken, we chose a drying temperature of 105 °C and an automatic drying mode, which is automatically terminated once the mass (weight) constant is reached. The principle of the moisture analyzer OHAUS MB25 is based on a weight reduction of the measured sample due to its heating that is caused using the heat source of the moisture analyzer, which is a halogen emitter. The drying temperature for this analyzer can be set ranging from 50 °C up to 160 °C.

For determining the mean statistical particle size which is a constant for a specific set $\bar{x}$, we applied so called RRSB distribution. For fine-grained materials that are products of grinding different substances, an exponential relationship was found by Mr. Rosen, Mr. Rammler and Mr. Sperling that quite accurately characterizes the distribution of particle sizes in certain grain materials. With respect to the percentage expression of the relative residual on the sieves R, that is determined by the network analysis, this relationship can be expressed in the latter Bennett's adaptation (hence the RRSB distribution) as follows:

$$R = 100\, exp\left[-\left(\frac{x}{\bar{x}}\right)^{n}\right] \tag{1}$$

where R – aggregate relative residual on the sieves (%); x – dimension of specific particle (limited by two consecutive sieves) (mm); $\bar{x}$ – mean statistical particle size (mm); n – material constant (–).

Setting the tension limits

The measurement is aimed at determining the tension limits, depending on the load size of the barley malt and the malt crush.

Measurement of shear cohesion and friction properties of bulk materials, respectively the determination of the limit tensions as a relation of the barley malt load and malt crush load was conducted on the apparatus (Figs 3, 4), which was adapted to measure the properties of bulk materials. The principle of the measurement on the mobile prototype device is based on the current readings of normal and tangential force during the bulk material slipping or shifting on the mat.

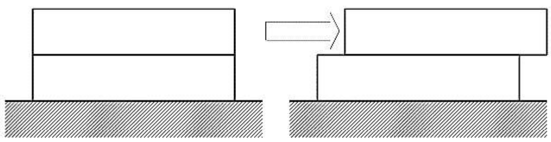

Figure 3. The principle of apparatus operation for measuring shear cohesion and friction properties of bulk materials.

Overall, the friction is generally dependent on dilatation and contraction, consistency, displacement acceleration, lugs' resistance to prevent breaking, and size of normal load.

When determing of limit tensions in relation to a load size of the barley malt and the malt crush on the prototype device, which was adapted to measure the properties of bulk materials. The measurement procedure is as follows:

- using a electric motor 1, the upper square chamber 2 slides down the lower square chamber 3;
- in the dividing gap between the chambers 4 is the bulk material stressed by tangential force T (N);

- normal force N (N), exerted by the weight 5 acting on the malt through the loading plate 6;
- depending on the size of the deformation, the force can be determined T (N) (the floor plan of the body in the chamber is known).

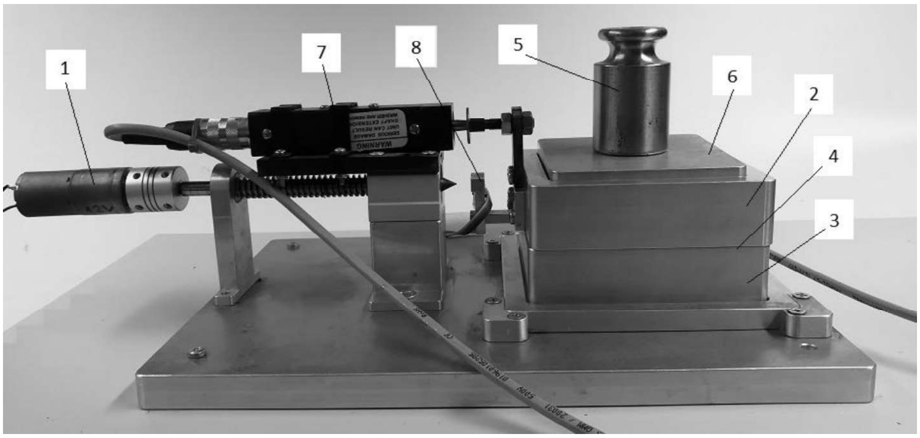

Figure 4. Prototype device for measuring shear cohesion and friction properties of bulk materials. Annotations: 1 – electric motor; 2 – the upper square chamber – movable; 3 – the lower square chamber – fixed; 4 – the dividing gap between the chambers; 5 – weight; 6 – loading plate; 7 – shift sensor; 8 – deformational component with strain gauges for measurement of the force. The device is complemented with measuring electronics and evaluation software.

