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Characterization of material properties of renewable biobased powder for 3D printing using the traditional moulding sand test methods of foundry technology

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ABSTRACT

Bio-based powders are produced from renewable resources such as plants, agricultural waste, or even algae. These materials offer a compelling alternative to conventional plastics, which are often obtained from fossil fuels. New types of powder materials for the 3D printing process need to be characterised. They play an important role in 3D printing technology. Based on the results from testing, process parameters can be adjusted. There are currently no standardised methods for the testing of 3D printing materials. The moulding sand material has the same material properties as the renewable bio-based powders used for 3D printing.

In order to efficiently characterise the material, conventional foundry sand testing methods were considered. In this study, the existing testing facilities of the foundry industry were used to test the properties of Miscanthus, a plant in the grass family.

The results show that the universal testing machine can be used for general characterisation of relevant material properties, but modifications to the specimen geometry and testing technology are required for in-depth investigation of new powder materials for the 3D printing process.

1. Introduction

Additive manufacturing technology has been implemented in many industry fields. Additive manufacturing processes belong to the main group of primary shaping according to DIN 8580, which describes the manufacturing of a solid body from shapeless material. The unique feature is that no specific tools or shapes are required to create a solid body. This has the benefit that extremely complex geometries can be realized. Depending on the starting material and the solidification principle there are a variety of different additive manufacturing processes available (Fritz and Schulze, 2008).

Binder jetting is an additive manufacturing (AM) technique that uses a liquid binder to selectively bond particles of a powdered material, layer by layer, to create three-dimensional objects. Compared to other additive manufacturing processes, the 3D printing - binder jetting method offers great potential because a high build rate can be achieved with a range of materials from ceramics to metal to inorganic powder, such as gypsum, with relatively low investment and operating costs. In the last few years the renewable biobased materials have attracted increased attention owing to their distinctive properties (Kottlorz, 2014; Schirmer *et al.*, 2021; Xie *et al.*, 2023).

However, there is no standardized test procedure for the mechanical properties of 3D printing materials. The testing of the mechanical properties of materials, which are used in the area of low mechanical stress, is particularly inconsistent. Nevertheless, it is important, especially when developing new powder materials, to know their mechanical properties in order to evaluate possible applications.

In general, materials such as sand, soil, powder, or rock flour are classified as granular media (granular friction materials). A literature review of this topic should also include other technologies, such as foundry technology or powder technology since the properties of these substances are similar to those of cohesive friction materials (Kadauw, 2006). The mould sand has similar material properties to those of renewable, biobased powders for 3D printing. For molding sand, there is a long-used methodology to characterize the mechanical properties. The motivation for this research is to investigate the applicability of already proven test methods from the foundry technology for the characterization of the

mechanical strength of 3D-printing materials and to determine a suitable test method.

