Hexcrete

Modular and recyclable paper clay formwork

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This project combines 3D printing and conventional hand-building of unfired clay to leverage each strength in creating custom, zero-waste, reusable formwork. The fabrication method relies on the plasticity and water-solubility of clay in an unfired state to permit the production of larger, more complex clay formwork. This is achieved through the aggregation of 3D-printed units with hand joinery. Since unfired clay possesses limited strength and struggles to hold its weight, shredded paper was introduced. The research first explores the compressive strength of clay with various ratios of added paper. The process of creating paper clay is explained, and its ratios are documented. Next, fabrication case studies at multiple scales are introduced to explore paper clay's viability as a formwork. The paper clay self-demolds as it dries, shrinks, and falls off the concrete form. This allowed all the clay to be conserved. All clay from the test was rehydrated and recycled to be reused. The fabrication tests demonstrated the effectiveness of the fabrication workflow. The results point to future research that may reduce the embodied carbon emissions of concrete casting through formwork recycling.

Keywords: *Formwork, Circular Design, Recyclable, Clay, Additive Manufacturing*

INTRODUCTION

Concrete is one of the most common building materials (UNEP, 2016). The number of projects utilizing concrete construction continues to increase (Leder et al., 2020). 35% of the annual world's solid waste is created by building construction (Llatas, 2011). The creation of concrete products accounts for up to 7% of global emissions (Anderson and Moncaster, 2020). Concrete structures have contributed significantly to this problem since single-use formworks are often needed to cast concrete. Formwork is 35 to 50% of a construction project's total cost (Peurifoy and Oberlender, 2011). Reducing formwork waste could create a more sustainable method for creating complex concrete structures.

Traditional formwork for the fabrication of straightforward geometries allows for simple formwork. The lack of geometric freedom of standard formwork systems has motivated many to develop methods for creating novel concrete casts with fabric, subtractive, and additive manufactured formwork.

Fabric formwork has been examined due to its limited material use and capacity to craft complicated forms. The scale of these investigations has varied from facade panels (Kudless, 2011) to small pavilions (Sarafian et al., 2017; Popescu et al., 2020). Fabric formwork applications are limited due to the necessary tension, making it challenging to create large structures.

Milled formwork using Expanded PolyStyrene (EPS) has been used to create concrete formwork

(Martins et al., 2015; Kudless, 2018). A great deal of waste is produced by the milling of the EPS stock and its discarding after casting. Wax and ice have been milled to create formwork (Sitnikov et al., 2019) but require stringent conditions limiting their applications.

Additive manufacturing has been utilized with diverse materials to create formwork. It can provide a method for creating complex designs with little waste compared to subtractive methods. 3D-printed formwork waste is created through the tedious de-molding process since many 3D-printed plastics cannot be recycled. Flexible filaments have been used, allowing easier de-molding (Peters, 2014). Another thread of 3D printed formwork research has utilized water-soluble material such as Polyvinyl Alcohol (PVA) to create complex formwork (Doyle and Hunt, 2019). Since this formwork is removed by soaking the cast in water, the cast can be highly ornate, allowing undercuts and small geometries. This formwork method is limited in its scalability and applications.

This paper builds on a growing body of research investigating 3D-printed clay as formwork. Previous research has explored 3D-printed clay formwork without significant manipulation post-printing (McGee and Peller, 2018, Sutherland et al., 2018; Bruce et al., 2021). While previous work involving clay 3D printing of double-curved forms has relied on curved printing surfaces and complex toolpaths (Anton and Abdelmahgoub, 2018), this project focuses on the joinery of multiple units to create intricate geometries. Clay dries and shrinks after the casting, allowing it to be collected, rehydrated, and reused. This recycling process allows for zero formwork waste.

This project introduces a way to combine 3D printing and conventional hand-joining methods to create larger and more complex formwork. Additionally, it explores the integration of shredded paper to increase the clay's strength while reducing its weight. This process is documented through a series of compression tests to ascertain the most robust ratio of clay to paper. Next, fabrication case studies at multiple scales are introduced to gauge the viability of the fabrication method.

METHODS

This section outlines the material testing, the process for creating paper clay, and formwork fabrication workflows. It discusses the fabricated mockups that tested the viability of the formwork system and material.

Material Testing

The formwork needed to be self-supporting and usable in an unfired state. Ceramic sculptors use paper clay to create lighter, stronger pieces that can be more easily manipulated before firing.

