Material extrusion printer for pastes based on a commercial desktop filament printer for plastics

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Abstract New materials are constantly being developed for additive manufacturing. Therefore, they are ideally trialled and tested in small quantities first. Particularly in the development of pastes from bio-based residues, the rapid adaptation of the material with regard to process parameters is of crucial importance.
Based on a low-cost, commercially available material extruder for plastics (MEX-TRB/P), an extruder for processing pastes is being developed with the aim of minimising the work steps involved in installing the material container and keeping assembly, disassembly and cleaning as simple as possible.
All the components required for the extruder can either be manufactured with MEX-TRB/P or are available as easily accessible purchased parts. The required STL files for the components and a list of other purchased components for the extruder will be made available as open source via the SAMSax platform, among others. The extruder is controlled via Klipper on Repetier Server.

Keywords: Additive Manufacturing, Material Extrusion, Pastes, Material Development

1 Introduction

With almost one million devices sold in 2022, desktop 3D printers are very widely available (prices under 5,000 USD) [1]. The majority of printers sold are material extrusion - thermal reaction bonding / plastics machines (MEX-TRB/P) used to extrude plastic filament or granulate. Material extrusion systems for pasty materials (chemical reaction bonding; MEX-CRB) are unfortunately only commercially available to a limited extent even though this technology is increasingly gaining in importance, as a wide variety of compounds (e.g. from bio-based residues) can be processed into 3D components without requiring significant use of energy. Global research activities on the development of sustainable material systems that can be processed using AM are constantly increasing in the face of climate change and environmental pollution. Especially in the stage of basic research, the use of small quantities (≈50 ml) of material is common to find optimal recipes. This results in an urgent need for a desktop MEX-CRB printer for research facilities and R&D departments.

Bremmer [2] provided an initial overview on existing desktop MEX-CRB printers in 2020, which has been revised and updated (see **Table 1**). In the following, mentioned open-material desktop printers are presented and explained.

In addition to large printers, Stoneflower also offers clay kits. Nozzles with a diameter of up to 2 mm are available for their smallest open-material extruder. The VX 3D from Zmorph is offered with the paste extruder, which was already used and customised by *Rosenthal* [3]. *Bremmer*'s overview also featured the company Structur3d, that has since been off the market and is therefore not considered further. A clay kit and also the small printer Delta WASP 2040 Clay are offered by the company WASP S.r.l. based in Italy. The tank size for this machine is very large at 3 litres, compressed air is required and cleaning and commissioning the printer is very time-consuming. The WASP clay extrusion system is therefore not suitable for small material tests.

Table 1. Overview of desktop paste printers on the market

Company Printer name	Nozzle sizes in mm	Capacity in l	Mass in kg	Price in 2024 (approximated)	Print bed size in mm
Stoneflower Standard Ceramic KIT	0.5, 1.0 1.5, 2.0	0.5	5.4	700 EUR	Depending on printer
Zmorph VX 3D	2.0, 4.0	0.1	28.7	5,500 EUR	235 x 250 x 165
WASP WASP 4020 Clay	1.5, 2.0	3.0,5.0	40.0	3,300 EUR	Ø200 x h400
WASP WASP Clay Kit 3.0	1.5, 2.0, 3.0	3.0	15.0	750 EUR	Depending on printer
3D Potter 3D PotterBot 10 Micro	3.0, 4.0 5.0, 6.0	1.0	17.0	3,300 EUR	280 x 265 x 305
VormVrij LUTUM® 4M PRO Clay Printer	0.6, 1.2, 1.6, 3.5, 7.0	1.0 kg	60.0	5,000 EUR	250 x 250 x 400
Tronxy Moore 1	1.0, 2.0, 3.0	0.5	7.5	450 EUR	180 x 180 x 180
Tronxy Moore 2	1.0, 2.0, 3.0	0.5	10.0	650 EUR	255 x 255 x 260
Eazao Zero	0.6, 1.5, 3.0	0.5	unknown	830 EUR	150 x 150 x 240

Another supplier of small desktop printers is 3D Potter. Their printers are controlled via a Rasberry Pi. The smallest tank for these machines has a volume of almost 1 litre and only two tanks and four nozzles of 3 - 6 mm are included as standard equipment. An additional tank costs 70 EUR to quickly change materials and keep them in stock.

