PolyBrick H2.0

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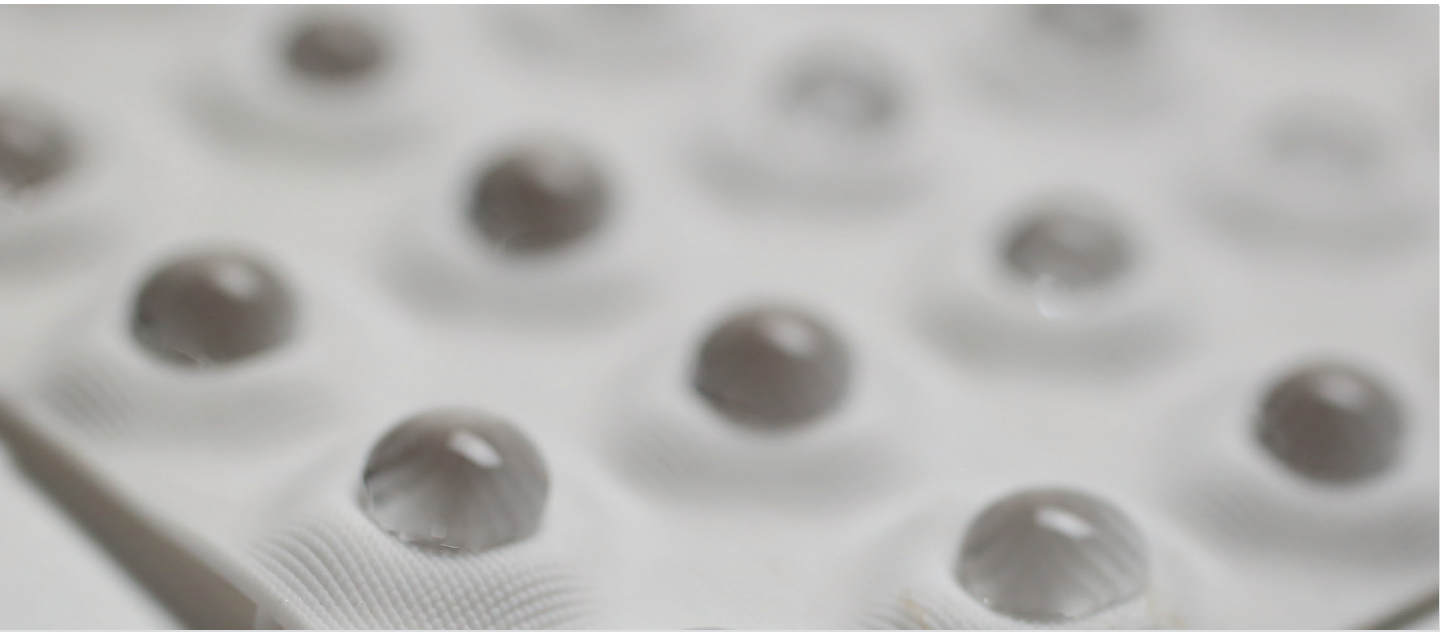
Internal Bone-based Hydraulics in Bricks Through Controlled Water Flow From Micro-texturing and Surface Chemistry



ABSTRACT

This project emerged from collaborative trans-disciplinary research between architecture, engineering, biology, and materials science to generate novel applications in micro-scale 3D printed ceramics. Specifically, PolyBrick H2.0 adapts internal bone-based hydraulic networks through controlled water flow from 3D printed micro-textures and surface chemistry. Engagement across disciplines produced the PolyBrick series at the Sabin Lab (Sabin, Miller, and Cassab 2014). The series is a manifestation of novel digital fabrication techniques, bioinspired design, materials inquiry, and contemporary evolutions of building materials. A new purpose for the brick is explored that is not solely focused on the mechanical constraints necessary for built masonry structures. PolyBrick H2.0 interweaves the intricacies of living systems (beings and environments combined) to create a more responsive and interactive material system. The PolyBrick 2.0 series looks at human bone as a design model for foundational research. PolyBrick H2.0 merges the cortical bone hydraulic network with new functionalities as a water filtration and collection system for self-preservation and conservation as well as passive cooling solutions. It also pushes the ability of 3D printing techniques to the microscale. These functionalities are investigated under context for a better construction material, but its use may extend further.

INTRODUCTION

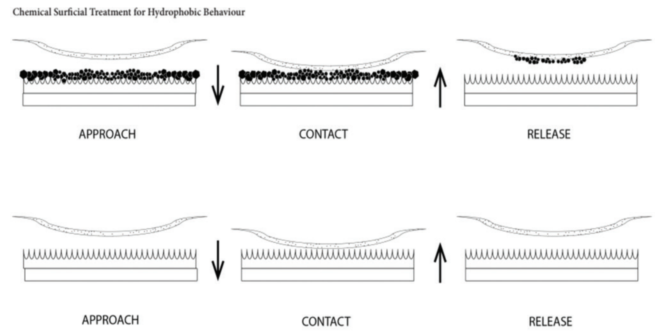
Dynamic and multifunctional materials are changing how we design the built environment. Fired brick has been a reliable construction material with high compressive strength, increased water resistivity, high durability, and easy assemblage, but has the potential for improved properties. Novel functionalities and fabrication through 3D-printing techniques fashion the brick as applicable to contemporary building construction as it surpasses its structural use with internal networks and treated surface texturing to self-preserve, conserve, and tailor itself to its architectural structure and environment. The new functionalities are introduced into this variation of PolyBrick 2.0 through a variety of micro-textures on the ceramic surface in conversation with specific glazing chemistry and applications. Ceramic materials, like fired brick, often deteriorate due to their ability to retain moisture. A wet environment grows mold and organic material, which weakens the brick (Hughes, Bargh 1982). This mold is a detriment to the building's lifespan and inhabitants' health (EPA 2014). Introducing a water collection and filtration system in the brick can help redirect the harmful qualities water has in the brick to beneficial ones:

1. as water will naturally nucleate on the brick surface due to the lower thermal conductivity of the ceramic material than that of air, redirection of the water condensed on the brick towards a collection point will conserve the water for reuse and will remove the water from the brick for self-preservation;

2. water's high specific heat helps to passively regulate the temperature of the brick and provides a more homeostatic temperature in the structures built with it;

3. the filtration and surface collection systems can be customized to specific environments and geometries due to the vocabulary developed for both surface texturing and surface glazing, along with the flexibility that comes with a 3D-printed brick.

