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Editorial

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Daniel Richards graduated from the Manchester School of Architecture in 2009 with a BA (Hons) and BArch in Architecture and an MA in Architecture and Urbanism. In 2013, he completed his PhD at the Manchester Institute for Research and Innovation in Art and Design (MIRIAD) at Manchester Metropolitan University (MMU). In 2013, he began a 2-year postdoc position at the Novel Computation Group within the Informatics Research Centre at MMU, focusing on developing algorithmic design tools for architectural design. In 2015, he took a lectureship at Lancaster University,

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Additive manufacturing is one of many digital fabrication techniques that are opening up new design possibilities for architecture and disrupting traditional modes of material production. To address this shift, architects need new strategies to exploit emerging (and future) geometric, material and/or project delivery possibilities that are associated with file-to-factory methods, on-site/off-site fabrication, prototyping, and efficient physical properties facilitated by increasing simulation and design automation, just to name a few.

Whilst a wide range of additive manufacturing research is represented in architectural design literature, the majority of this work has sought to explore the technology at relatively small scales, with the viability of scaling up being a key issue. Furthermore, after decades of limited materials and processes, emerging trends in multimaterial printing, expanded material palettes, and enhanced machining options with large-scale robotics, are transforming how and what we can construct.

We received a number of high-quality manuscripts from researchers around the world and presented within this special issue are what we believe to be state-of-the-art explorations into the application of additive manufacturing in architecture. We would like to take this opportunity to extend our genuine acknowledgement to all the authors and reviewers for their cooperation in providing the content for this issue. We wish all readers an enjoyable and informative reading experience of the leading edge, international research and development projects featured here.

1 Introduction and background

Building upon eight years of design research by Sabin on 3D printed nonstandard clay components and digitally steered ceramic bricks, components, and assemblies, this paper documents our latest work and research in the PolyBrick series. The production of ceramic blocks and tiles has a long technological and design history. Ceramic modules of standard measurement have been used as a building block and replacement of stone for many centuries. Ceramic bricks and tiles, so ubiquitous in their application in the built environment, have surprisingly lacked recognition as a viable building component in contemporary architecture practice until now. The PolyBrick series, recently on view as part of the exhibition, Imprimer Le Monde (Printing the World), at Centre Pompidou in Paris, is our latest endeavor under the topic of digital ceramics in the Sabin Design Lab at Cornell University. The project showcases next steps in the integration of complex phenomena through 3D printed ceramic components and variegated assemblies. As documented previously, this work includes advances in digital technology, 3D printing, advanced geometry, and material practices in arts, crafts, and design disciplines (Sabin et al., 2014).

Producing a ceramic part involves a progression of unique phases: greenware, bisque firing, and glaze firing. Greenware is the state before clay is kiln fired. During this state, clay can be manipulated through processes of coil building, hand forming, throwing, or slip casting to name a few. A clay body can be mixed with glaze or resins and can also exist in liquid or leather hard state before it is formally restrained into ceramic post-firing. The modules used in the Polybrick series along with previous explorations were printed either directly from a 3D printer or slip cast from a mould made from 3D Printed Positives. Recent innovations in 3D printing technology have enabled ceramic parts to be printed from resin-based stereolithography printers. The clay body used in these cases consists primarily of porcelain (due to fine clay particle size) and epoxy resin, but other clay bodies can be mixed for custom formulas. This innovative porcelain and resin clay body has been used for our most recent iteration of the Polybrick series (Figure 1).

Figure 1 *PolyBrick* 1.0 in greenware stage after being excavated from the 3D printer and cleaned (see online version for colours)

Source: Photo courtesy of Cooper Hewitt Design Museum and Sabin Design Lab, 2016

The first phase of the PolyBrick series features the use of algorithmic design techniques for the digital fabrication and production of nonstandard ceramic brick components for the mortarless assembly and installation of the first fully 3D – printed and fired ceramic brick componentry. Seeking to achieve a system, which required no additional adhesives or mortar, we looked to traditional wood joinery techniques as a means of interlocking adjacent components. We developed a customised tapered dovetail in which the direction and severity of the tapering is dependent upon the local geometric orientation of each component.

PolyBrick 2.0 is generated with the rules, principles and behaviour of human bone formation (Figure 2). This allows for the production of variegated bricks that are light and porous at the top of the wall and dense at the base to carry load and maintain efficient structural integrity while also amplifying material and formal expression.

