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A controlled shaping method through the shrinkage of clay

Lukas GOSCH[a]*, Hana VAŠATKO[a], Julian JAUK[a], Elizabeta ŠAMEC[b], Irena ŽIVKOVIĆ[c] and Milena STAVRIC[a]

*Institute of Architecture and Media, Graz University of Technology
Kronesgasse 5, 8010 Graz, Austria
lukas.gosch@tugraz.at

[b] Department of Engineering Mechanics, Faculty of Civil Engineering in Zagreb, Croatia
[c] Faculty of Applied Arts, University of Arts, Belgrade, Serbia

Abstract
This research proposes a new controlled shaping method of thin-walled clay elements. A clay layer is applied to a carrier material, in order to use the shrinkage behaviour of clay as a shaping agent. This shaping process utilises the change of ratio of adhesion forces through the bond of a planar carrier material with a wet clay layer on its surface, and cohesion forces in clay, during the drying process. Afterwards, the geometry of clay ranges from single curved to double curved three-dimensional shapes that open up the possibility of using this method for creating spatial structures. The main advantage of the proposed method, as opposed to standard methods of shaping clay elements, is the use of van der Waals` attractive forces formation while drying, as active and controlled actors. This approach allows the production of three-dimensional forms without any kind of casting, formwork or elaborate scaffolding while using only secondary force formation during the drying process. The proposed method is corroborated by a sequence of experiments that evaluate the newly formed material and its reshaping process. According to the obtained results, the elements were shaped through the developed method and fired, while the carrier material was removed and reused once the clay elements were fully dried. The fired elements were assembled in a case study, in order to demonstrate the proposed method.

Keywords: clay, shrinkage, shaping method, lightweight, paste-based extrusion

1. Introduction
While the main objective of conventional structural design is to limit deformation, with the right type of material and topology, it can also be used for form-giving. Although such construction principle has been applied to traditional materials such as softwood and bamboo in the past and was revived for some large-scale projects in the 20th century (Lienhard et al. [1]), further exploration of potential applications mostly stagnated until the advent of new simulation strategies and the ability to integrate material behaviour into them (programs like SOFISTIK and ABAQUS (Nicholas und Tamke [2], Wood [3])).

There are two main applications of bending activation: as a form-giving and self-stabilising strategy in static structures (Menges et al. [4], Schleicher et al. [5]), or as a compliant mechanism in kinetic structures (Mühlich et al. [6], Puystiens et al. [7]). This work focuses on the former application, with emphasis on self-shaping. Exploring ways to apply self-shaping to the creation of curved structures contributes to energy- and resource-efficient fabrication based on the intrinsic properties of the material rather than on formwork (which leads to material waste) and heavy machinery. The application of self-shaping in architecture is mainly concerned with materials such as wood (Correa et al. [8], Rüggeberg and Burgert [9], Grönquist et al. [10]) and biocomposites (Mogas-Soldevila et al. [11]). A combination of 3D-printed meta-structures and wood as an actuator has recently been the focus of research (Özdemir et al. [12], Cheng et al. [13]).

Clay has received little attention in research on self-shaping (Zhang and Le Ferrand [14]), especially for architectural applications. This is surprising as clay is a material that can be processed easily, has ecological benefits, such as local availability and reusability (Bechthold et al. [15]) – clay mixtures can be extruded and 3D printed without extensive equipment (Falin et al. [16]) and, once fired, has mechanical properties well suited for lightweight structures. Furthermore, it has high resistance properties against moisture, fire, acid alkali and frost (Liu et al. [17]), which makes it a high performance material. Aim of this research is developing a new controlled shaping method of thin-walled structural ceramic elements.

2. Methodology

The method of this research was carried out through material experiments and a case study, as there are no numerical models on self-shaping structural behaviour of clay to accurately predict deformation. The samples were composed of a layer of wet clay mixture applied onto several carrier materials (CMs) in order to evaluate shaping qualities of those through their drying process. Several parameters were identified that influence the introduced shaping process: the amount of water in clay, the type of application, the dimensions and the geometry of the sample, the ratio and thicknesses of the clay layer to CM, and the drying time and environment. In order to have a clear overview of the applied methodology, the process was divided into following phases: 1) finding a suitable clay mixture and CM, 2) defining the type of application of clay on the CM and 3) establishing a fitting drying environment and monitoring system. After completion of the final phase, the samples were measured, compared and evaluated. Finally, the developed method was utilised to produce a proof of concept shell structure as a case study.

