Influence of Particle Dimensions in Liquid Deposition Modeling 3D Printing with Wood-based Materials

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Additive manufacturing (AM) using wood-based materials offers new bioeconomic possibilities for sustainable product design and waste valorization. This study examined the influence of wood particle size and shape on the properties of pastes processed by Liquid Deposition Modeling (LDM). Softwood sawdust separated into nine particle size ranges and ground wood powder were analyzed. The materials were mixed with water and methylcellulose as a natural binder, printed into test specimens, and evaluated for shrinkage, density, and flexural strength. Finer particles led to higher densities (up to 0.38 g/cm³), flexural strengths (up to 4.8 MPa), and elastic moduli (up to 436 MPa), while larger particles limited the filler content and reduced mechanical performance. Grinding decreased particle slenderness and promotes greater material density, thereby improving mechanical strength. These findings demonstrate that particle characteristics strongly influence paste printability and mechanical performance, providing a basis for the further development of resource-efficient wood-based materials for sustainable manufacturing.

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Keywords: 3D Printing; Additive manufacturing; Liquid deposition modeling; Wood particle size; Slenderness

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INTRODUCTION

Additive manufacturing (AM), or 3D printing, encompasses processes to produce goods in which materials are deposited layer by layer. The material used remains almost entirely in the finished workpiece or is available for the production of the next one. The increased use of lignocellulosic materials, alongside very high material efficiency, makes an important contribution to Industry 5.0, which is characterized by its strong focus on sustainable production systems (Alves *et al.* 2023). The usage of ambient temperature extrusion can reduce energy consumption in 3D printing (Faludi *et al.* 2019). Furthermore, upcycling waste materials from the wood industry promotes the circular economy (Meyer *et al.* 2024).

The AM processes differ in both deposition mechanisms and the materials used (Gibson *et al.* 2015). In most cases, wood in AM has been used in combination with thermoplastics (Krapež Tomec and Kariž 2022). In the Fused Deposition Modelling (FDM) process used for this purpose, the proportion of wood is limited to a maximum of approximately 40%. An alternative is LDM (Liquid Deposition Modelling), which is sometimes also called Paste Deposition Modelling (Schunemann and Silve 2013) or Dough Deposition Modelling (Gardan *et al.* 2016). Here, the lignocellulosic filler (*e.g.*, wood powder) is mixed with water and bio-based adhesives and processed additively as a paste-like suspension. With this process, wood contents of up to 90% are possible (Rosenthal *et al.* 2018). Furthermore, it is much more energy-efficient than other additive manufacturing processes, *e.g.*, FDM (Faludi *et al.* 2019).

In an initial phase of material development, various binding agents were identified that are suitable for additive processing of wood waste using the LDM process, *e.g.*, carboxymethylcellulose (Bodenschatz and Rosenthal 2024), cellulose nanocrystals and xyloglucan (Kam *et al.* 2019), chitosan (Sanandiya *et al.* 2018), methylcellulose (Rosenthal *et al.* 2018), and starch (Kaufhold *et al.* 2019). These binder systems have enabled the development of diverse prototypes, including formwork for concrete structures (Khan *et al.* 2023), seating elements (Cohen *et al.* 2024), table frames (Bodenschatz and Rosenthal 2024), acoustic (Cohen and Barath 2025), and non-structural building components (Jain *et al.* 2025) or upholstered stools (Fig. 1).

Fig. 1. Hybrid upholstered stool constructed from round corner elements made from additively manufactured wood-based paste (Bodenschatz and Rosenthal 2024) and traditional wood panel materials (U. Bodenschatz)

An increasing focus is being placed on wood as a filler. Kaufhold *et al.* (2019), Rosenthal *et al.* (2018), Meyer *et al.* (2024), and Jain *et al.* (2025) tested native spruce, beech and oak wood as well as recycled wood-based materials (medium-density fiberboard (MDF) and oriented strand board (OSB)). In most cases, the wood particles were ground. Up to three fractions of different particle sizes were used.

However, few studies have examined a more differentiated view of the influence of the particle dimension, *i.e.*, that work with a larger number of sieve mesh sizes and consider the particle geometries. Because it can be assumed that grinding has an influence on the degree of particle slenderness, this influencing factor must be taken into account. To reduce energy consumption, it is advisable to avoid the grinding process in industrial applications.