Figure 2 PolyBrick 2.0 is generated with the rules, principles and behaviour of human bone formation

Source: Photo courtesy of Cooper Hewitt Design Museum and Sabin Design Lab, 2016

PolyBrick 3.0 takes our material investigations to the next level. Synthetically designed with advanced bioengineering, these DNA steered bricks exemplify the cutting edge and future of biologically informed clay and ceramic building blocks in architecture. The prototypes utilise 3D printed clay, hydrogel and synthetic DNA. Unique IDs stamped with DNA in the form of a ‘C’ for Cornell fluoresce within the PolyBrick clay body. As can be noted in Figure 3, Brick stamping has a long history where variegated size, shape and stamping indicate place, date of construction and type, and thus serve as invaluable historical documents. With our unique DNA stamps and glaze, we explore the possibility of live signatures and dynamic surface techniques, coupled with nonstandard bricks in the context of living matter and digital ceramics.

2 Bioengineering background

DNA, the information storage molecule for biological systems, is also now known as a material for engineering. Notably, by using DNA as building blocks, varieties of structures across scales have been designed and constructed from nanoscale to macroscale (Seeman, 2003; Rothemund, 2006; Tan et al., 2011; Yang et al., 2014; Jones et al., 2015), including various efforts to mimic and recreate structural components already seen in the fields of architecture and mechanical engineering (Yan et al., 2002; Liu et al., 2004; Ding and Seeman, 2006; Douglas et al., 2012; Liedl et al., 2010; Simmel et al., 2014; Benson et al., 2015; Marras et al., 2015; Gerling et al., 2015).

The significance of DNA-based structure is within the property of the molecule itself. Thanks to its well-defined double helix structure measuring 2 nm diameter and 0.34 nm/base pair, precise structures can be designed in DNA at nanoscale level. Sequence-specific hybridisation (i.e., only complementary sequences can form into double helix) enables formation of DNA building blocks into designated structures by self-assembly. Thermodynamic behaviour during this self-assembly process can be easily predicted in silico and utilised in design. By incorporating biological properties of DNA such as protein expression, additional functionality beyond the DNA molecule can be realised. Furthermore, by using a (bio-)chemical toolbox of DNA such as enzymatic reactions, modifications, and conjugations, further manipulation and functionalisation of the structures can be also realised.

Figure 3 Fired clay stamp for bricks; restored; 2254BC–2218BC (see online version for colours)

Source: Photo courtesy of British Museum

Among varieties of methods available to create DNA-based structures, DNA hydrogel is one of the most straightforward approaches to directly bridge molecular-scale DNA design and our macroscale world by 3-dimensional networks made from DNA. This approach enables us to utilise DNA as a bulk-scale material for practical real-world applications, including cutting-edge architectural components in the near future as we project through PolyBrick 3.0. Hydrogels fall into two categories based on types of crosslinks, such as chemical gel (using covalent bonding) and physical gel (using non-covalent bonding and/or physical entanglements). Both types of hydrogels are already achieved by DNA (Um et al., 2006; Lee et al., 2012). Physical DNA hydrogels, especially hydrogels made by enzymatic approach, are currently considered as a feasible route to create bulk-scale DNA materials due to its efficiency in cost and simplicity in design. Enzymatic polymerisation processes synthesise long single-strand DNA from templates, which form into DNA networks via physical entanglement and hybridisation.

Since the template used in this polymerisation process can be designed from scratch, we can easily embed functionalities to this DNA hydrogel from sequence level.

Using DNA hydrogel as a bulk-scale material unfolds a new direction within the field of architecture. The most obvious first step is to utilise DNA hydrogel as an added informational or functional layer, alongside the physical construction of other materials. Sequence information embedded in forms of DNA hydrogels can be used as an identification tag for architectural components; here, we emphasise that the DNA itself is playing an essential role to storage data (nucleic acid memory), which potentially allows further durability (long-term memory) and information density compared to conventional electronic memory (Church et al., 2012; Goldman et al., 2013; Zhirnov et al., 2016). In addition, biological properties of DNA hydrogels can be utilised by protein expression. Chemical properties of DNA can be exploited by using selective DNA-DNA interactions (hybridisation), chemical modifications of DNA, and also by linking wide varieties of other functional molecules to these components. Incorporating DNA hydrogel into the modules that make up our built environment can dramatically influence how we perceive, make us of, and archive our surroundings. This secondary layer of information can produce smarter buildings and bring about the potential for adaptive architectures and responsive materials. For example, Skyler Tibbits and the Self-Assembly Lab at MIT have been pioneering research in programmable matter. Their publication DNA disPLAY explored the potential to CNC-print DNA and therefore produce drawings through custom patterning programmed through their own developed software platform (Kara'in et al., 2014). Khademhosseini, Yin and colleagues explored self-assembly of hydrogel modules by utilising sequence-specific interaction of DNA (Qi et al., 2013).