2.1. Material

The following sections describe the process of preparing the clay mixture and the type of CMs used. Several factors are discussed, such as the application and bond of the two materials, their removability prior to the firing process and their reusability.

2.1.1. Clay mixture

The material used was dry clay powder, type 209, obtained from the company Goerg & Schneider. 30% of water was added to the clay powder, calculated from its dry weight. The amount of water in the mixture had the initial purpose of achieving a certain viscosity to be precisely extruded by the 3D printer, which is further described in subsection 2.2. Secondly, the water percentage was maximised to increase shrinkage and therefore the extent of the shaping process. For homogenisation, the mixture was stirred by an industrial mixing machine 12CR-KIP from the local company Rauch for 30 min.

2.1.2. Carrier material

To ensure a connection of clay onto a surface, pressure is needed. Due to the thereby occuring pressing of clay while being printed or manually applied to a surface, it exhibits a connection to the underlying surface until it is dried. Shrinkage usually happens once the clay is dry enough, yet still moldable, to detach from the printing bed in order to shrink uniformly. Flat elements will either shrink only along the horizontal axis or crack to relieve stresses.

An initial comparison was made both with and without a CM. After the drying process, the clay sample with CM allowed shrinkage movement along the vertical axis as well. Once the corner points got elevated, this resulted in double-curved surfaces from planar elements. The sample without CM shrank and cracked while remaining planar (Figure 1). This led to the conclusion that a bond of the clay layer with a CM is essential for achieving double curved surfaces.

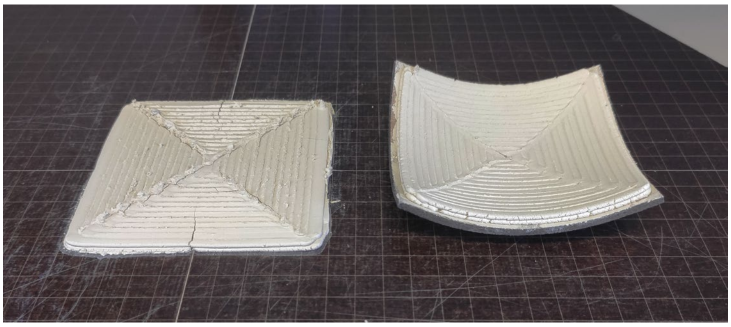


Figure 1: Comparison of samples without (left) and with carrier material (right)

A series of CMs was tested and evaluated regarding their bonding properties with clay and shaping qualities of the clay layer, as well as their detachment and reusing after the drying process. Selection of CMs was influenced by the following factors: 1) sustainability criteria, such as biodegradability and reusability, and 2) economic criteria, i.e. affordability and availability. Besides CMs made from locally harvested cellulosic fibres, such as flax and hemp, the main focus remained on special paperboard with a high density named Finnpappe, and cork, as they exhibited potential after preliminary experiments. Another material fulfilling these criteria, which has previously shown potential, was a type of felt named Gautschfilz, which is a waste product of traditional paper production. CM samples of 100 x 100 mm with thicknesses from 1.5-3 mm (Figure 2) were prepared to evaluate and compare their bond with a corresponding 3 mm wet clay layer. They were laser-cut from mats and flattened with a heat press when necessary. All CMs used in the experiments are listed and described in Table 1.

