INTERNAL STRESSES OF BIOMASS COMPOSITIONS

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Abstract

Relevant resources for biomass energy production are cereal straw residues and emergent vegetation from wetlands. This bulk herbaceous biomass is a material with low density. Density of briquetted straw and reed has been increased from 60 kg m^{-3} to 1000 kg m^{-3}. The storage, dosage and mixing of biomass bulk materials before compacting are necessary, which requires working knowledge of the bulk properties of materials. The angle of repose of straw, reed and peat particles was investigated. It was stated that angle of repose of straw and reed varies between 45–55 degrees. The angle of repose of peat particles varies between 37–50 degrees. The stress ratio between horizontal and vertical stress is important for equipment design. This ratio was investigated for different size particles of straw, reed and peat. Stress ratio of straw particles varies between ~0.6–0.71.

Key words: stalk materials, biomass briquettes, angle of repose, bulk properties.

Introduction

Ecological and economical situation in the world is increasing the demand for renewable energy sources with less impact on environment. There is a growing public concern about the environmental implications of in-field burning – air pollution, damage to the countryside, and the risk of accidents. This has led to a consideration of alternatives, notably the potential for using straw as a competitively priced fuel. Utilizing cereal straw residues and vegetation from wetlands (overgrown lakes with common reed) for energy consumption will enable the employment of more people in the countryside. Spruce environment will recruit tourists.

Herbaceous biomass is a material with low density. Density of briquetted straw and reed has been increased from 60 kg m^{-3} to 1000 kg m^{-3}. From preceding measurements it was ascertained that durability of straw and reed briquettes has to be increased therefore different compositions of straw, peat, reeds, etc. were tested. It was established that adding 50% of peat to straw or reed increases durability of briquettes 2.2 times.

In order to design silos, feeders, mixing and flow promoting devices for briquetting process it is necessary to know flow properties of bulk solids. The loading, storage container discharging and automatic feeding process depend on internal stresses acting in the biomass volume. Knowledge of the stresses acting in chopped biomass is important for many applications:

- storage container and hopper design for strength,
- storage container and hopper design for flow,
- loads on feeders and inserts,
- driving torque of feeders.

Many of the problems are associated with the bin and hoper design: the material does not exit from a hopper fast enough or material is cohesive enough that the particles form arch bridges or domes that hold overburden material in place and stop the flow completely. Dead spaces in the bin can prevent a bin from complete discharge of the material [5].

To prevent stacking and arching of the material it is necessary to investigate the dimensions and form of flow promoting devices accordingly to bulk material properties. One of properties is the angle of internal friction. The angle of internal friction is a measure of the force required to cause particles to move or slide on each other. Internal friction is influenced by many parameters including particle surface friction, particle shape, hardness, particle size, etc.

The Mohr stress circle represents the stresses in cutting planes, which are inclined through all possible angles [5]. Using the Mohr stress circle for predicting stresses in different locations of the storage bin it is necessary to know the stress ratio λ of stress σ_h (horizontal stress) to stress σ_v (vertical stress). Several methods are known for obtaining stress ratio λ. One of them is calculation of λ from the angle of internal friction of the bulk material. Obtained results give insufficient accuracy. Stress ratio measured directly from a uniaxial compression test [3,4] is more accurate because the process in the cylinder by direct measuring more like processes happened in real technological processes in silos, feeders, mixing and flow promoting devices.

In the Research Laboratory of Mechanics of the Latvia University of Agriculture, research on mechanical properties of straw, reed and peat particles has been made. Values of the angle of internal friction and stress ratio λ have been experimentally established.

Material and methods

Preceding measurements ascertained that durability of straw and reed briquettes have to be increased therefore different compositions of straw, peat, reeds, etc. were tested. It was established that adding peat to straw and reed increases durability of briquettes.

In order to design silos, feeders, mixing and flow promoting devices for briquetting process it is necessary to know the mechanical properties – flow properties of above mentioned bulk solids.