Clay is one of the notable links between current materials used in architecture and DNA. Our recent research revealed that a certain type of clay forms hydrogel with DNA. We found that this clay-DNA hydrogel can prevent digestion of DNA, and even enhance the efficiency of protein expression, which suggests that the clay environment might have helped protection and created a localised concentration of biomolecules in early stages of life (Yang et al., 2013). From engineering perspectives, this high affinity between clay and DNA, a direct connection between inorganic and organic materials, can be utilised as a feasible route to add a functional layer to architectural components. By using DNA hydrogel as an interface to biological systems, a programmable function such as protein expression can be integrated into clay-based building systems at an architectural scale. This direct connection between DNA and architecture will enable realisation of interactive and programmable matter, based on biological and biochemical principles. Here we realised the first step of integration of two layers by glazing DNA hydrogel to the clay components.

3 Clay: plasticity and form negotiated in contemporary digital design and industry

The use of clay can be found throughout countless aspects of everyday life, ranging from building materials to dish-ware and automotive brakes. With reference to the building industry, we find industrial companies dealing with ceramics to produce building components that utilise a range of innovative technologies in tandem with traditional and time-tested production techniques. Modern architectural ceramic factories utilise clay extrusion and stamping for quickly reproducible parts. They also engage slip casting, ram pressing, and hand pressing to produce large scale but smaller production parts. In early stages of prototyping and mould-making, some manufacturers have integrated CAD/CAM technologies such as 4-axis CNC machining and hot wire cutting. This process was not suddenly introduced out of context but instead evolved naturally through a discovery that digital fabrication and new technologies could add richness, intelligence, and optimisation to production and output. In this same respect, we see our live DNA signatures and nonstandard components as a future source of output for the next generation of biologically steered digital ceramic fabrication, including self-assembly and adaptive glazes at the architectural scale (Figure 4).

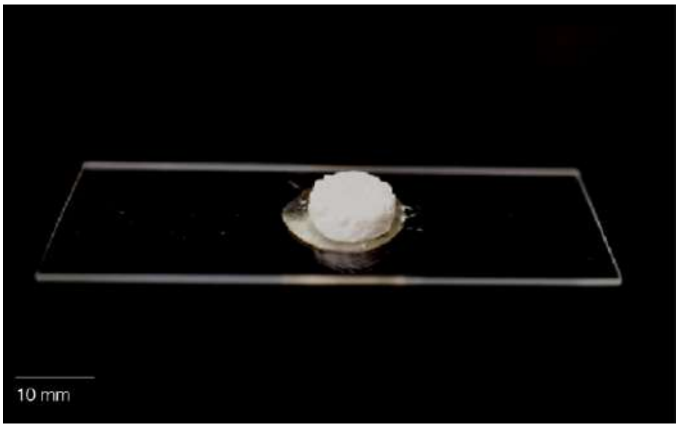
Figure 4 The ringling museum of art's facade shows us how digitally fabricated ceramic componentry can operate in conjunction with responsive custom glazes. Facade designed by Machado Silvetti Associates and Boston Valley Terra Cotta (see online version for colours)

Source: Photo courtesy of Boston Valley Terra Cotta

The process of glazing fired ceramic pieces also has a wide range of seemingly unexplored potentials in the realm of building-scale applications. Associated most prominently in the ceramic arts, glazing is a critical step in the production of ceramic bricks and tiles. It assures the weather-proofing and longevity of the ceramic massing. Acting effectively as a coating of glass fuzed and fired to the clay surface, glazing can be investigated further through industrial glass manufacturing. Since the development of Photochromic lenses in the 1960s by Roger Araujo at Corning Glass Works, these responsive glass surfaces have increased in scale and have become far more approachable in cost (Ritter, 2007). Photochromic glass responds to lighting conditions by becoming dark when exposed to considerable sunlight and becomes clear when conditions require no additional shading. Considering the potential for further development of surface treatments to ceramics, this photochromic glazing technology (only considerable at architectural scale within recent years) could inform how we use ceramics in our buildings and how glazing strategies could help negotiate passive heating/cooling strategies in their function as adaptive surfaces. Our DNA steered glazes provide unprecedented examples of tunable adaptive ceramic surface treatments for future architectural application.

