3D Printing Architecture

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Abstract This paper will focus on the research and collective work of Emerging Objects, a MAKE tank, that is transforming materials into sustainable buildings for the future using additive manufacturing. Humble and traditional building materials, such as salt and soil, can be transformed into sophisticated building materials through additive manufacturing. Waste materials such as sawdust and chardonnay grape skins and seeds are converted for use in 3D printing and turned into bricks, blocks, and tiles for construction assemblies. The use of additive manufacturing technologies and radical, alternative materials, will allow architects and engineers to impact the way buildings and cities will be constructed in the future.

Keywords Additive manufacturing · 3D printing · Paste extrusion · Powder materials · Architecture · Sustainability

Introduction

What if the world's waste materials could be transformed into sustainable building materials for the future? Can humble and traditional building materials, such as salt and mud, become sophisticated building materials for the twenty-first century? How can technologies such as additive manufacturing impact the way we attempt to solve social problems such as housing? These are all contemporary concerns that architecture must address if it is to stay relevant. The case studies discussed in this paper attempt to answer some of these questions through material experimentation and innovation and by prototyping new structures. Chardonnay grape skins are an agricultural waste product that is left to rot in the field, in the *Cabin of 3D Printed Curiosities* it is used as a local building material. Many proprietary powders and

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resins used in 3D printing are very expensive, the materials used for 3D printing described in this paper including soil and salt are either free or very low cost which makes 3D printing more accessible. The *Saltygloo* is printed using local salt from the San Francisco Bay and the *MUD Frontiers* project uses locally harvested wild soil and clay from the jobsite, eliminating the need to purchase and ship materials around the world.

Each of the three case studies described in the paper is easy to assemble with unskilled labor. Blocks, tiles, and puddled coils, printed with inexpensive equipment, are connected using simple fasteners such as Velcro, screws, or simply gravity, to hold parts into place making the 3D printing building components easily handled and aggregable to create larger structures. Developing one's own materials and using simple assembly methods for 3D printed parts open the door for new material compositions within geometrically complex forms, and it also reduces cost and allows for new color variations and textures. The use of local, indigenous, and recycled materials in additive manufacturing not only addresses issues around the future of sustainability and economics but it also creates new, contemporary craft, and architectural traditions.

The Case Studies

Salt

The *Saltygloo* (Fig. 1) is an experiment in 3D printing using locally harvested salt from the San Francisco Bay to produce a large-scale, lightweight, additively manufactured structure. In the landscape of the San Francisco Bay Area, employing only the sun and wind, 137,000 tonnes of sea salt are produced each year, making salt

Fig. 1 Saltygloo. (Color figure online)

a locally available building material. The salt is harvested from 110-year-old salt crystallization beds in Newark, California, where salt water from the bay is brought into a series of large evaporation beds. Over the course of three years, the brine evaporates, leaving 13–16 cm of solid crystallized salt that is then harvested for food and industrial use. From this landscape, a new kind of salt-based architecture created through the lens of 3D printing and computer-aided design is realized, inspired by traditional cultures that employ the building material found directly beneath their feet, such as the Inuit Igloo. It is named *Saltygloo*, because it is made of salt *y* glue; it is made of a combination of salt harvested from the San Francisco Bay and glue derived from recycled plant-based resins that come from by or waste products and do not displace food-based agriculture, which makes for an ideal 3D printing material and strengthening infiltrate, called Super Sap by entropy resins [1], one that is not only strong and waterproof but also lightweight, translucent, and inexpensive.

The form of the *Saltygloo* is drawn from the forms found in the Inuit Igloos (Fig. 2), but also the shapes and forms of tools and equipment found in the ancient process of boiling brine. Additionally, each tile is based upon the microscopic forms of crystallized salt. The 330—3D printed salt tiles (Fig. 3) that make up the surface of the *Saltygloo* are connected with removable binder clips to form a rigid shell that is further strengthened by connecting the closed clips to lightweight aluminum rods flexed in tension, making the structure extremely lightweight and able to be easily transported and assembled in only a few hours—in many ways it is a salt tent.