The angle of internal friction is an important flow property for calculating minimum outlet dimension of silo to prevent arching as well as critical rathole diameters. Furthermore, it is possible to estimate the stress ratio λ of the

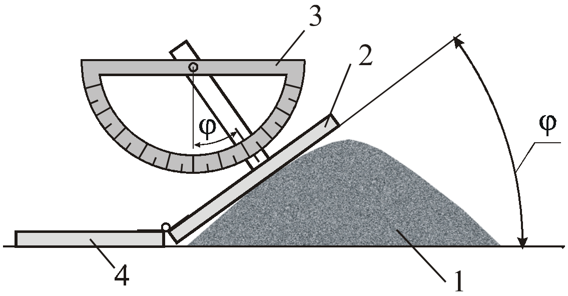

Fig. 1. Measuring of the angle of repose:
1 – bulk material, 2 – contact ledge, 3 – scale of angle,
4 – support.

bulk material. The angle of internal friction can be calculated from the angle of repose [6]. The angle of repose is a characteristic of solids, which characterizes the piling or stacking nature of particles. The angle of repose is considered to be mostly a measure of the internal friction between the particles as a whole, but not between individual particles. It is used in a number of correlations and estimates for behavior properties of the bulk solids. The best use of the angle of repose is to determinate the size of a pile of bulk materials, either volume or ground area that such pile will occupy.

The angle of repose is measured accordingly to Figure 1. Chopped to different length, reed and straw stalks with moisture content less than 10% are used for obtaining the angle of repose. Stalk material is sieved, then divided into the following fineness groups: 3 – 5, 2 – 3, 1 – 2, 0.5 – 1, and < 0.5 mm.

Bulk material is filled in cylinder and by lifting cylinder bulk material is poured out on the horizontal surface (Fig.2).

The angle of internal friction φ for different materials gives different relations with the angle of repose. For many materials, the angle of internal friction is approximately 2°–8° less than the angle of repose.

Coefficient of internal friction *f* is expressed from the angle of internal friction by equation:

$$f = \mathrm{tg}\varphi \, . \qquad (1)$$

In a bin filled with solid bulk material this material acts at the base of a bin and also on the walls with the horizontal stress σ_h. For the stress calculation, a bulk solid is considered as a continuum instead of single particles. Because of this the methods of continuum mechanics can be applied. If different sloped cuts through an element of bulk solid are considered it can be seen that different shear and normal stresses are acting at the different cutting planes. This is shown in a simplified way in Figure 3 where the stresses σ_h and σ_v, which act in different directions, differ from each other.

The stress ratio λ between horizontal and vertical stress is important for storage equipment design. Often the equation of Kèzdi (2) is used for the estimation of the stress ratio λ [1]:

$$\lambda = 1 - \sin\varphi \, , \qquad (2)$$

where

φ – angle of internal friction.

The German standard DIN 1055 part 6 [2] recommends the following equation, which is based on equation (2):

$$\lambda = 1.2 \cdot (1 - \sin\varphi) \, . \qquad (3)$$

The use of eq. (3) results in higher wall loads in the upper area of silo, i.e. wall normal stresses σ_h and shear stresses τ_α are greater than those calculated on the basis of eq. (2). Therefore, the load assumption for the structural design is on the safe side with eq. (3). To be on the safe side for applications where the maximum vertical stress is important (e.g. for the calculation of the feeder load or the maximum vertical stresses), the smaller λ should be used because it yields higher vertical stresses.

The values of the stress ratio calculated according to equation (3) in the practice are not correct in many cases because the stress ratio depends on a lot of parameters that are not taken into account in eq. (3). According to ISO-guideline TC98/SC3/W65, stress ratio can be measured directly from a uniaxial compression test [3].

Figure 3 shows an element of bulk solid in a bin filled with bulk solid (the inner walls assumed to be frictionless). The stress σ_v is acting on the element of bulk solid in the

Fig. 2. Obtaining of the angle of repose.