This functionality in the brick drew inspiration from evolved species that have efficient dynamic structures. The study of the human cortical bone revealed a hydraulic system that provides information and inspiration to the moisture (and heat) filtration system of the PolyBrick. Functionalizing through texturing was inspired by the pitcher plant and rice leaves. The pitcher plant consists of distinguished zones that have different microstructures and chemical compositions. Its slippery zone, covered with lunate cells, prevents the escape of prey from the plant, while also providing important biomimetic parameters to consider for the



1 Texturing of the Pitcher Plant

(top) The diagram depicts how the properties of the epicuticular surfaces in the pitcher plant improves trapping efficiency as they affect the locomotion of prey. Pictures a, b, and c depict an intact surface of the upper wax zone when d, e, and f show the lower layer of the wax zone and how its geometry results in a slippery substrate where insect pads easily detach (Lixin et al. 2009);

(bottom) Morphology of a pitcher plant

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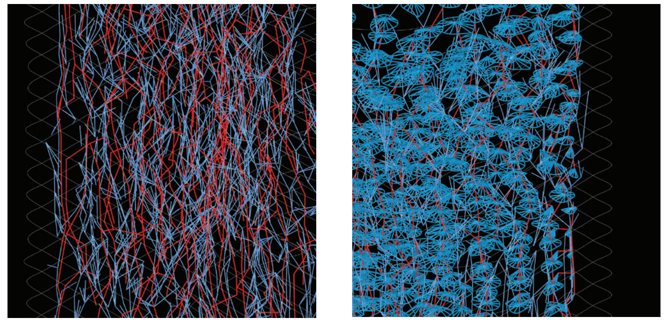
surface design of the brick in order to shed water (Figure 1). Rice leaves contain microgrooves—waxy bumps that repel and direct flow—to allow for self-cleaning (Thompson 2013).

Investigations into moisture collection in other systems help inform the research direction for the system in PolyBrick. The Warka Water Tower is a successful instance of moisture collection, designed by Arturo Vittori and Andreas Vogler. It looks at air flow and convection to develop a hybrid system that collects potable drinking water from dew and moisture in the air for water scarce regions in Ethiopia at a low-cost. The hybrid system consists of juncus stalks and a nylon/polypropylene droplet condensing mesh that drains by gravity to a collection container (Nguyen 2014). At MIT, another research group studied the fog harvesting capability of woven meshes and looked at geometry, surface wettability, length scales, densities, and coatings of different chemistries and characteristics to inform optimal mesh conditions for fog harvesting (Park et al. 2013). Surface tensions, drag forces, and aerodynamics were considered, but for this meshing research and the Warka Tower, both systems relied on surface texturing and chemistry to achieve the desired effect.

These precedents for water collection systems and flow control led to this iteration of the PolyBrick series; it focuses on surface texturing and surface chemistry to functionalize the ceramic brick to serve additionally as a moisture collection, and further, filtration material.



2 Model of the Hydraulic System of the Cortical Bone: (left) The blue lines depict the Haverian canals and the red depict Volkmann's canals that run parallel to the length of the bone; (right) The additional blue webbing represents the canaliculi networks for each osteon

BACKGROUND

Through modelling the internal architecture of the cortical bone, its use as a filtration network became evident. Through collaboration between students and faculty of architecture, materials science, and bioengineering, the hydraulic network of the bone study took on a new direction. The material study that influenced the micro-texture and glaze chemistry vocabulary for ceramic surface application provided novel functionality to PolyBrick 2.0.

Previous iterations of the PolyBrick integrated studies of the human cancellous (spongy) bone into the brick design. The bricks are 3D printed using a FormLabs 2 printer and its PreForm software to digitally fabricate the algorithmically-generated bricks, which use the bioinspiration of the cancellous bone porosity to create a mechanically stronger brick for building construction.

The research relating bone and brick was extended to the human cortical (compact) bone. Previous work looked at the efficient and dynamic transportation network in the cortical bone and methods to generate its canal system digitally to simulate the hydraulic network within the bone structure (Jingjing Liu, Yao Mi, Jingwei Qian, Xiaohang Yan). The cortical bone is a collection of functional osteon units. Each osteon houses a Haversian canal in its center (runs parallel to the length of the bone) and canaliculi canals (run perpendicular to the length of the bone) that feed into its Haversian canal (Mishra and Tate 2003). Volkmann canals run at angles to connect the Haversian canals of the osteons (Figure 2).

Higher hydraulic conductivity occurs the closer canaliculi are to the Haversian canal. Canaliculi are arranged parallel to increase hydraulic conductance by decreasing resistance. The model is built using Rhino 3D Modelling software and Dendro, a volumetric modelling plug-in for Grasshopper. Simulating cortical bone conductivity in the lacuno-canalicular networks resulted in small radial webs of narrow "canalicular" canals organized in layers, which are vertically connected with wider, continuous "Haversian" canals. These Haversian canals are allowed to diverge and converge with secondary canals similar to Volkmann canals. The model also allows for the customization of the density of the canal system within the set boundaries.