This study addresses this gap by analysing the physical properties of LDM 3D-printed test specimens made from native softwood particles from nine sawdust fractions and one sample of ground wood powder.

EXPERIMENTAL

Materials

The test specimens were prepared from methylcellulose (Carl Roth/, Germany, CAS No.: 9004-67-5, viscosity: 3660 mPa s), which behaved as a binder, water and softwood particles, acted as a filler. The wood particles were sourced from HS Timber Productions GmbH in Kodersdorf, one of the largest sawmills in Germany with an annual sawing capacity of over one million cubic metres of spruce and pine wood. Sawn timber is produced using profiling technology, which generates wood chips as a by-product. The particle samples were collected from a storage facility containing sawdust from sawing operations. Wood chips that are too small to produce thermomechanical pulp are temporarily stored (Fig. 2). The particles were then air-dried. In addition, the softwood powder Lignobest® C200 from Holzmühle Westerkamp GmbH, was used.

A B

Fig. 2. Sampling at the HS Timber Productions wood particle storage facility (A) and dried particle material (B)

Methods

Sieve analyses of the sawdust and wood powder were performed using a vibrating sieve shaker (AS 200 control; Manufacturer, Retsch, Germany) with a ~100 g material load, 1.2 amplitude, and 45 min sieving time. Results represent the mean of four repetitions. Nine mesh sizes were used: 1000, 800, 600, 400, 200, 100, 75, and 50 µm).

Particle geometry was determined by light microscopy (ZEISS AX10). The particles were placed on a glass slide, and images were captured at randomly selected points without pre-selection. Two concentric circles were placed over the centre of this image (Fig. 3).

In the following analysis, only those particles were measured that lay completely within the first circle. If fewer than 50 particles were present within the inner circle, particles that had their origin in the first circle but extended beyond it were also accounted for. If necessary, the measurement area was then expanded to the second circle. Insufficient separation of the particles on the slide could lead to clustering. Such areas were not measured as it was not possible to precisely distinguish individual particles. The ImageJ programme was used to measure the lengths and widths of each particle, and the slenderness ratio was calculated as a ratio of length to width.

Material mixtures were prepared for each sieve fraction of the sawdust, for the wood powder, and their combinations.

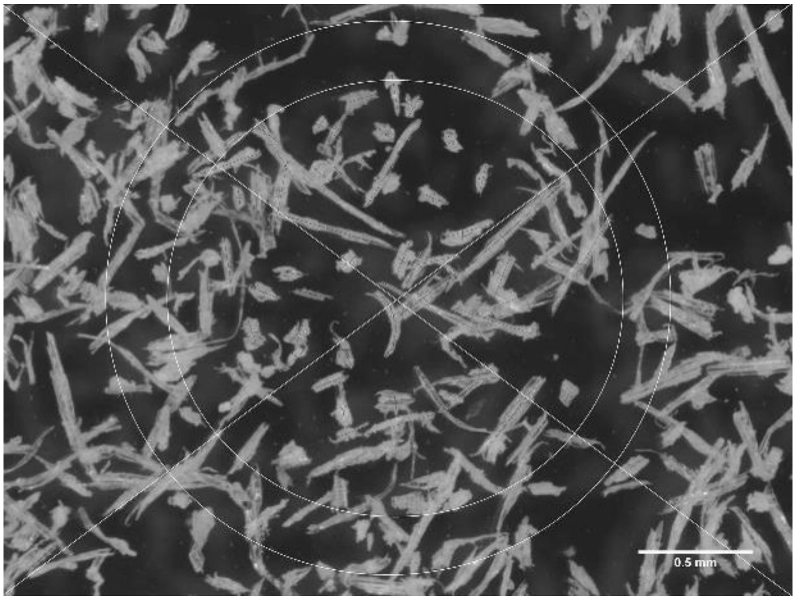


Fig. 3. Light microscopic particle measurement of softwood sawdust (screen fraction 50 to 75 µm)

A standard Cartesian 3D printer (ZMorph VX Mooltitool 3D Printer, Poland) equipped with a modified extruder head was used to print the samples. The modified paste extruder is shown in Fig. 4. It consists of a cylindrical plastic cartridge with an internal diameter of 27 mm and a height of 120 mm, an outlet nozzle with an internal diameter of 8 mm and a length of 51 mm, and a stepper motor that moves a piston towards the outlet via a lead screw. Voxelizer 1.4.18 software was used for slicing. Printing was carried out with a traverse speed of 1 mm/s. The layer height was 4 mm for all printed parts, whereby the first layer was reduced to 3 mm to improve adhesion to the print bed.

