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Rheology of Agricultural Bulk Material

Determination with a Triaxial Experiment

Using the finite element method (FEM) in bulk mechanics leads to the question on which model can be used for the mechanical behaviour of bulk material. For this the Drucker-Prager approach, supplemented with a flow cap, has proven itself. For a new constitutive law, the material parameters from compression and shear experiments, but also from an element experiment with a triaxial cell, were ascertained.

The Finite Element Method (FEM) represents an efficient method of calculating stress distributions in bulk material silos. This method also offers possibilities of optimal dimensioning and analysing of hopper inserts in core flow silos in accordance with the cone-in-cone principle [1].

Using the finite element method (FEM) in bulk mechanics leads to the question on which model can be used for the mechanical behaviour of bulk material. An objective of the study is therefore to implement a feasible material model in the numerical calculation method selected.

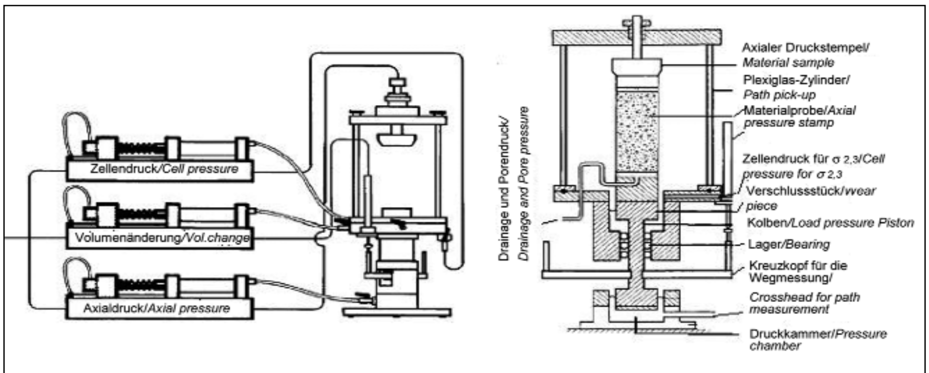

Fig. 1: Triaxial cell

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Keywords
Bulk material, rheology, triaxial experiment

Literature

Books are marked by •

[1] • *Schuricht, T.*: Analysen des Fließverhaltens von Schüttgut in einem Kernflusssilo mit Einbautrichter. Dissertation, TU Braunschweig, 2004

Objective

The following objectives are formulated under scientific aspects:

- For the application of the Finite Element Method (FEM) a constitutive law suitable in engineering terms is to be modelled for the outflow of compound feed mixtures from a core flow silo with hopper insert. The approach according to Drucker-Prager and its extension with a flow cap proves suitable for this.
- The calibration of the material parameters should only be carried out with ring shear experiments in the first steps and using a triaxial cell for the hydrostatic compression and for the conventional triaxial compression in the further development.

Calibrating the material parameters

For a new constitutive law the material parameters from compression and shear tests, i.e. element tests with a triaxial cell are to be determined. These element tests include the cylinder compression test, the hydrostatic compression and the conventional triaxial compression. With the aid of the cylinder compression tests it is possible here to calibrate the elastic material parameters. The hydrostatic compression makes it possible to determine the compressible properties of the material, applying pressure on all sides. The conventional triaxial compression test serves hereby to determine the form change of a material sample when this is exposed to axial load for the various constant values of the lateral pressure.

Experimental equipment

A triaxial system was available to execute the element experiments (*Fig. 1*). The entire triaxial cell could be clamped optionally in a path-controlled universal testing machine ZWICK-Z020. For the experiment the granular material sample was brought into in a cylindrical initial geometry with the aid of a vacuum cell and fixed in the desired form with a paper wrapping and rubber membrane. A volumeter makes it possible to calibrate volume changes in the material sample as a function of defined pressure changes during the experiments. These pressure changes are continuously recorded during loading by a fine-pressure inclined tube pressure gauge, or by the fine pressure measuring device AIRFLOW-500®. The evaluation of the volume and axial extensions measured leads to the output of the cross extensions in the material. The cross sectional representation (*Fig. 1*) of the triaxial cell used shows the built-in condition of the material sample prepared. The path-controlled test facility serves primarily to analyse the material failure and to assess the post-failure behaviour in monotone triaxial experiments with different lateral pressures and rates of deformation specified. The focus of these examinations lay on the use of the force-controlled test facility with which the plastic material behaviour was analysed in cyclical relieving and re-loading experiments. A loading device guides the axial force F_a via the loading beam onto the loading plunger of the triaxial cell (*Fig. 1*).

