Empirical determination of the compression behaviour of miscanthus round bales

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***Abstract*—Miscanthus x giganteus (miscanthus) is a renewable raw material and a climate-friendly alternative to fossil fuels. However, to utilise the energy crop economically, technical prerequisites are required to cultivate, harvest and transport miscanthus in large quantities. As there is little knowledge about the material behaviour of miscanthus, tests were carried out on miscanthus round bales. The test results provide information about the compression behaviour of miscanthus and thus form the basis for optimising large-scale processing of miscanthus.**

During the tests, conventional round bales of miscanthus were compressed in a customised pressing box by a descending hydraulic pressing plunger. In each of five test series, a round bale of miscanthus was first compressed up to a pressure of 4 MPa and then up to a pressure of 8.5 MPa. The pressure increases approximately linearly to the density of the bale at the beginning of the pressing process. The linear increase in force is transitioning into a nonlinear compaction behaviour as soon as the bale has reached the density of the previous maximum compaction. The measuring points of all test series in this range can be described by a single trend line, which can be approximated by a quadratic function. When the plunger is lifted, the bale is relieved and its density decreases. The decompression of the bale corresponds to the linear curves that describe the compression behaviour at the start of the subsequent pressing process.

In summary, three key characteristics of the pressing process were identified from the pressing tests: The initial linear increase of the pressing force, the subsequent quadratic progression and the relaxation behaviour. The approximated curves for describing these findings describe the measurement results with a normalised absolute deviation of 8.8 % and make it possible to describe the pressing process schematically

Keywords—Bioenergy, Renewable raw material, Miscanthus, Material properties, Compression tests

I. Introduction

One of the biggest challenges of our time is to move materials management towards circularity. This requires the development of bioeconomic value chains. Miscanthus, a perennial plant that originally comes from the East Asian region and occurs in different species, represents a potential raw material for such a value chain [1]. The genotype Miscanthus x giganteus [1] was brought to Denmark by Aksel Olsen in the 1930s and cultivated there for the first time in Europe [2]. It has been observed that the plant has good adaptability and is suitable for the climatic conditions in Europe and North America [2]. This makes miscanthus one of the few C4 grasses that occur naturally in temperate climates [3]. C4 grasses are characterised by the property that they have a special photosynthetic pathway. Compared to C3 grasses, they have the advantage that they have higher efficiencies in terms of radiation, water and nitrogen consumption [4]. Due to these properties, miscanthus is predestined for the production of sustainable electricity, heat and synthetic fuel.

Even though there is great global potential for miscanthus as a raw material, it has not yet been possible to utilise this economically due to a lack of technology and machinery. One of the biggest challenges on the way to highly scalable utilisation of miscanthus currently lies in the compression of the material. For example, conventional baling presses used to harvest miscanthus achieve densities of 150 to 250 kg m^{-3}. In order to make the transport of miscanthus economical, significantly higher densities should be achieved.

This requires the development of new pressing processes. However, there is little knowledge about the material behaviour of miscanthus. Kaack and Schwarz [5, 6] have investigated the mechanical properties of miscanthus as a function of various influencing factors. Initial findings on the compression behaviour of miscanthus can be found in the research of Miao et al. [7]. It was shown that there is a non-linear relationship between the contact pressure and the density.

The pressing tests presented in this article are intended to provide further information about the compression of miscanthus, especially miscanthus round bales. The aim is to demonstrate the relationship between the contact pressure and the density by means of a schematic diagram. The results of the tests should form the basis for designing new baling processes.

II. Materials and Methods

A. Analysed miscanthus round bales

The material analysed is Miscanthus x giganteus, which was grown in southern Germany. The material was harvested in spring 2022 and wound into round bales using a conventional baler. Subsequently, the round bales were stored for about a year. At the time of the trials, the bales had a moisture content of approx. 11%. During the trials, five round bales were analysed, which differed in size and weight according to Table I.