With its LUTUM printers, the manufacturer VormVrij offers a range of table-top printers that all have to be operated with compressed air. Nozzles are available from

1 mm to 7 mm and the layer height is limited to 3 mm. The printers are robust, but very heavy at 60 kg. There are also three low-cost printers on the market. The Tronxy Moore 1 and 2, as well as the Eazao Zero, are table-top devices with a separately mounted extruder and a hose guide up to the nozzle. Nozzles from approx. 0.6 - 3.0 mm are available. It should be noted that with an inner tube diameter of 6.5 mm, tough materials cannot be printed due to wall friction, cleaning the tube system is very time-consuming and a large proportion of the material in the tube remains unused.

Furthermore, there are also special 3D printers for food, for example from the company Procusini, but these are only suitable for special materials and cartridges filled with them. The Choc Creator V2.0 Plus from the company Choc Edge works with a 30 ml syringe as a material storage container and has a nozzle diameter of 0.8 mm. However, this printer can only be used for chocolate and is not open source based. 3D printers for concrete (e.g. from the company m-tec) are also for sale, but only utilized with much larger material quantities e.g. for house construction.

All these machines have in common that they are not designed for processing small quantities of different materials or are not very flexible in terms of nozzle size. Quick material changes are not possible and the cleaning effort is high due to the many components that get in contact with the paste.

In particular, small devices with volumes of less than 500 ml, which are used for different materials and have not been optimised exclusively for clay, are not yet commercially available. However, in order to test small quantities of material individually and to ensure a quick changeover between materials, a piston extruder for pastes was developed, called 3D-Paste Extrusion Development Toolhead (3D-PEDT). Due to the simple design of printers for the MEX-TRB/P, which are often based on open-source technologies, and the similar functional principle for MEX-CRB, the promising approach to convert a commercial MEX-TRB printer into a MEX-CRB printer was used. The nozzle diameters should be changeable in a range from 0.5 mm to 8 mm in order to be able to scale the developed materials to large devices later on. The aim of this publication is to widen distribution of the 3D-PEDT and provide worldwide accessibility to all necessary data.

Regarding materials, the use of concrete, clay and also food in paste extrusion is state of the art and commercially available on the market. But there are also research activities for other materials, which shows, that there is an urgent need for machines specialized in material development.

Rosenthal [3] has carried out basic research with wood and various binders such as cellulose. In the "GreTA" research project, cork was successfully brought onto the stage as a material for theatre props using gelatine [4]. *Sauerwein* [5] compared the binder sodium alginate with various fillers. Alginate has generally proved to be a suitable binder and prototypes have been produced from mussel shells and alginate. At the moment, the publications mentioned are still focussing on testing the applicability of the new materials. Therefore, small desktop 3D printers are favourable for the production of test specimens and well suited for this application.

2 Approach - Machine development

2.1 Initial situation

The basis for the newly developed extruder 3D-PEDT is the previous modification of the Zmorph extruder by *Rosenthal* [3] shown in **Fig 1**. This can be mounted on a conventional table-top printer (MEX-TRB/P). Standard commercial syringes (original B. Braun 50 ml Perfusor® syringe without cannula, Art. No.: 131246) with a maximum capacity of 70 ml are used as material storage containers. This volume has proven to be suitable for testing and developing new pasty materials. The amount of paste fitting inside one of these syringes is sufficient to print one bar-shaped test specimen according to *Rosenthal* [3].

Fig. 1. Modified extruder by *Rosenthal* [3]

With this extrusion system, it is necessary to screw the syringe to the linear-driven piston including the motor with the help of a mount. The syringe, linear drive and motor are then only held in position by friction on the machine by pressing the syringe into a fixture, which reduces repeatable placement with the same accuracy in the z-direction.

Table 2: Necessary steps for changing the material with old setup

Step	Description of the step to be performed
0	Fill the syringe with paste
1	Press rubber piston onto piston adapter and lubricate
2	Place syringe holder onto syringe
3	Press syringe with syringe holder onto piston adapter with rubber piston
4	Mount syringe holder and syringe on extruder with 1st screw
5	Mount syringe holder and syringe on extruder with 2nd screw
6	Place the nozzle on the syringe
7	Install the syringe with extruder device in the syringe holder
8	Connect the plug for the power supply to motor and distance sensor
9	Switch on the power supply of the printer
10	Start the printing process
	Total time for step 1 to 9 = 80 seconds

The steps from **Table 2** are currently required to start the printing process with a new material using the *Rosenthal* setup. Some of the individual assembly steps are very time-consuming and require a certain amount of manual dexterity to ensure that the printhead is functional and fitted accurately. The final removal and cleaning of the extruder after the printing process is just as time-consuming. The motor must also be dismounted completely to change the material inside the syringe.

