

Material Design and Analysis for 3D-Printed Fiber-Reinforced Cement Polymer Building Components

Ronald Rael

Department of Architecture
University of California Berkeley
Berkeley, CA 94720-1800
+1 510 207 2960
rrael@berkeley.edu

Virginia San Fratello

Department of Design
San Jose State University
San Jose, CA 95192-0089
+1 510 207 8620
virginia.sanfratello@sjsu.edu

ABSTRACT

The creation of building components that can be seen as sustainable, inexpensive, stronger, recyclable, customizable and perhaps even repairable to the environment is an urgent, and critical focus of architectural research. In the U.S. alone, the construction industry produced 143.5 million tons of building-related construction and demolition debris in 2008, and buildings, in their consumption of energy produce more greenhouse gasses than automobiles or industry.

Because the inherent nature of 3D printing opens new possibilities for shaping materials, the process will reshape the way we think about architectural building components. *Digital materiality*, a term coined by Italian and Swiss architects Fabio Gramazio and Matthias Kohler, describes materiality increasingly enriched with digital characteristics where data, material, programming and construction are interwoven (Gramazio and Kohler, 2008). The research aspires towards this classification through the use of parametric modeling tools, analytic software and quantitative and qualitative analysis.

Rapid prototyping, which is the automatic construction of physical objects using additive manufacturing technology, typically employs materials intended for the immediate analysis of form, scale, and tactility. Rarely do the materials used in this process have any long-term value, nor does the process - except in rare cases with expensive metal prototyping - have the ability to create actual and sustainable working products. This research intends to alter this state of affairs by developing methods for 3D printing using concrete for the production of long-lasting performance-based components.

Keywords

Cement, Polymers, 3D Printing, Rapid Prototyping, Fabrication, Materials, Digital Design

LEAVE BLANK THE LAST 2.5 cm (1") OF THE LEFT
COLUMN ON THE FIRST PAGE FOR THE
COPYRIGHT NOTICE.

MATERIAL INFORMATION

The word concrete comes from the Latin word "concretus" (meaning compact or condensed), the perfect passive participle of "concreto", from "com-" (together) and "cresco" (to grow). The development of concrete has evolved for over two thousand years. The Romans used quicklime, pozzolana and aggregate or rubble to build concrete structures such as the Pantheon and the Baths at Caracalla. In 1756 John Smeaton rediscovered concrete by mixing hydraulic lime and powdered brick as aggregate. These mixtures produced concrete with a comprehensive strength comparable to the mixes that we use today. The mixes that we most frequently use today include:

Portland cement: which consists of a mixture of oxides of calcium, silicon and aluminum. Portland cement and similar materials are made by heating limestone (a source of calcium) with clay, and grinding this product (called *clinker*) with a source of sulfate (most commonly gypsum).

Water: Combining water with a cementitious material forms a cement paste by the process of hydration.

Aggregates: Fine and coarse aggregates make up the bulk of a concrete mixture. Sand, natural gravel and crushed stone are mainly used for this purpose. Recycled aggregates (from construction, demolition and excavation waste) are increasingly used as partial replacements of natural aggregates, while a number of manufactured aggregates, including air-cooled blast furnace slag and bottom ash are also permitted.

When initially mixed together, Portland cement and water rapidly form a gel, formed of tangled chains of interlocking crystals. These continue to react over time, with the initially fluid gel often aiding in placement by improving workability. As the concrete sets, the chains of crystals join up, and form a rigid structure, gluing the aggregate particles in place. During curing, more of the cement reacts with the residual water (hydration).

Concrete is inherently weak in tension as the cement holding the aggregate can crack. The addition of steel reinforcement to concrete in the 19th century solved this

problem. In addition to adding steel reinforcing bars, we now add steel fibers, glass fiber, or plastic fiber to carry tensile loads. Thereafter the concrete is reinforced to withstand the tensile loads upon it.

