Chapter 7: Cement

Cement

The word concrete comes from the Latin word “concretus”, meaning compact or condensed and grown together. The most basic recipe for concrete is comprised of aggregates of various sizes that form a compact mass, portland cement, and water. [Figure 111] When combined with aggregate and water, the portland cement crystallizes and fuses the matrix together into a synthetic stone.

The development of concrete has evolved for over two thousand years. The Romans were among the first to use concrete in buildings using a mix of quicklime, volcanic ash and rubble to build structures such as the Pantheon. During the Middle Ages, concrete technology crept backward, and after the fall of the Roman Empire in 476 AD, the techniques for making concrete were lost for almost 1,000 years until the discovery in 1414 of manuscripts describing those forgotten techniques rekindled interest in building with concrete.

It wasn’t until the late 1800’s however, that the technology took a big leap forward. This time in France, where attempts were being made to improve traditional rammed earth by introducing cements and limes into the compaction of soil between formwork. In 1744, John Smeaton “rediscovered” concrete in England by mixing hydraulic lime and powdered brick as aggregate for the Eddystone lighthouse house in Devon. Smeaton’s mixtures produced concrete with a comprehensive strength comparable to the basic mixes that we use today, and his recipe for hydraulic lime became what is known as Portland cement.

Concrete became a common building material in Europe in the late 19th century and was pushed into prominence by engineers such as François Hennebique who pioneered reinforced concrete by introducing metal to the technology to increase its tensile strength. By the 20th century concrete had become a global material - generic and normalized - used in almost every country in the world. Now in the 21st century concrete has become the dominant material used in construction in Asia, primarily China and India, and has become, by far, the most widely used building material in the world.[[1]](#footnote-1) According to the United Nations Environment Program, in 2012 alone, the world used enough concrete to build a wall 89 feet high and 89 feet wide around the Equator.[[2]](#footnote-2) From 2011 to 2013, China used more cement than the United States used in the entire 20th century.[[3]](#footnote-3) It is estimated that ten billion tons of concrete are produced worldwide each year, which translates to two tons of concrete per person per year in the United States, this means unrivaled amounts of natural resources are being depleted annually to produce concrete. Of equal concern is the issue that the production of Portland cement releases enormous quantities of carbon dioxide into the atmosphere. Additionally, one billion cubic meters of water are used each year in the production of concrete, demanding an urgent call for concrete design and production to become more ecologically responsive in the 21st century, as the planet cannot continue to consume concrete at the current rate.

Early advanced concrete development grew out of experimentation through trial and error, and not purely scientific knowledge. This continues to be one of the most unique characteristics of concrete—it is an ever-evolving material despite its ubiquity— and endless testing occurs in buckets on jobsites as well as in sophisticated laboratories. Unlike steel and glass, concrete is still a material that anyone can experiment with in order to create novel and original results, aggregates can be used to change the weight and visual properties of cement, one can find recycled sawdust, metal shavings, glass microspheres, and Carrera marble dust all mixed with the cement in order to create entirely new mixtures with novel traits.

There are countless recipes for concrete; it is always able to be customized. A standard formula is never a given, it is something that is always made from scratch—homemade. Recipes can be mixed, poured, vibrated and cured to launch a chemical reaction that turns liquid into solid – rather like baking. Experienced workers are even known to taste the admixture in order to identify its stage of development, and in many parts of the world, making concrete is integrated into domestic life.[[4]](#footnote-4) In Sao Paulo, Brazil, a women’s collective makes precast concrete building components during the weekdays, which are assembled together during the weekends when more people are available. The ease with which one can make concrete, the many purposes it can serve, and the incredible strength of the final material are simultaneously what have made this material the most ubiquitous material used in architecture and construction today.[[5]](#footnote-5)

Concrete is so prevalent, most of us can look out the window of the building we are in right now and see something made of concrete. Simple prefabricated concrete pavers or modest concrete block buildings abound in most towns and cities. On the other hand, In Japan, one can find examples of the most superfine, polished concrete buildings such as Tadao Ando’s Church of Light in Osaka. In India, at Chandigarh, Le Corbusier’s béton brut, or the rough, unfinished exposed concrete surface that reveals all the marks of the formwork can be found. Entire cities, such as Brasilia, the capital of Brazil, are made of concrete. In China, the massive Three Gorges Damn, used 21 million cubic yards of concrete, and is the largest concrete construction in the world. On the other hand, fiber reinforced ultra high performance concrete is being used to make very thin, delicate, lattice like rain screens and slender bridges that have strengths exceeding traditional concrete. The number of applications in the built environment for concrete is as many and varied as the possible recipes for making concrete.