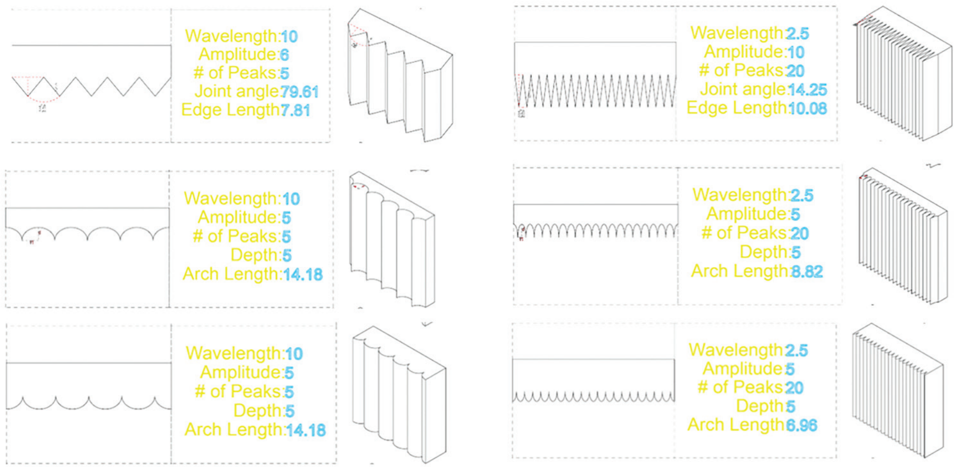
An understanding of the internal structure of the bone and its network provided bioinspiration for new design and fabrication strategies for PolyBrick. The bone is built from units of osteons that interconnect. Looking at each osteon as a brick unit inspired possibility for embedding additional properties within the part-to-whole relationships of brick units. This redefines the purpose of a brick and its relationship with adjoining brick units—as a (filtration) system of PolyBrick units each slightly varied (with its particular "texture and glaze" vocabulary) in its design to achieve desired global value (self-preserve and conserve).

METHODS

Typology Generation & COMSOL Multiphysics

Reducing surface roughness to submicron scales is promising to achieve sustainable dropwise condensation due to lower resistance to the PW-Cassie transition. This induced hydrophobicity helps deter the diffusion of water into the ceramic (Zamuruyev et al. 2014). Three typologies underwent initial passes to evaluate the role of surface geometry on the movement of water in the brick; these typologies and their iterations may be seen in Figure 3.

Wave texture typologies are generated using a custom Grasshopper script that generates a surface and then divides the width curve with progressively higher density. Profile curves are lofted into closed, solid polysurfaces for mesh conversion and future analysis.



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3 Surface Topographies—these diagrams are sample topography iterations for three different morphologies:

The top row shows the first type, the triangular grooves; the middle row, the second type, has the least surface area exposed for condensation, the points built from the negatives of hemispheres; and the last row is the inverse of the second type

A COMSOL diffusion model was built using its mass transfer of diluted species module in which simple diffusion through a brick material with natural convection on its surface is modelled. The governing equation for the transport of diluted species in porous media model is:

$$\varepsilon_p \frac{\partial c}{\partial t} + u \cdot \nabla c = \varepsilon_p D \nabla^2 c \qquad (1)$$

D is the diffusion coefficient, *epsilon* is the porosity, *c* is the concentration of water in mol/m^3, *t* is time in seconds, and *u* is Darcy's velocity. All surfaces initially have 0 concentration of water. There is a no flux condition of the back of the surface texturing since the brick is semi-infinite in relation to the size of the texturing. On all other surfaces of the geometry, there is a natural convection flux condition specified. The material properties are specified for a "brick" material in the materials library. The typologies of the brick surfaces were built in Rhino 3D software and imported into COMSOL as a DXF file. The meshing was physics-controlled, and the computation uses finite element analysis. The physics-controlled mesh is a tetrahedral mesh generated by the COMSOL software to resolve the geometry to convergence. The mesh size was set to be "fine" or "extra fine" and edges were systematically resolved with that resolution. Various slices were made in the material to mark its water concentration at steady state to compare the effects of surface geometry on the diffusion of water under the same control environment.

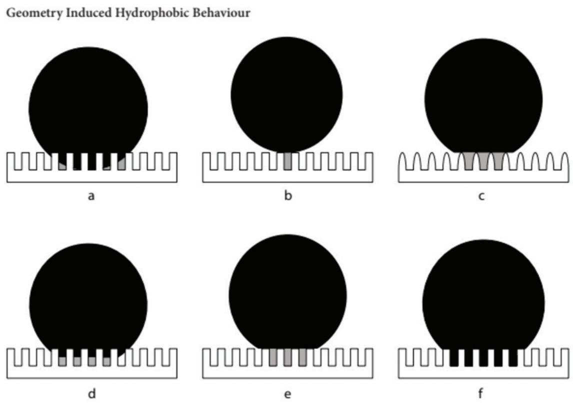
3D Printed Surfaces

Simulation confirmation of the significant consequences of surface typologies probed the investigation into the scale and density of the texturing. Zamuruyev et al. combined the study of capillary pressure gradients with wettability gradients to examine water condensation on a patterned surface. Their surface was fabricated with a specific microscopic topography and further treated with a chemically inert low-surface energy material. It produced a reliable hydrophobic self-cleaning micropatterned condensing surface that did not require the growth of nano-features or a hydrophilic-phobic patterning. The micro-features were trapezoidal and facilitated the droplet transfer from the Wenzel to Cassie state (Figure 4), reducing the droplet critical diameter. This prevented the formation of a liquid film that occurs on most surfaces; prevention promotes continuous dropwise condensation (Figure 5). In our research, we produce a reliable hydrophobic micro-textured surface for controlled water flow with the innovative use of micro-scale 3D printing of porcelain material in a Formlabs Form 2 printer.

Directionality of the condensation was controlled through a specifically designed wettability gradient of the micropatterning starting with the most hydrophobic coating to the least hydrophobic (Figure 6). Their micro-grooves ranged from 4 µm to 110 µm, and the wetting angle increased as the grooves grew in size. Analysis of the data showed that doubling the groove diameter increased the wetting angle by around 5°. Since optimal hydrophobicity occurs at 180°, the data showed that microgrooves around 300-400 µm may give maximal results (Figure 7).