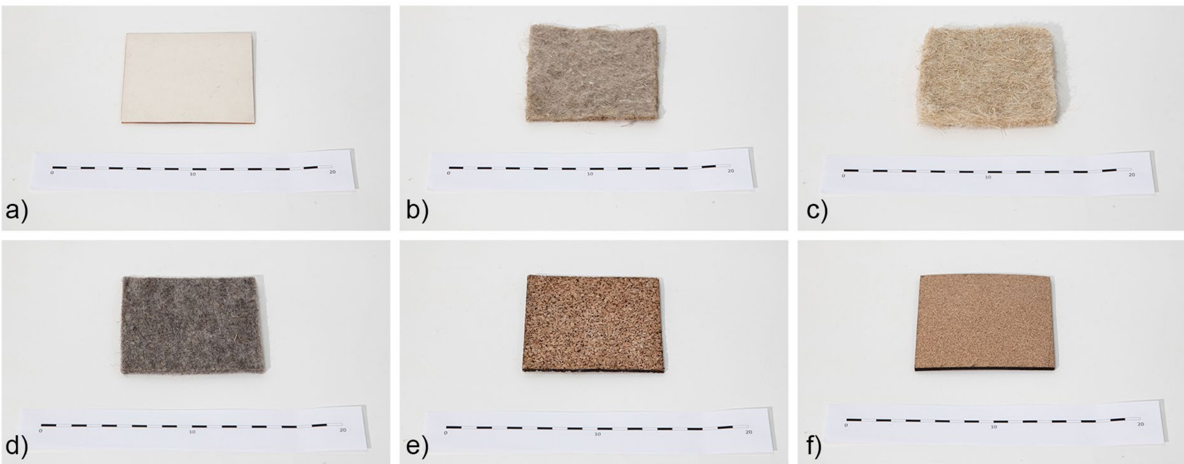


Figure 2: Carrier materials: a) paperboard, b) flax, c) hemp, d) felt, e) cork 1, f) cork 2

Table 1: All tested CMs and their corresponding descriptions

Nomenclature	Material	Thickness
FP	Cardboard	1.5 mm
FL	Flax	2.5 mm
HE	Hemp	3 mm
GF	Felt	3 mm
C1	Cork 1 (grain size ~3 mm)	3 mm
C2	Cork 2 (grain size ~0.5 mm)	3 mm

2.2. Application

The application of the wet clay mixture onto a CM was carried out in two manners: firstly, manually with a mould, and secondly, by paste-based extrusion. The shaping quality, as described in section 3.1., was then evaluated and taken into account for further experiments. Each of the application methods is described in the following sections.

2.2.1. Mould

Manual application of clay in a mould led to a consistent layer thickness and proper bonding of the two materials. CMs were placed inside a cardboard mould and the wet clay mixture was applied. The excess material was then spread and removed with an acrylic glass squeegee, evenly from the centre towards each of the four inner edges of the mould. This process was repeated until 12 samples were prepared for the drying phase.

Manually adding clay to a mould had the benefit of being a quick operation after the moulds were made, as they were reused as soon as the clay layer was applied. This method provided control over the layer thickness and the surface quality of all samples. However, the method was labour intensive, as each element required mould fabrication and consequently produced waste. It was not considered beneficial for mass customisation of individual elements. Additional factor that was determined as unfavourable was the direction of applying clay into the mould – clay particles were oriented according to the movement of the squeegee and the pulling of the material.

2.2.2. Paste-based extrusion

Another method used was paste-based extrusion, which was executed by a Delta WASP 40100 Clay printer and a self-customised printing path. A nozzle with 4 mm diameter was used for extruding two layers of clay with a total thickness of 3 mm on each CM sample. Prior to printing, the surface area of the CM was covered with a thin layer of wet clay, in order to increase its bonding with clay extruded from the printer. First tests with a zigzag-distribution indicated that the printing path is influencing the shaping process in large measures (Figure 3a). Consequently, a symmetrical printing path on two axes parallel to the edges was created by offsetting square paths towards the centre (Figure 3b). This approach was sufficient for some CMs, however, an adequate bond of the clay layer with C1, C2, FL and HE could not have been reached, as start and stop of the extrusion caused the detachment of clay and the CM. Therefore, a continuous printing path was developed for both layers, which avoids start-stop functions and travel paths (Figure 3c). The distance of the printing paths was computed in a way that by overlapping the extruded clay, a closed surface of the sample was ensured. As samples cracked on weak areas, where printing seams of those layers aligned in multiple layers, the printing path was once again optimised in a way that those seams were alternating (Figure 3d). Paste-based extrusion was a favourable method for producing mass customised samples and was considered successful for a symmetrical distribution of clay onto the CMs, as further elaborated in section 3.