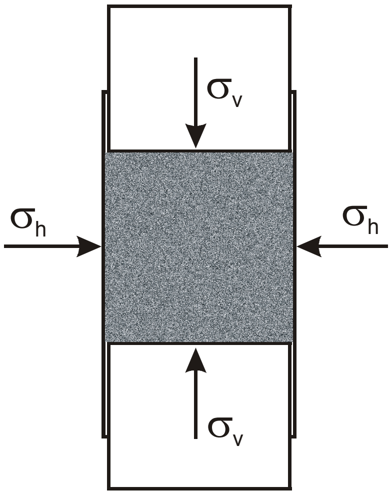

Fig. 3. Bulk material element:
σ_v – vertical stress, σ_h – horizontal stress.

vertical direction (note: in bulk solids mechanics compressive stresses are defined as positive stresses). The stress σ_h prevails in the horizontal direction as a result of the vertical stress. The ratio of stress σ_v to stress σ_h is defined as the stress ratio λ.

Stress ratio λ is calculated as a proportion of horizontal and vertical stresses [4]:

$$\lambda = \frac{\sigma_h}{\sigma_v}. \tag{4}$$

Experimental equipment design for estimating of stress

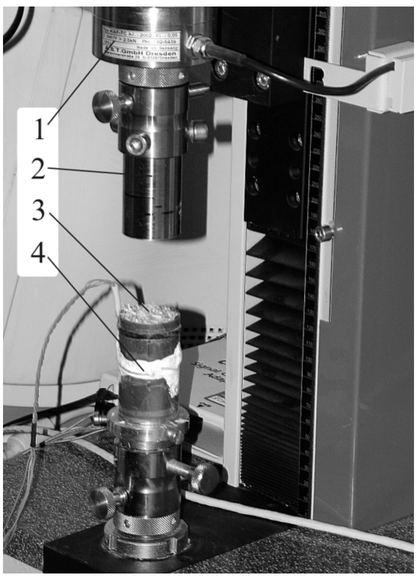

Fig. 4. Device for measuring horizontal stress:
1 – load cell, 2 – piston,
3 – bulk material, 4 – cylinder
with strain gauge.

ratio λ is shown in Figure 4. Horizontal stresses of material acting on the walls of the cylinder 4 leads to tension deformation of those thin walls. The deformation is proportional to the stresses σ_h and is measured using strain gauges. Fixed vertical stress is obtained with ZWICK testing machine of materials. As a result of compression in the bulk material, vertical σ_v and horizontal σ_h stresses arise (Fig. 3). Output voltage from strain gauges through the transducer *PicoScope - 212* is collected to PC. Chopped to different length reed and straw stalks with moisture content less than 10% are used for estimating of stress ratio λ. Stalk material is sieved, then divided in to following fineness groups: 5 – 7, 3 – 5, 2 – 3, 1 – 2, 0.5 – 1, and < 0.5 mm.

Strain gauges are calibrated by using oil pressure in active part of the cylinder.

Change of vertical stress in the range from 0.54 to 2.7 MPa was used for stress ratio calculation.

In figure 5, the bulk solid element from Figure 3 is shown again. No shear stress is acting on the top and bottom of the bulk solid element in figure 3 and also on the walls of the bin (assumed as friction less) in horizontal direction. A triangular-shaped element is considered, cut from bulk solid element in Figure 3. The normal stress σ_α and the shear stress τ_α acting in the plane, which is sloped at an angle α to the y-direction, are calculated from equilibrium of forces on the triangular element. This results in the following equations:

$$\sigma_\alpha = \frac{\sigma_v + \sigma_h}{2} + \frac{\sigma_v - \sigma_h}{2}\cos(2\alpha), \tag{5}$$