2. Materials and Methods

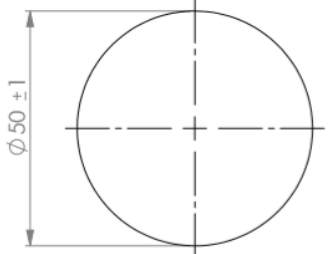



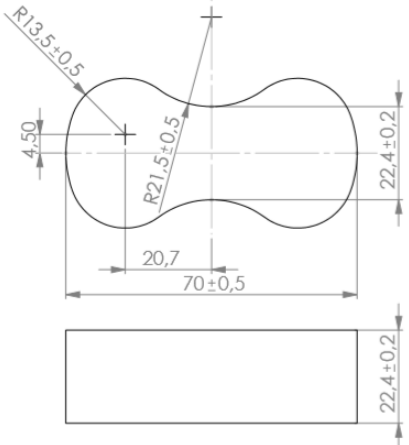

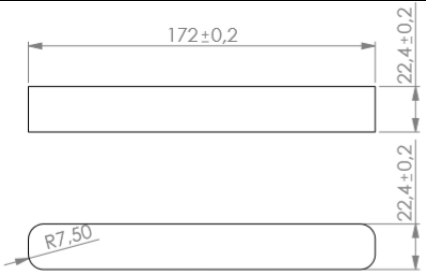

Strength test device

Using the universal test machine for the determination of the mechanical properties of moulding sand, one can determine the mechanical properties of moulding sand, such as compressive strength, shear strength, tensile strength and bending strength (Figure 1). This process can also be applied to 3D-printing materials. The sample preparation and the determination of the test are defined in the VDG-Merkblatt P31 and P38 of the German Foundry Association. VDG Data Sheets P31 and P38 are important guidelines in the field of foundry technology published by the German Foundry Association (Bundesverband der Deutschen Gießerei-Industrie, BDG). They provide detailed information and test procedures for specific aspects of moulding material testing in the foundry industry (VDG, 1997). The loading speed used in the subsequent strength test is $25 \text{ g/cm}^2/\text{second}$, corresponding to around $0.25 \text{ N/cm}^2/\text{second}$. The unit results from the functional principle of the testing machines. The tension, which increases linearly over time and loads the test specimen, is applied by means of a lever and a movable mass. The speed of movement of the mass is therefore dependent on the loaded cross-section of the respective test body (Lexikon, 2024). An overview of the test specimen shape to be used for the respective strength tests is given in table 1.



Fig. 1: Universal test machine for the determination of mechanical properties of moulding sand (Multiserw-morek.pl, 2024).

Table 1: Overview of the strength specimen options of the universal test machine

	Sketch of the specimen in cross-section (size in mm)	Specimen position on the machine	Test parameter
Compression test	 <p>Sketch of a circular specimen with diameter $\varnothing 50 \pm 1$ mm.</p>		<p>loaded cross-section: 19.6 cm^2</p> <p>load range: $0 \dots 2 \text{ MPa}$</p>
Shear test	 <p>Sketch of a rectangular specimen with height 50 ± 0.8 mm.</p>		<p>loaded cross-section: 25 cm^2</p> <p>load range: $0 \dots 1.56 \text{ MPa}$</p>
Tensile test	 <p>Sketch of a tensile specimen with dimensions: $R13.5 \pm 0.5$, 4.50, $R21.5 \pm 0.5$, 20.7, 70 ± 0.5, 22.4 ± 0.2.</p>		<p>loaded cross-section: 5 cm^2</p> <p>load range: $0 \dots 2.5 \text{ MPa}$</p>
Bending test	 <p>Sketch of a bending specimen with dimensions: 172 ± 0.2, 22.4 ± 0.2, $R7.50$.</p>		<p>loaded cross-section: 5 cm^2</p> <p>testable range: $0 \dots 264 \text{ MPa}$</p>

Powder and binder materials

Powder materials for 3D printing must meet the requirements of being able to be applied to the construction platform as thinly, densely and homogeneously as possible. This requires a certain particle size distribution and morphology (Fritz and Schulze, 2008; Schirmer et al., 2021). Another requirement is the reactivity of the powder material with the corresponding binder.

Renewable raw materials, used for the production of powder materials are miscanthus, a member of the grass family, wood flour, fruit stone and mussel powder. The particle size distribution and the morphology are shown using the example of miscanthus in figure 2.

In this research, a new type of miscanthus powder was used. The powder consists of finely prepared miscanthus fibres (see figure 2 for particle size distribution) and 17 wt % polyvinyl alcohol (PVA) powder.

Liquid binders are mixed with the powder before printing; activation is achieved by printing an aqueous solution onto the powder bed. Miscanthus powder is mixed with 84 % of a water-based binder. Additives in the binder are 2-propanol, glycerine and sodium dodecyl sulfate.