Cement and 3D Printing

Traditional concrete can be poured continuously on site, precast off site, sprayed, or tilted up. All concrete however requires formwork, the making of which is a laborious construction process that requires skilled labor. Formwork can vary dramatically, from lumber and plywood wood fastened together using hand tools, to heavy equipment lifting large, prefabricated forms that require heavy machinery to set into place. There is a redundancy that is a fundamental component of concrete construction, which is that a wooden building is constructed first, into which concrete is poured, and after which it is dismantled—and this comes at an environmental and economic price. In the U.S., formwork costs up to 60% of the total cost of construction and often formwork is discarded after use.[[6]](#footnote-6) However, in the case of 3d printing concrete, there is no formwork, which means that some potential advantages of 3D printing concrete include lower labor costs associated with building formwork, increased complexity without specialized labor, greater accuracy, less waste produced, and less water used. All, which add up to make 3D, printed concrete potentially more sustainable and accessible to an even wider array of concrete gourmands.

There are a variety of 3D printing concrete methods currently used at the construction scale, these include both extrusion and jet binding techniques. Contour Crafting, an extrusion technique, developed and patented by Dr. Behrokh Khoshnevis at the University of Southern California in 1996, initially began as a novel ceramic extrusion and shaping method as an alternative to the emerging polymer and metal 3D printing market. In the year 2000, Dr. Khoshnevis and his team, began to focus on construction scale 3D printing of cementitious pastes. Contour Crafting works by quickly laying down cement outlines in the shape of a room or building in a layer-by-layer fashion that gradually increases in height as the layers build up to shape a wall.

At the same time 3D printed concrete and cement are being developed by engineers and scientists in laboratories at major research universities, students and home enthusiast are also hacking robots and 3d printers in order to develop new recipes for 3D printing concrete. Andrey Rudenko, a contractor, used open source software to build a concrete 3D printer in his garage and printed a small backyard castle for his children. Students at the Bartlett in London developed a fabrication method that combines the two already existing concrete 3D printing methods: extrusion printing and powder printing. A robotic arm extrudes a linear path of concrete, which is then supported by granular material until the concrete cures.

Powder based 3D printing of portland cement polymer was developed and patented by Professor Ronald Rael, of Emerging Objects, at the University of California. In powder based printing, all binding particles used in the concrete mix must fit through a 35-picoliter print head and all cement, aggregate and reinforcement must be smaller than 0.010”. These dimensions seem extremely small but the end result is that 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, complex ornamentation and detail, structural thinness and translucency. Materials are stronger and lighter than typical concrete. Typical concrete cures to 3000 psi but the powder based cement polymer cures to 4700 psi in compression when mixed with fiber reinforcement. 3D printing with cement means there is zero waste and each 3D printed cement part can be customized without the need for expensive, unique or disposable formwork.

Bloom is an experimental pavilion that employs 3D printed portland cement at an architectural scale. [Figure 112] It is a 9-foot tall freestanding tempietto with a footprint that measures approximately 12 feet by 12 feet and is composed of 840 customized 3D printed cement blocks. The floral motif embedded in the surface of Bloom is derived from traditional Thai flower patterns and is mapped cylindrically onto the surface of the structure. This creates a figural pattern comprised of openings in the surface that produce stunning visual effects of light, shade and shadow on the exterior and interior. From the exterior the pattern is most striking from a distance or when viewed through the screen of a digital camera, which creates a surprise upon photographing the structure from up close. On the interior one can find an internal structural grid that carries the forces of the weight of the cement blocks to the ground. [Figure 113]

The individual blocks were printed on a print-farm of 11 powder 3D printers, with a special cement composite formulation comprised of iron oxide-free portland cement. [Figure 114] Iron oxide imparts a gray color to cement, and its removal makes these 3D printed blocks much lighter in color.

The blocks are enumerated to designate their position in the overall structure and assembled into 16 large, lightweight prefabricated panels, which can be assembled in just a few hours. [Figure 115] [Figure 116] [Figure 117] Also, 3D printed cement requires no formwork and produces no waste and the support material can be reused to produce more blocks. Coupled with the portland cement is an ecologically derived UV resistant polymer that that uses plant-based materials that do not compete with food sources or displace food-based agriculture, and reduces the greenhouse gas emissions from production of resins by 50% over conventional petroleum based epoxies. Each 3D printed block is coated in the UV resistant polymer for additional strength.

The curvilinear form of the overall structures provides added stiffness to the thin, lightweight shell, not unlike the thin masonry structures of Uruguayan architect and engineer, Eladio Dieste—particularly *Iglesia Cristo Obrero*—Jefferson’s serpentine brick walls at the University of Virginia, and *Torqued Ellipse*, by Richard Serra, all of which inspired the form of Bloom in the early phases. In plan, Bloom is a curved cruciform shape that rises 9 feet to meet the same shape rotated 45 degrees, creating a torqued “x” shape with an entrance 45 degrees off its primary axis. [Figure 118] The undulating form and spaces recall an elephant’s foot or, when coupled with the flower pattern on the surface, the traditional mud houses of the Tiebele people in Ghana — a reference to the earliest inspirations for 3D printing by Emerging Objects.