$$\tau_\alpha = \frac{\sigma_v - \sigma_h}{2}\sin(2\alpha). \tag{6}$$

If equations (5) and (6) are plotted on a σ, τ – diagram (normal stress vs. shear stress diagram), the resulting curve is a Mohr stress circle with its center at $\sigma_m=(\sigma_v+\sigma_h)/2$ and radius $\sigma_r=(\sigma_v-\sigma_h)/2$ (Figure 5). The Mohr stress circle represents the stresses in cutting planes, which are inclined through all possible angles α. Each Mohr stress circle has two points of intersection with the σ – axis (because the sin-function becomes zero for all multiples of π, τ_α in equation (6) becomes zero for $\alpha=0$ and for $\alpha=\pi/2$). The points of intersection indicate the two cutting planes in which the shear stress τ is equal to zero. The normal stresses acting in these planes are called principal stresses. The larger stress is indicated with σ_1 ("major principal stress") and the smaller one with σ_2 ("minor principal stress"). The position of the Mohr stress circle is defined exactly by the two principal stresses.

In the example considered in figure 3, no shear stress is acting in the horizontal and vertical planes. Hence, these planes are the principal stress planes. The vertical stress σ_v has to be set equal to the major principal stress σ_1 because $\sigma_v > \sigma_h$. Therefore the horizontal stress σ_h is the minor principal stress, σ_2 [5].

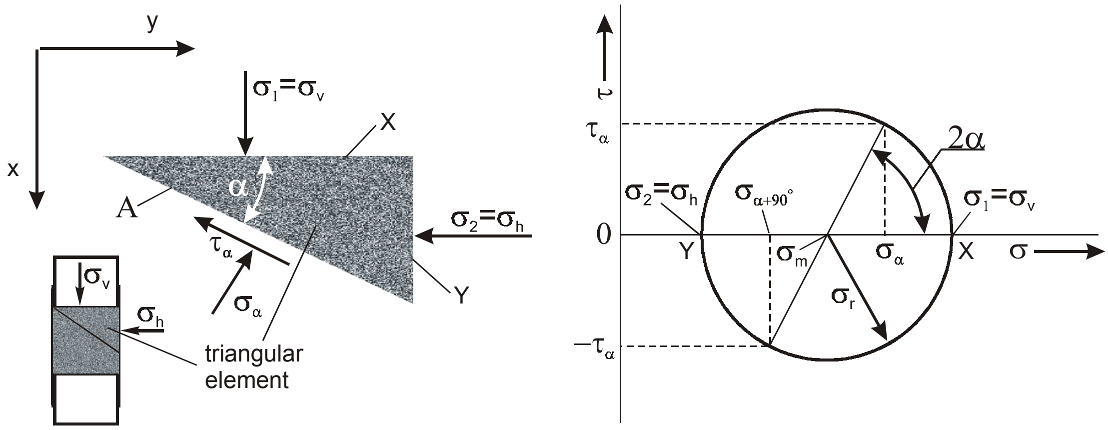

Fig. 5. Fofce eqilibrium on an element of bulk solid, the Mohr stress circle.

Results and discussion

The angle of repose has been obtained in dependence on the particle size of the bulk material (reed, straw and peat). It was stated that size of particles has relevant influence on the angle of repose. Particles with size less than 1 mm achieved value of the angle of repose $\varphi \approx 45°$, but particles greater than 5 mm – 55°. The range of the angles of repose for straw and reed particles is nearly similar. Peat particles less than 1 mm reach angle of repose ≈ 37° (see Fig. 6). The mass-flow and funnel-flow limits in silos are well known and have been used extensively in proper design; the limits for hoppers depend on the hopper half-angle Θ, the effective angle of internal friction φ and the wall friction angle ϕ. Once the wall friction angle and angle of internal friction have been determined by experimental means, the hopper half angle Θ may be determined as a function $\Theta=\phi(\varphi,\phi)$.

Stress ratio λ obtained by equation (3) is influenced by particle size of the bulk material (Fig. 7). Consider stress ratio λ of particles greater than 2 mm established that λ is quite similar for all investigated biomass materials. On average, calculated stress ratio for investigated materials ranged within 0.3–0.5. It conforms to results obtained by other researchers (0.3 to 0.6) [5].

The results of direct measuring of horizontal stress σ_h in dependence on vertical stress σ_v are shown in Fig. 8. The stress ratio λ calculated accordingly to eq. 4 shows no dependence on vertical stress. Experimental obtained stress ratio of straw particles varies between ~0.5–0.72 for particle size 0.25 to 7 mm (Fig. 9).