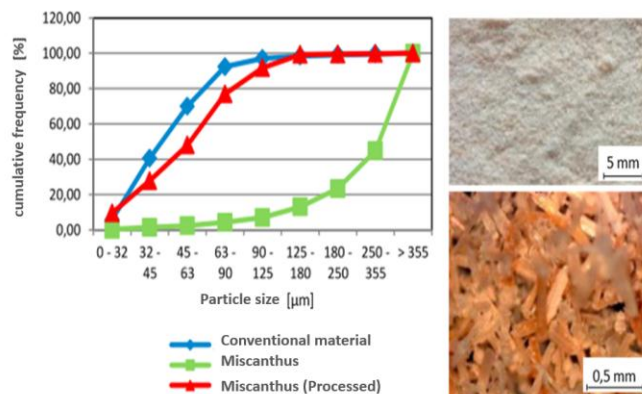


Fig. 2: Particle size distribution and morphology of miscanthus powder [10].

Preparation of specimens

All test specimens were manufactured with the ZPrinter310, Z CORPORATION, BURLINGTON, USA. The manufacturing parameters used are listed in table 2. Figure 3 shows the orientation of the test specimen in the sample holder. Following the sample preparation, all test specimens were stored at low humidity until they were tested.

Table 2: Overview of the manufacturing (3D Printing) parameters

Material	Layer thickness	Saturation	Binder / Volume ratio		Post treatment
			Core	Shell	
Miscanthus	0,1 mm	150 %	0,161222	0,322443	2 h in drying box at 80 °C

Experiments

All strength tests were carried out with the universal test machine LRu-2e from MULTISERW MOREK, Brzeźnica, Poland. A room temperature of approx. 21 °C was kept in the test environment. Before the test, the mass of each test specimen was determined using the TE4101 balance from SARTORIUS AG, Göttingen with an accuracy of 0.1 g. In addition, the dimensions of the test specimens were checked with using a slide caliper. Immediately after the preliminary examination described above, the test specimen was placed on the sample holder and tested. The position of the test specimens for compression, tensile and

shear strength tests can be seen in figure 3. The test position of the bending specimens is shown in figure 4. The direction of loading is generally chosen so that the highest possible strength is achieved with regards to the anisotropy of the strength of 3D printed bodies.

After the test, the respective test result was read on the digital display with one decimal place in N/cm². For each test, five specimens were examined for each material. The maximum value that can be applied by the universal test machine during the tests is shown in table 1.

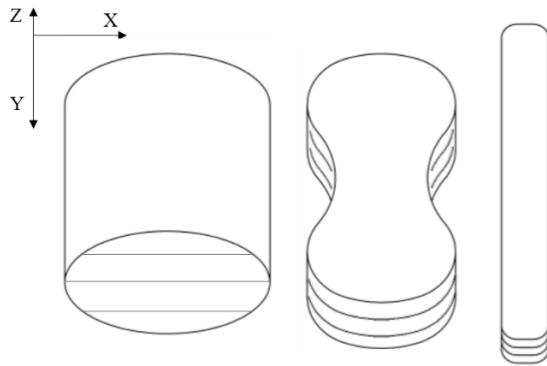


Fig. 3: Schematic overview of the position of the test specimen during manufacturing (3D Printing).

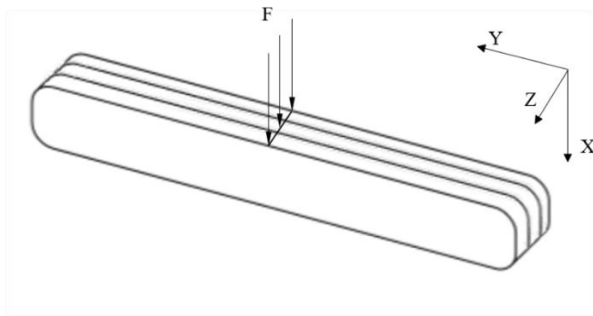


Fig. 4: Direction of load on the bending specimen.