The height of the upper and lower chamber is 30 mm, the floor area of the chamber 8,100 mm^2. Load weights were used for loading 100, 500, 1,000, 2,000, 3,000, 4,000 and 5,000 g. The weight of the load plate was 219.68 g.

For the incoherent bulk materials, the maximum tangential stress is dependent. τmax in areas of normal tension σ described by:

$$\tau_{\max} = f \cdot \sigma \quad (2)$$

where $\tau_{\max}$ – maximum tangential stress (N); σ – normal tension (N); f – coefficient of internal friction (Pa) (Feynman et al., 2011).

For the cohesive bulk materials, the ratios are more complex and can be characterized as follows:

a) dependence of the maximum tangential stress τ_{max} to normal tension σ in area of its impact, which is a characteristic of the yield strength or the yield curve, varies with the degree of material consolidation. (The consolidation means a compression of material by known force for a known period of time prior to the actual measurement);

b) the previous dependence for a given consolidation level only applies to a certain range of normal tensions, and a limited tension from above σ_e. The consolidation level can be characterised by maximum main tension σ_{le} associated with Mohr´s circle, which is in contact with the yield strength characteristics at their endpoint (Fig. 5);

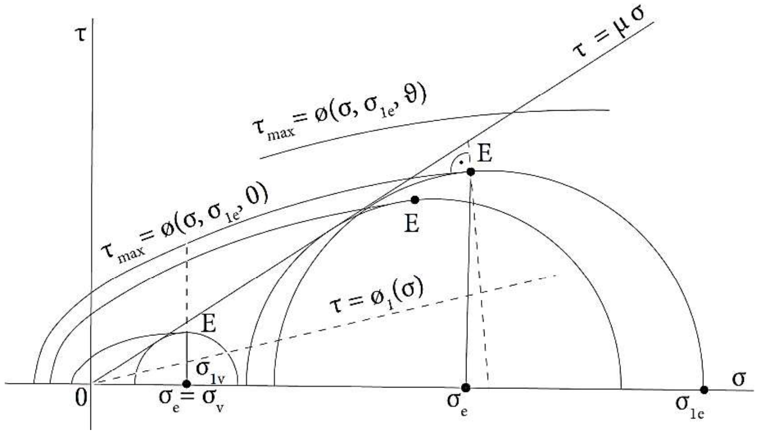

Figure 5. The Mohr's circle (Maloun, 2001).

c) once the yield strength is reached τ_{max}, when tension is $\sigma_v < \sigma_e$, it leads to a 'plastic' deformation (materials movement) that will transform into a new, lower consolidation level $\sigma_{le} = \sigma_{lv}$, that means into a yield strength characteristics with a endpoint $\sigma_e = \sigma_v$;

d) the envelope of Mohr circles passing through the endpoints of the yield strength characteristics can be called a characteristic of the effective yield strength. This describes the behavior of a cohesive bulk material during a continuous change of the consolidation level;

e) if the compressed material remains at rest, its cohesion is increased;

f) the dependence of tangential stress during external friction to the normal tension is approximately linear, similar to that of cohesive materials. (Maloun, 2001; Feynman et al., 2011).

RESULTS AND DISCUSSION

Determination of the mathematical and physical parameters

The results of the moisture content establishing of the individual samples of processed raw materials are shown in Table 1.

Table 1. The results of the moisture content establishing (drying temperature 105 °C)

Physical parameters	Light barley malt		Colored barley malt	
	Whole grain	Crushed grain	Whole grain	Crushed grain
Humidity, %	1.904 ± 0.01	1.997 ± 0.13	1.877 ± 0.07	1.983 ± 0.1

Furthermore were determined another selected mechanical and physical parameters of the colored and light barley malt and the malt crush (see Table 2). Grain size was determined by network analysis. The Program Statistica 12 (StatSoft 2014) was used for statistical evaluation.

Table 2. Mechanical and physical parameters of the colored and light barley malt and the malt crush

Physical parameters	Light barley malt		Colored barley malt	
Density, kg m^{-3}	1,110		1,180	
Volume weight, kg m^{-3}	570		535	
Friction angle, °	32		34.5	
	Whole grain	Crushed grain	Whole grain	Crushed grain
Size, mm	3.6 ± 0.11	0.91 ± 0.15	3.48 ± 0.13	1.05 ± 0.13

Setting the tension limits

In the following figures (Fig. 6 to 9) are shown the courses of the limit tensions for the barley malt and malt crush in relation to the load size from 100 to 5,000 g. The graphs show the force course on the deformation member, which shows a gradual increase in pressure until the upper cell is slid off, while the chamber moves with an almost constant force course. The size of the tangential force is determined by the grain consolidation and the magnitude of the normal force.