The mix for use in the 3D printer is similar yet varies in composition from the traditional mixes used. The traditional processes used vary dramatically, from hand tools to heavy industry, but result in the concrete being placed in a formwork where it cures into a final form. In the case of 3D printing concrete there is no formwork or mould. There is, however, the constraint that all binding particles used in the concrete mix must fit through a 35 Pico liter print head and all cement, aggregate and reinforcement must be smaller than 0.010".

The Portland cement serves the same purpose as it does in a traditional mix, however, other bases, hydrators and adhesives are added to promote hydration and help the object maintain its shape. Additionally, finely chopped binders are used to help reinforce the material and a liquid element is sprayed through the ink jet head to help bind the material.

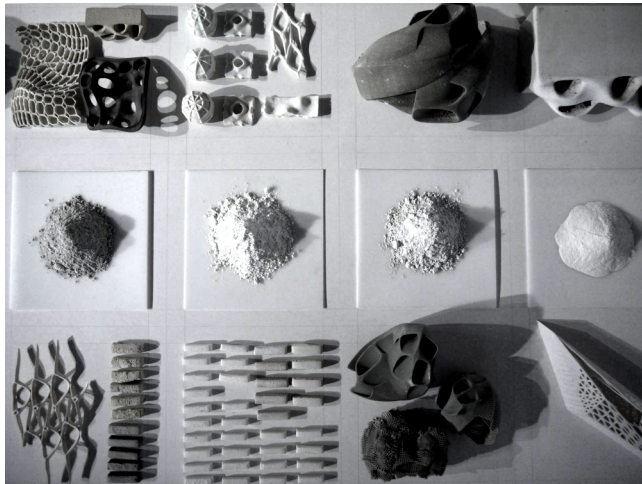


Figure 1. Cement, aggregates, concrete samples, 3D printed models

3D PRINTING

The 3D printer lays down a thin layer of the dry, powdered concrete mix, then using an ink jet sprays the image of one 'slice' of the 3D object or in this case the RCMU (rapid concrete masonry unit), onto the dry mix. The wet parts of each layer hydrate into rock-hard concrete, and the rest remains in a powder form that can be brushed off later. Because concrete cures via a chemical reaction – hydration—no air is required for curing, so the next layer can be deposited immediately.

The cycle of laying down concrete and binder with the binder is repeated over and over, stacking layer upon layer, building up a solid object inside the pile of dry, powdered

concrete mix. The dry concrete mix acts as a support structure during the printing process, so objects may have an undercut which is unseen in traditional concrete casting.

Once the concrete cures enough to handle, which typically takes about 12 hours, the finished object can be lifted out of the powder bed. The dry mix used to support the concrete object during printing can be recycled. Printing an intricate and unique concrete part would only consume a few dollars worth of material, would incur no cost for formwork and very little labor costs. Additionally compared to printing with z corps proprietary blend, the costs are considerably lower. The Z Corp™ polymer / plaster powder, at its cheapest, is \$3 a cubic inch and the 3D printed concrete costs mere fractions of a cent per cubic inch.

CEMENT BASED MEDIA

The initial impetus to work with concrete as a 3D printed material was driven by an installation designed by Ronald Rael and Virginia San Fratello entitled *Earthscrapers*. *Earthscrapers* imagines the potential of employing Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) processes in the construction of a proto-architectural landscape—one where the building material source and the building itself are seamless. The project also imagines a future scenario for the material and the process as a scalable technology—one that also dissolves the role of the architect and builder. We both envisioned printing full-scale buildings and achieving full scale building components with in situ aggregates in a manner that merges the roles of the designer and the geomorphologist.



Figure 2. *Earthscrapers* exhibit demonstrating multi-part assembly systems for 3D Printing

For the *Earthscrapers* exhibit we were uniquely interested in connecting the 3D printed material to the landscape therefore we started by printing various materials including clays, sands and ashes. Ultimately we decided to print a small amount of Portland cement mixed with a large

portion of sand. The resulting concrete prints proved to be very stable, strong and have the effect of looking like earth due to the amount of natural aggregate within the mix.