3. Results and Discussion

Compression test

During the compression strength test, the miscanthus test specimens, shown in figure 5, initially bulged outwards evenly over the sample holder jaws (red markings) on the top and bottom, which resulted in a notch effect. As the press increases the outer areas of the test specimens become detached, and the test specimens fails shortly afterwards. The detachment of the outer areas was concentrated on the part of the circumference where the bonds between the layers of the test specimens are primarily exposed to stress (see figure 3). This phenomenon causes cracks and the specimens subsequently failed. The test specimens, shown in figure 5 after the pressure tests, are typical for

all miscanthus specimens.

The results of the compressive strength test of the miscanthus samples, shown in figure 6, indicate that the fluctuations in the imaging accuracy, which result from the varying mass of the test specimens, have a negligible influence. By compliance with the tolerances thus be assessed as being suitable for the strength test. The mass of a test body allows conclusions to be drawn about the imaging accuracy of the test body with regards to their respective volume. Since the stressed area of the test specimens in all further tests was significantly smaller than in the compressive strength test, compared to the test specimen volume, it can be assumed that the negligible influence also applies to all other tests carried out in this study.

The mean value of the compressive strength of the miscanthus test specimens was 0.048 MPa. The value is one order of magnitude smaller than the compressive strength of samples made from apricot kernel flour with the same binder (PVA) (Zeidler *et al.*, 2018). The difference could result from the significantly lower bulk density of the miscanthus powder. In addition, the pressure samples made from apricot kernel flour have a smaller dimension with a diameter and a height of 20 mm. Smaller samples have a higher compression strength, as the time between the wetting of the layers in the printing process is shorter, resulting in a stronger bond between them. In addition, there are a greater number of statistical defects, such as incompletely wetted layers, in larger samples. A general applicability of the compressive test to 3D printed materials can thus be inferred (Feng *et al.*, 2015).



Fig. 5: Miscanthus test specimen during (left) and after the pressure test (middle, right)

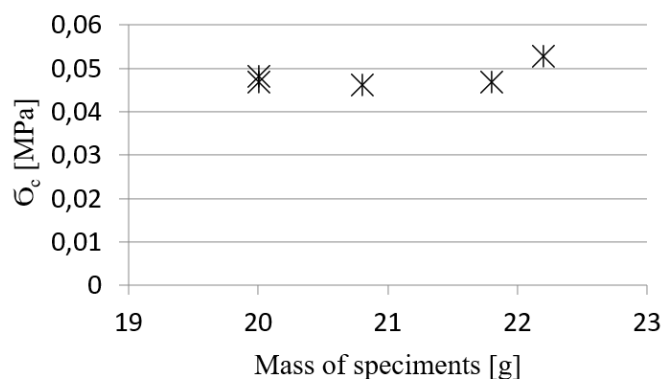


Fig. 6: Compressive strengths of the miscanthus test specimens as a function of their mass.

Shear test

The mean value of the shear strengths σ_s of the miscanthus test specimens was 0,026 MPa. During shear tests of miscanthus specimens, their elasticity leads to impermissible contacts between the test specimens and the sample holder (see figure 7). The test results are therefore limited because the area tested does not have to withstand the entire load applied due to the supporting effect of the contacts.

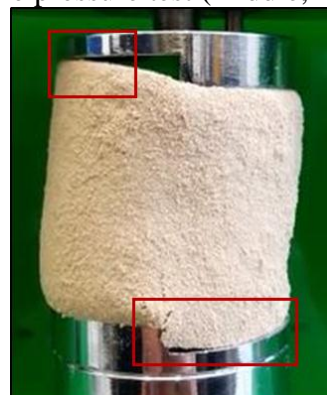


Fig. 7: Impermissible contact surfaces during the Shear test.

Tensile test

All miscanthus tensile test specimens tear outside the smallest cross section at an average tensile strength σ_T of 0.073 MPa (figure 8). The failure in the clamping area of the sample holder is due to the elasticity of the material, which increases during the test. This creates a notch effect in the clamping area, which causes the breakage.