Methods: 3D printed mould making: During the earliest phases of testing, our team sought to identify whether the clay and DNA hydrogel would adhere to one another. Test substrates were produced using a 3D printed mould making process, resulting in disks 10 mm in diameter. These disks act as critical solid surfaces of clay and their dimensions are determined based on the size of the sample holder (glass slide, 25 × 75 mm) for the microscope, and to comply print plate restrictions from our Ember 3D printer. By binding the clay disks to standard glass slides, microscopic observation became possible (Figure 5). These compatibility tests used a high fire clay body in unfired state. This body is considered slip, as it exists in liquid form and has a viscosity similar to a thin pancake batter. Slip is typically used for slip casting, a process where this liquid clay is poured into plaster moulds to create complex forms for artistic or industrial purposes. The choice was seemingly appropriate, as the small scale of our disks demanded delicate injection. This slip was released into each well via medical syringe. It dried at room temperature, uncovered (at first and covered thereafter), and shrank approximately 10% during the drying process. Building upon previous work engaged in digital ceramics within Jenny Sabin Studio and Sabin Design Lab, we were able to translate knowledge of drying times, slip casting, and mould making to this micro-scale production process (Jenny Sabin Studio, 2013). We found that while working at this scale is highly unconventional for ceramic arts, the physical environment and material constraints remain the same.

Figure 5 Clay disk showing results of early mould making process and setup prior to microscopic testing (see online version for colours)



Source: Photo courtesy Shogo Hamada and Luo Lab, 2017

As initial tests demanded production of disks with simple geometries, positive forms were printed using Autodesk's Ember printer. The Ember produces durable parts, resilient enough to withstand the mould making process and with a high quality surface finish in comparison to other 3D printers. The Ember printer has an accuracy of 25 microns on the x/y plane and a 10 micron layer thickness along the z axis. This is currently one of the highest resolution printers available on the consumer market. Ember uses a photopolymer resin with digital light printing (DLP) stereolithography technology. With integration of a connected ecosystem via Autodesk's Print Studio Software, our team is able to design our moulds in Rhinoceros 3D Modelling software, export the file as a stereolithography (STL), and print easily using Print Studio. Control of scale is preserved during the printing process, only hindered by the clay body's tendency to shrink as moisture evaporates from the clay base.

Once the print was completed on our Ember, these disks were cleaned using isopropyl alcohol and adhered to an acrylic glass panel (Figure 6). With a 1.5 inch acrylic box built around it, this formwork was ready for mould-production. Smooth-on's Dragon Skin silicone rubber was poured into this formwork and released from its surrounding case after a one hour drying time. When producing silicone moulds, it is important to pour on a perfectly flat surface and to cover the positives considerably past their highest point, to ensure the mould is stable and reliable. Air bubbles and imperfections in the silicone can be removed by vigorously vibrating the silicone before it dries entirely. Without ample material, the silicone will warp and produce parts that do not reflect their original cast positives. Silicone rubber of this type is often used for casting small components due to its memory (ability to retain minuscule details) and flexibility. The silicone rubber will keep its shape until stretched and can release cast components without damaging them. Because of unfired clay's brittle and delicate nature, this material was essential to our process. Shrinkage of the clay body too aided the process of mould releasing.