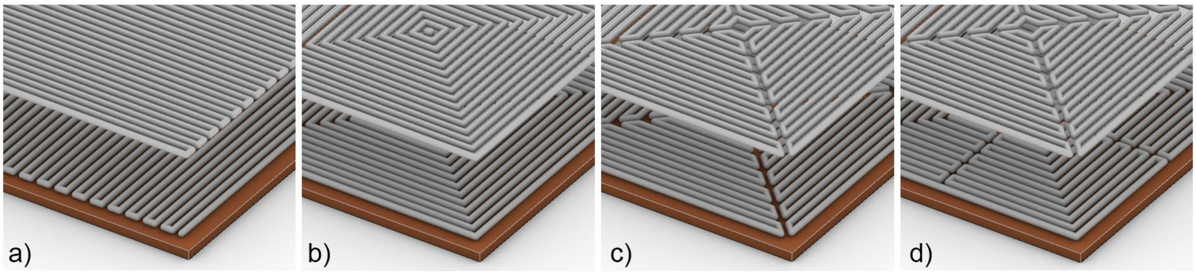


Figure 3: Printpath development, a) zigzag; b) offset; c) continuous; d) continuous with alternating edges

2.3. Drying

The drying process was carried out by putting the samples in an average room climate, i.e. an uncontrolled environment (UE), and simultaneously in a controlled environment (CE). The latter was achieved by building a custom-made box, where the relative air humidity was kept at 80% by an Arduino controlled ventilation of fresh air or addition of vaporised water. The temperature was a factor that was not taken into account, but was ranging from 18-22°C throughout the drying process. Both sets of samples were compared afterwards and are further exemplified in section 3.3.

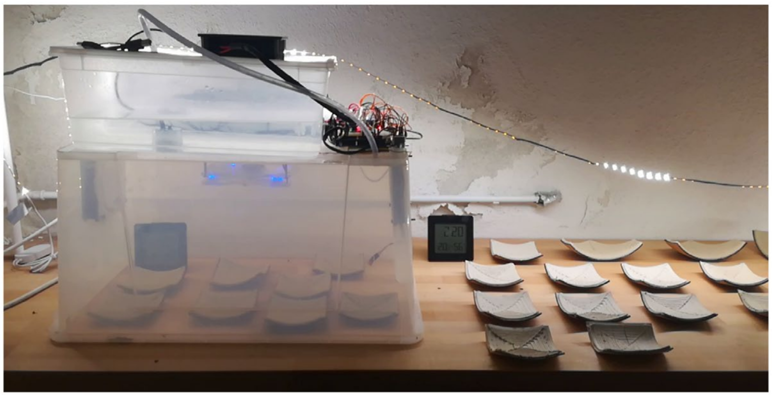


Figure 4: Drying setup with CE (left) and UE (right)

The drying process was monitored by filming the samples from 12 to 24 hours, depending on their drying time. Humidity sensors and thermometers were put inside and outside of the box to better understand their influences on the shaping process.

3. Results

This section evaluates: 1) the properties of the samples after the shaping process by determining their deviation values, 2) their compatibility with a certain CM, cracking and detachment from the CM after drying, and 3) compares the two types of drying environments, as well as the two application methods.

3.1. Shaping properties

After reaching a bone-dry state, the height of the corner points and midpoints of the sample's edges were measured with a 0.1 mm tolerance, which added up to eight measurements per sample. The gained data allowed a comparison of samples on a numerical level and indicated qualitative evidence of shaping properties. Also, samples that cracked or detached from their CMs were identified.

To describe the quality of the shaping process, positions of corner points as well as edge-midpoints and their deviation from the average within the sample were determined. The deviation values are abbreviated as 1CD to 4CD (**C**orner point **D**eviations) and 1MD to 4MD (**M**idpoint **D**eviations) and were measured individually for each sample (Figure 5). Application in a mould is abbreviated as **M** and application through paste-based extrusion as **P**. The nomenclature of the samples starts with the description of the drying environment (UE or CE), followed by the CM, application method and the number of each individual sample. For example: CE_C2_M_6 refers to a sample dried in a controlled environment, CM = cork 2, manual application, 6th sample.