For the processing of materials with short pot lives, such as geopolymers, the complex assembly steps are undesirable and a hindrance. A new design, considering the printing experience gained to date, is intended to simplify the handling of the device and to reduce the time for material changes. In order to be able to process higher viscosity pastes, the new design of the extruder 3D-PEDT also includes a more powerful motor. The connection points of the extruder were designed for the low-cost table-top device Creality Ender 3 S1 and must be adapted accordingly for other devices.

2.2 Mechanics

The material is dispensed using quick-change syringes. These are inexpensive at 0.85 EUR per piece and, depending on the application, also enable compliance with hygiene regulations.

The components of the toolhead should consist of commercially available, inexpensive purchased parts or be easy to manufacture using MEX-TRB/P. Overall, it should be possible to build the extruder using simple and common hand tools. The printed parts are designed in such a way that they are very easy to print. In this case, a polyamide plastic filament reinforced with glass fibres (PA6 with GRP) was used for printing, as this material is temperature-resistant and has good mechanical properties. However, the components can also be printed using cheaper materials. The durability of the components is of secondary importance in this case, as they can be replaced quickly.

The entire extruder can be mounted on standard MEX-TRB/P printers. Due to the total mass of approx. 1.15 kg and the height of the design, the use of printers in portal design with a moving print bed is preferable, e.g. Anet A8 or printers from Prusa or Creality. The assembly of the developed extruder is shown in **Fig. 2**. The individual components are described in the following.

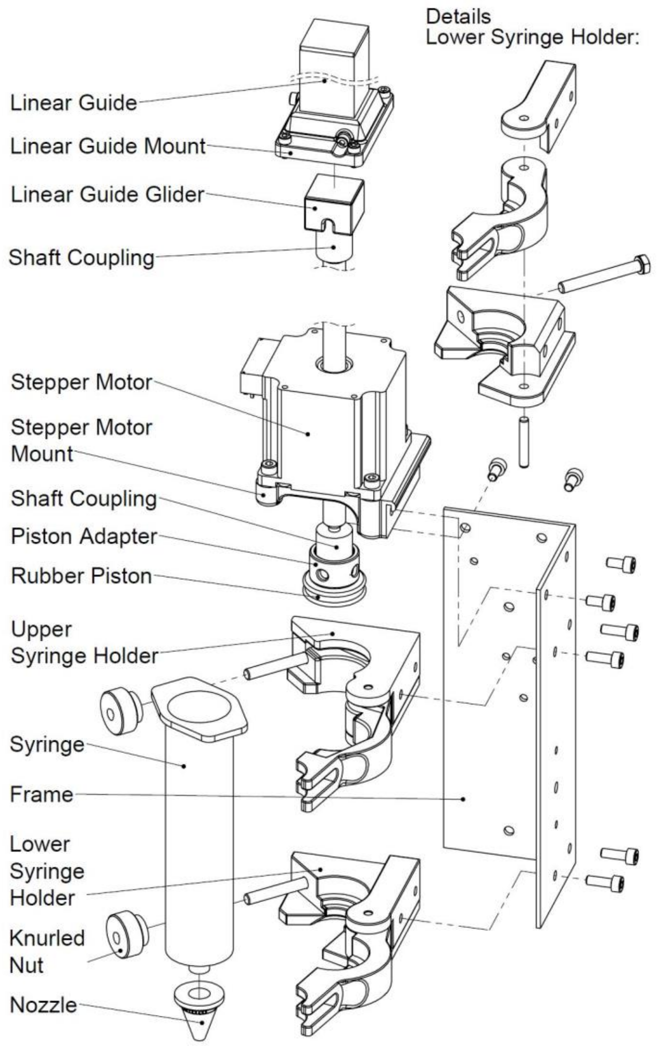

Fig. 2. Assembly drawing of the 3D-PEDT

Frame

An aluminium L-profile was used as the frame in order to provide a large mounting surface and to reduce the size of the individual parts to be printed using MEX-TRB/P. The extruder can be attached easily to a wide variety of axis systems via the two flat sides. All other components are connected via screws to the aluminium L-profile. Threaded inserts were pressed into the printed parts to allow a robust assembly.