To measure the strength of the clay, 3D printed cubes were fabricated (8 cm x 8 cm x 7 cm) using two types of clay, porcelain and stoneware. The 3D printed clay test cubes were compression tested by stacking weight on top until failure. The first tests were conducted when one print was bone dry (completely dry) and the other leather hard (partially dry). The bone-dry pieces were extraordinarily brittle and held less weight. Therefore, it was determined that the material in the leather hard state was optimal. Porcelain was the most robust clay type tested, carrying the most significant weight when leather hard. It held approximately three times the weight of the stoneware.

The next stage integrated various ratios of paper to clay. The same cube design was printed to test the strength at 15%, 25%, and 35% paper to porcelain clay. The test concluded that these additions successfully reduced the material's weight while increasing its load capacity. The 25% paper-to-clay mixture withstood the most load and had the least shrinkage (Table 1). The paper fibers can be seen within the clay (Figure 1).

Table 1
Data from material testing

Test Number	1	2	3	4	5	6	7
Paper (%)	0				15	25	35
Clay Body	Porcelain		Stoneware		Porcelain		
Clay (g)	N/A				964	850	737
Fibers (g)	None				170	283	394
Unit Size	8.255 cm x 8.255 cm x 7.26 cm						
Moisture (%)	>50						
Initial Weight (g)	425	422	422	422	405	399	394
Final State	Bone Dry	Leather Hard	Bone Dry	Leather Hard			
Final Moisture (%)	14	39	15	43	44	46	48
Final Weight (g)	340	369	332	391	349	346	335
Load Capacity (kg)	25	23	8.6	19	33	39	39

Figure 1
Paper Fibers

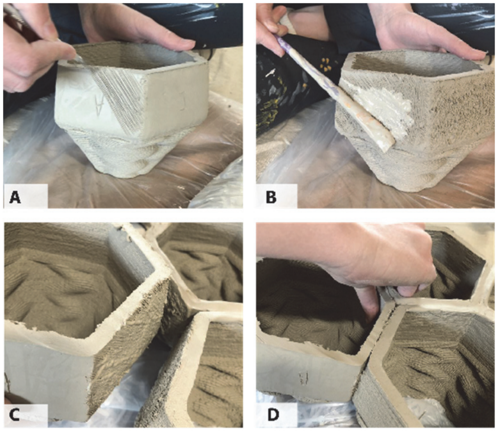


Figure 2
Unit Joinery (A) scratching of the lower half, (B) applying the liquid clay to the surface, (C) aligning the correct sides, (D) applying pressure to weld units.

Paper Clay

Recycled printer paper and newspapers were collected from the university's library. They were shredded using a household paper shredder. The shredded paper was soaked using tap water in a 20-liter bucket for 3 minutes. The soaking softens the paper before emulsifying the mixture using a handheld emersion blender. This created a pulp. The blending required approximately 10 minutes.

The porcelain clay was cut into 2.5 cm cubes and placed into a 20-liter bucket to which water was added incrementally. The mixture was incorporated using an emersion blender. This allowed for the creation of a pourable liquid clay or slip. The paper pulp was then mixed with the clay until smooth.

The mixture was first placed on linen attached with clamps to a wooden frame, allowing some excess water content to be removed and then transferred to plaster slabs. The mixture was dehydrated on plaster slabs until the optimal viscosity for 3D printing clay was reached, approximately 24 hours. This soft clay holds its shape but can be easily extruded through a nozzle. It was then removed from the plaster and worked by hand or wedged to remove air bubbles before its use for 3D printing (Figure 5).

Preliminary Formwork Tests

The first test used a set of units measuring 25.4 mm x 25.4 mm x 50.8 mm (Figure 3). The design utilized hexagonal tiling. Each unit had a top and bottom half of the geometry, each with a distinct role. The bottom allowed the units to be joined and

Figure 3
Top and side formwork, cast formwork, and the resulting cast for iterations 1 (top) and 2 (bottom).