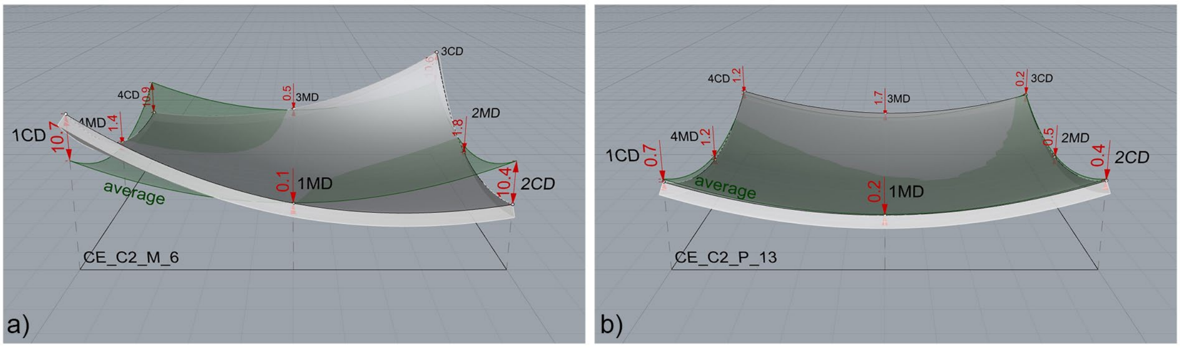
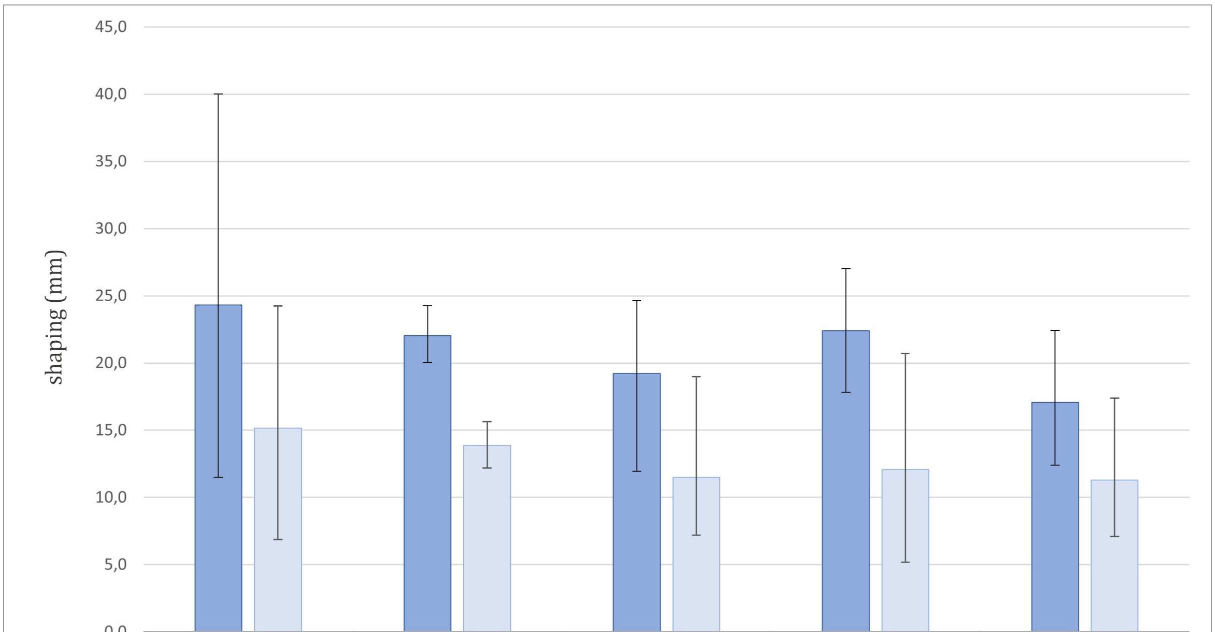


Figure 5: a) point deviations in CE_C2_M_6 with a maximum of 10.7 mm, compared to b) CE_C2_P_13 with a maximum of 1.7mm

Mean values for each sample group (determined by the CM and type of application) are displayed in Figure 6. The deviations of corner and midpoints are shown with error bars in relation to the mean value of samples in millimetres.