The plastic nature of both concrete and 3D printing offer up a powerful material solution to recent generative design processes in architecture, which often feature organic, doubly curved surfaces and complex ornamentation. The *Earthscrapers* exhibit explored a range of complexly curved forms. It also explored thinness and attempted to push the limits in terms of extracting thin surfaces and thin structural elements from the printer bed. Several of the complexly curved, fiber reinforced concrete prints were easily 1/16 of an inch thick which would be very difficult, if not impossible, to cast using traditional methods of mould making. Making the 3D printed models and objects that were on display in the *Earthscrapper* exhibit was an active process where software, geometry, material, fabrication and production were simultaneously linked. The complexity of form was limited by thinness and slump. If the form were not allowed to cure in the bed for at least 12 hours the concrete object would fail. Additionally, the success of the mix depended on the amount of binder being laid down at each successive interval. For example, if the binder was sprayed at full capacity the concrete print would slump therefore the binder level should be set at .75.

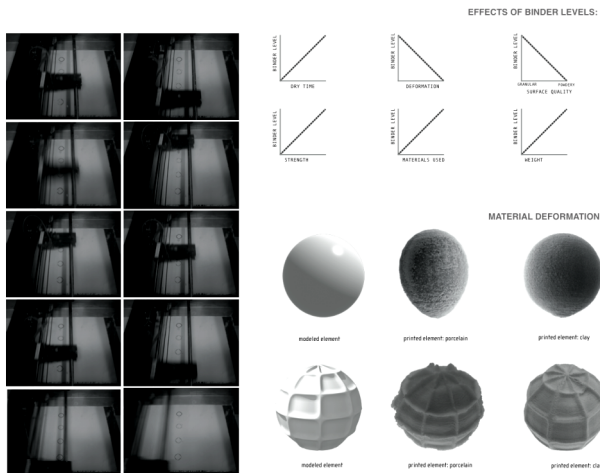


Figure 4. Binder level tests

The designs for the models and objects that we printed for the *Earthscrapers* exhibit were based on the exploration of complex geometries. We used software applications such as Top Mod that allowed us to dynamically change the topology of 2-manifold polygonal meshes to explore structural skins. Also used were Blender and Modo to explore texturing, twisting and deformed surfaces and Rhinoceros to explore part to whole relationships, paneling and how these 3D printed pieces might interlock and connect.

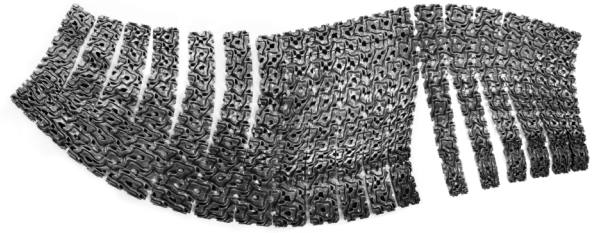


Figure 5. Photo of models that study unfolded relationships

The 3D printed models were placed in a landscape made of the same aggregate in order to simulate environments where desertification, erosion, mining and dredging have shaped the landscape. These places have become the theoretical material sources, sites and contexts for the forms and spaces created in the proposal.

BUILDING COMPONENTS

The production of part to whole assemblies for the *Earthscrapers* exhibit led us to initiate new 3D printing research, involving the development of non-standard geometric architectural concrete masonry units that are weather proof, solar responsive, store or filter water, hold plant life, contain embedded technologies, create insulation barriers between interior and exterior surfaces, dissipate seismic forces and many other possibilities offered by this nascent and potent process. For the first set of prototypes, we chose to develop building units that are weather proof and porous to the extent that they have apertures in them that can direct and filter light and are able to support vegetation. The units are applied to a doubly curved polysurface that acts as a building enclosure. Each unit is then panelized to the surface creating an assembly of variegated and unique parts. The units are designed to be fastened to each other and the final structure will be completely self-supporting and will not require secondary scaffolding. The final product is the scale of a room and is composed of 1200 3D printed concrete units.