Fig. 4. Modified paste extruder with stepper motor, cartridge, nozzle and connecting elements (reprinted with permission from Emerald Group Publishing, Rosenthal *et al.* 2023)

The shrinkage was measured as shrinkage in the z-direction, as it can be assumed that, given the layered structure, greater drying-induced deformation occurs in the vertical direction than in the horizontal plane (x- and y-directions). A simple 'tower-shaped' test specimen was found to be sufficient for this measurement (Fig. 8, 9): a single-walled hollow cylinder with an external diameter of 40 mm and a height of 11 layers (limited by the cartridge volume of 70 mL).

The height of each tower was measured using a caliper, first immediately after the printing process had finished and secondly after a drying period of at least 7 days, in order to test long-term stability. The percentage reduction in the sample height served as a measure of shrinkage.

The flexural specimens were printed as elongated rectangles measuring 12 mm in height, 20 mm in width and 200 mm in length (three layers). During the drying process, they were placed between two parallel screens, thereby preventing warping. After drying, they were sanded to cuboids measuring 9 × 18 × 200 mm (Fig. 5). The flexural strengths were determined using a universal testing machine (TIRATEST 28100) in accordance with the DIN 52186 standard.

Fig. 5. Printed and sanded specimens for flexural strength measurement (reprinted with permission from Emerald Group Publishing, Rosenthal *et al.* 2023)

Finally, the volume and mass of the fragments from the bending tests were determined using a caliper and a laboratory balance, and the density was calculated from these values.

RESULTS AND DISCUSSION

Particle Size Distribution

An initial visual assessment of the particle material from HS Timber Productions (Fig. 2) showed a high proportion of coarse shavings. The sieve analysis revealed that wood particles with a size of more than 1 mm, mainly fragments of bigger wood chips, made up more than 75% of the total sample.

Particles smaller than 200 μm accounted for only 2.2%. The wood powder Lignobest C200 from Holzmühle Westerkamp was substantially finer, with only 11% of the particles being larger than 75 μm (Table 1).

Table 1. Particle Size Distribution q3 and Q3 of Softwood Particles from HS Timber Productions and Softwood Powder Lignobest C200 from Holzmühle Westerkamp

HS Timber Productions			Westerkamp Lignobest C200		
Fraction (µm)	**q3 (%)**	**Q3 (%)**	**Fraction (µm)**	**q3 (%)**	**Q3 (%)**
			< 25	0.15	0.15
< 50	0.15	0.15	25 to 50	67.14	67.29
50 to 75	0.29	0.45	50 to 75	21.77	89.06
75 to 100	0.36	0.81	75 to 100	8.60	97.66
100 to 200	1.43	2.23	100 to 200	1.78	99.44
200 to 400	3.98	6.21	200 to 400	0.19	99.64
400 to 600	5.60	11.82	400 to 600	0.19	99.82
600 to 800	5.97	17.79	600 to 800	0.07	99.89
800 to 1000	6.71	24.49	> 800	0.11	100.00
> 1000	75.51	100.00			

Note: q3: density distribution; Q3:cumulative distribution

Slenderness

As shown in Fig. 6A, the slenderness ratio (median) of the sawdust from HS Timber Productions ranged between 1.8 and 4.8 across all particle sizes. The slenderest particles are found in the < 50 µm fraction, while those with a more compact shape are found in the 600 to 800 µm fraction. There was a tendency for the slenderness ratio to decrease with increasing particle size. For the Lignobest C200 wood powder sample, the slenderness ratio (median) ranged from 1.9 to 2.4 (Fig. 6B). The differences between the particle fractions were notably less pronounced here.