	C2_M	C2_P	C1_P	PB_P	GF_P
mean CP	24,306	22,048	19,232	22,413	17,091
mean MP	15,154	13,877	11,479	12,091	11,292

Figure 6: Mean values in mm with error bars for control points (CP) and midpoints (MP)

In order to evaluate the difference between M and P in terms of application, the same numerical analysis was applied for all samples (Figure 5). C2 was the only CM tested with both application methods, whose results are explained in the following paragraphs.

3.2. Sample evaluation

The following subsection evaluates 100 x 100 mm samples fabricated with M and P application methods. Clay was applied on all CMs mentioned in Table 1, however, hemp and flax were excluded from this analysis. These CMs were too flexible and due to their long fibres (10-30 mm), their surfaces appeared inhomogeneous, which led to clay not bonding during its application. The rest of the CMs are analysed by describing their shaping quality, cracking and detachment. A figure of dried samples is attached to each of the sample groups, consisting of 12 samples (CE in the first row, and UE in the second).

Manually applying clay on C2 resulted in highly irregular shaping within the sample group, but also within individual samples (Figure 7). The extreme deviations were analysed, but no pattern according to their placing during the drying process was documented. The shaping was therefore defined as random. 58.3% of the samples cracked.

Figure 7: C2_M – manually applied clay on cork 2

Paste-based extrusion was considered the most favourable application method. It was therefore applied in all of the following sample groups. For C2, it resulted in the best shaping quality from all CMs, as seen in the lowest deviation values (Figure 5). The overall impression of the samples exhibits uniform shaping (Figure 8) and a low cracking percentage (12.5%).

Figure 8: C2_P – paste-based extrusion of clay on cork 2

Printing clay on C1 was also considered successful, as no samples cracked or detached from their CM (Figure 9). The shaping quality was, however, considered not as good as in C2, because the samples exhibited higher deviation values.

Figure 9: C1_P – paste-based extruded clay on cork 1

Paperboard was considered impractical as a CM, as all samples cracked. Besides the cracks, the shaping itself was almost single-curved (Figure 10) and therefore exhibited high midpoint deviations (as seen in Figure 6). This was most likely determined by the anisotropic orientation of the fibres in the paperboard.

Figure 10: PB_P – paste-based extruded clay on paperboard

Felt performed well as a CM and no samples cracked or detached (Figure 11). However, the deviation values were relatively high when compared to C2, so it was not pursued as a final CM.

Figure 11: GF_P – paste-based extruded clay on Gautschfilz

3.3. Drying environment

The two types of drying environments (UE and CE) were defined by several stages that appeared in the process: start and end of shaping, and reaching the point of bone-dry state (Figure 12). The samples had to be completely dried out, since firing needed to be executed as a final step in the production process for a structural application. Also, reaching a bone-dry state is necessary for firing, which makes the material suitable for building components (Bechthold et al. [18]). Both drying and firing durations influence the total production time of the element.

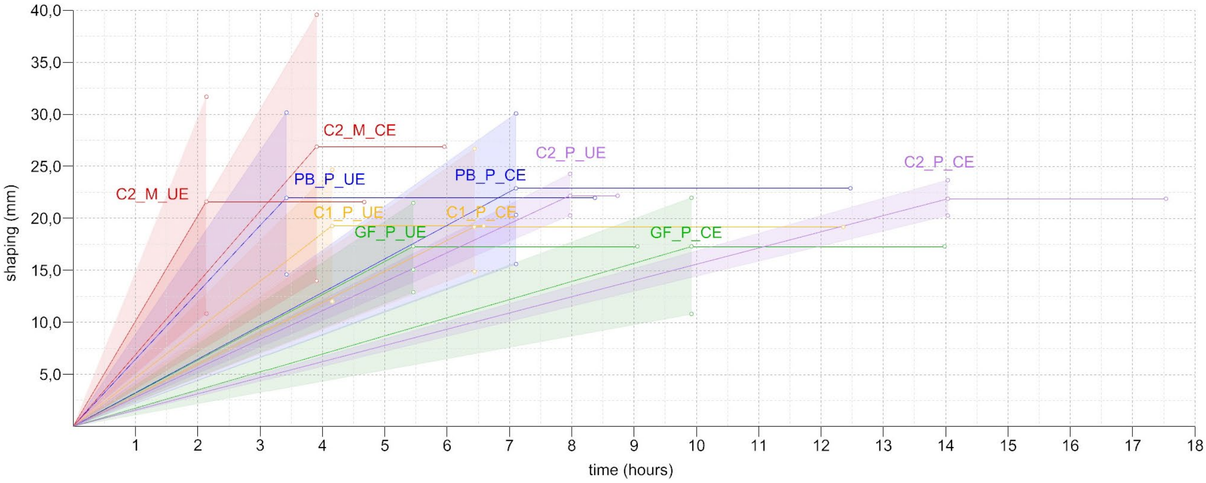


Figure 12: Average shaping values (lines) and deviations (areas) per CM in millimetres and reaching of bone-dry state in hours