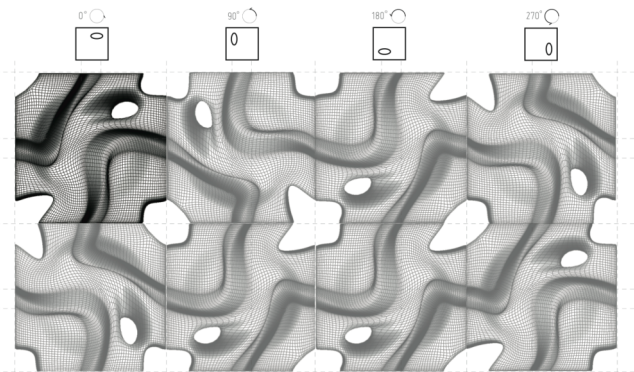


Figure 6. *Karakusa* multiple-part assembly of tiles

IMPACTS

One of the benefits of this research is that through rapid manufacturing, differentiated geometries can be created that would be impossible to create by hand or require expensive machinery to produce or reproduce. Because the process requires no formwork, concrete components can now be *mass-customized and contextualized*, employing the flexibility of CAM systems, rather than mass-produced, allowing design parameters to be quickly changed and tested without incurring costs associated with labor and retooling. Thus, the process bypasses several of the steps involved in traditional pre-cast concrete production, which include form making, extraction, etc., making it possible to go directly from file to fabrication.

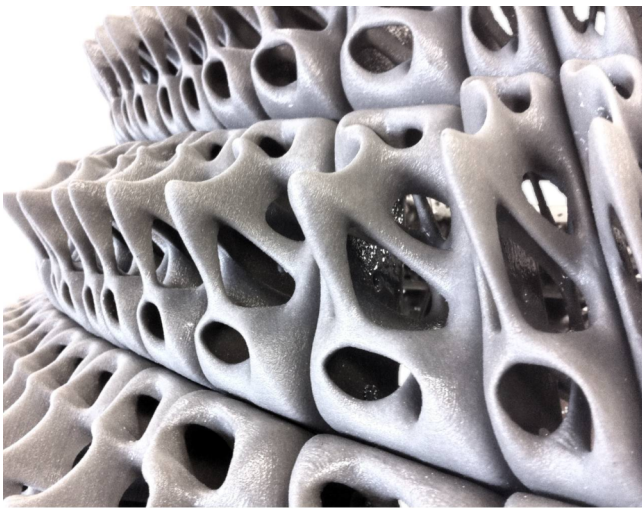


Figure 7. 3D printed concrete polymer multiple-part assembly

Another benefit is the greatly reduced material cost. If the cost of molding and formwork is 35 to 60 percent of the cost of a concrete structure, then 3D printing in concrete offers tremendous cost saving to the construction industry. A third benefit of 3D printing concrete is that the excess cement and aggregate can be recycled. Thus the 3D printing of durable components raises questions regarding expense, durability, speed and size.

EXPENSE

Currently, all commercial forms of rapid prototyping are incredibly expensive. This expense comes in three forms—equipment, material, binder and time. While much innovation is being developed to make rapid prototyping equipment more accessible, the costs of consumer and professional grade rapid prototyping equipment is generally in the 10s of thousands of dollars. Material expense is also considerable. All commercially available equipment offers its own proprietary materials. These materials are generally exorbitantly expensive. Additionally, there is generally a

very limited material palette for use with each piece of equipment, making the use of multiple materials even more economically unrealistic since if one was to consider a material assembly of different materials it would require multiple machines from different manufacturers. In many cases, materials are also meant for prototyping only and long-term viability of a prototype is unlikely. In many cases, additional materials are required for the production of a rapid prototyped object. Binders, which aid in adhering materials together or post-processing materials to harden or finish a material are also often proprietary and an added expense. Additionally, extraction of materials also requires solutions that wash away supporting structures or several man-hours are required to excavate, extract or remove parts. If we consider that time = money, the slowness of rapid prototyping, which can take several hours or days to produce a single object, means that only a limited number of objects can be produced given the availability of resources (numbers of machines, availability of materials and availability of time).

DURABILITY

Most rapid prototyping materials in use today are considered only for short term examination, analysis and utilization. In many cases, the materials have no structural durability. They are made of friable powders that are laminated with glues or binders. Many of the more durable plastics are not resistant to ultra-violet light or can not withstand high temperatures. Metals and glass must be sintered at low temperatures and can be porous and fragile. Methods to strengthen these materials are also expensive. These limitations makes the transition from prototyping to manufacturing improbable given many of the current technologies, materials and processes.