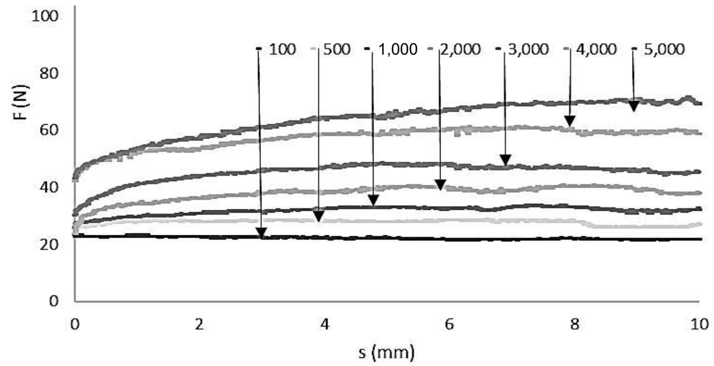

Figure 6. The graph of force dependence on length - light barley malt – whole grain.

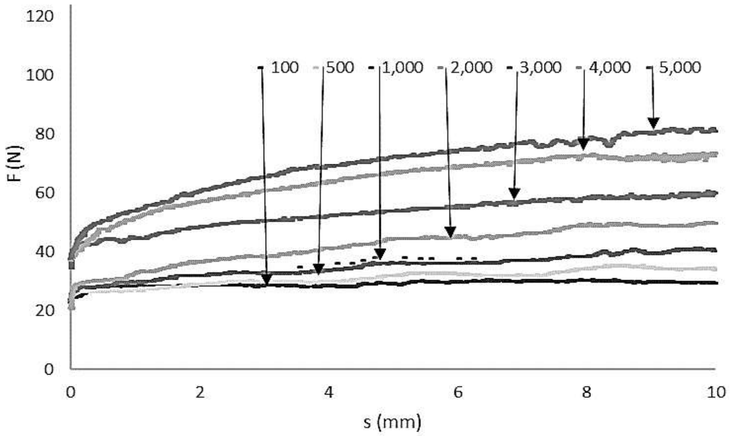

Figure 7. The graph of force dependence on length - light barley malt – crushed grain.

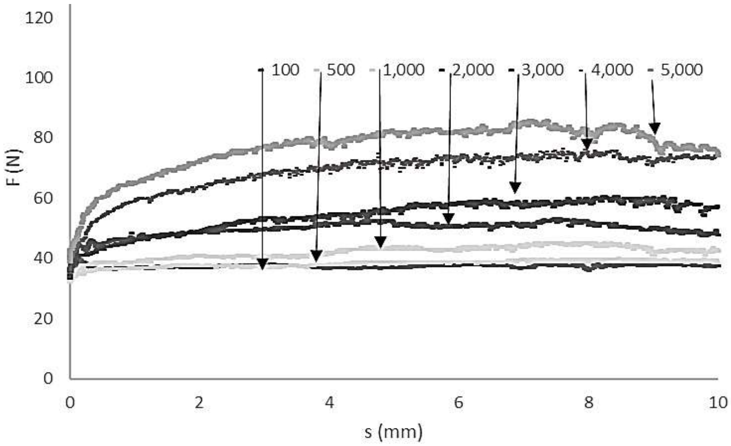

Figure 8. The graph of force dependence on length - colored barley malt – whole grain.

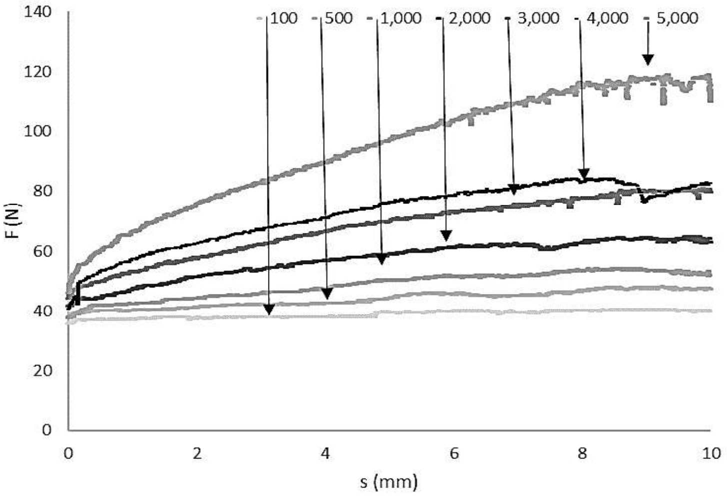

Figure 9. The graph of force dependence on length - colored barley malt – crushed grain.