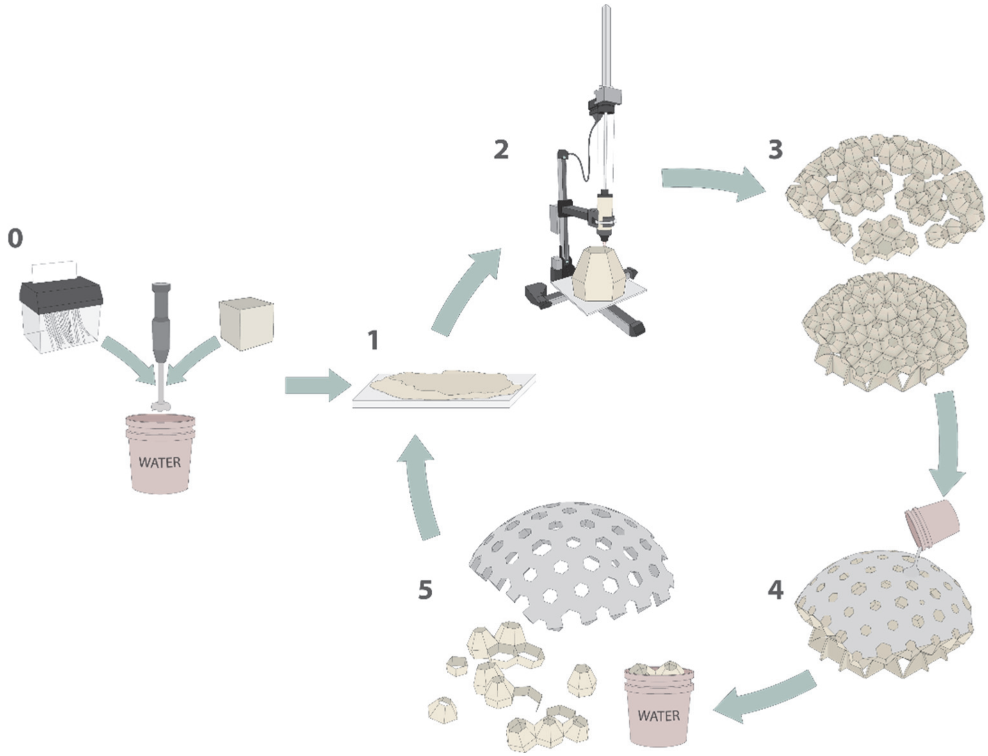
aggregated into the desired formwork. The top of each unit held the casting material. The units were printed using a single spiralized curve. These units were printed using a 2 mm diameter nozzle.

The 17 units were tessellated into an arch using hexagonal prisms. The units were joined using traditional ceramic methods. The bottom faces of the units were scratched or scored using a feather wire tool for clay sculpting. Then a medium paintbrush applied porcelain slip or liquified clay to the surface. The slip acts as an adhesive. Slip is created by adding water to clay in a container and mixing with an emersion blender until a thick liquid is formed. The units were then pressed together by hand or welding the units to create the formwork (Figure 2). All the edges of the formwork were then patched with flat slabs of clay. It was discovered that the bottom portion of the formwork could be shorter, allowing for less material to be used and print times to be expedited.

The second iteration tested the possibility of applying custom patterning through toolpath manipulation on the top of the unit (Figure 3). A zig-zag pattern was applied to utilize a series of clay overhangs. The unit's texture was explored through 3D printed tests to find the best overhang distance

Figure 4
Unit texture test (top), the second iteration (bottom).

Figure 5
(0) Creating paper and clay mixture 1-2 hours, (1) letting the clay dry on plaster 12-24 hours, (2) printing units 15 minutes per unit, (3) Assembling formwork 1-2 hours, (4) Casting 1 hour, (5) Removing clay and soaking in water 10-12 hours.



for the loops to provide the greatest texture (Figure 4). The texturing proved successful and created a unique texture on the cast. It was noted in this iteration that using one regular hexagon unit resulted in gaps between units as they were assembled further away from the center. Thus, multiple unit types would be needed to create a geodesic dome.

Large-Scale Formwork Test

The next test increased the scale of the units (approximately 16 cm x 14 cm x 12 cm), resulting in a 1-meter dome. This design used five base shapes: four hexagonal and one pentagonal (Figure 6). The top of each unit varied in aperture size and pattern. Fifty-two units were printed in total. These units used a nozzle (6 mm) 3 times larger than the prior iterations. This allowed for a larger bead width for the single spiralized print creating a stronger unit.

Since the units were printed individually, the limitations of the print's volume and the size of the tube were not a hindrance.

To prevent the units from drying, while others were 3D printed, each was wrapped in plastic and stored in a container. This was important because the casts needed to remain in the leather hard or partially dry state. This is the most robust state prior to firing clay. If the clay were to desiccate to a bone-dry (dehydrated) state, it would absorb too much of the casting material's water, weakening the formwork and resulting in a failed cast.

