Materiality and digital technologies: concrete experiments for the built environment

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Abstract

Purpose – This paper presents the applied research and design work on innovative and sustainable building products developed by an undergraduate architecture seminar course. It presents the case for innovative uses of cement-based products, while framing the proposals within a global shift toward environmentally responsive and bio-integrated materials.

Design/methodology/approach – The methodology utilizes a process of hybridization between digital fabrication and analog making methods that is framed within the larger design discourse and that intersects the digital design process with material know-how. The approach engages local problematics and applies advanced technology and the integration of natural behaviors to develop a rich applied design method.

Findings – Through the presented work and proposed building products, critical findings and outcomes emerge, ones that relate to the design process itself and others to the designed products.

Originality/value – The research presented here proposes novel approaches to cement-based building systems utilizing digital and analog fabrication, and original design solutions that engage with their context and provide active and crucial environmental performance.

Keywords Digital fabrication, Materiality, Environmental performance, Building materials, Hybrid materials, Sustainable concrete

Paper type Research paper

1. Introduction

The rapid development of advanced technologies today, namely in prototyping and three-dimensional fabrication, is allowing unparalleled investigations of form, material and making, right from the designer's desktop. This has had a major impact on architecture and the production of space and building systems, as designers move toward more computer-based production techniques. However, at no time has material know-how become more necessary, as the digital interface creates a disconnection with the more tactile design process. A parallel interest in natural behaviors has also emerged trying to hybridize natural behaviors into the designed objects, generating for many designers an aim to produce active and environmentally productive prototypes. Equally so, designers have been looking back closely at local and specific methods of making, attempting to move away from the generic products pervading global architecture to generate more locally relevant alternatives.

This paper presents an applied research method that focuses on explorations in materiality as a design framework (Brown *et al.*, 2013) and on intersecting material know-how with advanced tools and fabrication. It posits the possibility for applying such an iterative material/digital design method to offer new environmental alternatives to concrete

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composites, the most abundantly used building material by far. It advocates for integrating natural behaviors to embed an active performance in novel composites and alternatives. It also advocates for the iterative use of digital fabrication tools to influence the design process and material outcome, not serve merely as prototyping tools.

This paper thus presents the above framework and illustrates alternative results through the work of senior undergraduate students in the architecture research elective I teach. It presents the unique ways in which each project approaches such intersections from design to fabrication and from material behavior to technological constraints, and how the results can provide environmentally performative possibilities for local applications.

2. Digital fabrication and digital craft

Digital fabrication today has become a crucial means of production, allowing the direct application of three-dimensional digital models into physical prototypes. Through various technologies, such as computer numerically controlled (CNC) routers (CNC machines) and 3D printers, it has transformed the ways in which designers produce physical objects, moving the means of production from the industry into the designers' desktop, particularly with the proliferation of low-cost technologies. Accordingly, the role of the designer has shifted to be both the creator and the maker, enforcing the understanding of technology and material constraints as inherent parameters within the design process. Dimitris Papanikolaou (2012) interlinks technological constraints with design conception where designers must today holistically incorporate machine, material and computational constraints in their design process.

This hybrid of the designer/maker has brought forth the notion of digital craft, linking the digitalized creation process to a crafts-inspired process of making. In his seminal work, from 2008, Branko Kolaveric defines the notion of "digital craft" in his text "The Risky Craft of Digital Making" (Kolarevic, 2008) and refers to Malcolm McCullough's (McCullough, 1996) definition as "*an emerging set of material practices based on digital media that engage both the eye and the hand, albeit in an indirect way.*" He outlines several key attributes to this new craft, such as the embedding of material understanding in the digital design process, the linking of the hand and the mind in the fluid form-making workflow, the iterative process of testing prototypes in various models, and the circular feedback between the physical prototype and the digital file. In that, he relates the traditional understanding of craft as an art relying on a hand–mind relationship, on material know-how and varied iterations to the current digital design and fabrication processes. In a recent work, Antoine Picon (2020) argues that more recent shifts in the digital in architecture have been in the notion of materiality itself and further argues for the necessity that the digital shift in design aligns with the urgency of environmental issues and climate change.

Consequently, this enforces the importance of not only the digital counterpart in the design process but more significantly the material part. The methods of physical testing, trial and error, and material know-how, become essential within the design process as parallel and symbiotic resources to the digital forming process. This must be coupled with embedding an "environmental consciousness" within the process toward affecting necessary change for the built environment.