TABLE I. CHARACTERIZATION OF THE EXAMINED MISCANTHUS BALES

Bale no.	**Properties**		
	Volume in m³	***Mass in kg***	***Density in kg m⁻³***
1	0.178	28.3	159
2	0.181	28.8	159
3	0.257	46.2	180
4	0.236	41.3	175
5	0.126	25.1	200

The mechanical properties of the individual miscanthus stems were randomly sampled. The values measured were within the ranges determined by Kaack and Schwarz [5] as part of a large-scale field study for Miscanthus stems. According to them, miscanthus stems consist of 8 to 13 internodes, each of which is 120 to 260 mm long and 7 to 12 mm in diameter. Both the length and the diameter of the internodes tend to decrease with increasing height. In total, the miscanthus stems reach a length of 1.6 to 2.4 m. [5]

The trend that the values decrease with increasing height of the internodes and nodes also applies to the moment of inertia, the modulus of elasticity and the bending stiffness. In addition, there are differences between the material properties of the nodes and the internodes, with the nodes having a higher modulus of elasticity but a lower bending stiffness than the corresponding internodes. The modulus of elasticity of miscanthus ranges from approx. 2 GPa at the highest internode to approx. 8 GPa at a node near the ground. The flexural rigidity assumes values in the range between approx. 0.5 and 5 N m^2, the moment of inertia ranges from 10,000 to 65,000 m^4. [5, 6]

B. *Experimental setup and test procedure*

A Wagner P800 hydraulic press and a customised pressing box were used to press the miscanthus round bales. The schematic structure of the test stand is presented in Figure 1. The pressing system has a nominal force of 8 MN and a stroke of 830 mm. The internal dimensions of the pressing box are 776 mm wide and 596 mm deep, and it is open at the top so that the pressing stamp can enter from above.

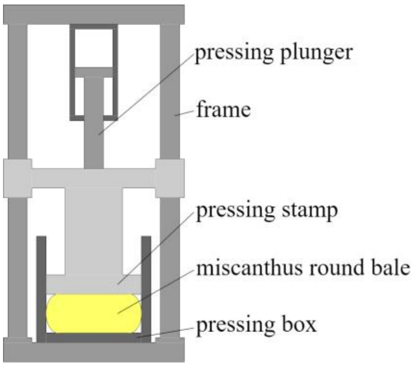

Fig. 1. Experimental Setup

The pressing tests involve five test series, in each of which a different miscanthus round bale was analysed. Each test series consists of two consecutive compressions. In the first compression, the pressure is increased to approx. 4 MPa, in the second compression to approx. 8.5 MPa. Between the pressings, the pressing plunger is moved upwards to relieve the pressure on the bale. During the pressing processes, the path travelled by the plunger and the pressing force applied are recorded. From the position of the plunger and the dimensions of the pressing box, the volume and thus the density of the miscanthus bale can be determined at any time. The contact pressure is calculated from the pressing force and the area of the pressing stamp.

C. *Evaluation methods*

To derive a characteristic scheme for the pressing process, functional equations are required to approximate the recorded measuring points. These functional equations are optimised and evaluated using the following key indicators.

The mean absolute error (MAE) is regarded as an easy-to-interpret key indicator. It represents the mean value of the difference between the predicted value *y´* and the measured value *y* for a number of *n* measuring points (Eq. (1)). By dividing the MAE by the mean value of the measured values $\bar{y}$, the normalised mean absolute error (NMAE) can be determined (Eq. (2)).

$$MAE = \frac{1}{n}\sum_{k=1}^{n}|y' - y| \quad (1)$$

$$NMAE = \frac{MAE}{\bar{y}} \quad (2)$$

Similarly, the mean square error (MSE) is defined as the average of the squared differences between the predicted value *y´* and the measured value *y* of *n* measurement points (Eq. (3)). In addition to the distance between the predicted and measured values, the MSE also takes into account the scatter of the predicted values. It is therefore well suited for evaluating the quality of an approximation.

$$MSE = \frac{1}{n}\sum_{k=1}^{n}(y' - y)^2 \quad (3)$$

III. RESULTS AND DISCUSSION

A. *Observations*

The pressure-density curves determined for the five test series are shown in Figure 2a-2e. During the first pressing processes of the five test series, the pressure initially increases approximately linearly to the density. From a certain density, in the range between 250 and 300 kg m^{-3}, the relationship between the pressure and density changes to a non-linear one. The contact pressure increases to approx. 4 MPa until the first pressing process is completed. The plunger then moved upwards to relieve the pressure on the bale. It was not technically possible to record the pressure during the relaxation process. However, it was observed that the density of the bale was noticeably reduced by the relaxation.

An approximately linear relationship between contact pressure and density can also be recognised at the start of the second pressing processes. The linearity is given until the density is reached up to which the miscanthus bale was compressed during the first pressing process. During the subsequent compression, the contact pressure increases non-linearly to the density. Again, the contact pressure is increased up to a fixed value, in this case approx. 8.5 MPa. In contrast to the first pressing process, the maximum contact pressure is maintained for a few seconds during the second pressing. The bale is compressed even further while the contact pressure remains the same. However, compression is much slower and eventually comes to a standstill. Relieving the pressure on the bale leads to its relaxation again.