Figure 6 Ember 3D printer print plate shown with six disks to act as positives for the mould making process. Resolution and finish quality may be noted here (see online version for colours)

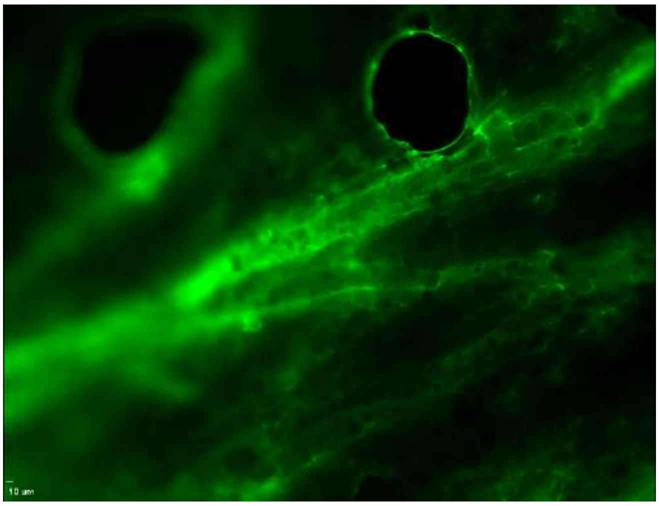
Source: Photo courtesy Sabin Design Lab, 2017

Noting our success in adhesion (see Figure 7), our next iteration involved the production of 3D printed disks with imbedded geometry to create legible letters and words. These letters became troths or motes for DNA hydrogel deposition (Figure 8). The constraints we dealt with in this instance pertain to our font size. Edge details and wall height are relevant parameters. We explored a series of depths, thicknesses, and scales of lettering in order to test how the DNA hydrogel would respond to and sit within these lettered wells or motes.

Our first attempt was to inscribe 'Sabin Design Lab' within a 4 mm diameter circle, meaning each letter had a spacing of approximately 750 microns. This test was not successful, as our mould making process did not produce accurate enough troths due to rigidity of the clay body and detail reading at such scale with silicone rubber. Testing continued and letter size was increased to 1.5 mm, then eventually 3 mm.

Our 3 mm test with depth of 1 mm produced the fluorescing C that is shown in Figure 9. Single letters at a larger scale (but still within our 10 mm disk) were far more reliable during early stages of testing for DNA hydrogel deposition and in retaining detail after the casting process.

Figure 7 Fluorescing clay body visible through microscopic photography, showing adhesion between DNA hydrogels and clay disk (see online version for colours)

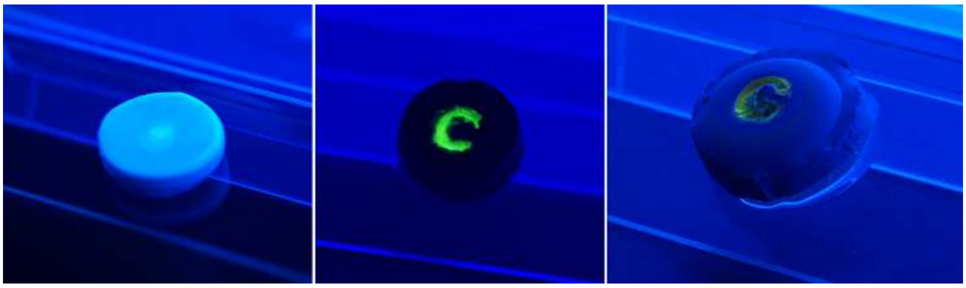


Source: Photo courtesy Shogo Hamada and Luo Lab, 2017

Figure 8 Positive formwork created from 3D printed disks and acrylic glass box (right) with silicone rubber mould and slip cast disks shown in liquid state (left) (see online version for colours)

Source: Photo courtesy Sabin Design Lab, 2017

Figure 9 Comparison showing unfired (left) and fired (centre) disks, directly printed from Ember 3D printer. Original bisque-fired stoneware test (right) acts as comparison. Unfired disks contained resin, which prevented adhesion and proper penetration into clay body. Centre and rightmost examples used 50 uL of RCA-based DNA hydrogel stained by final 5x of SYBR Green I (see online version for colours)