CE increased drying times from 2-10 hours, depending on the CM. Moreover, paste-based extrusion application increased drying time and decreased point deviations when compared to manual application in a mould (C2_P and C2_M). From all printed samples of all CMs, differences of point deviations in CE and UE were insignificant. Also, C1 samples dried faster and had higher point deviations than C2. The cause of such behaviour may lie in the higher grain size of C1, which allowed greater porosity, and thus the exchange of air and humidity through the CM.

4. Case study

The gained knowledge of the developed shaping method was incorporated into a case study to show the potential for a structural application. The mockup shell structure was based on a truncated icosahedron with hexagonal and pentagonal elements, which were shaped through the introduced method, detached from their CM, and then fired in an oven at 1250°C peak temperature. Hexagonal elements measured 200 mm and pentagonal 166 mm in diameter in their flat and wet state, which led to a combined shell structure measuring 570 mm diameter and 285 mm height. The final element's thickness measured 2.5 mm with a weight ranging from 49-82 g. The clay mixture described in 2.1.1. was distributed by Delta WASP 40100 Clay printer and applied to C2 with two layers and one continuous printing path with alternating edge alignments (Figure 13).

Figure 13: Elements for the case study: a) at the beginning of the drying process, b) at the point of reaching bone-dry state

The drying and shaping phases were then executed in an uncontrolled environment, as repercussions of a CE and UE were insignificant. The elements reached a bone-dry state after 23 hours, which is longer than the samples tested in 3.2, due to their larger dimensions. They were detached from their CMs, fired and connected with 3D printed flexible clamps made from Eco PLA. The CM was flattened by a heated pressing machine to be used again.

Figure 14: The final case study showing a dome structure made from multiple double curved elements

5. Conclusion

We developed and applied a shaping method which utilises hydrogen secondary bonds between a wet clay layer and a CM to gain specific forms throughout the drying phase. By a paste-based extrusion approach, thin, lightweight, single or double-curved ceramic structures can be created through mass customisation of planar elements, without the use of elaborate scaffolding, casting or other traditional shaping methods. Main limitations of this method lie in scalability and maximum dimensions of elements, predefined by layer thickness, mass and gravity, as well as print bed dimensions and oven size. This research is mainly focused on CMs, application methods and shaping properties. To reduce parameters involved in shaping behaviour, mentioned in section 2, one broadly available, standard clay type mixed with water in a consistent ratio, was used for all experiments in this research.

To conclude results, cork with a grain size ranging from 0.2-0.5 mm, referred to as C2, has proven higher shaping qualities as compared to other CMs. Regarding clay application, a continuous printing path without travel paths or start-stop operations, which also includes alternating edge alignments in layers, has proven to be most sufficient for an even application and best bonding properties of the two layers. Furthermore, cork has proven to be a reusable CM.

More research is needed in order to evaluate other clay types, mixtures and additives, as well as effects of different printing paths, the geometrical design of the sample and varying layer thicknesses within one element. Additional parameters that potentially influence the shape of single elements are perforating the CM by having slits longitudinally and transversely and restricting deformation in certain areas of the CM.

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References

[1] J. Lienhard, H. Alpermann, C. Gengnagel and J. Knippers, "Active Bending, A Review on Structures where Bending is used as a Self-Formation Process," *International Journal of Space Structures*, vol. 28, pp. 187-196, Sep. 2013.

[2] P. Nicholas and M. Tamke, "Computational Strategies for the Architectural Design of Bending Active Structures," *International Journal of Space Structures*, vol. 28, pp. 215-228, Sep. 2013.