From the Mohr's circles (Fig. 10 to 13) the internal friction angle and the consolidation stress (Table 3) were determined.

Table 3. The internal friction angle and the consolidation stress

Physical parameters	Light barley malt		Colored barley malt	
	Whole grain	Crushed grain	Whole grain	Crushed grain
Consolidation tension, Pa	2,602.3	3,158.3	3,775.3	4,339.5
Internal friction angle,°	43.95	56.38	44.44	57.52

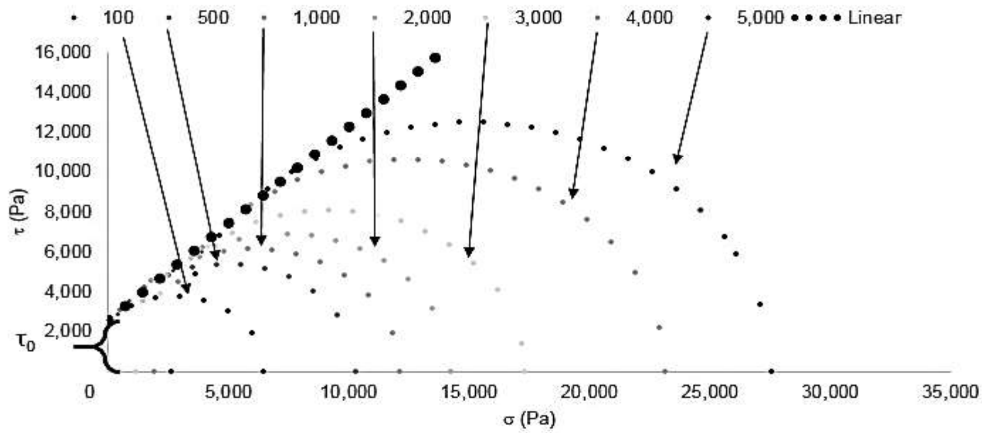

Figure 10. Mohr's circle for the light barley malt – whole grain.

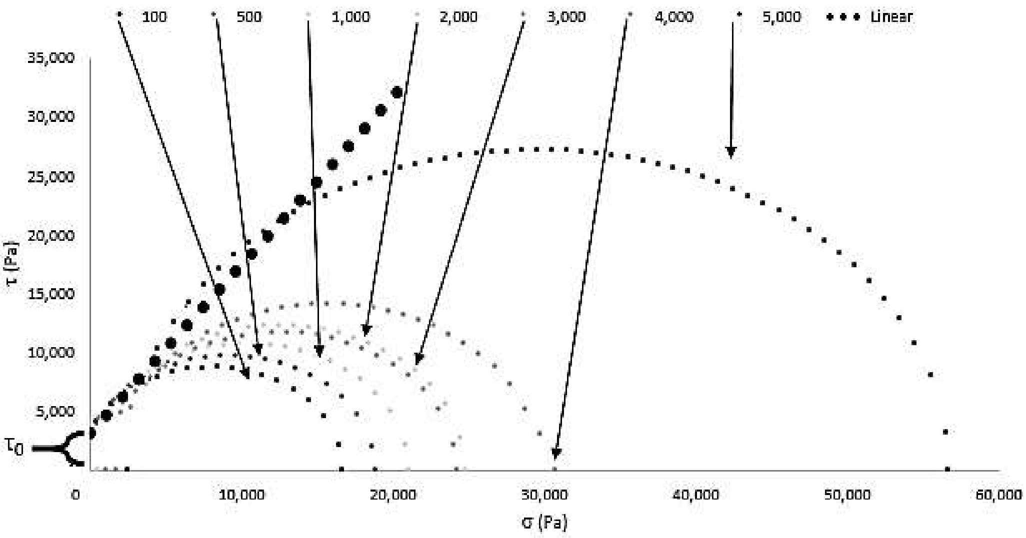

Figure 11. Mohr's circle for the light barley malt – crushed grain.

It was verified by measuring that the whole grain of pale malt has a lower consolidation tension by 556 Pa than the crushed grain. The whole grain of colored malt has a lower consolidation tension by 564 Pa than the crushed grain. The difference in the consolidation tension between the whole grain and the crushed grain of pale and colored malt is the same.