The consideration of all determined pressure-density curves shows that the gradient of the linear curves at the beginning of a pressing process is approximately the same. Only the second pressing process of the fifth test series represents a recognisable outlier, in which the gradient is significantly smaller. For this reason, this pressing process was not taken into account for the further analysis of the linear curves.

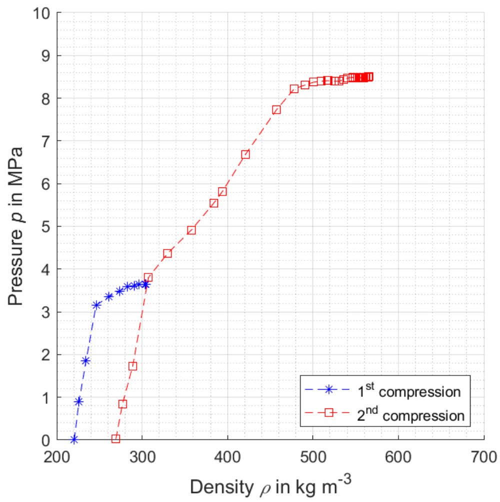

Fig. 2a. 1st test series

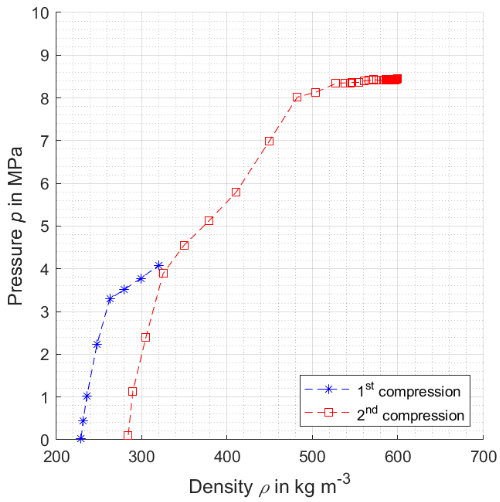

Fig. 2b. 2nd test series

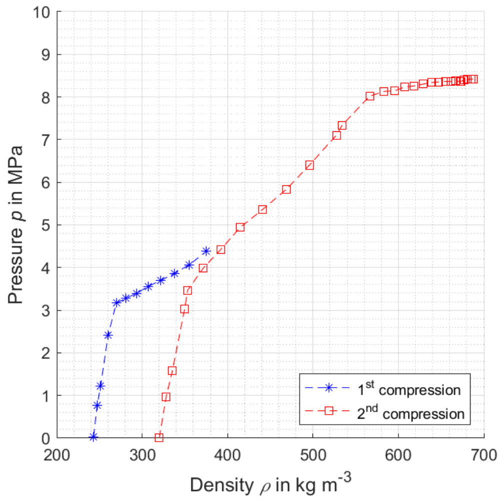

Fig. 2c. 3rd test series

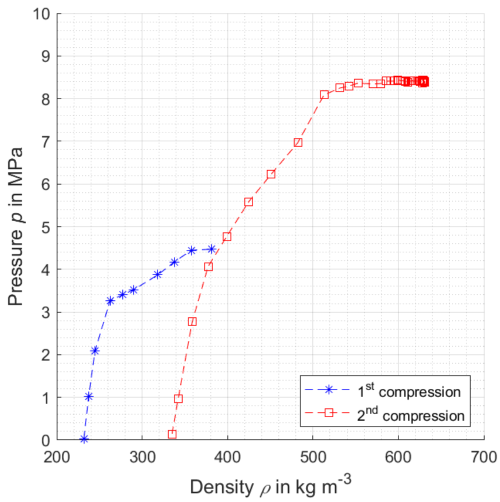

Fig. 2d. 4th test series

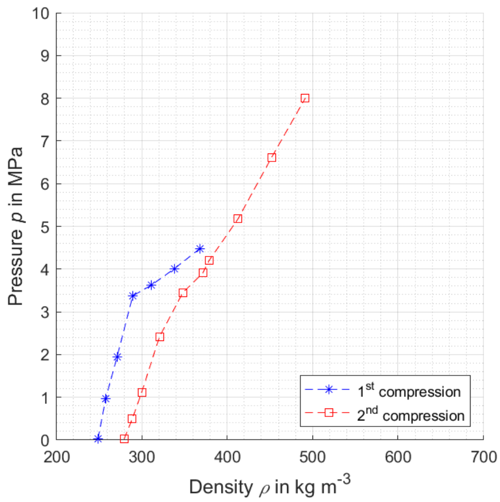

Fig. 2e. 5th test series

B. Interpretation

According to the observations described, the pressing processes can be divided into four areas: a linear area at the start of a pressing process, a non-linear area during further compaction, the post-compaction when the maximum contact pressure is maintained and the relaxation. The post-compaction was not investigated further, as it is primarily highly dynamic pressing processes that are of interest.