This iteration was the only one to require a substructure to construct the formwork. This, too, could be recycled and reused (Figure 6).

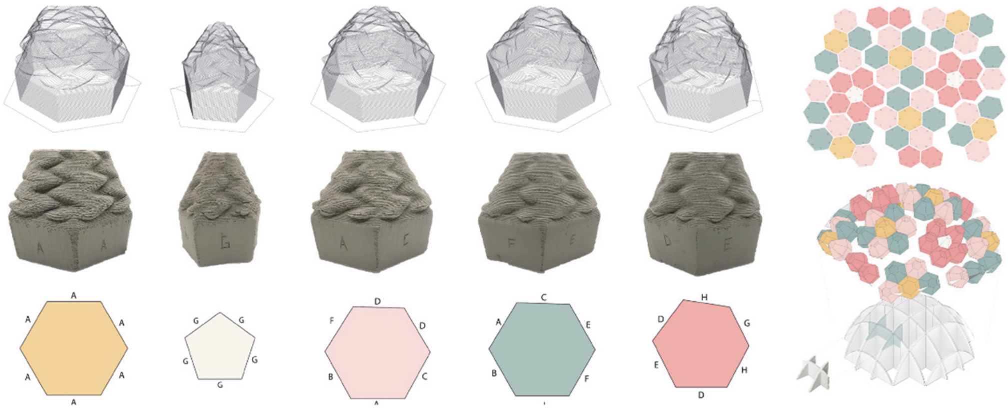


Figure 6
Five final unit designs, the layout, assembly, and structure with a 3D printed formwork call out.

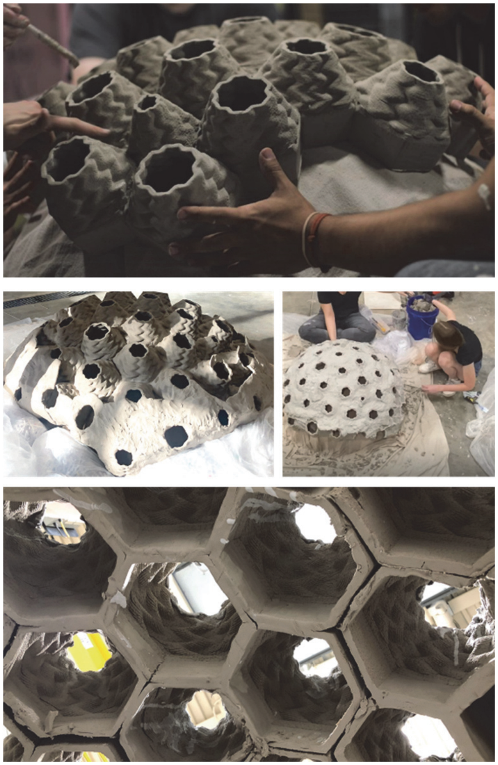


Figure 7
Assembly (top), formwork before casting (center left), removal of formwork (center right), clay formwork before removal (bottom).

The substructure was subdivided using the clay printer's bounding box and printed in paper clay. Therefore, it, too, could be recycled and reused (Figure 6).

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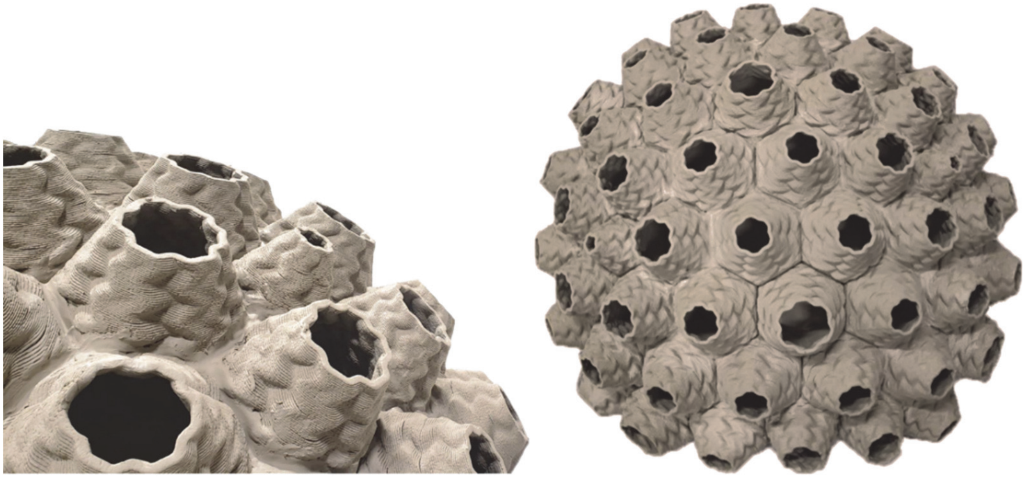
The units were first joined into small groups of 5 to 6 before being fully assembled. The assembly took under an hour with a 4-person team (Figure 7). In conjunction with the formwork, the compressive strength of the paper clay subframe supported the casting material.