Contact Angle Tests

Contact angle testing provides a measure to understand the nucleation and critical radius of the water droplet. It is an indication of the hydrophobicity or hydrophilicity of the surface treatment from interfacial forces as well as directionality, flow, and control. Wettability testing for different



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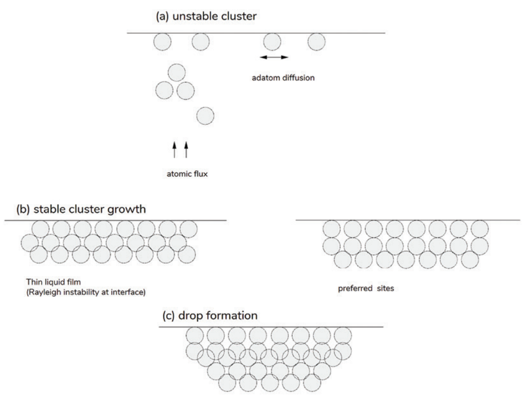

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4 Cassie State v. Wenzel State—When a flat surface is partially wet, it can take two forms: the Cassie-Baxter state has air gaps between the droplet and substrate causing a suspension, and the Wenzel state in which the entire droplet wets the surface (adapted from Attinger et al. 2014)

5 Surface Wetting—Demonstrating the atomic movement of various ways in which a flat surface can be wetted (adapted from Sikarwar et al. 2013)

topologies and surface chemistries are conducted using a contact angle analyzer under ASTM conditions of 21°C and 65% relative humidity. Protocol consists of using droplets of deionized water with samples ½ inch in width and about 1 mm in height. The wetting angle is calculated using

$$\cos\theta = \frac{x^2-y^2}{x^2+y^2}, \tag{2}$$

where *x* is the half width of the droplet and *y* is the center height. Both *x* and *y* are measured using the analyzer.

Glazing

The glazing composition is as important to the finished piece as the ceramic 3D printed clay is. The glazing has its customary use for PolyBrick as a protectant. It both toughens the ceramic and increases its water resistance. In traditional masonry brick, increased mud, dust, and moisture accumulation from weathering enhances mold growth greatly. Mold growth leads to the ultimate deterioration of the brick.

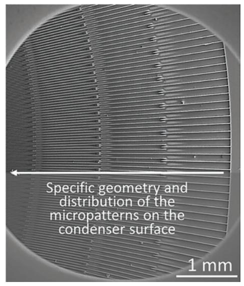
Glazing has a second function as a chemical treatment to the PolyBrick. Variations of the glaze can increase the hydrophobicity or -philicity of the PolyBrick surface to alter the amount of moisture that accumulates on it. Water accumulation occurs due to rainfall as well as nucleation from temperature fluxes in a day's cycle and the temperature equilibrium delays between the environment and the more insulating PolyBrick ceramic material.

Recent research developed water harvesting abilities from hydrophilic slippery rough surfaces. Dai et al. showed how hydrophilic surfaces are better at improving water coalescence. These surfaces produce more visible droplet densities and are better shedding water. Surfaces consist of directional micro-grooves, and the nanotextures (only) are infused with the hydrophilic coating. The combination of a larger surface area from the nanotexturing with the hydrophilic slippery interface, and the directional liquid repellency of the microgrooves, allow for nucleated droplets in the Wenzel state to be removed rapidly. Hydrophilic surfaces are more energetically favorable for water vapor and small water droplets to nucleate (Dai et al. 2018).

Inspired by existing natural structures and constructed to allow for directional liquid spreading, Xu et al. produced a chemically homogenous and morphologically heterogeneous surface for the continuous and controlled directional water transportation. They used an anisotropic approach to surface coating. A hydrophobic/superhydrophobic coating guides the directional motion of water drops and can control flow along horizontal and gravitational directions (Xu et al. 2018).

Looking at the results of Knies et al. on superhydrophilic ceramic glazes, zinc oxide (ZnO) was selected as an addition to the glaze to help obtain the hydrophilic functionality to be implemented on the surfaces of the PolyBrick to allow for water removal from the brick.

The glazes used for PolyBrick are: Opulence 346 White Glaze (hydrophilic), Opulence 346 White Glaze + ZnO (superhydrophilic), and NanoSlic® NS-110 coating (hydrophobic and oleophobic). The ZnO was from Pure Organics and is a non-nano, uncoated grade. The glaze is applied through a sponging procedure. For the white glaze and white + ZnO glaze, the bisque-fired (at cone 06) clean ceramic surface was cooled and submerged in water for 2-3 seconds and air dried for another 2 seconds. The glaze was lightly



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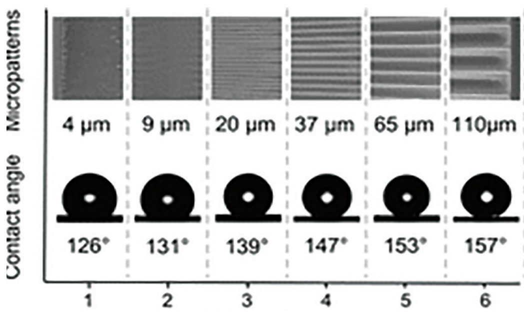

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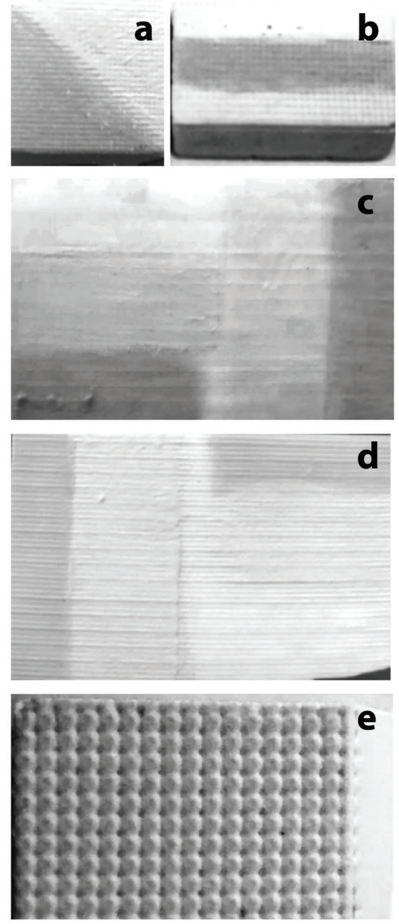
6 Micropatterning—
Different sized micro-grooves are embedded on the surface to guide the water towards the center of the surface, in the direction of the white arrow (Zamuruyev et al. 2014)

7 Effectiveness of Micropattern Looking at Contact Angle—
A series of wetting test results are presented for each varied spacing size for the groove (Zamuruyev et al. 2014)

soaked onto a sponge and applied to the surface and repeated once to ensure sufficient glaze while preserving texturing. The recipe consisted of a 7:3 ratio white glaze to 5 mL water. The ZnO glaze was 4:3:4 white glaze to ZnO powder to water. The ceramic piece was then glaze-fired at cone 4.