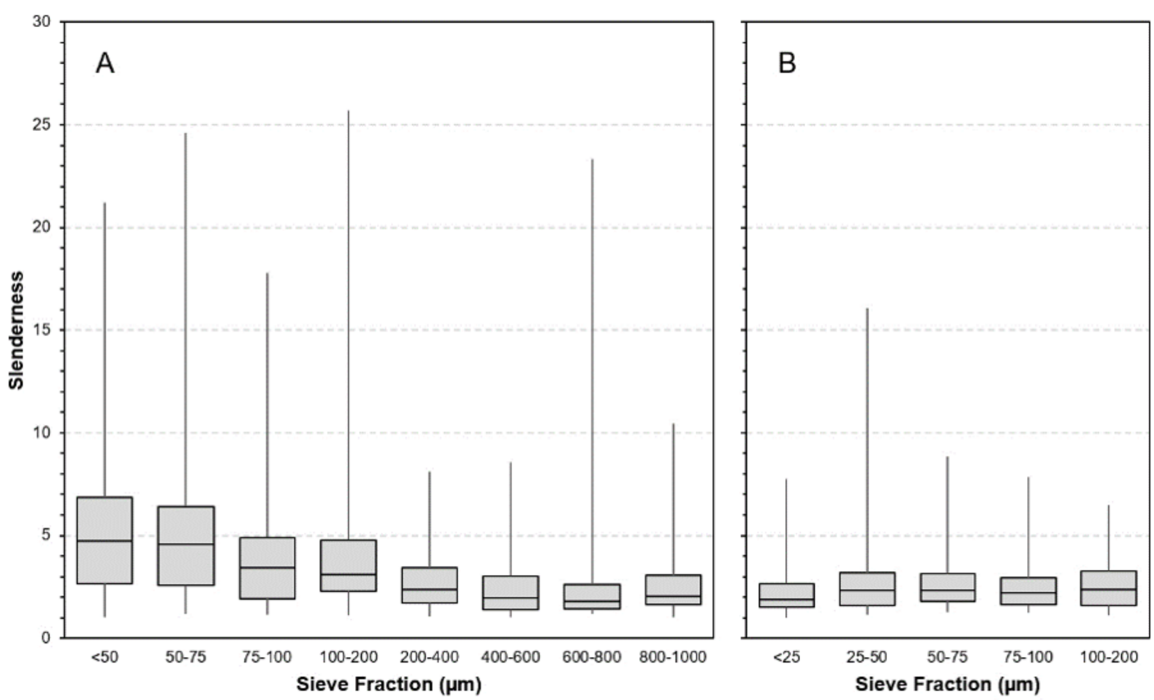


Fig. 6. Slenderness ratio of individual sieve fractions of sawdust from HS Timber Productions (A) and Lignobest C200 wood powder from Holzmühle Westerkamp (B)

When comparing both particle samples, the sawdust from HS Timber Productions showed higher values for the slenderness ratio in most cases. The wood powder from the Westerkamp wood mill undergoes a grinding process, which reduces the slenderness ratio. In the case of the 100 to 200 µm sieve fraction, the values were 3.09 (Kodersdorf) and 2.38 (Westerkamp). The difference was even more pronounced in the 50 to 75 µm sieve fraction, where the median values were 4.59 (Kodersdorf) and 2.32 (Westerkamp) respectively.

Scanning electron microscope (SEM) images show a larger proportion of elongated cell and cell wall fragments in the wood particles from HS Timber Productions, for example in the 50 to 75 µm sieve fraction (Fig. 7A). In contrast, the softwood powder Lignobest C200 from Holzmühle Westerkamp (Fig. 7B) shows greater roughness on the particle surface, most likely caused by the grinding process.

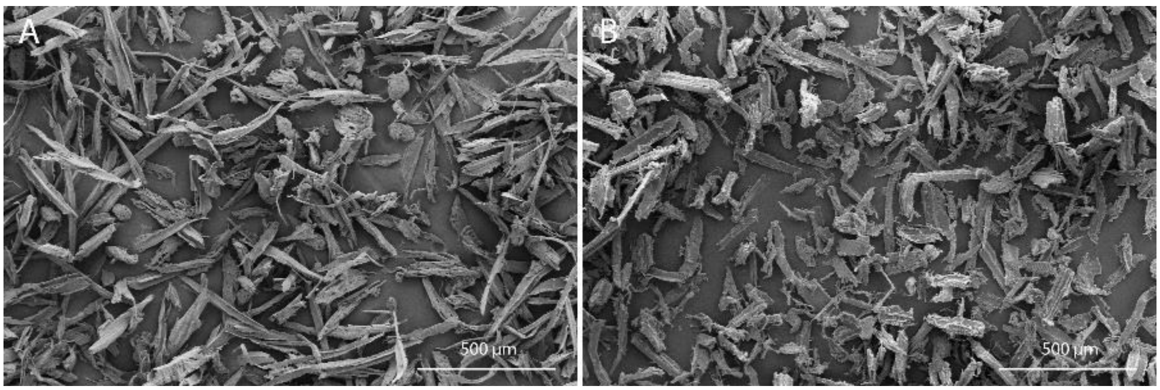


Fig. 7. SEM images of the 50 to 75 µm sieve fraction of softwood particles from HS Timber Productions (A) and Lignobest C200 softwood powder from Holzmühle Westerkamp (B)