To further analyse the initially linear and subsequently non-linear relationship between contact pressure and density, the measuring points of all tests were divided according to their affiliation to the two areas, see Figure 3.

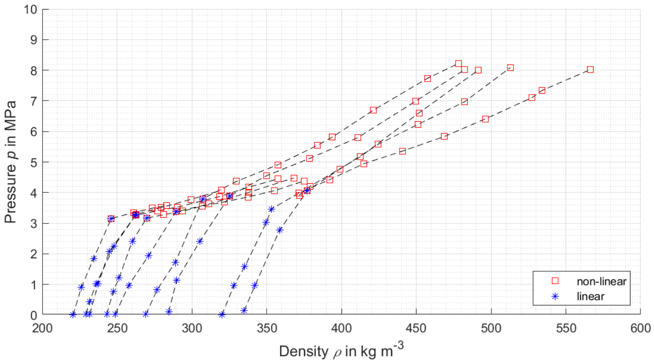

Fig. 3. Allocation of measuring points into linear and non-linear behaviour.

a) Linear material behaviour

For the linear progressions of the i pressing processes, the assumption was made that they can be described by the set of functions $p_i(\rho)$. In the corresponding linear equation Eq. (4), the gradient m is the same for all pressing processes, while the Y-intercepts c_i differ.

$$p_i(\rho) = m \cdot \rho + c_i \tag{4}$$

An optimisation was carried out using the MSE to identify the common gradient m and the Y-intercepts c_i . The parameters determined are listed in Table II. Figure 4 contains the visualisation of the linear equations with the corresponding measurement points. The quality of the linear approximation can be indicated by the evaluation indices shown in Table III.

TABLE II. PARAMETERS FOR LINEAR APPROXIMATIONS

Compression	Parameters		
	i	***m***	***c_i***
1st test series, 1st compression	1	0.0964	-20.87
1st test series, 2nd compression	2		-25.94
2nd test series, 1st compression	3		-21.88
2nd test series, 2nd compression	4		-27.16
3rd test series, 1st compression	5		-23.00
3rd test series, 2nd compression	6		-30.71
4th test series, 1st compression	7		-21.93
4th test series, 2nd compression	8		-32.07
5th test series, 1st compression	9		-24.14

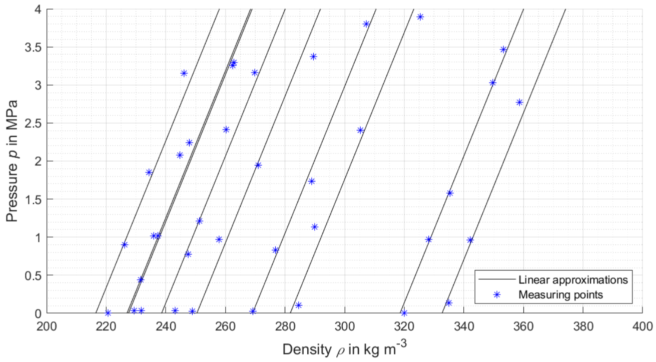

Fig. 4. Linear approximations of measuring points.

TABLE III. PARAMETERS FOR NON-LINEAR APPROXIMATIONS

Approximation	Key indicators		
	MAE in MPa	***NMAE in %***	***MSE in MPa²***
Linear set of functions	0.173	10.5	0.046
Quadratic function	0.413	8.4	0.289
Exponential function	0.409	8.3	0.304
Power function	0.418	8.5	0.301
Linear set of functions + quadratic function	0.257	8.8	0.356

b) Non-linear material behaviour

Three different approaches were investigated to approximate the measuring points in the area with non-linear behaviour: a quadratic function, an exponential function and a power function (Eq. (5-7)). The function parameters a, b, c were determined by optimisation using the MSE and can be obtained from Table IV.

$$p(\rho) = a \cdot \rho^2 + b \cdot \rho + c \tag{5}$$

$$p(\rho) = a \cdot e^{b \cdot \rho} \tag{6}$$

$$p(\rho) = a \cdot \rho^b \tag{7}$$

The quality of the approximations using the three different approaches differs only slightly according to the key indicators listed in Table III. Even though the MAE is smallest with the exponential approach, the quadratic approach proves to be the most promising due to the lowest MSE. Figure 5 shows the measuring points associated with the non-linear range and the determined quadratic approximation.