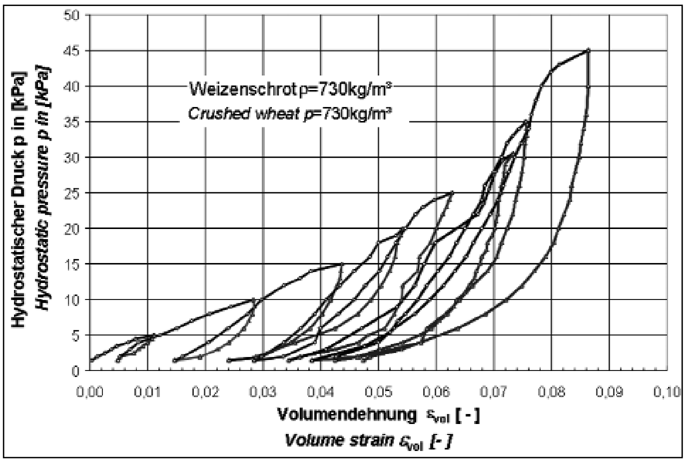


Fig. 2: Hydrostatic compression of crushed wheat

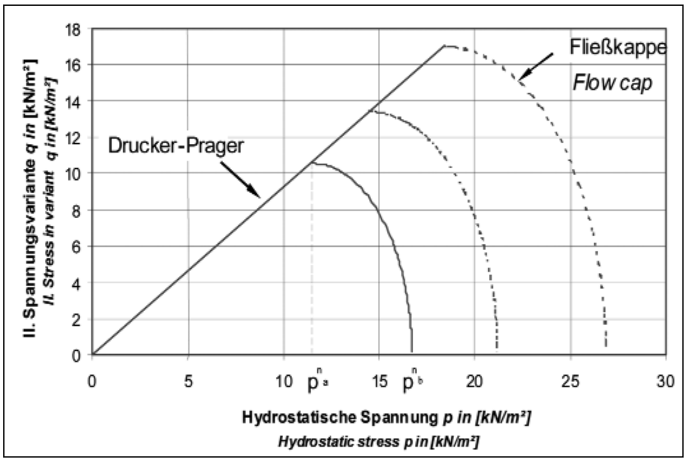


Fig. 3: Closed flow condition with flow cap

Experimental programme

The following experiment variants were executed under quasi-static conditions: Hydrostatic compression experiments, cylinder pressure experiments, and conventional triaxial experiments (*Table 1*).

With the aid of the hydrostatic compression experiments it is possible to determine the stress-dependent compression modules in the first loading, relieving and reloading area and the parameters of the plastic-contractant components of elasto-plastic material laws. The uni-axial experiments with unimpeded side extension, i.e. the cylinder pressure experiments, comprise the joining together of supplementary parameters for the following triaxial compression experiments. A main part of the element experiments is formed by the conventional triaxial experiments. These serve to measure the volume changes and to record the stress-dependent parameters.

Experiment results

Hydrostatic compression

Figure 2 shows a representative course of an experiment with the stress and deformation behaviour of a hydrostatic compression experiment by way of example. The typical connection between hydrostatic stress and volume extension shows strong compactions for the first two compaction cycles and weaker compactions in the last two cycles. The averaged elastic compression modulus of the respective first loading is K=384 kPa and is applied for the numerical simulation of the elastic initial stress condition in simultaneous filling of the silo. Here the compression modulus K follows from the linear rise of the stress-deformation course of the first loading to

$$K = \frac{dp}{d\varepsilon_v} \quad (1)$$

Cylinder pressure experiment

The values for the modulus of elasticity E and for cross contraction μ result from the uni-axial cylinder pressure experiment. In this experiment the sample body is exposed to axial loading without the action of the lateral pressure σ_3. Material parameters from force-controlled experimental procedures with first loading, relieving and reloading are available. The calculation of the modulus of elasticity E is performed by evaluating the first loading in the σ_1-ε_1 diagram.

Conventional triaxial compression

With the monotone loading increase of the axial force, it is possible to determine the fundamental information about the material behaviour as a function of various lateral pressures σ_3 successfully in the triaxial experiment. This includes the mobilised angle of friction:

$$\varphi = \arcsin \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3} \quad (2)$$

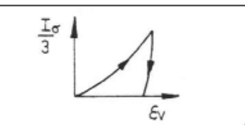
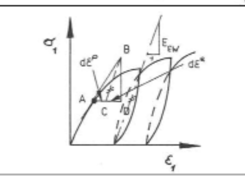
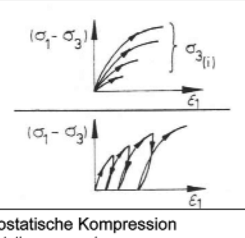
To determine stress-dependent material characteristics the focus of the element tests lay on force-controlled cyclical triaxial tests to evaluate the first loading operations E_B, the relieving operations E_E, the reloading operations E_W and the mean relieving and reloading operations E_{EW} as a function of various lateral pressures σ_3.

Flow cap

The closed flow condition can now be constructed with the work carried out to determine the elastic and plastic parameters of the material behaviour. If an increasing hydrostatic stress condition develops, the flow cap serves to limit the open flow cone and conditions the stress reduction in the compressible bulk material. No experimental analyses could be carried out for the form of the flow cap. For simple modelling the eliptic geometry of a flow cap has proved successful. *Figure 3* shows the closed flow condition in conclusion, assuming an ideal plastic flow cone to Drucker-Prager and an elliptic flow cap.

Conclusions

With the aid of triaxial experiments it is possible to obtain the material characteristics of agricultural bulk materials that are needed to calculate bulk material stresses using the FEM method. Above all the real bulk material stresses can be approximated better by calculation with the new material law to Drucker-Prager with the supplement of a flow cap as flow limitation [1].

Versuchsart *Method of test*	σ_3 kPa	Be- und Entlastungsregime *Load and load reduction strategy*	Versuchsdurchführung *Test procedure* KS Kraftsteuerung *KS strength control* WS Wegsteuerung *WS way control*
HK	5 10 40 45		KS
ZDV	0		WS KS
KTK	5 10 15 20 30 40		WS KS

HK - Hydrostatische Kompression
- *hydrostatic compression*

ZDV - Zylinderdruckversuch
- *cylinder compression test*

KTK - Konventioneller triaxialer Kompressionsversuch
- *conventional triaxial compression test*

Table 1: Applied experimental variants for element experiment