The friction angle of the whole grain pale malt is less by 0.49° than the colored malt, the crushed pale malt is lower by 1.14° than the colored malt. The friction angle of the barley is in according to (Horabik & Housinek, 2002) 27.8°± 0.4° when humidity at 10% and 33.2 ± 0.5° when at 20%, in according to (Öztürk & Esen, 2008) 19.5° when at 10% and 22.5° when at 14%, and in according to (Moya et. al., 2013) 24.8° when at 8.83%. The friction angle of malting barley is 43.95° for the whole grain, this increase is due to its germination and the grain drying. This modification of the barley's mechanical parameters must be taken into consideration when designing a transport system where the external friction angle changes on average by 7°, which influences a design of malt silos.

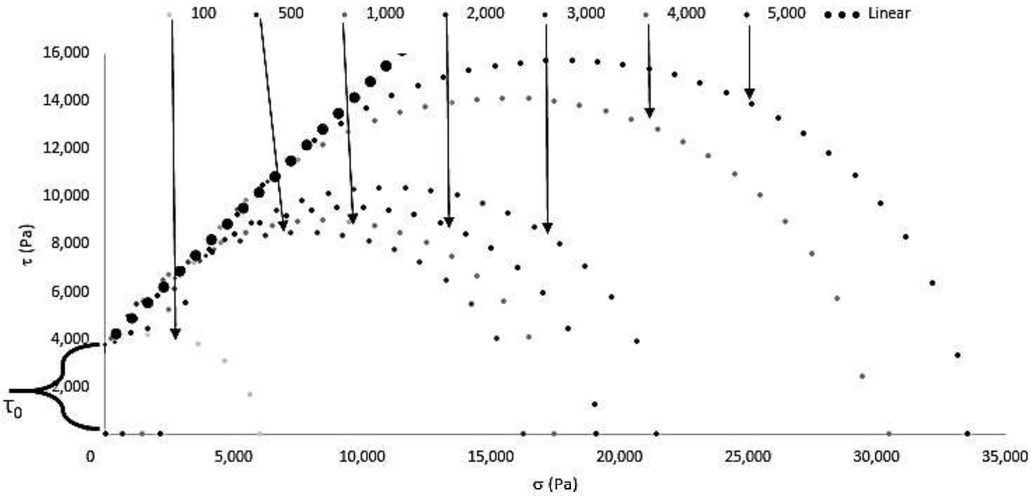

Figure 12. Mohr's circle for the colored barley malt – whole grain.

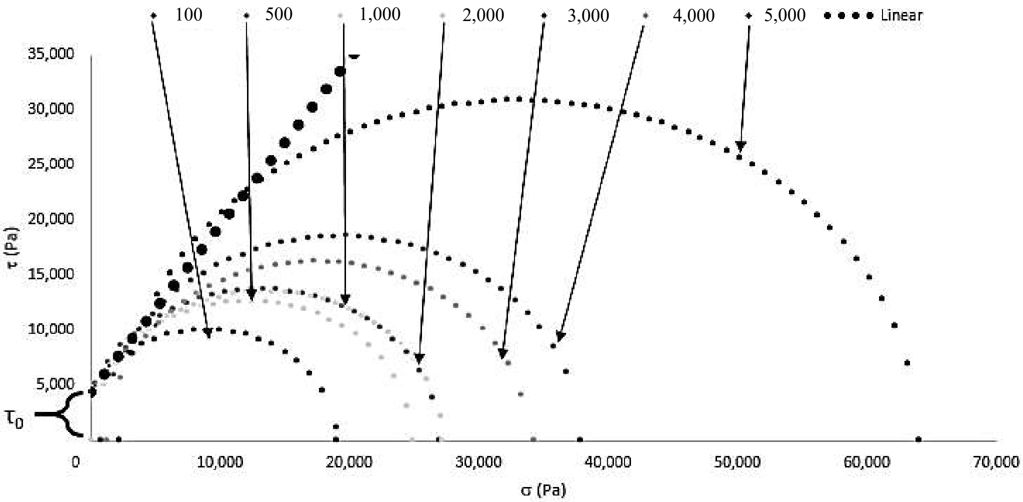

Figure 13. Mohr's circle for the colored barley malt – crushed grain.

CONCLUSION

The importance of determining the tension limits lies in the fact that based on their knowledge we can make calculations of storage and manipulation devices with loose bulk feed and consider a possibility of buckling arches formation that interfere with the function of the device and subsequently use it as a source data for DEM modeling in warehouse management.

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