The more sloped areas of the clay formwork needed to be patched with a layer of clay to hold the casting material (Figures 7 and 8). The casting required several layers of material with varying viscosities and multiple rotations to fill the formwork consistently. The clay formwork was allowed to dry, which resulted in it shrinking and falling off the cast. The resulting cast was successful (Figure 9).

Clay Recycling

The clay formwork was conserved for reuse. Water was added to the dried clay to create a liquid. The

Figure 8
Final Formwork



liquid clay was strained to remove undesired casting material or foreign objects. The clay was dried on plaster slabs to decrease its moisture for approximately 5 hours. This process allowed it to return to the desired viscosity required for 3D printing. Once the clay is removed from the plaster, it is worked by hand or wedged before its placement in a sealed container to remove air and inhibit further desiccation (Figure 5).

RESULTS + DISCUSSION

While creating paper clay was time-consuming, this portion of the formwork process can be done after the mixture is successfully created since it is fully recyclable.

Since only some of the clay is recovered and the paper will decompose within a year, additional clay will need to be used and new paper introduced. Further testing will need to be conducted to determine how many times the paper clay can be reused.

The joinery was straightforward, allowing those with limited experience to participate effectively. Applying the paper clay to the formwork seams is good practice for sealing the connections. The miniature mockups were easier to tesselate and did not require a substructure. As a result of the reduced slope of these tests, the casting was more straightforward than the large-scale fabrication test. The thicker bead of the 3D print did not allow the texture to be as prominent in the large-scale cast, although it permitted the formwork to withstand the more significant load of the casting material. The use of paper clay proved successful in its ability to hold considerable weight without deformation.

As a result of the casting struggles when fabricating the dome, it may be easier to cast the pieces in their smaller groups, remove the formwork, and place them using the paper clay substructure. This might also allow the units to forgo storage in plastic since the formwork could be created faster and cast as printed.

The current formwork and unit design limits the patterning to one side of the cast. While the top face is not unpleasant, it would be more attractive if it had clay formwork determining its design.

The material conservation was successful. Straining the paper clay removed substantial concrete and other debris, making it integral to the process since the material is used for 3D printing and needs to fit through a small nozzle.