The NS-110 coat was applied after the ceramic was bisque fired (cone 06) and glaze fired (cone 4). 2 mL of NS-110 was added for every square centimeter of surface. It was then air-dried overnight to harden to 9H (Figure 9).

Glazing variations are applied to the outer texturing and inner transport canal depending on the needed functionality. The crystallization of CuO nanoparticles as tenorite on the glassy interface of the coating resembles the surface of hydrophobic leaf surfaces. This metallic glaze is a glassy coating based on copper pigment that has hydrophobic properties with contact angles with water of 115° and has bactericide characteristics (Reinosa et al. 2013). This glaze is a suggestion for the specifically textured inner canals in the PolyBrick to hydrophobically transport water and prevent any molding from potential leftover moisture residue.



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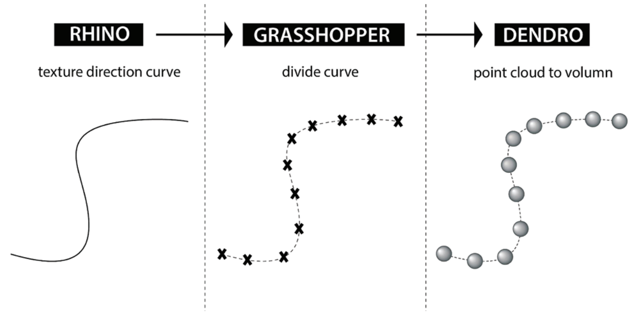
8 Glaze Patterns on Bisque-Fired Textured Surfaces—The white color is glazed with the white glaze + ZnO, taupe (pictured as gray) is with only white glaze, and the whitest (color of bisque fired ceramic) are glazes with the NanoSlic. (a) The white and white + ZnO glaze was applied to the 650 µm dotted texture diagonally across the grid of dots; (b) The 800 µm dotted texture is glazed horizontally with white glaze +ZnO, white glaze, and white glaze + ZnO alternating; (c) The100 µm dotted texture is glazed with different blocks of the three glazes; (d) The 300 µm microgrooved rows is glazed with different blocks of the three glazes; (e) The 800 µm dotted texture is coated with the NanoSlic

Fabrication Techniques:
Computational Design & 3D Micro-scale Printing

Generating and manipulating micro-textured geometries is the primary challenge of the fabrication process. Due to computing limitations within Rhinoceros 6, only a limited number of textured geometries can be generated and successfully exported. When the texture density reaches a certain threshold (hardware dependent), the software experiences runtime errors that result in exits or invalid mesh outputs. This problem is alleviated with a Grasshopper plug-in, DENDRO (by ecrlabs) that is a volumetric based modeling plug-in built on the OpenVDB library. It allows the conversion from mesh, point, and curve into volumetric data, enabling a computationally lighter modeling process. The micro-texture is generated as groups of voxel data clusters instead of individual 3D



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objects. Mesh generation through DENDRO produces micro-texturing with greater ease and precision.

When producing mesh for the dot typology, the voxel size (VS) for the model needs to be at least 33% smaller than the smallest texture bit radius (*r*). To achieve higher mesh resolution and precision, the VS is universally set to VS = *r* * 0.26. Additionally, the isovalue is set to 0.01, bandwidth to 0.01, and mesh adaptivity to 1.0 for maximum mesh size variations. However a higher mesh adaptivity, which helps generate a mesh model with a lower polygon count and smaller STL file size, extends computation time. This setting is adjusted in consideration of the dimensions of the final model.

The models were 3D printed using PreForm, a proprietary software for Formlab printers. Ceramic resin requires heavier support structure, and it is recommended to use a support density between 0.8-1.10. The support size should not be smaller than 1.2 mm. In order to avoid excessive ceramic particle adhesion, the surface models are tilted on the X or Y axis at angles ranging from 40-60°.

The printed model is washed for 3 minutes with 91% isopropyl alcohol using formwash. Because the fine texture can be eroded with excessive wash time, it is not recommended to submerge the ceramic model in the ISO tank for more than 5 minutes.

Research shows the texture dimensions to be critical for a response to water properties. Hydrophobicity and hydrophilicity on the surface is only achievable by physical means (geometrical forms) when its scale is small enough to be in conversation with water surface tension and wetting properties. Dimensions larger than the microscale would only achieve the same properties through chemical treatment. Printing resolution is critical for achieving optimal spacing between each individual micro-groove (100 µm). Having adequate spacing distance helps to maintain texture resolution during the glazing process (Figure 10).

RESULTS

Typology Generation & COMSOL Multiphysics

Through a COMSOL Multiphysics mass transfer simulation of the three surface typologies on a brick, the effect of surface texturing is evident. From our COMSOL simulations (Figure 11), the second typology was simulated and observed to allow for the lowest concentration of water diffused. The third typology was close in magnitude to the second typology, in the concentration of water it allowed to diffuse through, but the first typology allowed through an additional magnitude of water concentration. This simulation helped inform the more beneficial geometries for pushing forward in the fabrication process.