The inherent optical properties of the salt make it translucent (Fig. 4) and shimmer and allow for light to permeate the enclosure and highlight its structure. The grainy crystals of the salt tiles are tactile, they feel gritty, grainy, and abrasive, and they communicate the use of one of humankind's most essential materials not only through vision but also through touch.

Printing with local salt in an inkjet printer greatly lowers ecological lifecycle impacts when compared to other materials and 3D printers. In tests conducted by Jeremy Faludi at the University of California Berkeley using the ReCiPe method [2], when the Zcorp inkjet is printing four salt parts together, which it did for the construction of the *Saltygloo*, it has 1/5th the ReCiPe endpoint-score per job as the next-best technology, PLA printed by small desktop FDM. The inkjet has roughly

Fig. 2 Community of igloos

Fig. 3 Close up of crystal tile form. (Color figure online)

Fig. 4 Saltygloo interior. (Color figure online)

1/38th to 1/40th the impact score per job as a polyjet printer, regardless of whether both are printing one part at a time or four parts at a time. ReCiPe is the most recent indicator approach available in life cycle impact assessment and the primary objective of the ReCiPe method, is to transform the long list of life cycle inventory results, into a limited number of useful indicator scores. The chart of Fig. 6 shows how 3D printing with salt on an inkjet printer compares to 3D printing with PLA, PET, and ABS on desktop FDM printer, printing with photopolymer resins on a polyjet printer, and resin in a SLA printer [3] (Fig. 5).

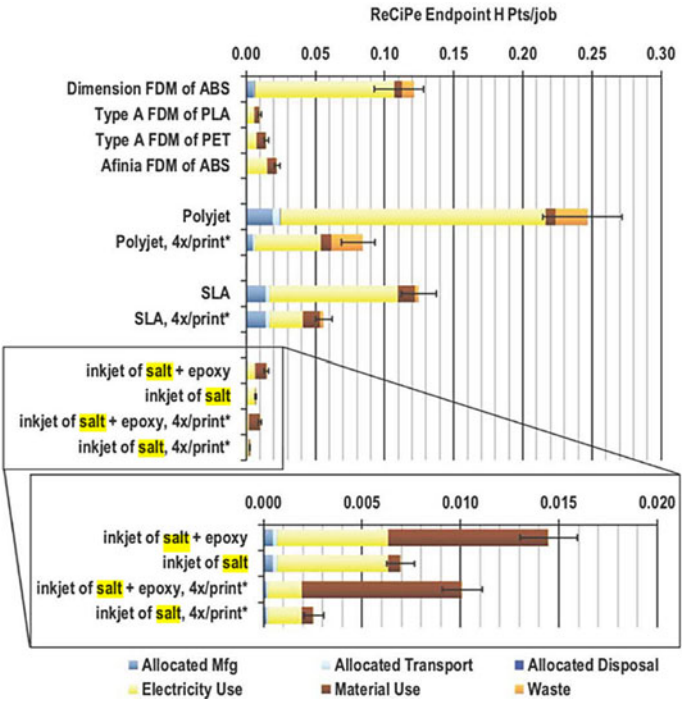

Fig. 5 Ecological impacts per job at maximum utilization scenarios. Scenarios denoted by (*) are four parts being printed simultaneously. Reprinted from [3], with permission. (Color figure online)

Soil

The use of ubiquitous, free, and sustainable materials such as local soils for 3D printing enables a more accessible, portable, and ecological approach to additive manufacturing at the architectural scale. The MUD Frontier project is addressing the challenge of creating accessible robotics for construction through the development of a mobile and lightweight, 3D printing setup that can easily be transported to the field or jobsite. The construction industry is the largest global consumer of raw materials and accounts for 25 to 40% of the world's total carbon emissions [4]. A return to mud as a building material attempts to correct the errors of a wasteful, polluting, and consumptive industry. Ecological and sustainable issues are at the forefront of conversations surrounding the future of construction and soil-based construction materials are the most "earth friendly" materials that exist [5]. Earth is a ubiquitous material and buildings made of local soils can be found in almost every region of the world. A large number of earthen building codes, guidelines, and standards have appeared around the world over the past two decades, based upon a considerable

Fig. 6 Robotic setup at the rubin center. (Color figure online)

amount of research and field observations regarding the seismic, thermal, and moisture durability performance of earthen structures opening the door for the nascent revival of building with earth.