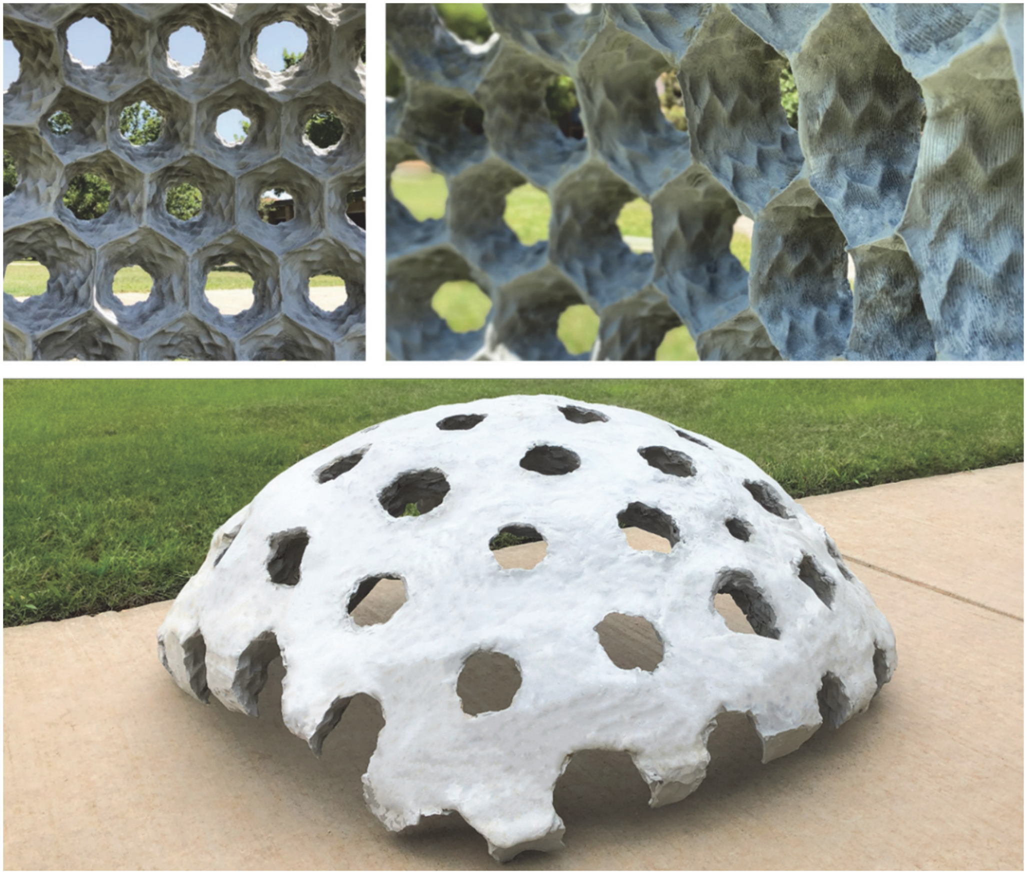


Figure 9
Final Vault

CONCLUSION

This research builds upon recent investigations into unfired clay 3D-printed formwork. This project moves the research forward through the integration of paper and brings historical methods of clay joinery into the workflow through hand building.

This formwork method allows for the creation of complex concrete casts. The ease of the formwork removal can allow for undercuts and other intricate geometries to be created that would otherwise be challenging to cast with conventional formwork systems.

The work discussed in this paper demonstrates the potential for a formwork system that could eliminate waste and lessen concrete fabrication's carbon footprint.

This research will scale up by introducing robotic printing using a clay extruder on a robotic arm.

Allowing the units to increase in size further permits this process to be applicable at a construction scale.

Future investigations will examine methods for integrating texture on both sides of the cast. This could eliminate the casting difficulties of the curved geometry by providing a top to the formwork. A double-sided casted form will be investigated through the fabrication of a wall. A wall would be advantageous since it would not require a substructure. This double-sided formwork would provide a more consistent seal than the clay slabs. The incorporation of reinforcement will be explored in future formwork testing.

REFERENCES

Anderson, J. and Moncaster, A. (2020). 'Embodied carbon of concrete in buildings, Part 1: analysis of published EP', *Buildings and Cities*, 1(1), pp. 198–217.

Anton, A. and Abdelmahgoub, A. (2018). 'Ceramic Components - Computational Design for Bespoke Robotic 3D Printing on Curved Support' in Kepczynska-Walczak, A and Bialkowski, S. (eds.) *Computing for a better tomorrow - Proceedings of the 36th eCAADe Conference,* 16-18 September 2018, Lodz, Poland, pp. 71–78. Available at: https://doi.org/10.52842/conf.ecaade.2018.2.071

Bruce, M. Clune, G. Xie, R. Mozaffari, S. and Arash A. (2021). 'Cocoon: 3D Printed Clay Formwork for Concrete Casting' in Bogosian, B. Dörfler, K. Farahi, B. Garcia del Castillo y López, J. Grant, J. Noel, V. Parascho, S. and Scott, J. (eds.) *Realignments: Toward Critical Computation Proceedings of the 41st Annual Conference of the Association for Computer Aided Design in Architecture*, 3-6 November 2021, Online, pp. 400-409. Available at: http://papers.cumincad.org/cgi-bin/works/Show?acadia21_400

Doyle, S. and Hunt, E. (2019). 'Dissolvable 3D Printed Formwork: Exploring Additive Manufacturing for Reinforced Concrete' in Bieg, K. Briscoe, D. Odom, C. (eds.) *Ubiquity and Autonomy: Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture*, 21-26 October 2019, Austin Texas, pp. 178–188. Available at: https://doi.org/10.52842/conf.acadia.2019.178

Jipa, A. and Dillenburger, B. (2022). '3D Printed Formwork for Concrete: State-of-the-Art, Opportunities, Challenges, and Applications', *3D Printing and Additive Manufacturing*, 9(2), pp. 84-107. https://doi.org/10.1089/3dp.2021.0024.