TABLE IV. PARAMETERS FOR NON-LINEAR APPROXIMATIONS

Function	Parameters		
	a	***b***	***c***
Quadratic function	0.000018992	0.002928	1.040
Exponential function	1.338	0.00338	-
Power function	0.002266	1.2941	-

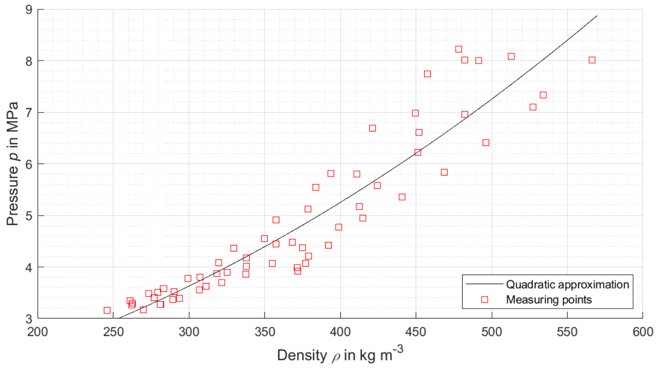

Fig. 5. Quadratic approximations of measuring points.

c) Relaxation behaviour

It was observed that the bale relaxes, i.e. that the density of the bale decreases as soon as the contact pressure also decreases. However, no measurement data could be generated when the pressing stamp was raised. Therefore, the observations of the subsequent pressing process are used in order to make statements about the relaxation behaviour of the bale.

It is assumed that the pressure required to retain the bale at a certain density during the relaxation process corresponds to the pressure required to compress the bale to this density in the subsequent compression process. Taking this assumption into account, the linear relationship found between pressure and density can also be applied to the decompression.

IV. Conclusion

The pressing tests carried out allow the conclusion that the pressing process can be divided into 2 sub-processes with different behaviour. Firstly, the increase in contact pressure over the density can be described using a linear approximation. The linear relationship exists until the density is reached up to which the material was compressed in a previous pressing operation. From then on, the compression behaviour is non-linear and can be approximated using a quadratic function. The approximations found can be used to reproduce the measuring points of the five test series with a MAE of 0.257 MPa. In relation to the mean value of the measuring points, this corresponds to a percentage deviation of 8.8 %.

If the contact pressure is reduced after pressing, the density decreases again. Assuming that the relaxation corresponds to the start of the subsequent pressing process, the linear approximation found is also valid for the relaxation process.

These findings can be summarised in a schematic diagram, see Figure 6. The diagram also contains the course of an exemplary pressing process and is intended to show how the pattern can be used as a basis for the design of compression processes for miscanthus. In the exemplary case, a bale with an initial density of 250 kg m^{-3} is compressed up to a contact pressure of 6.6 MPa. The bale thus reaches a density of 470 kg m^{-3} in the compression box. After the bale has been relaxed, it finally has a density of 400 kg m^{-3}.

Further material tests with miscanthus are planned to confirm the relationships found. In particular, the evaluation of the different approaches for describing the non-linear material behaviour and the process of relaxation requires further measurement data.

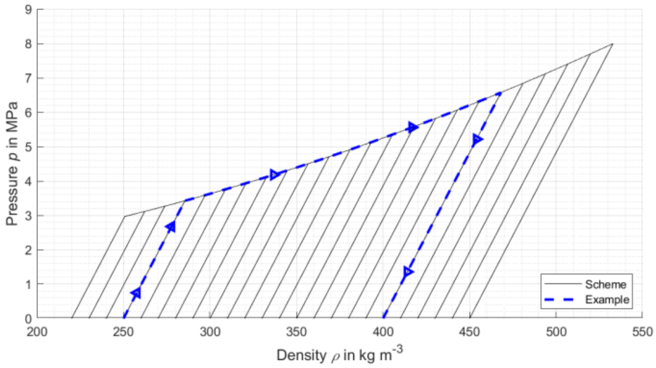

Fig. 6. Scheme for the compression of miscanthus round bales including an example.

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