SPEED

While the term rapid prototyping is suggestive of the speed in which designers can move from CAD to the visualization of a physical object, the production of a single rapid prototyped object, when weighed against the possibility of manufacturing, can be quite slow. In most cases, a single object can take several hours, if not multiple days, to produce. The extraction of materials can also be time intensive. Fragile parts removed from supporting structures or that are buried within the materials used in powder form can be time-consuming and laborious. As stated previously, the process often does not end when it is removed from the machine that produced it. Post-processing, which involves the stabilization, reinforcing or strengthening of the rapid prototyped object also can be time consuming due to the labor involved and the amount of time required for parts to set.

SIZE

While rapid prototyping technologies allow for the production of larger objects, the limitations of expense, speed and durability are still an issue. By increasing the size of production, expense and time are obviously increased putting the potential for manufacturing actual, usable objects at a greater distance. Increased sizes of equipment and increased amount of materials mean increased expenses as well. The production of larger objects means slower production times and the added cost of machine and man-hours in the production process. Size issues demand an obvious increase in material performance, since larger size parts must be to a certain degree, self-supporting. Larger spaces required by this process also represent pressures on resources.

PERFORMANCE ASSESSMENTS

The use of an organic adhesive in the concrete mix prevents the cement from joining with the water and slows the hydration of the cement; in most cases this is considered a drawback. The solution may well be to introduce an alcohol-based binder to the mix, which has had good results in initial tests as this additive is a water-soluble synthetic polymer that has high adhesive and emulsifying properties and high tensile strength. Ideally it will not only help the mix cure more rapidly but also cause it to be denser and have greater flexural strength.

A further development in seeking to strengthen the materials involves an infiltration process that appears to strengthen the units in two ways. The infiltration hardens the material by adding a secondary hardening component that joins the fibers to the concrete matrix while also simultaneously hydrating the material. The result is a hybrid concrete polymer. This infiltration has resulted in a remarkably strong product from a common rapid prototyping process. The highest performance thus far has been realized using a combination of fiber reinforced and infiltrated material with fiber mesh reinforcements running in the “Y” axis of the 3D printers’ build bed (see chart below). The fiber strands are oriented by the direction of the roller of the 3D printer. The unit failed at 4537 PSI at 14 days, which exceeds the minimum requirements of traditional concrete at 28 days.

The capability to 3D print at the scale of the building is gaining momentum and is certain to occur. Dr. Behrokh Khoshnevis, of the University of Southern California has developed a different printing technique called Contour Crafting (Khoshnevis, 2008). Contour crafting is a layered fabrication technology that has potential for automating the construction of whole structures as well as sub-components. Using this process, a single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run, embedded in each

house are all the conduits for electrical, plumbing and air-conditioning. They have recently collaborated with Caterpillar to fabricate a 6-foot wall.