Recipe Development

For Lignobest C200 softwood powder, Rosenthal *et al.* (2023) had already developed a formulation using methylcellulose as a binder based on a binder-water ratio of 1:20 (mixture ‘Wo1’). Building on this, the original plan was to determine the appropriate wood proportions for each sawdust sieve fraction of the softwood particles from HS Timber Productions, so that the resulting pastes could be processed using a piston extruder. However, preliminary tests showed that this was not possible for sieve fractions containing only larger particles. During extrusion, the methylcellulose gel separated from the wood particles. The adhesive was squeezed out, while some of the wood particles remained in the cartridge – a phenomenon already described by Jain *et al.* (2025). As a result, homogeneous, extrudable pastes could not be produced using the 200 to 400 µm sieve fraction (Fig. 8A) or any larger sieve fractions.

However, even with the finer particle fractions, clear differences can be seen compared to the ‘Wo1’ mixture with Lignobest C200 softwood powder as filler. While the latter produces a cohesive paste with a wood content of 5.4 g per 1 g MC and 20 g water, even lower wood contents in the softwood particles from HS Timber Productions permits cracks (Fig. 8B).

For the four sieve fractions < 50 µm, 50 to 75 µm, 75 to 100 µm, and 100 to 200 µm, the respective wood proportions that enable the preparation of an extrudable paste were determined (Fig. 9). When using bigger particle fractions, both the internal cohesion of the mass and the surface homogeneity are reduced. In addition, the findings reported by Kaufhold *et al.* (2019) and Jain *et al.* (2025) were confirmed: as particle size increases, the maximum possible amount of wood particles that can be added to the mixture decreases considerably.

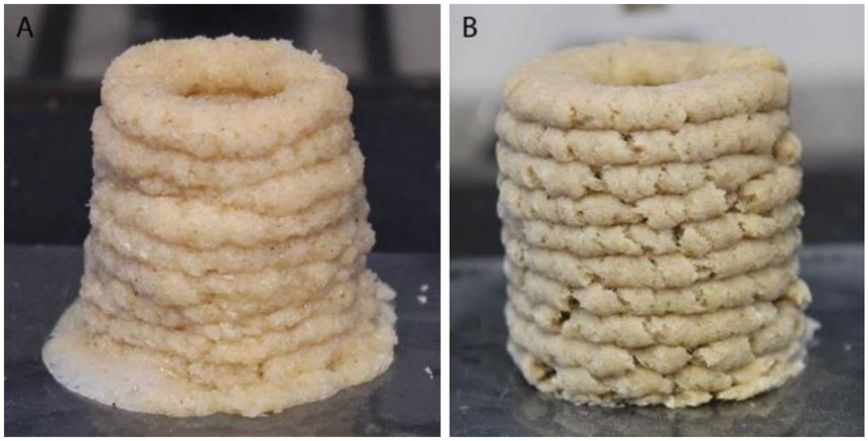


Fig. 8. 3D printing of inhomogeneous MC-water-wood mixtures: (A) binder-particle separation when using the 200 to 400 µm sieve fraction (ratio 1:20:3.6) and (B) crack formation in a mixture with the 75 to 100 µm sieve fraction (ratio 1:20:4.1)