Linear drive

As the use of a non-captive linear stepper motor with an integrated spindle drive in design has already proven useful, it was also integrated into the new design. A NEMA 23 size motor with a 200 mm long 10 x 2 trapezoidal threaded spindle and a peak force of 938.9 N was selected (nanotech LA561S20-A-TSCA). Due to the non-captive design, it is necessary to design a separate linear guide. However, due to the relatively low accuracy requirements, this can be significantly lighter than commercially available solutions. Motors of this type are available from various manufacturers. Compared to NEMA 17 motors, not only the force applicable is significantly higher, but the bearings installed in the motors can also withstand these higher forces. This makes it possible to extrude pastes with a higher viscosity.

The motor is connected to the frame via the MEX-TRB/P printed stepper motor mount, **Fig. 2**. The motor is deliberately not centred via the flange in order to enable concentric alignment with the syringe attached underneath. This is essential, as geometric deviations are to be expected when manufacturing the components using MEX-TRB/P.

Linear guide

The force is applied directly and centrally to the piston of the syringe, which is why no further load-bearing linear guide is required. However, to enable linear movement of the spindle, it must not rotate. In the design offered by Zmorph, rotation is only prevented by friction of the syringe piston, which is firmly attached to the spindle. Still this is not always sufficient, and an unwanted rotation can lead to an undefined feed rate.

In the new extruder design the rotation of the spindle is prevented by an aluminium square tube as linear guide, which guides the corresponding piston. The piston and the attachment of the square tube to the motor are manufactured using MEX-TRB/P.

The piston is connected to the spindle by means of a simple shaft coupling and is greased in the square tube. This design makes it possible to use different spindle diameters and stepper motors with and without machining the ends, as shaft couplings are available as standard parts in a wide range of sizes. The square tube also protects the grease-lubricated spindle during operation from dust and further contamination and ensures the personal safety of the operator during printing, since the moving parts are covered.

Syringe mount and nozzle

The nozzle can be additively manufactured either using MEX-TRB/P or, if possible, using vat photopolymerization to achieve a lower roughness inside the nozzle. The used syringes are identical to *Rosenthal's* setup, the threads are drilled out accordingly and only the outer diameter of the Luer-Loc connection is used for attaching the nozzles. This allows nozzle diameter up to 8 mm.

The syringe is mounted in two hinged holders. This enables a quick change of material. In particular, if quick-release knurled nuts are used, the material can be changed with just a few hand movements. The upper syringe mount counters the syringe and prevents it from sliding up when the plunger is pulled back. The lower fixture centres both the syringe and the attached nozzle, which is held in a defined position so that the Z height does not need to be adjusted when changing the syringe. At the same time, the nozzle is prevented from slipping off the syringe at high pressures.

The holders are each manufactured in three parts using MEX-TRB/P. This enables production without support structures. The parts are connected by the bolts, that connect the syringe mounts to the frame as well, **Fig. 2**. A pressed-in 4 mm pin is used as the hinge. The piston of the syringe is replaced by the MEX-TRB/P piston adapter, which holds the rubber piston, and is connected to the spindle of the linear motor via a shaft coupling, 3. The 3D-PEDT is shown in **Fig. 3**.

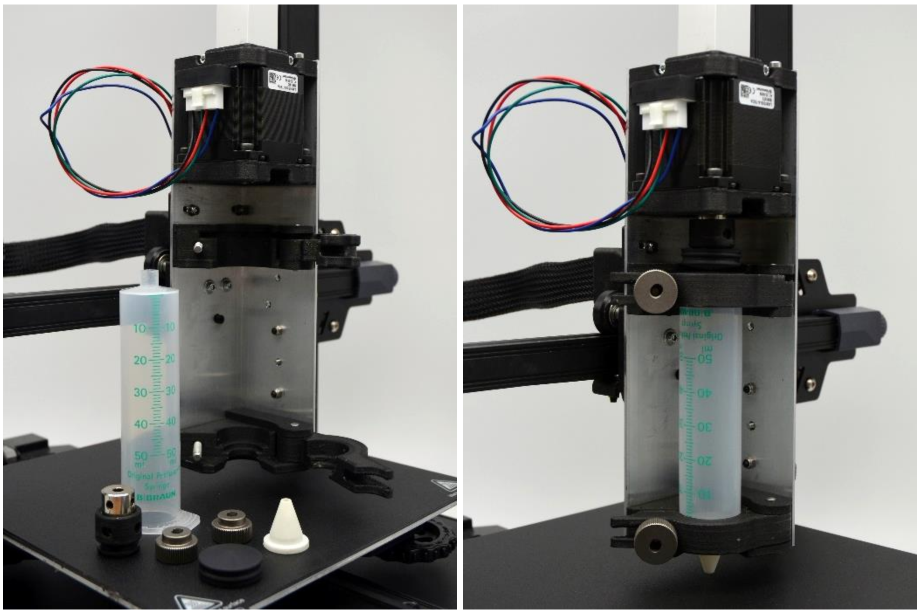

Fig. 3. 3D-PEDT with parts (l) and assembled (r)

2.3 Electronics and software

The effort required to convert the electronics depends on the 3D printer model used for the conversion. Only the output used for the extruder's stepper motor is required to control it and the current required for the used stepper motor must be considered.