The value of stress ratio obtained in direct measuring is ~1.7 times higher than the value of stress ratio calculated from the angle of repose. The trend of dependence of the stress ratio on particle size is similar in the both measuring methods.

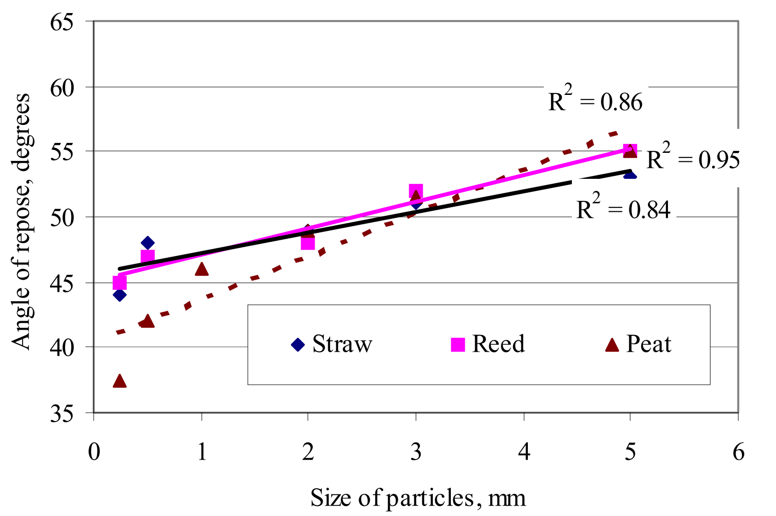

Fig.6. Dependence of the angle of repose on particle size.

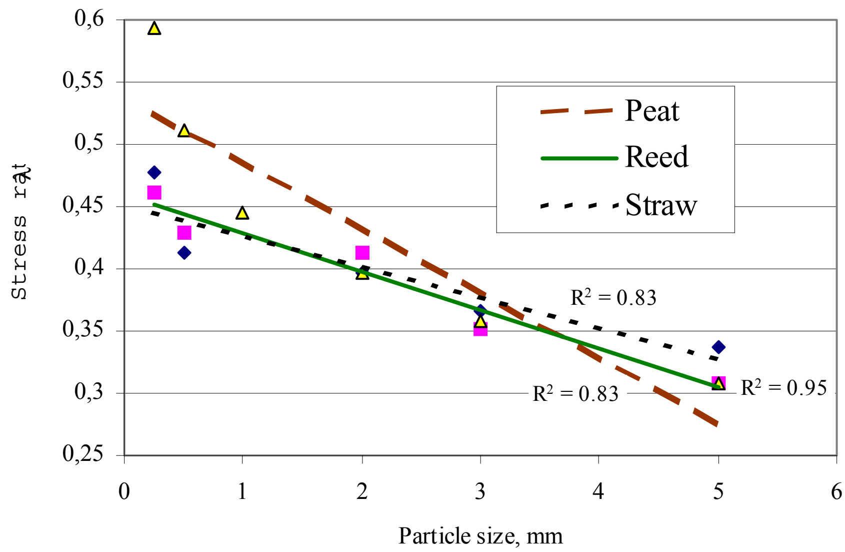

Fig. 7. Influence of particle size of the material on stress ratio λ (obtained by equation (3)).

Direct measuring of stress ratio λ in the material arises great stresses in axial direction, which causes the material flow and stresses in radial direction. Physical process in the cylinder using method of stress ratio direct measuring conforms to physical process in technological equipment – silos, feeders, mixing and flow promoting devices. The values of the stress ratio which are calculated according to equation (3) and DIN 1055 part 6 [2], respectively, are not correct in any case because the stress ratio depends on a lot of parameters which are not taken into account in equation (3). Therefore, the load assumption for the calculation of silos wall strength is on the safe side with the stress ratio λ obtained in direct measuring, but the smallest λ is recommended for applications where vertical stress is important (e.g. for the calculation of the feeder load or the maximum vertical stresses).