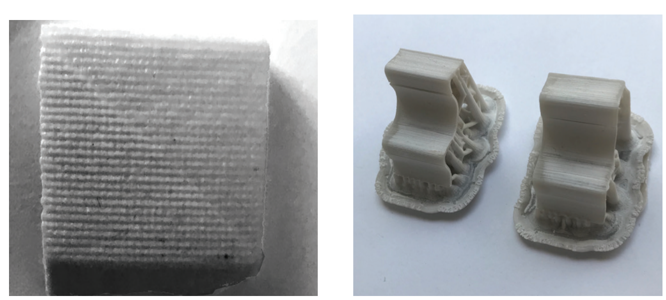
3D Printed Surfaces

Different sizes within the micron scale for two different surface textures were printed (Figure 12). One consisted of grids of dotted textures that protruded from the surface, and the other were grooves similar to the second typology explored earlier. This typology was modified slightly for the printing purposes. The angles were less severe to prevent breakage.

Contact Angle Tests

The following data was collected for six (6) different surface textures that were glazed with Opulence 346 White Glaze (see table below). All condensation presented itself in the Wenzel state.

Contact Angles for Opulence 346 White Glaze	
1 mm striped	Θ = 11.42º
800 µm dotted	Θ = 13.69º
650 µm dotted	Θ = 73.74º



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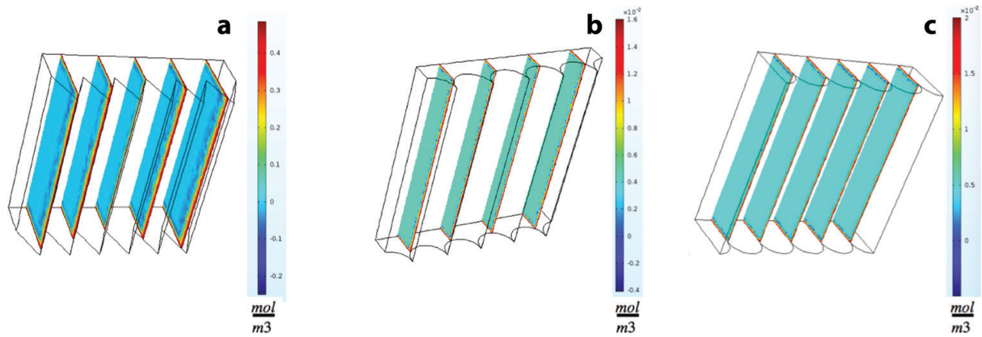
9 Software Workflow—The micro-texturing is built using a three-step workflow for volumetric generation

10 Resolution Lost During Glazing—The printer does not have definitive XY resolution; current prototypes prints are achieved through leveraging Z-axial resolution, and in order for the surface texture to be printed with distinctive resolution, it is critical to orient the model so no regions are printed parallel to the resin tank



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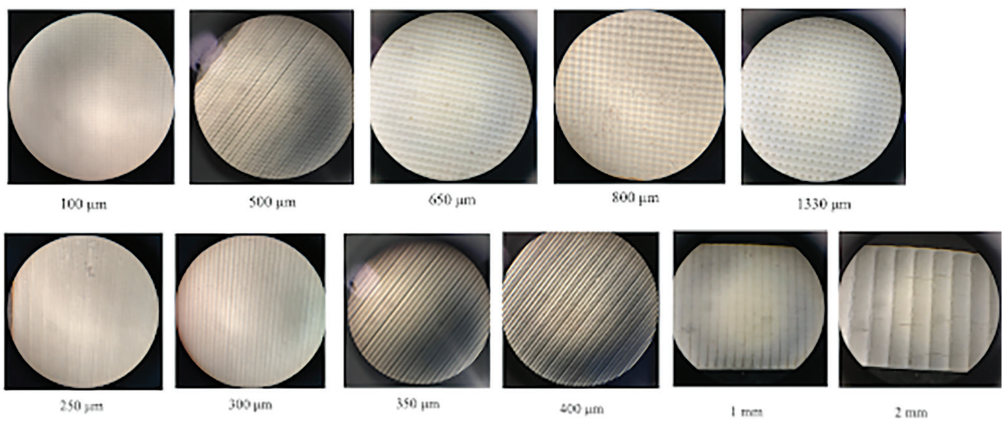
11 COMSOL models looking at the effect of surface geometry—All three different initial surface typologies were evaluated for its ability to diffuse water under the same environmental conditions: Surfaces diffuse through concentrations up to (a) 0.4 mol/m3, (b) 0.016 mol/m3, and (c) 0.02 mol/m3. Surface (b) is shown to be the best at resisting the diffusion of water



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12 COMSOL models looking at ceramic surfaces with micro-textures—The variations on geometry and sizing are shown: the top row consists of protruding dots on a grid, and the bottom row are rows of microgrooves; all figures show the ceramic pieces that were 3D printed and bisque fired on cone 06

The larger textured surfaces had a contact angle around 0° (immeasurable). When comparing the white glaze to the white glaze + ZnO, the one with ZnO consistently showed to have a contact angle 5-10° less than the same texturing with the white glaze.

Glazing

The sponging technique was an effective means to implement the chemical properties onto the textured surface. A scraping and dipping technique did not prove effective as both reduced texture resolution. Additionally, glazes that were too diluted did not protect the surface from absorbing water. Trials ran in which the water ratio was 80% of the glaze or more were unsuccessful in coating the surface with glaze. Contact angle testing for this case was 0° for white glaze and ZnO + white glaze when the glazing was too diluted, because many unglazed surfaces remained. Ceramic unglazed surfaces absorb water readily.