The Scara robotic 3D printer (Fig. 6) that was developed for this endeavor is combined with a continuous flow hopper that can print wall sections and enclosures up to 2200 mm diameter circle and 2500 mm tall, structures considerably larger than the printer itself. The setup can be carried by 1–2 people and relocated in order to continue printing.

The printer is able to 3D print local soils directly from the print site in order to demonstrate the possibilities of sustainable and ecological construction in a two-phase project that explores traditional material craft at the scale of both architecture and pottery. The clays harvested for the projects are free, as they can be dug directly from the ground or surrounding region where the walls, enclosures, and pottery are being printed.

Phase I of the MUD Frontier project took place along the USA—Mexico border in El Paso, Texas and Ciudad Juarez, Chihuahua, where earthen architecture and clay pottery of the Mogollon culture (A.D. 200—1450) define the archeological history of the region. Excavated pit houses and above ground adobe structures defined the historic architecture of the region.

A large 3D printed adobe structure was also manufactured using largely the same material as the pots, but with the introduction of sand. The vessels reveal the nature of the local geology and the creativity of local ceramic artisans from the contemporary Jornada Mogollon region. The fired earthenware exposes a range of clay complexions: greens, browns, purples, wheat, pink, and red colors that speak to the nature of mono-, bi-, and polychrome traditions that developed over time. The structure and vessels were produced with the intent of connecting the forefront of digital manufacturing with the traditional coiled pottery techniques, and subterranean and adobe architecture of the borderland regions between Texas and New Mexico in the USA and the state of Chihuahua in Mexico.

During Phase I the robotic setup for printing the large structure was installed at the Rubin Center Gallery in El Paso, Texas, which sits very close to the border wall. The gallery was maintained at a constant temperature of approximately 20 °C. A mixture of five parts locally sourced sand and three parts clay was mixed with chopped straw and water and pumped through the printer. The layer height of each mud coil is 30 mm and each coil is between 40 and 60 mm wide. The overall structure is 213 cm tall and 180 cm wide and took seven days to print at approximately 300 mm per day (Fig. 7).

Phase II of the MUD Frontier project took place in the high alpine desert of the San Luis Valley which spans southern Colorado and northern New Mexico in the USA (Fig. 8). The second phase of the research reflects the earthen construction of the Indo-Hispano settlers of the valley and the local Rio-Grande pueblo culture. The

Fig. 7 MUD frontier large-scale structure and vessels at the rubin center gallery as part of the new cities, future ruins exhibit. (Color figure online)

Fig. 8 Fabrication setup. (Color figure online)

temperature of the valley floor fluctuated from a high of 30 °C during the day to 6 °C at night. The desert environment was sunny, windy with some rain over the sixty days of printing. It was observed that printing was most successful when the weather conditions were dry, sunny, and most importantly, windy. The mud mixture used was wild, dug directly from the ground, sieved to a particle size of less than 6.35 mm, and mixed with chopped straw and water. The clay/sand/loam mixture in this region has historically been used to make mud bricks and mud plaster for local buildings and there is a tacit understanding among the community about where to dig for the mud and how moist it should be. The mixture proved to be very well suited for 3D printing coiled mud structures (Quentin Wilson, an adobe expert living and building in this region of southern Colorado and northern New Mexico, recommends using the jar test to identify a mixture that is less than 30% clay [6]). The layer height of each mud coil is on average 30 mm and each coil is between 40 and 60 mm wide. Four structures were printed of varying dimensions; however, it was observed that under ideal weather conditions an average of 400 mm in height could be printed per every 24-hour period.