In the case of the Creality Ender 3 S1 printer used for the setup explained in this paper, a circuit board was manufactured as an adapter to the original extruder cable. The auto levelling touch sensor, which is included in the standard equipment of the printer, is also connected via the circuit board.

Switches to limit the stroke of the syringe were omitted since these are not necessary and would require customised firmware. The open source firmware Klipper was utilized for easy adaptation, as it works with a clearly structured configuration file. In addition to the microcontroller boards mainly used for printer control, a Raspberry Pi or a comparable supported single-board computer is therefore required for the conversion.

Slicing can be carried out using standard programmes for MEX-TRB/P, e.g. open source programmes like Cura Slicer or Prusa Slicer. Only the inner diameter of the syringe must be set as the filament diameter and all temperature values must be set to 0°C. Furthermore, the nozzle diameter and extrusion widths, as well as the speed must be adjusted according to the materials to be processed, see **Table 4**.

2.4 Evaluation and publication

The new design of the extruder 3D-PEDT has reduced the complexity of the syringe change, thus reducing the time required significantly, see **Table 3**. The extrusion system, including the motor, remains permanently attached to the printer. Only syringe filled with material/paste needs to be mounted. The printer can be set up and homed before the syringe is attached, as the relevant parts stay in place.

Table 3: Necessary steps for changing the material for the extruder 3D-PEDT

Step	Description of the step to be performed
0	Fill the syringe with paste
1	Press rubber piston onto piston adapter and lubricate
2	Mount piston adapter on spindle with shaft coupling
3	Place nozzle on syringe
4	Insert the syringe into the two open holders
5	Close lower holder and secure with knurled nut
6	Close upper holder and secure with knurled nut
7	Start the printing process
	Total time for step 1 to 6 = 35 seconds

This open source hardware (OSH) publication is intended to create a platform that enables the replication of the extruder 3D-PEDT with commonly available parts and self-manufactured parts using MEX-TRB/P. The motivation for an open source hardware publication lies in the great need for a MEX-CRB desktop printer, which the authors have recognized in many discussions with researchers from other institutes. Each institute has developed its own solutions, but not all of them succeed in developing efficient machines to the same extent, as many are more specialized in the field of material development. As the Chair of Additive Manufacturing at TUBAF works on material and machine/process development in an interdisciplinary manner, it was possible to develop a printer that can and should also drive forward research at other institutes.

The costs for the required parts amount to approx. 170 EUR as of May 2024 (excluding connecting elements and filament costs). The publication of the CAD data as in STEP files allows the customisation of the components. STL files to print the parts without modification, as well as part lists and software configuration files, are published on the specially created GitHub project website 3D-PEDT [6]. Furthermore, the project is publicised via online exchange platforms for 3D models, the Institute's homepage (https://tu-freiberg.de/fakult4/imkf) and the SAMSax platform (https://samsax.de/). SAMSax is a simul+-funded living lab that aims to use additive manufacturing for the transformation of local waste materials into new products and materials. The first applicable residual materials were identified and applications realised [7].

3 Approach for paste extrusion

The pastes tested with the 3D-PEDT already reflect a wide range of materials: geopolymers, wood powders, textile fibres, residual materials from the agricultural and forestry sector and even foodstuffs like biscuit dough have been printed successfully. As a limiting factor for the processability of pastes, the maximum particle size d_{pmax} of the particles in the mixtures was observed. The particles should be at least eight times smaller than the nozzle diameter d_n used, see **formula 1**. In principle, the paste should either be self-curing, such as cement, or an adhesive or binder must be added to the material. Experience shown that a binder amount of 5 to 15 wt.% of the dry mass is usually sufficient.

$$d_n \geq 8 \times d_{pmax} \qquad (1)$$

No special tools are required to mix the pastes, but electric appliances such as hand mixers, hand blenders, food processors and laboratory mixers can also be used, as well as handsets. The paste should have the consistency of soft modelling clay or a firm cake cream. For checking the viscosity of the paste, it should be squeezed out of a syringe manually, using the plunger and piston provided, and form a uniform/smooth strand of material, that can be deformed easily without cracking.