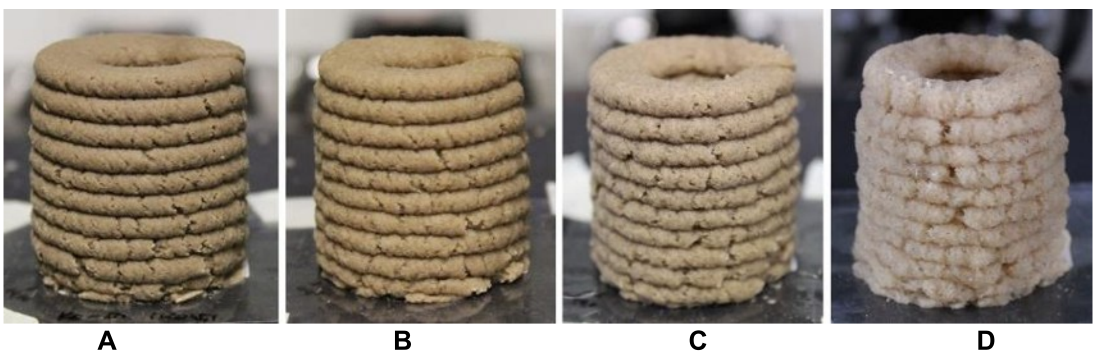


Fig. 9. 3D printing of the MC-water-wood mixture (1 g MC, 20 g water) with different fractions of softwood sawdust (HS Timber Productions): A: < 50 µm (5.1 g), B: 50 to 75 µm (4.1 g), C: 75 to 100 µm (3.9 g), and D: 100 to 200 µm (3.3 g)

Shrinkage

The shrinkage of additively manufactured cylindrical objects in the z-direction was determined for both the four sieve fractions of wood particles from HS Timber Productions and for Lignobest C200 softwood powder. Shrinkage values ranged from 7.7% to 20.2% (Fig. 10). A variation of the wood content showed that shrinkage can be reduced by using higher wood contents. The shrinkage values also decreased as the particle size increased. These data suggest that the coarser particles did not clump together as closely as the finer particles, a conclusion supported by the density values of the dried materials in Table 2.

Unexpectedly, the sieve fraction < 50 µm showed lower shrinkage values than the wood powder, even though the latter contained larger particles (see Table 1). This result may have been caused by the different slenderness ratios. In addition to larger dimensions, the slenderness of the particles could also prevent contraction of the material composite during drying.

High wood content in the mixture leads to desirable low shrinkage on the one hand, but on the other hand it can lead to undesirable cracking. For the mechanical tests, the mixing ratio used for each sieve fraction (Table 2) was the one at which the occurrence of surface cracks remained limited, and, at the same time, shrinkage was as low as possible.

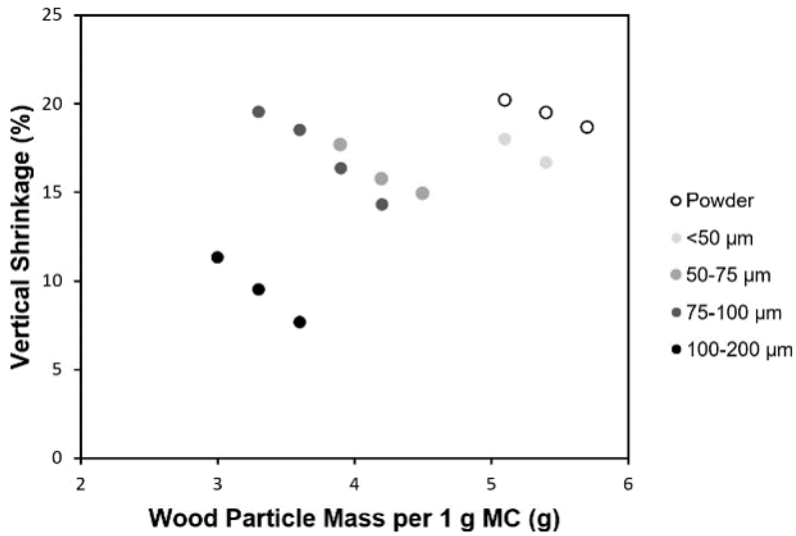


Fig. 10. Shrinkage of 3D-printed test specimens of the MC-water-wood mixture (1 g MC, 20 g water) with fractions of softwood sawdust (HS Timber Productions) and the softwood powder (Lignobest C200, Holzmühle Westerkamp) (N = 1)

Flexural Strength, MOE and Density

The flexural strength of the dry specimens produced from the four fractions of softwood sawdust ranged between 1.3 and 2.9 MPa, while the flexural modulus was between 109 and 272 MPa. As particle size decreased, the density varied between 0.22 and 0.32 g/cm³ (Table 2). There was a clear correlation between particle size on the one hand and flexural strength, modulus of elasticity (MOE), and on the other hand there was a correlation to density. The finer the wood particles, the higher the strength and modulus of elasticity. As the particle size decreases, the density of the material produced also increases. Part of the increase in strength can be attributed to this.