Source: Photo courtesy Shogo Hamada and Luo Lab, 2017

3.1 Methods: direct 3D printing of ceramic material

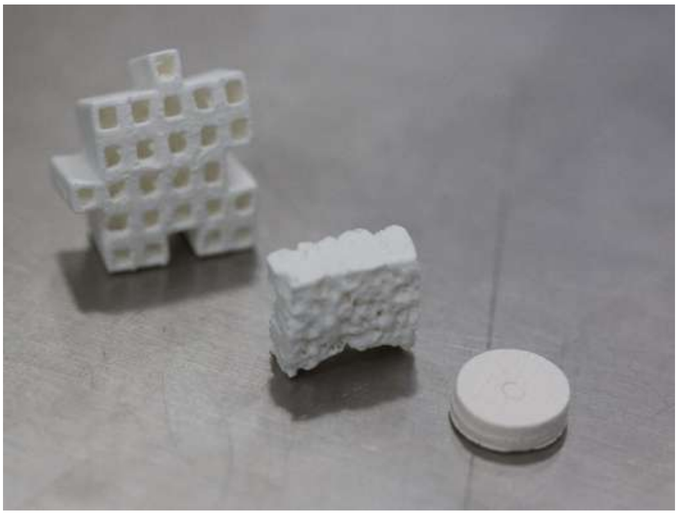
The final phase of testing sought to do away with mould making in this experimentation process and instead, directly 3D print the PolyBrick using Autodesk's ember printer and a printable porcelain based resin. In PolyBrick 1.0, we explored the possibility of 3D printing high fire clay stoneware using a simple custom clay base and binder rather than the proprietary gypsum based powder (Sabin et al., 2014). This was done using a powder based Z Corp printer, which depends upon ink printing technology to produce large, but not nearly as precise parts. Here, we sought to experiment with non-standard printing resins, which would ideally address the need to print high resolution ceramic components via stereolithography 3D printing technology.

Our team explored the possibility of using Porcelite, a product produced by Tethon 3D. Porcelite is a ceramic resin, which is both UV-curable and ultimately can be fired. The solution is composed of part resin and part porcelain, which contains finer grained particles than our high fire stoneware from PolyBrick 1.0. After firing, the 3D printed forms are pure ceramic pieces, since chemical agents are fired at a temperature of 1810 degrees (or higher). As mentioned, this porcelain clay body is different than high fire stoneware slip and therefore concerns arose as to whether the DNA hydrogels would also be compatible with porcelain. Our team printed two batches of six PolyBrick disks using Porcelite resin. One batch of disks remained unfired, while the other was kiln-fired to Cone 06 and therefore became bisque-ware. These disks were printed with a diameter of 12.5 mm, but fired examples shrank after the bisque firing process. Porcelain typically has a shrinkage rate up to 15% during the firing process, depending upon what temperature they are fired to.

The disks were successful in printing, however, soft and uncured porcelain resin remained in each well, requiring careful excavation to loosen the material. The disks were printed with wells parallel to the print bed, however, we suspect that printing wells perpendicular to the surface would reduce the pooling of uncured Porcelite resin. Alongside these tests, examples of PolyBrick 1.0 and 2.0 were also printed at a scale similar to the PolyBrick 3.0 disks (Figure 10). Indentations from PolyBrick 1.0 were legible when printed perpendicular to the print bed, helping to justify our predictions. The distinct benefits of directly printing Porcelite include high accuracy and predicable firing.

After firing and taking measurements, we can understand shrinkage rates and therefore account for these in our modelling software, which is useful for simulating and predicting tolerances for larger assemblies of brick units.

Figure 10 PolyBrick 1.0, 2.0, and 3.0 (left to right) shown in bisque-fired state and printed using Porcelite on Ember 3D Printer (see online version for colours)



Source: Photo courtesy Sabin Design Lab, 2017

3.2 *Methods: processing and imbedding DNA hydrogels*

Physical DNA hydrogels were created by using an enzymatic approach called rolling circle amplification (RCA), similar to our previous and upcoming reports (Lee et al., 2012). Circularised DNA templates with final 100 nM of concentration with equimolar of short primer DNA hybridised to the template, were prepared for RCA reaction. DNA strands were polymerised starting from primers using RepliPHI Phi29 DNA polymerase (Epicentre; Madison, WI) and formed into DNA hydrogel after 48 hours of incubation at 30°C; DNA hydrogels were then glazed to clay disks. SYBR Green I (Thermo Fisher Scientific; Waltham, MA) was used to stain DNA hydrogels (final 1x concentration for fluorescence microscopy; 5x concentration for bulk-scale clay-DNA demonstrations).