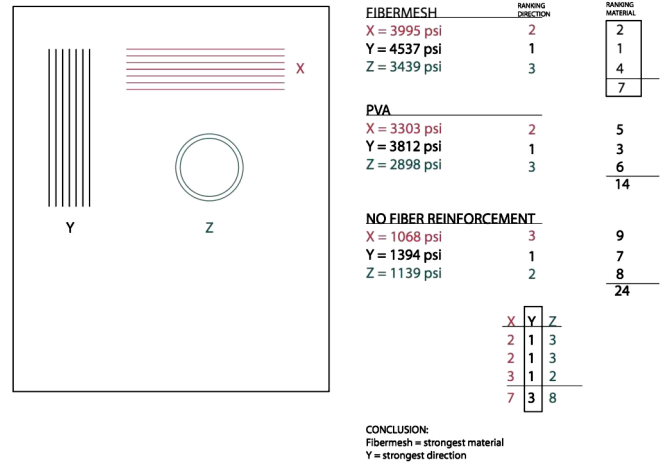


Figure 8. Chart showing strength testing results

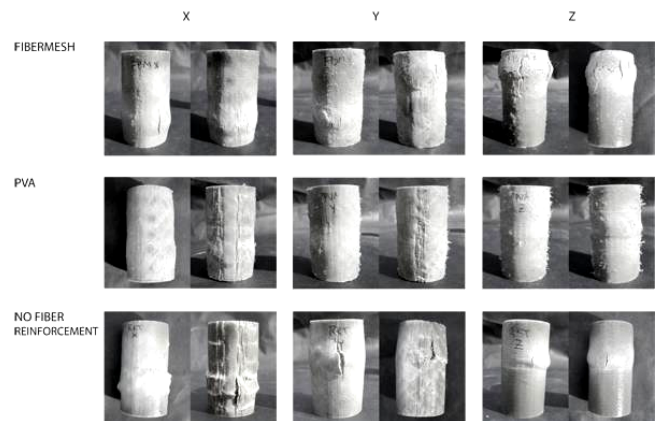


Figure 9. Photographs of structural tests

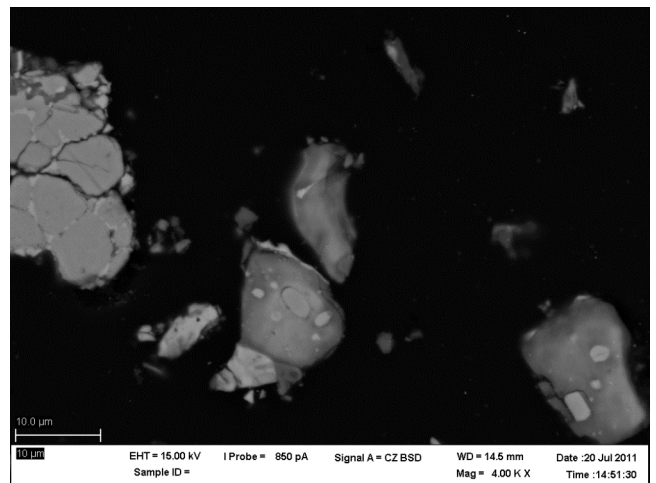


Figure 10. Electron microscope scan of cement particles

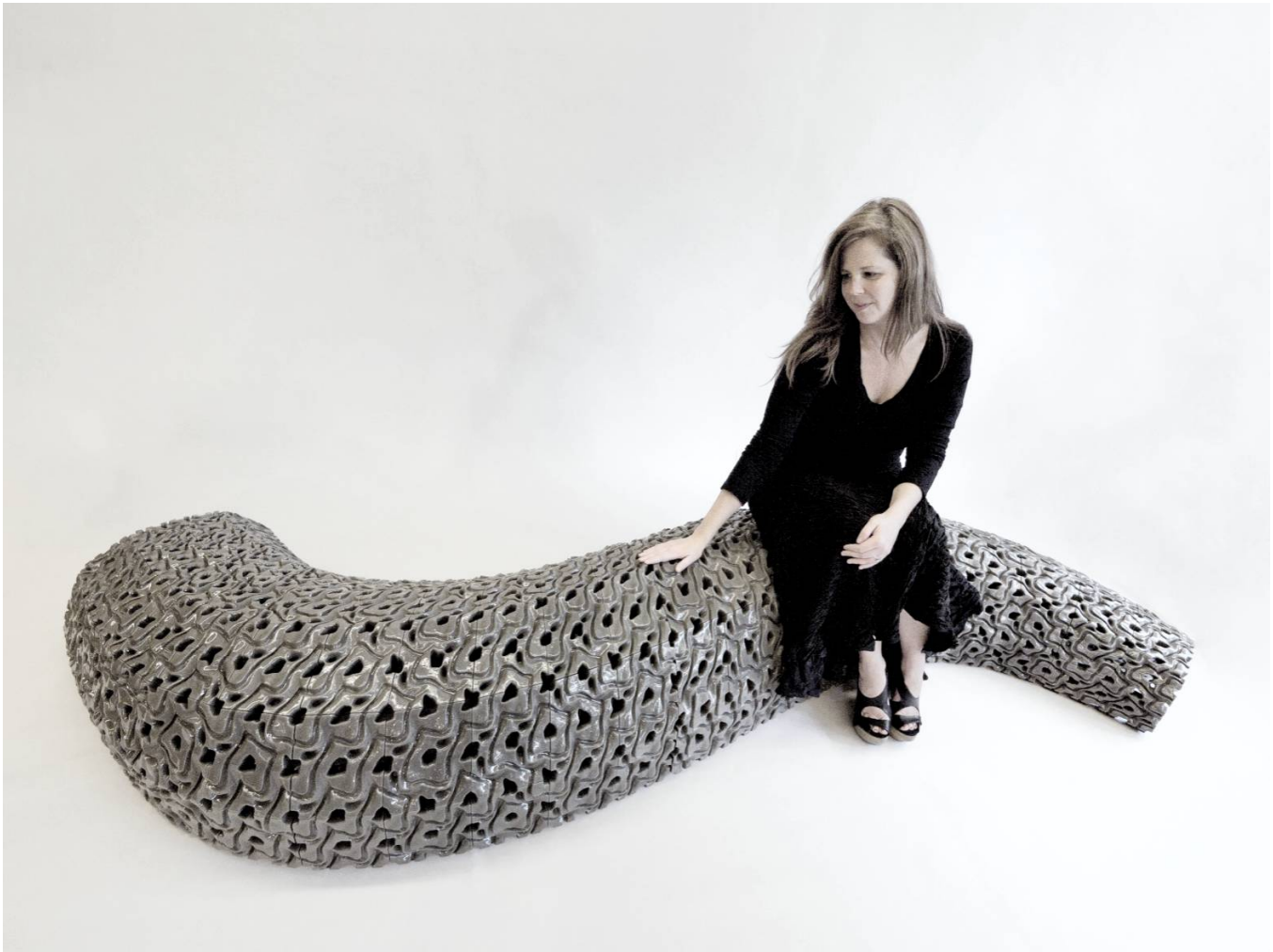


Figure 11. Completed cement polymer bench

Rael and San Fratello are currently collaborating with Enrico Dini of D-Shape, to develop materials for 3D printing on an architectural scale. Dini is the inventor of the largest 3D printer in the world, which is a 10' x 10' x 10' 3D stereolithic printer that creates models entirely out of artificial sandstone using CAD-CAE modeling technologies and CAD-CAM software to control the plotter. The printing proceeds in 5-10mm layer segments and, in the end, produces a structure that has strength characteristics reminiscent of standard Portland cement.

ACKNOWLEDGMENTS

We thank the following individuals and organizations for their knowledge, support and assistance: Dr. Mark Ganter of the Solheim Additive Manufacturing Laboratory in the Mechanical Engineering