3. Nature as a design element

The natural environment has evidently been the essential model upon which architecture, the man-made environment, has long been shaped. According to Petra Gruber (Gruber, 2011), biomimetic design, or design modeled from natural systems, has existed as long as architecture itself, from cave dwellings to early translations of natural systems to form the built environment. She distinguishes between bio-inspired design and biomimetic design, where the latter differs through its concern with the embedded systems and inherent logic within nature rather than its form or aesthetics. It is however important to note that biomimetic design relies on a referential mode of translation, where the systems of nature are considered as external references to be simulated.

Today, the accessibility to advanced software has given architecture the capacity to model complexities and behaviors found in nature, whether formally or as digital simulations. With these advancements, a deeper understanding of natural systems and their inherent behaviors is however fundamental to design environmentally active and conscious products. Brownwell and Swackhamer (2015), talk about a changing paradigm in today's design world, where a shift is happening from understanding nature as a binary opposite to the man-made world – as an environment that needs to be controlled – to recognizing it as an extension of the built habitat with a mutual influence from and on technology. Furthermore, they signal a move away from learning from nature at a referential level into more hybrid approaches in design, where natural products are directly immersed into the designed matter. They refer to this as an approach of engagement, incorporating organic matter directly in the designed product to create a symbiotic performative result.

Rashida Ng (Ng and Patel, 2013) further talks about the necessity to move toward more performative material products in design by directly embedding natural systems, bringing forth a more dynamic and responsive materiality in architecture. This approach, the move toward hybrid and active building products, is of interest to this work and paper. How can such intersections enhance the design of building systems so that they are embedded with a more "natural" capacity to respond to factors of environment?

Accordingly, and considering the design disciplines as having the responsibility to produce products with positive environmental impact, and given the allowances digital technologies are giving the designer today, it is imperative to engage with nature in a performative manner, to produce productive and environmentally relevant prototypes.

4. Concrete, its versatility and necessary environmental re-evaluation

Today, it is essential that we probe local resources for new building material applications and to define new possibilities that can benefit from advancements in technology, nature as model and digital fabrication. One of the main materials used in global construction is evidently concrete. Concrete is considered to be the largest manufactured product by mass, and the second most used element on earth after water (Scrivener *et al.*, 2018). The yearly production of concrete is massive, and results from the high demand for construction, as rapid urbanization continues to increase, which accordingly impacts the environment negatively due to heavy carbon emissions. The worldwide production of concrete reached 4.5 Gt in 2015, implicating more than 8% of global CO2 emissions (Miller *et al.*, 2018).

The reason concrete results in such a high carbon footprint is largely due to its production process and the emission of high CO_2 levels both from the energy required to produce Portland cement, its main component, and from the release of CO_2 through the chemical reaction in its production (Crow, 2008). Additionally, the extraction of Portland cement substrates and aggregates from quarries also has a direct immense impact on the natural environment.

The need for concrete in the built environment however continues to grow. Scrivener *et al.* indicate that the replacement of concrete will be difficult, due to its relatively low cost of production, local availability of raw materials in different regions, and its market history and confidence. What they suggest instead is a necessity to decrease the carbon impact of concrete through various strategies, including carbon capture and more efficient burning processes through efficient kilns and biofuels. Of interest to this paper however are particularly strategies in material innovation, through reducing cement quantities or through partial replacement of cement clinker by more efficient materials and byproducts.

A first approach to lowering concrete's carbon footprint is the integration of composite materials within the traditional concrete mix to reduce its cement concentration, thus reducing cement production's carbon footprint. Some examples of composites that have resulted from this approach include replacing part of cement clinkers with fly ash, a byproduct of waste incinerators (Xu and Shi, 2018), or optimizing the mix with a higher efficiency limestone-cement clinker that requires less mass (Shannon *et al.*, 2017).

A second approach also happens at the material level, but instead involves making the resulting concrete mix itself environmentally performative by actively removing carbon dioxide from the air. An interesting application is the self-cleaning or photocatalytic concrete, which works by reaction of sun rays and titanium dioxide in the mix and helps dissolve surface dirt and absorb $N0_2$ from the surrounding air (Sopov *et al.*, 2020).