Table 2. Physical Properties (Mean ± Standard Deviation, N = 5) of MC-water-wood Mixture with Fractions of Softwood Sawdust (HS Timber Productions)

	Ingredients (g)			Flexural Strength	MOE	Density
Fraction	Water	MC	Wood	(MPa)	(MPa)	(g/cm³)
< 50	20	1	5.1	2.88 ± 0.12	271.5 ± 17.4	0.32 ± 0.01
50 to 75	20	1	4.2	1.97 ± 0.14	161.8 ± 15.3	0.27 ± 0.01
75 to 100	20	1	3.9	1.60 ± 0.12	142.3 ± 11.5	0.24 ± 0.00
100 to 200	20	1	3.3	1.27 ± 0.12	108.7 ± 18.3	0.22 ± 0.01

In the investigations described so far, the individual particle size classes were only used separately. Subsequent experiments examined the physical properties of printing pastes that combined the 100 to 200 µm sawdust fraction from HS Timber Productions and Lignobest C200 wood powder. Different percentage mixture ratios were used. The reference points were mixtures containing either only the sawdust fraction 100 to 200 µm ('Du') or the Lignobest wood powder ('Po') as filler (Table 3). The mixture names reflect the different proportions: 'DuPo64', for example, consists of 60% of the mixture 'Du' and 40% of the mixture 'Po'.

Table 3. Physical Properties (Mean ± Standard Deviation, N = 4 (Shrinkage) and 8 (Flexural Tests)) of MC-water-wood Mixture with Sawdust from HS Timber Productions (Fraction 100 to 200 µm) and Softwood Powder Lignobest C200 from Holzmühle Westerkamp as Filler

	Ingredients (g)				Vertical	Flexural	MOE	Density
Mixture	MC	Water	Saw dust	Wood powder	**Shrinkage (%)**	**Strength (MPa)**	**(MPa)**	**(g/cm³)**
Du	1	20	3.30	0	12.3 ± 0.2	1.33 ± 0.12	117.0 ± 18.5	0.23 ± 0.01
DuPo82	1	20	2.64	1.08	15.8 ± 0.4	2.42 ± 0.34	218.5 ± 21.6	0.26 ± 0.00
DuPo64	1	20	1.98	2.16	19.3 ± 0.9	3.48 ± 0.47	327.1 ± 27.4	0.30 ± 0.01
DuPo46	1	20	1.32	3.24	20.5 ± 0.2	4.66 ± 0.55	428.9 ± 47.6	0.33 ± 0.00
DuPo28	1	20	0.66	4.32	20.8 ± 0.5	4.78 ± 0.52	412.6 ± 46.5	0.36 ± 0.00
Po	1	20	0	5.40	19.8 ± 0.5	4.77 ± 0.33	435.8 ± 18.5	0.38 ± 0.01

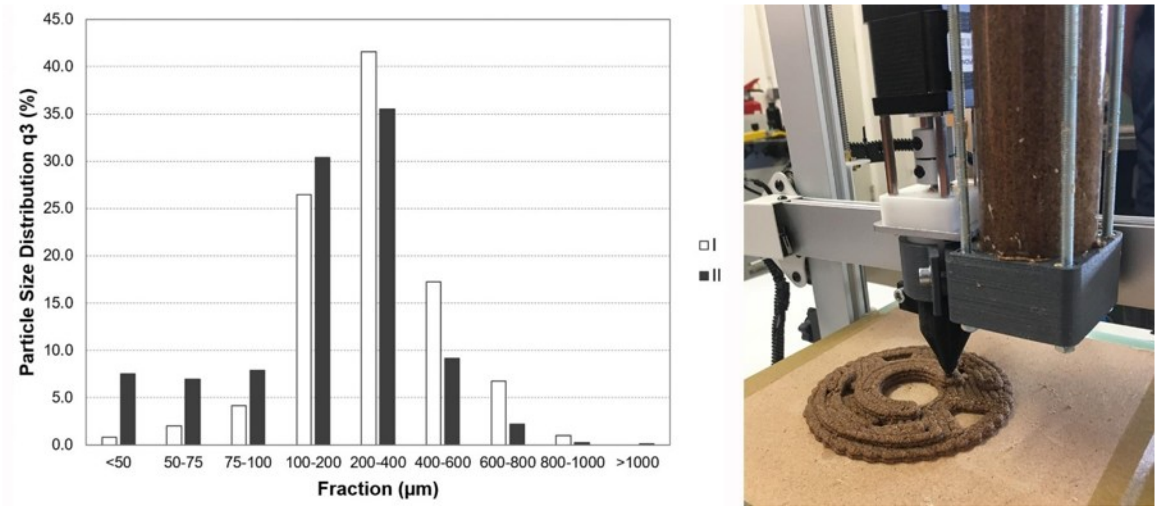
With increasing proportions of finer wood powder and decreasing proportions of coarser particles, the density increased from 0.23 g/cm³ to 0.38 g/cm³ (Table 3). Vertical shrinkage increased with increasing wood powder content up to a mixing ratio of DuPo64 from 12.3% to 19.3% and then remained almost constant even with higher wood powder content. Flexural strength and modulus of elasticity increased up to the DuPo46 mixing ratio (from 1.33 to 4.66 MPa and from 117 to 429 MPa, respectively), after which both properties showed little further change.