The research during phase II was conceptualized under four themes: The Hearth, Beacon, Lookout, and Kiln. The Hearth explores the decorative aspects of structure (Fig. 9). The structural reinforcement of double-layer earthen walls creates a simple interior environment and an exterior that has structural expressiveness. The thin mud wall construction is reinforced using local, rot-resistant juniper wood, to hold the interior and exterior coiled walls together. The wood sticks extend beyond the walls

Fig. 9 3D printed hearth. (Color figure online)

of the structure on the outside and are flush on the inside, referencing the cultural differences between the architectural traditions of pueblo and indo-hispano buildings. It also recalls traditional African architecture such as the Mosque in Djenne, where the wood sticks protruding from the building are not only decorative but also used as scaffolding. The interior holds a 3D printed mud bench, surrounding a fireplace that burns the aromatic juniper (Fig. 10).

The beacon is a study in lightness, both illumination and weight. It explores how texture and the undulation of the 3D printed coil of mud can produce the thinnest possible structural solution for enclosure. These coils are then illuminated at night contrasting the difference between the concave and convex curves that create the mud walls. The lookout is an exploration in structure and is a 3D printed staircase that is made entirely of mud. A dense network of undulating mud coils is laid out to create a structure that can be walked on. This also demonstrates how wide, yet airy, walls

Fig. 10 Fireplace and mud bench. (Color figure online)

can create interior enclosures that represent possibilities for insulation, especially in the harsh climate of the San Luis Valley which can drop below −29 °C in the winter. The Kiln explores several of the techniques discussed, including undulating /interlocking mud deposition to create structural and insulative walls. The Kiln is also used to enclose an area that draws in oxygen and keeps in heat to fire locally sourced clay fired with juniper wood, which burns hot.

The *MUD Frontier* project reexamines and conceptually unearths ancient building traditions and materials using twenty-first-century technology and craft coupled with local skills to explore new possibilities for ecological and local construction techniques. Based on the research so far, the robotic printing of local soils shows promise for the rapid creation of robotically crafted, geometrically complex, buildings that are durable and structural, using wild clays that have historically proven successful in building construction. Upon their 40th anniversary, the Smithsonian Magazine announced the 40 most important things they believed one should know about the next 40 years. Number one on their list was that "Sophisticated Buildings will be made of mud" [7]. *MUD Frontiers* aims to see this prediction become a reality.

Chardonnay

The 3D printed tiles made of chardonnay grape skins on the façade of the *Cabin of 3D printed Curiosities* have been described as a box of exquisite chocolates—the facade is composed of 3D printed *Planter Tile*s that create a living wall of succulents (Fig. 11a). The chardonnay grape skins are a deep, warm brown that evokes the buttery bitterness of chocolate. They have an herbaceous scent that is complemented by the succulents in the tiles. The reuse of local waste materials that has been shaped through digital processes engenders a new aesthetic, one that is part of a new vernacular that

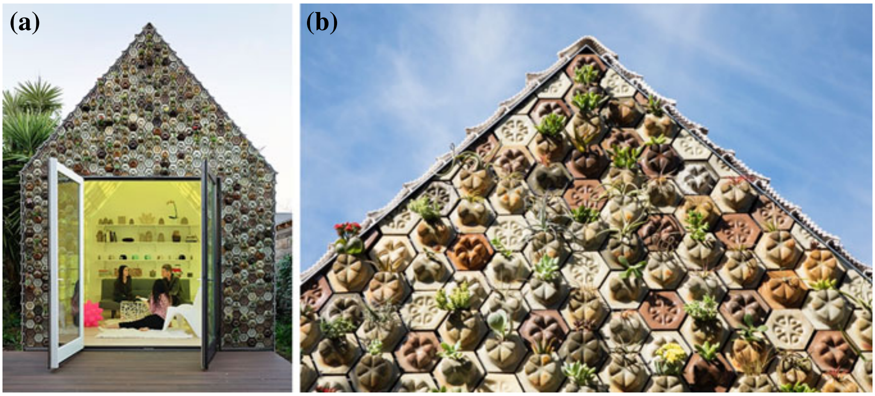

Fig. 11 Planter tile façade on the cabin of 3D printed curiosities. (Color figure online)

takes advantage of materials in local waste streams and nascent global technologies such as 3D printers (Fig. 11b).