The results show the possibility of determining the tensile strength of miscanthus test specimens by means of positive clamping.

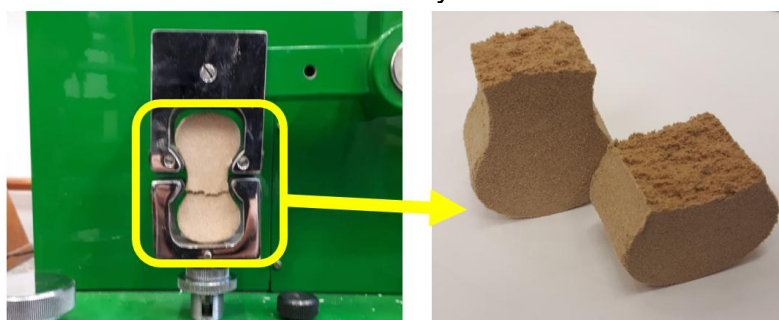


Fig. 8: The fracture position and fracture surface of the specimens during the Tensile test.

Bending test

The bending test, known as flexural testing, was carried out for 9 test specimens and the mean value for bending was 0.266 MPa. In the bending test of the miscanthus specimens all test specimens generally fail in the middle. In isolated cases, however, as shown in figure 9, the fracture runs slightly outside of the most heavily stressed, central area. This can be explained by irregularities in the printing process, which results in areas of different strength. The resulting crack

is therefore not straight because it follows the path of structural weakness. It is also worth noting, that none of the miscanthus samples breaks completely, since the material has a high degree of elasticity. As such, an effect of this phenomenon on the comparability of test results cannot be ruled out. To avoid specimens that are not completely broken, the travel of the upper jaw may be increased. The measured values scatter only slightly around the mean value of the breaking strength (figure 9).

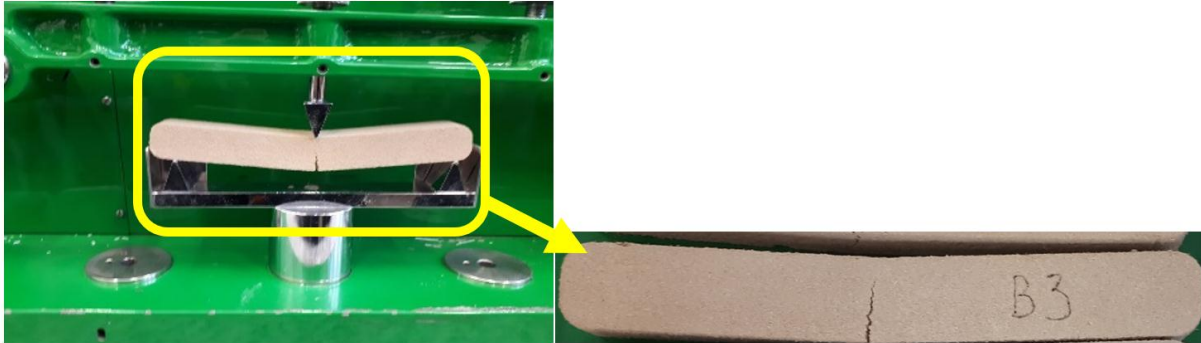


Fig. 9: Breakage after the test and results for the miscanthus specimen during the flexural test.

4. Conclusion

In the present study we examined the applicability of moulding sand testing used in the foundry industry after VDG-Merkblatt P31 and P38 of the German Foundry Association to determine the mechanical strengths of 3D printing materials. This was accomplished by the determination of the mechanical strengths, such as compression, tensile, and bending strength tests of specimens made of renewable biobased powder. Results suggest that the test methods and the machinery used are generally suitable, but modifications of the specimen geometry and the test facility are needed for a more comprehensive examination of the material properties of new 3D printing materials, such as miscanthus.

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