Department on the University of Washington, Artist Ehren Tool, Professors Richard Shaw and Claudia Ostertag (Berkeley), The Department of Art Practice (Berkeley), The Hellman Family Fund, California Berkeley, Luxology; Research assistants: Emily Licht, Nick Buccelli, Kent Wilson.

REFERENCES

1. Beasley, Phillip, Alice Cheng and Sean Williamson. *Fabrication: Examining the Digital Practice of Architecture*. Proceedings of the 2004 AIA/ACADIA Fabrication Conference. University of Waterloo, 2004.
2. Ganter, M. 2010. Plaster powder V2. Open3DP. Available at <http://open3dp.me.washington.edu/>
3. Gramazio, Fabio and Koher, Matthias. *Digital Materiality in Architecture*. Lars Müller Publishers. 2008
4. Khoshnevis, B. 2008. Caterpillar Inc. funds Viterbi 'Print-a-House' construction technology. Contour Crafting.
5. Kolarevic, Branko. *Architecture in the Digital Age: Design and Manufacturing*. Spon Press, New York, NY. 2004.
6. Zain, N. M., N. H. Hassan, M. Ibrahim, and M. S. Wahab. 2011. "Solid Freeform Fabrication of Prototypes using Palm Oil Fly Ash Prototypes via 3D Printing", *Journal of Applied Sciences*, 2011