The San Francisco Bay Area is experiencing a housing crisis; never before has the cost of real estate, new construction, and rent been so high. Because of this emergency situation, cities around the Bay Area have relaxed their zoning laws, design review process, and permitting requirements in order to allow home-owners to build secondary structures on their lots. These relaxed laws opened the door to for the *Cabin of 3D Printed Curiosities* to be built. The cabin takes advantage of these relaxed codes and laws and brings many of material, software, and hardware experiments together to demonstrate the architectural potential of additive manufacturing on a weather tight, structurally sound building. All of the cabin's componentry are produced in a microfactory, the print farm, which is located nearby the site of the cabin.

The roof gable and east and west facades are clad in 3D printed ceramic tiles that serve as a rain screen (Figs. 12a, b). The clay for the tiles comes from California. Designed for easy assembly, these tiles are made to be hung on a building facade or interior. The surface of each ceramic tile visually emulates a knitting technique called the seed stitch. G-code is used to control each line of clay as it is 3D printed to create a loopy texture that looks like seeds scattered across the surface. While all ceramic tiles are printed from the same file, each tile is intentionally unique as a product of

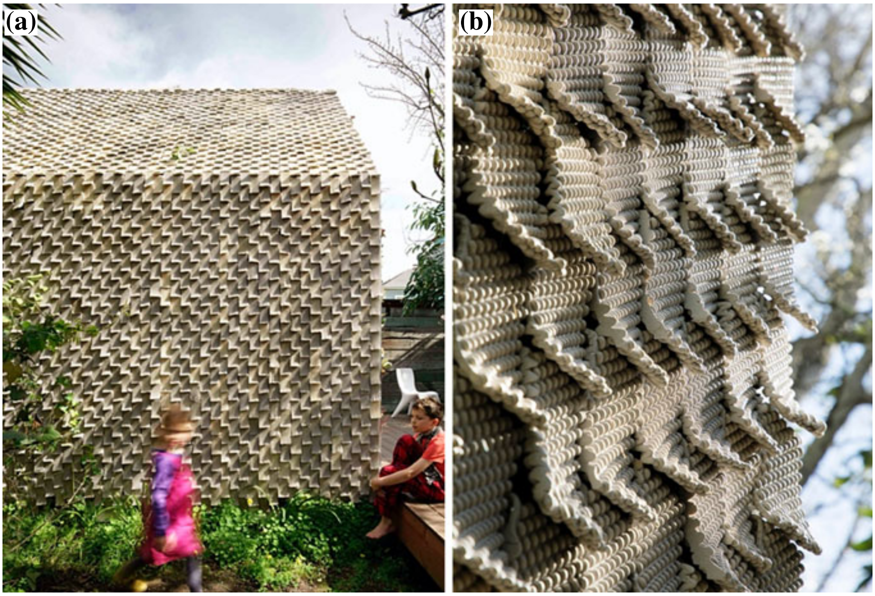

Fig. 12 3D printed ceramic tiles on façade. (Color figure online)

fabrication, during which the tiles wave back and forth, causing the printer to pull at the line of clay and creating longer and shorter loops toward the end of each tile, producing a distinct machine-made texture that is different every time.

The *Cabin of 3D Printed Curiosities* represents the first steps to a future that we can embrace for both its functionality and beauty. It solves problems around architectural issues that we face every day, it brings value to the occupant's lives and it has a strong connection to its locale technologically, geologically, and agriculturally through the use of materials and additive manufacturing.

Conclusion

The *Cabin of 3D Printed Curiosities*, the mud pavilions, and *Saltygloo* all speak to the possibility of a future that is just emerging, a future that takes advantage of powders that come from dust, waste, and traditional materials, on their journey to becoming part of a twenty-first-century architectural terroir that influences the meaningful crafting of objects and buildings. As pointed out by Gareth Williams, "In order to retain relevance in the modern world, craft must engage with contemporary concerns. One of the most pressing issues today is the impact of production, consumption and disposal of goods upon the earth's resources and ecological balance" [8]. 3D printing also raises questions about its role in craft and how it might make bespoke architecture more accessible, as the objects and buildings produced are not necessarily handmade but are customized, however the close connections between design, iteration, technique, material behavior, and analysis, and manufacturing suggest that 3D printing, especially when coupled with modes of production that employ materials from sustainable resources and waste streams, is a contemporary form of manufacturing with increasing relevance.

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