An important qualitative result of the Mohr stress circle analysis is that shear stresses can occur in bulk solid at rest. This is impossible for a fluid at rest (in contrast to fluids, bulk solid can have a sloped surface even at rest). Therefore, a representation of the stresses (fluids: pressures) in different cutting planes of a fluid at rest in a σ, τ – diagram would yield a stress circle with the radius zero (equation (5) with $\sigma_h=\sigma_v$ yields $\tau_a=0$).

In summary, the following can be stated with regard to the stresses acting in bulk solids:

- A bulk solid can transmit shear stresses even if it is at rest.
- In different cutting planes different stresses are acting.
- Stress conditions can be represented with Mohr stress circles [5].

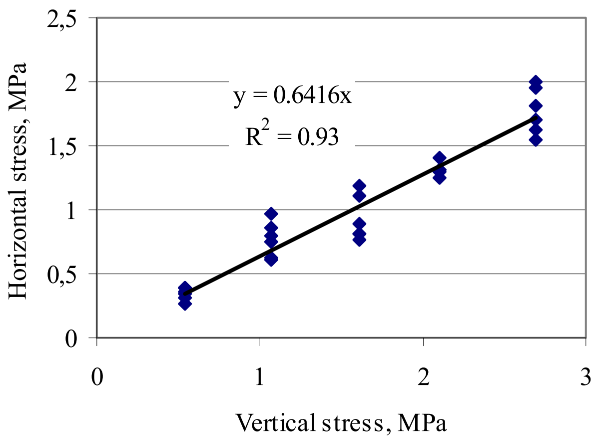

Fig. 8. Stress ratio.

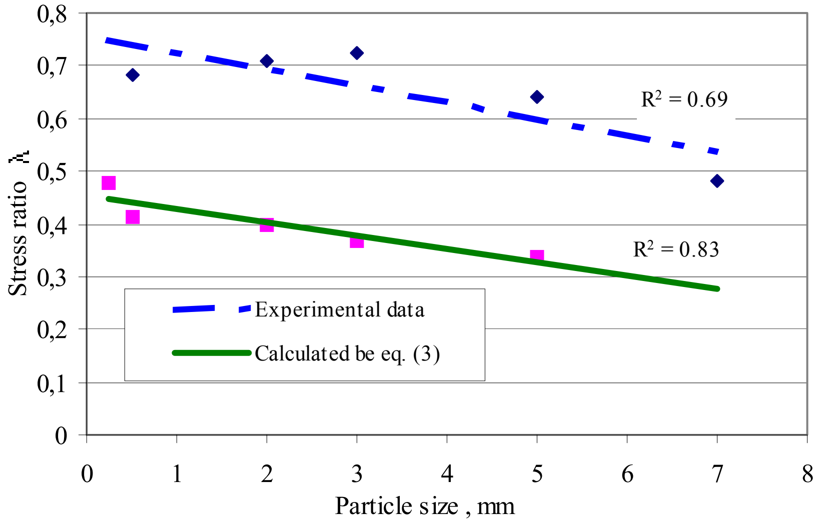

Fig. 9. Stress ratio of different–size straw particles.

Conclusions

1. The angle of repose is dependent on the size of biomass material (straw, reed, peat) particles, increasing of particle size leads to increasing of the angle of repose. The angle of repose for straw and reed is in the range from 45° to 55°, but for peat it is 37° to 50°. The ranges of the angle of repose for straw and reed particles are nearly similar.

2. Experimentally obtained stress ratio of straw particles varies between ~0.5–0.72 for particle size 0.25 to 7 mm.

3. Experimentally by direct measuring obtained values of stress ratio λ are ~1.7 times higher than λ values obtained from the angle of internal friction.

4. The load assumption for the calculation of silos wall strength is on the safe side with stress ratio λ obtained in direct measuring (higher value), but the smallest λ is recommended for applications where vertical stress is important (e.g. for the calculation of the feeder load or the maximum vertical stresses).

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