Fig. 4. Test specimen from wood paste

Two different geometries were selected for testing: a cuboid with the dimensions of 95 mm x 22 mm x 22 mm (see **Fig. 4**) and a hollow cylinder with an outer diameter of 40 mm and a height of 70 mm. The cuboid can be used to determine shrinkage and warping after drying, as well as to determine the scaling parameters. The printing result is affected by flow rate and printing speed as well as the drying conditions. A higher drying temperature results in a faster drying process, but a more pronounced warping. The degree of warping is significantly influenced by the moisture content of the paste [8]. **Fig. 4** shows an example of warping at the bottom right corner of a specimen dried at room temperature. The extrusion factor used can be determined by measuring the width of the extruded line in the last layer to be deposited, taking into account the layer height [8]. Furthermore, the cuboid can be ground after drying and sawn into four cubes with an edge length of 20 mm to be used for further experiments such as compressive strength and density analysation. The hollow cylinder is used to test the in-print stability in height regarding compression caused by the material's own weight of the following layers and the extrusion forces that effect the specimen during the printing process. The acting forces are dependent on the flow rate and the relative movement of the nozzle to the already extruded material. The maximum printing height of a material can be estimated by measuring the in-print stability. The maximum build height is limited by the material volume of the syringe and is significantly influenced by the drying process and time of the printed material. The maximum print height of slow drying materials is largely dependent on the relative movement of the nozzle to the printed object. Depending on the slicing programme, the simple test specimens are already available as pre-configurable geometries. Successfully used slicing parameters are summarised in **Table 4**. The hollow cylinders should be printed in spiral vase mode without solid layers and the cuboids with an infill setting of 100 %.

Table 4. Successfully used slicing and printing parameters

Parameter	**Value**	**Example**
Maximum particle size	Given or measured	0.5 mm
Nozzle diameter	8 times the maximum particle size	4.0 mm
Layer height	3/8 nozzle diameter	1.5 mm
First layer height	Layer height - 0.5 mm	1.0 mm
Extrusion width	same as the nozzle diameter	4.0 mm
Overlap (extruded lines)	25% of the nozzle diameter	1.0 mm
Speed for printer movement	10 mm/s	variable

Pastes should not be stored for too long in a moist state, as they can spoil easily. Dry storage of the raw materials is preferable.

It is not recommended to print directly onto the print bed, as the moist pastes are difficult to detach from the build platform without damaging the printed part. Instead, paper, plastic sheets or film should be used on top of the print bed as an underlay. Paper absorbs moisture and is more permeable to air, whereas film and plastic sheets allow crack free shrinkage of the printed part during the drying process without wrinkling. Furthermore, it was observed that the heated print bed of the commercial MEX-TRB/P can be used to increase material adhesion to the print bed with the paste extrusion process as well.

Two examples of successfully printed materials are wood powder and geopolymer. Wood powder, a residual material from the scenery production, was provided by a theatre workshop. After mixing it with 15 wt. % alginate as a binder, water was added until a kneadable mass was achieved. The printing parameters used for the wooden paste are shown in **Table 4**. The geopolymer, i.e. a cement-free concrete from fly ash and mineral grit from rhyolite (35.5 wt. % each) as well as 28.5 wt. % alkaline activator solution and 0.5 wt. % alginate were mixed with water and successfully printed, see **Fig. 5**.

Fig. 5. Printed parts from wood paste (l) and geopolymer (r)

4 Discussion and outlook

The presented 3D-PEDT is a capable extrusion system for the development of new materials for additive manufacturing with pasty materials, in comparison to commercially available devices. The time required for the material change has been significantly reduced due to the more efficient process design. Cleaning the extruder after use is easy, as the components that come into contact with the paste can be completely removed without the need for disassembly of other components. Due to a powerful motor, even highly viscous pastes can be processed without further issues.

Updates and future developments of the extruder 3D-PEDT will be regularly posted on GitHub [6]. In addition to the download area for the component data, an exchange platform for the advancement of the machine and developed materials is also conceivable. For the future processing of temperature-sensitive materials above room temperature, an extension of the extruder with a heatable nozzle or a temperature-controlled material syringe is conceivable as the controls of MEX-TRB/P printers support this anyway. Such an addition and corresponding research will make further materials and binding mechanisms compatible with paste extrusion.

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