[3] D. Wood, *Material programming for fabrication : integrative computational design for self-shaping curved wood building components in architecture*. Stuttgart: Institute for Computational Design and Construction, University of Stuttgart, 2021.

[4] A. Menges, S. Schleichner and M. Fleischmann, *RESEARCH PAVILION ICD/ITKE*. In *Fabricate 2011: Making Digital Architecture*, DGO-Digital original, UCL Press, 2017, pp. 21-26.

[5] S. Schleicher, A. Rastetter, R. La Magna, A. Schönbrunner, N. Haberbosch and J. Knippers, *Form-Finding and Design Potentials of Bending-Active Plate Structures*. In M. Thomsen, M. Tamke, C. Gengnagel, B. Faircloth and F. Scheurer (eds.) *Modelling Behaviour*, Springer, Cham, 2015, pp. 53-63.

[6] M. Mühlich, D. Horvath, A. Körner, R. La Magna and J. Knippers, "Curated deformation - dynamic shape change of tessellated surfaces," in *IASS Annual Symposium and Spatial Structures Conference 2020/21, Guildford, United Kingdom, August 23-27, 2021*.

[7] S. Puystiens, M. Van Craenenbroeck, D. Van Hemelrijck, W. Van Paepegem, M. Mollaert and L. De Laet, "Implementation of bending-active elements in kinematic form-active structures – Part I: Design of a representative case study," *Composite Structures*, vol. 216, pp. 436-448, May 2019.

[8] D. Correa, A. Papadopoulou, C. Guberan, N. Jhaveri, S. Reichert, A. Menges and S.Tibbits, "3D-Printed Wood: Programming Hygroscopic Material Transformations," *3D Printing and Additive Manufacturing*, vol. 2, pp. 106-116, Sep. 2015.

[9] M. Rüggeberg and I. Burgert, "Bio-Inspired Wooden Actuators for Large Scale Applications," *PLoS ONE*, vol. 10, April, 2015.

[10] P. Grönquist, D. Wood, M. M. Hassani, F. K. Wittel, A. Menges and M. Rüggeberg, "Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures," *Science Advances*, vol. 5.

[11] L. Mogas-Soldevila, J. Duro-Royo, D. Lizardo, M. Kayser, W. Patrick, S. Sharma, S. Keating, J. Klein, C. Inamura and N. Oxman, "DESIGNING THE OCEAN PAVILION: Biomaterial

Templating of Structural, Manufacturing, and Environmental Performance," in *Future Visions: Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2015, Amsterdam*.

[12] E. Özdemir, L. Kiesewetter, K. Antorveza, T. Cheng, S. Leder, D. Wood and A. Menges, "Towards Self-shaping Metamaterial Shells: A Computational Design Workflow for Hybrid Additive Manufacturing of Architectural Scale Double-Curved Structures," in *Proceedings of the 2021 DigitalFUTURES, Springer, Singapore*, pp. 275-285.

[13] T. Cheng, D. Wood, L. Kiesewetter, E. Özdemir, K. Antorveza and A. Menges, "Programming material compliance and actuation: hybrid additive fabrication of biocomposite structures for large-scale self-shaping," *Bioinspiration & Biomimetics*, vol. 16.

[14] Y. Zhang and H. Le Ferrand, "Bioinspired Self-Shaping Clay Composites for Sustainable Development," *Biomimetics*, vol. 7.

[15] M. Bechthold, A. Kane and N. King, "Keramische Bausysteme : in Architektur und Innenarchitektur", Basel : Birkhäuser 2015, pp. 12-13, 56.

[16] P. Falin, N. Horsanali, F. Tvede Hansen and M. Mäkelä, "Practitioners' Experience in Clay 3D Printing: Metaphorical viewing for gaining embodied understanding," *FormAkademisk - forskningstidsskrift for design og designdidaktikk*, vol. 14.

[17] T. T. Liu, M. Q. Cao, Y. S. Fang, Y. H Zhu and M. S. Cao, "Green building materials lit up by electromagnetic absorption function: A review," *Journal of Materials Science & Technology*, vol. 112, pp. 329-344.

[18] M. Bechthold, A. Kane and N. King, "Keramische Bausysteme : in Architektur und Innenarchitektur", Basel : Birkhäuser 2015, pp. 12.