4 Results

After initially releasing our cast disks from their moulds, it became clear that slip casting would not be ideal for consistent production of components at the desired scale, as the meniscus becomes clearly evident on the upward facing side of these cast disks. While the downward facing side's smooth and uniform surface was critical for microscopic tests and in replicating inscription details, this meniscus is not ideal formally because it produces inherent inconsistencies in disk shape after drying. In addition to this, shrinkage rates were substantial, justifying the eventual use of directly 3D printed parts, which would alleviate much of this issue in the greenware state. For optimal drying, these clay test disks were covered partially with plastic sheets to minimise the risk of cracking and to control drying time. After drying and careful transport to our bio-engineering facility for testing, we found that the clay and DNA hydrogels did in fact bind and we were therefore able to proceed with further experimentation.

With successful tests showing adhesion between a stoneware clay body and DNA hydrogels, development continued by exploring the 3D printed Porcelite ceramic material. Upon printing and testing the Porcelite based disks, both fired and unfired disks were tested for material compatibility with the hydrogel. As was noted earlier, unfired disks contain both resin and porcelain, whereas the fired disks contain only porcelain clay particles. The unfired disk did not enable our DNA hydrogel glaze to penetrate into the C shaped cavity (as can be seen in Figure 9, left) or fuze to the surface of our clay body. The bisque fired variation of this disk (Figure 9, centre) is lighter in weight, more porous, and considerably more fragile. In comparison to slip cast (not 3D printed) stoneware examples, the DNA hydrogel glaze performed similarly. Both stoneware and porcelain tests showed glaze penetrating into the disk. The gel network remained on the surface and tension lead to C-shaped conformation (thus gel remained in accordance to its assigned shape). This is therefore evidence of the first directly 3D printed fired ceramic brick featuring a synthetic DNA glaze.

5 Discussion

PolyBrick 3.0 aimed to use DNA suspended in liquid form to build upon ongoing trans-disciplinary interest in architecture, emerging technologies, materials science, and biology. Through interpreting DNA as a glaze within the context of ceramics, PolyBrick 3.0 sought to use this glaze as a living signature, continuing a long-time tradition of embedding historical documentation within a ceramic brick. Our investigation existed at a unique micro-scale, a scale in ceramics that is rarely explored collaboratively by architects and scientists. Thanks to new 3D printing technology, developing an iterative and experimental dialogue between designer and scientist was made possible. We were able to use three dimensional design tools and craft-based mould making processes to facilitate the embedding of DNA hydrogels. Our earlier prototypes of PolyBrick 1.0 and 2.0 act as proofs of concept with reference to scalar potential and formal guidelines driven by generative design. These prototypes left unanswered whether they too could become host to code-able signatures, something that could eventually drive a fabrication and self-assembly process, including live and/or responsive glazes.

Throughout the duration of testing, our team depended primarily upon 3D printed moulds to translate form into a clay module. In order to eliminate lost information between 3D printed positive and clay disk, we shifted processes to direct 3D printing of PolyBrick 3.0 disks and noted that this was indeed possible. While tests at this scale enabled collaboration between architect and scientist, we were limited in our exploration of DNA hydrogel coding and embedding specified intelligence into these live DNA signatures.

6 Future direction

Building upon our first two iterations in the PolyBrick series, our first successful result in the integration of clay-based structures and DNA hydrogel suggest a future path towards realisation of programmable matter based on clay-DNA hybrid architectures. In summary, an overall micro-scale scaffold is provided by clay-based frameworks, and DNA hydrogel will provide functionality inside or on surface of the scaffold. This relationship may be regarded as similar to the hardware/software analogy; clay-based framework provides a hardware that can define the overall mechanistic behaviour and rigidity of the architecture itself; DNA layer provides a 'programmable' software layer that defines the behaviour inside (or surface of) the architecture. For instance, by incorporating protein expression, DNA hydrogel can define the output behaviour of components such as presenting different colours of the component by expressing varieties of fluorescent proteins, and also expressing enzymes for other colorimetric visualisation including chemiluminescence. Our DNA hydrogel-based protein production system has already achieved high-volumetric yield of protein production, which suggests the feasibility of this approach at macroscale (Park et al., 2009). Furthermore, we may integrate information processing and sensory abilities to the hydrogel layer by using DNA-based logic gates, sensors, and cell-free synthetic biology to enable programmable, adaptable, and bioresponsive behaviour beyond stimuli response to the component (Wang et al., 2017). These primitive but intriguing visions would hopefully ignite interests in further research ultimately towards the realisation of more active, responsive, adaptive, and intelligent architectures and component assemblies in the context of programmable matter and digital ceramics.

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