The results confirm previous studies with smaller sample sizes or fewer variants. The study by Rosenthal *et al.* (2018) had already indicated that mixtures containing coarser particles result in lower density and strength values. Jain *et al.* (2025) showed that finer wood particles increased compressive strength in beech, whereas the results for oak were inconsistent. Karsoun *et al.* (2024) used agricultural waste as filler but did not adjust the binder-water-wood ratio to the particle size, which in our study led to problems with cracks in coarser particles (Fig. 8B) and severe shrinkage in finer particles (Fig. 10). Nevertheless, their measurement results for all filler resources (apart from two outliers for sugarcane and rice straw in the 106 to 180 µm sieve fraction) showed a decrease in flexural strength with increasing particle size.

Regarding the different results obtained for the two material mixtures, one containing wood powder (Table 3, mixture 'Po') and the other the finest sawdust sieve fraction (Table 2, mixture '< 50') as filler, the hypothesis can be used as an explanation, according to which particles with a lower slenderness ratio (mixture 'Po') move closer together during drying. This would result in a more compact material composite, leading to higher values for density (0.38 *vs.* 0.32 g/cm³), flexural strength (4.8 *vs.* 2.9 MPa), and MOE (436 *vs.* 272 MPa).

Subsequent Practical Tests

After completing the scientific investigations, practical workshops were carried out with woodworking companies. The Tronxy Moore 2 3D printer, fitted with a modified screw extruder (Fig. 11B), was used for this purpose. The companies' own wood shavings from circular saws (different types of wood and wood-based materials) were sieved using a domestic sieve with a mesh size of approximately 1 mm. The resulting wood shavings samples contained particles of all size fractions, ranging from < 50 µm to 1 mm, with the majority of the shavings measuring between 100 and 400 µm (Fig. 11A). Extrudable pastes were produced from the wood shavings samples I and II, which were subsequently used successfully for the additive manufacturing of objects with an edge length of 10 to 20 cm.



A **B**

Fig. 11. Particle size distribution q3 (density distribution) of sawdust from two companies (A) and 3D printing of a paste made from carboxymethylcellulose (Baufan Bauchemie Zell-Leim) dissolved in water and wood particles from company II (weight ratio 1:15:4.5) using the Tronxy Moore 2 and a modified screw extruder with a nozzle diameter of 4 mm (B)

CONCLUSIONS

1. Particle fractions from softwood with a sieve mesh size of up to 0.2 mm can be combined with methylcellulose–water binders to produce pastes suitable for additive manufacturing *via* Liquid Deposition Modelling (LDM). Coarser particle fractions (which are generated in large quantities by profile chippers, for example) are unsuitable for the LDM process (at least when using small-dimension piston extruders). Preliminary tests using screw extruders have shown that mixtures of particles from carpentry workshops, which contain coarser shavings (mesh size up to 1 mm) in addition to fine shavings, can in principle be used. Further investigations are necessary to determine the required ratio of fine to coarse shavings.
2. As the particle size of the residual materials decreases, the achievable filler content, the shrinkage of the mass during drying, the density, flexural strength and modulus of elasticity (MOE) of the dried material increases.
3. Grinding reduces the particle slenderness, resulting in higher values for shrinkage, density, flexural strength and MOE.

4. Due to its mechanical properties, the material is primarily suitable for the material-efficient additive manufacturing of non-load-bearing objects where design requirements are prioritized. When combined with other materials (see Fig. 1), structural applications are also possible.

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