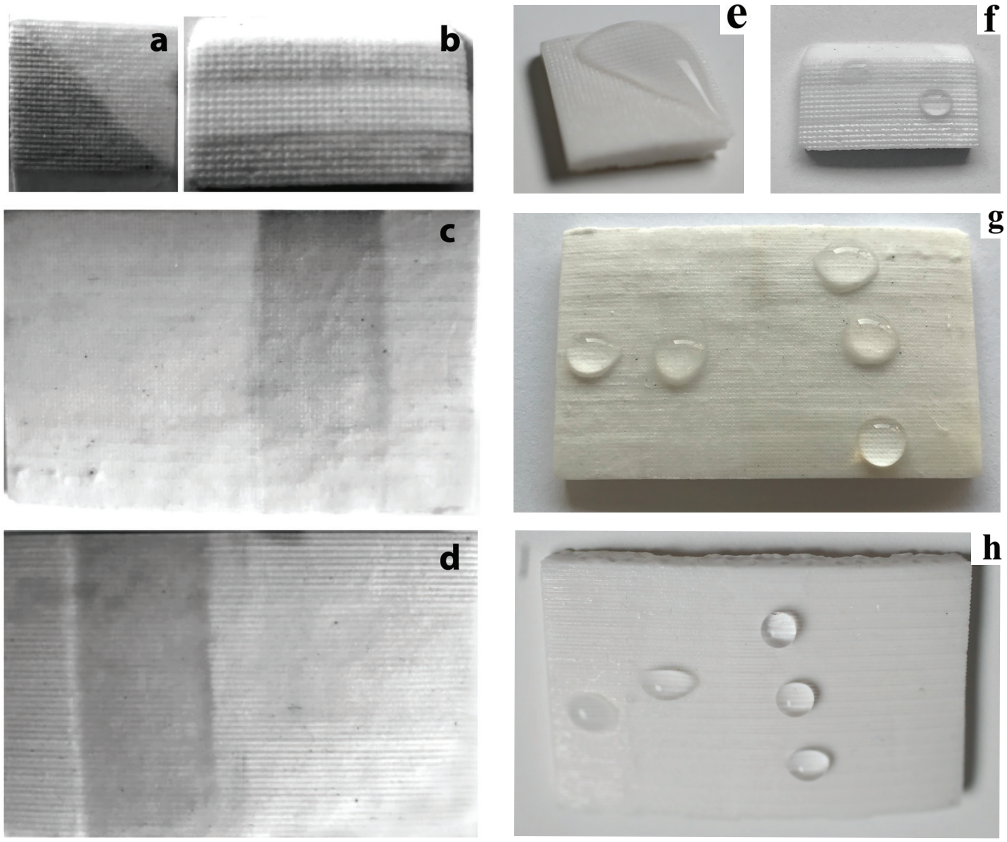
The three different glazes were applied to the different surfaces with varying patterns to test both the effects of texturing and glaze chemistry on the ceramic when water is present. The same surfaces are shown after glaze firing along with their water control tests. Testing results from adding water from a dropper onto the surfaces are shown in the pictures below to demonstrate the flow of water and how the texturing and glazing dictate flow (Figure 13).

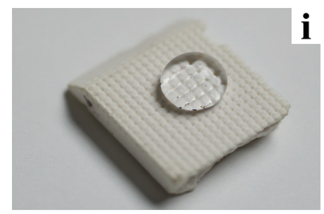
Additional surfaces were printed for further exploration of surface glazes and texturing on curved surfaces (Figure 14).

DISCUSSION

The micro-texturing and glaze chemistries showed success in controlling the flow of water. The dotting texture was only useful in controlling water around 800 µm and less. The white glaze + ZnO (superhydrophilic) glaze had the best mobility around the dotted textures. Water was deterred by the white glaze but attracted to the white glaze + ZnO. It was shown that a droplet can move diagonally, going against gravity (see Appendix).

Looking at the textures with rows of microgrooves, it was seen that the droplets moved along the direction of the striations and resisted gravity (tilted to 85°) when the force of gravity was turned perpendicular to the stripes. The droplet on the white glaze + ZnO resisted flow the most, and significantly so (until about 85° tilt) in both the parallel and perpendicular directions to the striation. The droplet on the white glaze rolled off steadily following the striation of the path and at a faster rate than on the dotted texture. The droplet on Nanoslic slipped off very rapidly and did so by forming almost a perfect sphere on the surface (contact angle of almost 180°) and detached from the surface. For both the dotted and striped textures, the smaller the





13 Water Flow Control (side-by-side comparison)—(a-d) show the glaze patterns on textured surfaces after glaze firing; (e-i) show the nature of how water wets the surface for each texture/glaze combination. Take note of the shape of the water droplet. All combinations had 1 droplet of water from the same dropper. (e) shows a 650 µm dotted texture with white glaze + ZnO on the top half of the diagonal and just white glaze on the bottom half. (f) has a drop of water on the superhydrophilic (white glaze + ZnO) area on top and another on the hydrophilic (white glaze) region below that. It is the 800 µm dotted texture. (g) had regions of white glaze, white glaze + ZnO, and NanoSlic. It is the 300 µm microgrooved row texture. (i) received only NanoSlic glaze (see Appendix).

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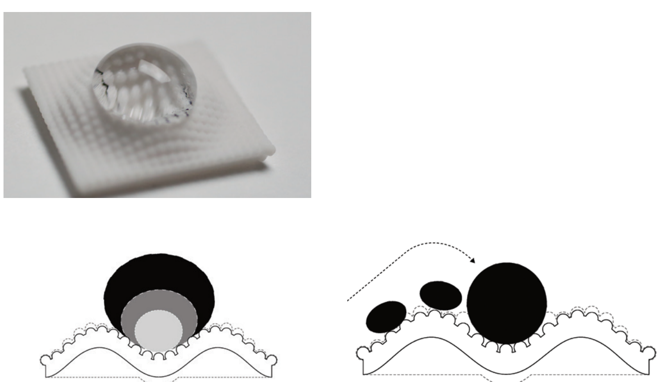
spacing was, the more surface area it had and when glazed with any of the three glazed, it was able to attach a water droplet better to itself (see Appendix).

These results are incorporated into a larger filtration network by enforcing elements of coalescence, discouraging surface attachment, hastening or delaying flow, and reshaping the natural behavior of water condensation



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14 Curved Surfaces (Examples)—(top) Investigation into 3 dimensional flow using dimpled surfaces; (right) The very center and rim of the dimple is covered with NanoSlic, the inside is covered with glaze + ZnO, and the outside is covered with glaze, a configuration that allows for water to travel up against gravity into the dimple; (left) If fully covered with NanoSlic, the water nucleates and grows until it hits critical mass

to our advantage. For large scale production, the glazing method could be spray-applied and is the suggested method because it can be sprayed on layer by layer to keep texturing resolution, but can quickly cover a large surface area.