Kudless, A. (2018). 'Confluence Park' in Anzalone, P. Del Signore, M. Witt, A.J. (eds.) *On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer-Aided Design in Architecture*, 18-20 October 2018, Mexico City, Mexico, pp. 154-159.

Kudless, A. (2011). 'Bodies in Formation: The material evolution of flexible formworks', in Integration through Computation: Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture, 13-16 October 2011, Alberta, Canada, pp. 98-105. Available at: https://doi.org/10.52842/conf.acadia.2011.098

Leder, S., Weber, R., Vasey, L., Yablonina, M., & Menges, A. (2020). 'Voxelcrete- Distributed voxelized adaptive formwork' in Werner, L. and Koering, D. (eds.) *Architecture and Fabrication in the Cognitive Age: Proceedings of the 38th Education and research in Computer Aided Architectural Design in Europe Conference*, Berlin, Germany, 16-18 September 2020, pp. 433-442, Available at: https://doi.org/10.52842/conf.ecaade.2020.2.433

Llatas, C. (2011). 'A model for quantifying construction waste in projects according to the European waste list', *Waste Management*, 31(6), 1261-1276. https://doi.org/10.1016/j.wasman.2011.01.023.

Martins, P. Fonseca de Campos, P. and Nunes, S. (2015). Expanding the Material Possibilities of Lightweight Prefabrication in Concrete Through Robotic Hot-Wire Cutting', In Martens, B. Wurzer, G. Grasl, T. Lorenz, W.E. and Schaffranek, R. (eds.) *Architecture and Fabrication in the Cognitive Age: Proceedings of*

the 33rd Education and research in Computer Aided Architectural Design in Europe Conference, Vienna, Austria, 16-18 September 2015, pp. 341-351, Available at: https://doi.org/10.52842/conf.ecaade.2015.2.341
McGee, W. and Peller, A. (2018). 'Elemental | Ornamental' in Anzalone, P. Del Signore, M. Witt, A.J. (eds.) *On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer-Aided Design in Architecture*, 18-20 October 2018, Mexico City, Mexico, pp. 198-203.
Peters, B. (2014). 'Additive Formwork 3D Printed Flexible Formwork' in Design *Agency: Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture,* Los Angeles, California, 23-25 October 2014, pp. 517- 522, Available at: https://doi.org/10.52842/conf.acadia.2014.517
Peurifoy, R. and Oberlender, G. (2011). *Formwork for Concrete Structures*. 4th ed. McGraw-Hill.
Popescu, M. Rippman, M. Van Mele, T. and Block, P. (2020). 'Knitcandela: Challenging the Construction, Logistics, Waste and Economy of Concrete-Shell Formworks', in Berry, J. Sabin, J. Sheil, B. and Skavara, M. (eds.) *Fabricate 2020: Making Resilient Architecture,* pp. 194–201, Available at: http://dx.doi.org/10.2307/j.ctv13xpsvw.30
Sarafian, J. Culver, R. and Lewis, T.S. (2017). 'Robotic Formwork in the MARS Pavilion: Towards the Creation of Programmable Matter' In Lamere, J. and Perreño Alonso, C. (eds.) *Disciplines and Disruptions: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, Cambridge, Massachusetts, 2-4 November 2017, pp. 522-533, Available at: https://doi.org/10.52842/conf.acadia.2017.522
Sitnikov, V. Eigenraam, P. Papanastasis, P. and Wassermann-Fry, S. (2019). 'IceFormwork for Cast HPFRC Elements.' in Bieg, K. Briscoe, D. Odom, C. (eds.) *Ubiquity and Autonomy: Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture*, 21-26 October 2019, Austin Texas, pp. 616-627, Available at: https://doi.org/10.52842/conf.acadia.2019.616
Sutherland, T.S. Marshall, W. and Lee, D. (2018). 'EndlessColumns' in Anzalone, P. Del Signore, M. Witt, A.J. (eds.) *On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer-Aided Design in Architecture*, 18-20 October 2018, Mexico City, Mexico, pp. 204-209.
United Nations Environment Programme, & International Resource Panel. (2016). Global Material Flows and Resource Productivity: Assessment Report for the UNEP International Resource Panel. Available at: https://wedocs.unep.org/20.500.11822/2155