Bloom is an excellent example of how portland cement can be used with powder based printing and very little water to create intricate and complex cement structures that have strengths comparable to more traditional concrete constructions. [Figure 119] As we move into the future of building with cement-based materials, it proves yet again to continuously allow itself to be reengineered – endlessly tested and retested to achieve multiple levels of performance. Thousands of years of evolution have demonstrated its robust characteristics, and it will continue to evolve as techniques in additive manufacturing become more commonplace in building and construction. [Figure 120]

Objects:

*Drum*

*Drum* is a study in large-scale, lightweight, 3D printeding with dark gray expansion cement. A simple flange based connection system holds the thin cement panels in compression and the overall spiral form cantilevers from the central fulcrum point. Each panel is held in compression using binder-clips allowing for quick assembly and disassembly. The cement prints are sandblasted to bring out the grain of each panel produced by the additive manufacturing process. [Figure 121] [Figure 122] [Figure 123]

*Rocker Vases*

The designs for the Rocker Vases are some of the first objects made for 3D printing with the cement material. The vases test thinness, excavation techniques, cantilevering strength of unsupported and unpolymerized material, detail and resolution.

The Rocker Vases themselves are intended to be balanced when empty. When plants or water is inserted into the vases, they tip one direction or the other, depending on the weight and distribution of the flower display. [Figure 124]

*Seed (P\_Ball)*

The *Seed (P\_Ball)* is 3D printed in gray cement polymer and sandblasted to appear matte and soft. *Seed* *(P\_Ball)* is the latest object in Andrew Kudless’s *P\_series*, projects that explore digital and physical processes of self-organization. In this specific prototype, a geodesic sphere is digitally inflated yet constrained by multiple points. This tension creates a series of undulating surfaces across the larger geodesic framework. The 3D printed prototype was created to help understand the visual, geometric, and fabrication issues involved in producing a larger cast concrete installation for the Berkeley Botanical Garden. The twenty 3D printed cement hexagons and twelve pentagons converge to form the sphere. [Figure 125] [Figure 126]

*SCIN Cube*

The *SCIN Cube* is a cellular solid—a transmaterial grouping characterized by high strength to weight ratios using the 3D printed cement polymer. The cube is comprised of a network of digital cellular bodies that are first relaxed to produce a more uniform field and then structurally differentiated in relation to their distance to the outside surface. The inner core’s cell edges are extremely thin and fragile yet are protected by the multiple layers of increasing more robust edges closer to the cube boundary. [Figure 127]

*Starlight*

*Starlight* is comprised of 32 parts assembled from 3D printed iron-oxide free portland cement with a patina inducing agent that creates an uneven, aged material. The thinness of the print allows for material translucency and the cement has a soft glow. Components are held together with nylon hardware. [Figure 128]

*Planter Tiles*

The *Planter Tiles* are 3D printed cement hexagonal tiles that close pack. The overall pattern is composed of 6 different tile patterns, 4 of which have the capacity to hold plant life. The petal motif on the tiles themselves visually ties together all of the planter tiles and non-planter tiles through the use of a 3 dimensional graphic. The tiles are printed with varying admixtures of aggregate combined with the portland cement to produce varying shades and tints of the cement color. The effect of using different cement formulations to print different tiles within the system creates a rich and textured surface covering. [Figure 129]

*Grab Tiles*

These tiles are designed with deep undercuts and doubly curved surfaces making them difficult, if not impossible, to cast using conventional methods. The looping and curving relief pattern on top of the tiles serve as ways to grab, touch and use the tiles. By inserting fingers and hands in the tiles, they can potentially serve as handles for use in cases where occupants may need assistance getting up or prevention in falling, such as in an elderly care facility. [Figure 130]

*Seat Slug*

The *Seat Slug* is a bio-morphic interpretation of a bench. The form is inspired by Flabelina Goddardi, the latest species of sea slugs discovered off the coast of California, and by the infinite tessellations of Japanese karakusa patterns. The seat slug blurs the lines between biology, technology, and furniture and is an exploration on function and form. It is constructed of 230 unique 3D printed cement blocks that are coated with organic resins to create a reflective, finished surface. [Figure 131]

1. James Mitchell Crow, “The Concrete Conundrum”, *Chemistry World* (2008): 62 [↑](#footnote-ref-1)
2. https://www.nytimes.com/2016/06/23/opinion/the-worlds-disappearing-sand.html?\_r=0 [↑](#footnote-ref-2)
3. “How China Used More Cement in Three Years Thank the US Did In The Entire 20th Century”, last modified March 24, 2015, https://www.washingtonpost.com/news/wonk/wp/2015/03/24/how-china-used-more-cement-in-3-years-than-the-u-s-did-in-the-entire-20th-century/?utm\_term=.a7bdd12a5a77 [↑](#footnote-ref-3)
4. Stanford Kwinter, “Is Concrete Dead or Alive” in *Solid States: Concrete in Transition Princeton*, ed by Michael Bell and Craig Buckley, (New York: Princeton Architectural Press, 2010), 39. [↑](#footnote-ref-4)
5. Adrian Forty, *Concrete and Culture: A Material History*, (London: Reaktion Books, 2012), 42. [↑](#footnote-ref-5)
6. Concrete Forms — A Formwork Formula: Tips for Success”, last modified January 21, 2009, http://www.forconstructionpros.com/concrete/equipment-products/forms/article/10302640/concrete-forms-a-formwork-formula-tips-for-success [↑](#footnote-ref-6)