CONCLUSION

FormLabs 3D Ceramic Printing was pushed to micro-level scales for programmable surface texturing. Surface tests demonstrated the ability to successfully control and direct the flow of water using surface micro-texturing and glaze chemistries. The toolbox built thus far plays with different shapes and geometries, but has not yet expanded to a “brick-scale,” which is large enough and has enough mechanical strength to support construction. To address the issues of water filtration, conservation, and adaptability, the results from this experiment will be initially implemented into larger brick and tile units.

A myriad of combinations can be used to texture and glaze the bricks based on the client’s specific desires. For instance, if the priority is to prevent water from entering and deteriorating the brick, the exposed outer surfaces of the brick will use the hydrophobic glaze and textures to direct flow away from the interior. A thin layer of internal canals on the near inside surface of the brick may be lined with specific glaze patterns to capture any moisture that may have entered. For use as a passive cooling system, the brick will contain a larger hydraulic network with points of hydrophobicity and -philicity to hasten and slow the water transport specific to what is desired.

Here, the vocabulary and fabrication methods are developed for new and added functionality within tiles and bricks. Further investigations are needed to determine increased control over curvatures as well as to link the conversation between this vocabulary and the specificities of the criteria for the system. Case studies into specific contexts, environments, and situations are recommended as the next steps to implement the results from this experiment into the larger design initiative.

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REFERENCES

Attinger, Daniel, Christophe Frankiewicz, Amy R. Betz, Thomas M. Schutzius, Ranjan Ganguly, Arindam Das, Chang-Jin Kim, and Constantine M. Megaridis. 2014. “Surface Engineering for Phase Change Heat Transfer: A Review.” MRS Energy & Sustainability 1(E4). doi:10.1557/mre.2014.9.

Building America Solution Center (BASC), U.S. Department of Energy. 2014. “Building Science Introduction - Moisture Flow.” Building Science Introduction - Moisture Flow. Accessed August 1, 2019. https://basc.pnnl.gov/information/building-science-introduction-moisture-flow.

Dai, Xianming, Nan Sun, Steven O. Nielsen, Birgitt Boschitsch Stogin, Jing Wang, and Tak-Sing Wong Shikuan Yang. 2018. “Hydrophilic Directional Slippery Rough Surfaces for Water Harvesting.” Science Advances 4(3): eaaq0919. doi:10.1126/sciadv.aaq0919.

Hughes, Randall E., and Barbara L. Bargh. 1982. “The Weathering of Brick; Causes, Assessment and Measurement.” Open-File Report, USGS Numbered Series 83-272. doi:10.3133/ofr83272.

Mishra, Sanjay, and Melissa L. Knothe Tate. 2003. “Effect of Lacunocanalicular Architecture on Hydraulic Conductance in Bone Tissue: Implications for Bone Health and Evolution.” The Anatomical Record 273A(2): 752-62. doi:10.1002/ar.a.10079.
Nguyen, Tuan C. 2014. “This Tower Pulls Drinking Water Out of Thin Air.” SmithsonianMag.com. Accessed August 1, 2019. https://www.smithsonianmag.com/innovation/this-tower-pulls-drinking-water-out-of-thin-air-180950399/.

Park, Kyoo-Chul, Shreerang S. Chhatre, Siddarth Srinivasan, Robert E. Cohen, and Gareth H. Mckinley. 2013. “Optimal Design of Permeable Fiber Network Structures for Fog Harvesting.” Langmuir 29(43): 13269-77. doi:10.1021/la402409f.

Reinosa, Julián J., Juan. J. Romero, Miguel A. De La Rubia, Adolfo Del Campo, and José F. Fernández. 2013. “Inorganic Hydrophobic Coatings: Surfaces Mimicking the Nature.” Ceramics International 39(3): 2489-95. doi:10.1016/j.ceramint.2012.09.007.

Sabin, Jenny E., Martin Miller, Nicholas Cassab, and Andrew Lucia. 2014. “PolyBrick: Variegated Additive Ceramic Component Manufacturing (ACCM).” 3D Printing and Additive Manufacturing 1(2): 78-84. doi:10.1089/3dp.2014.0012.

Sikarwar, Basant Singh, Sameer Khandekar, and K. Muralidhar. 2013. “Mathematical Modelling of Dropwise Condensation on Textured Surfaces.” Sadhana 38(6): 1135–71. doi:10.1007/s12046-013-0190-9.

Thompson, Valerie. 2013. “Rice Leaves and Butterfly Wings Provide Insight Insight into Nature's Best Self-Cleaning Surfaces.” Phys.org. Accessed August 1, 2019. https://phys.org/news/2013-01-rice-butterfly-wings-insight-nature.html.

Wang, Lixin, Qiang Zhou, Yongjun Zheng, and Shuyan Xu. 2009. “Composite Structure and Properties of the Pitcher Surface of the Carnivorous Plant Nepenthes and Its Influence on the Insect Attachment System.” Progress in Natural Science 19(12): 1657-64. doi:10.1016/j.pnsc.2009.09.005.

Warka Water. 2019. “Warka Tower.” Accessed July 15, 2019. http://www.warkawater.org/warka-tower/.

Xu, Chen, Rui Feng, Fei Song, Jia-Min Wu, Yu-Qiong Luo, Xiu-Li Wang, and Yu-Zhong Wang. 2018. "Continuous and Controlled Directional Water Transportation on a Hydrophobic/Superhydrophobic Patterned Surface." Chemical Engineering Journal 352: 722-29. doi:10.1016/j.cej.2018.07.073.

Zamuruyev, Konstantin O., Hamzeh K. Bardaweel, Christopher J. Carron, Nicholas J. Kenyon, Oliver Brand, Jean-Pierre Delplanque, and Cristina E. Davis. 2014. "Continuous Droplet Removal upon Dropwise Condensation of Humid Air on a Hydrophobic Micropatterned Surface." Langmuir 30(33): 10133-42. doi:10.1021/la5004462.

IMAGE CREDITS

Figure 8: © 2014 American Chemical Society, July 29, 2014
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