A third approach happens at the fabrication level rather than the material composition level through technological innovations in the making process. Robotic manufacturing with concrete is enabling not only innovation at the material level but also in the process of fabrication itself, removing the need for additional formwork or steel reinforcement. In the cement-based 3-D printing project by Gosselin *et al.*, large-scale material deposition through robotic additive manufacturing is used to create multifunctional structural elements without the need for formwork or additional support in an interdisciplinary process integrating geometrical studies with material behavior and printing process (Gosselin *et al.*, 2016).

However, more important innovations come in replacing the entire process of concrete production and cement extraction through more biological processes. Learning from coral reefs, this approach relies on the method of biologically grown materials using living organisms to bind aggregates together in a strong and durable composite that simulates the performance of concrete (Iezzi *et al.*, 2019). Examples such as the bio cement material, patented by Biomason, remove entirely the energy needs and heavy carbon footprint of traditional cement burning processes (Biomason, 2020). Using site-sourced aggregates, natural bacteria as a binding agent and a water medium, the resulting cement-like material is strong and durable and uses ambient temperatures only for its curing.

5. Material applications in concrete, a local potential?

Scrivner *et al.* (2018) note that the relatively low cost of cement production worldwide shows that it is essentially a "local material produced close to the site where it is used." However, they indicate that due to stringent international standards, innovation in cement production becomes constrained. They suggest that concrete production needs to become more adapted to local raw materials and locally relevant modes of production to radically reduce its environmental footprint.

Looking at the case of Lebanon, the built environment in its vast majority relies on concrete and cementitious products as main material systems by far. The wide use of concrete has had a major implication on the natural environment as quarries, especially uncontrolled and illegal ones, destroy major parts of the mountains and natural environment (Public Works Studio, 2019).

Demand for concrete and cement in Lebanon had been increasing consistently since the early 1990s, peaking at around 5.5 tons of production in 2016 (BLOM Invest, 2018). Although this number has been gradually decreasing, more so in 2019 and 2020 due to the local economic crisis, the sector's implication on CO2 emissions remains high. In a 2015 report by the Ministry of Environment, data show that the cement industry contributed to more than 95% of CO2 emissions produced by major local industries (MoE/UNDP/GEF, 2015).

The problem is not only the demand for concrete but also the lack of available sustainable practices that rethink how concrete is being used and how it can evolve to be a more sustainable material with environmental performance. Local cement companies list their aim for sustainable production and practices to reduce their carbon footprint, suggesting the use of alternative fuels, more efficient burning processes, and the use of waste byproducts and alternative raw materials. However, these initiatives remain at a development stage, with little seen repercussions on the built and natural environments.

For that, there is an urgent need for more critical applications using concrete in Lebanon and more research and development to happen between academic institutions and the industry. Potential collaborations between the two can also impact local advancements greatly in the field and help ameliorate the impact on the environment. This needs to happen with different approaches, through sustainable production processes, but also through innovation in material, fabrication and design.

6. Methodology and process

I have thus presented different notions that affect the design and material practice today, and how the processes of digital fabrication and using nature as design reference have both shifted toward a tactile and hybrid materiality with a concern for environmental urgency. I have focused on concrete as an essential local material that requires urgent alternatives and presented different approaches to more sustainable applications in concrete that rely on advancements in fabrication.

These notions form the framework through which I have developed the course New Territories, a senior professional elective in Architecture, that uses an applied design research method to develop innovative environmental applications for building products. This bottom-up approach engages research, trial and error, material testing, and digital tools and prototyping. It relies on the back and forth use of analog and digital tools in an iterative design process, using concrete and hybrid composites to design novel applications.

This type of methodology falls under the "design as scholarship" method, as an open process that follows a research trajectory on materiality (Brown *et al.*, 2013) where "material experiments are broader in nature with the aim of revealing unanticipated applications" rather than strict performance criteria. The research in the classroom is conducted as a studio laboratory, where an experiential learning through making is key. The research posits the following question: how can we design more environmentally performative building products in concrete using an applied process that intersects hands-on, material and digital fabrication?

All the resulting projects that will be described in the following sections followed the below phases in their design process:

(1) Research case studies, composites of concrete and natural behaviors;

(2) Focus on a site-specific environmental problematic;

(3) Work with concrete mixes and composites (in coordination with the engineering concrete lab);

(4) Develop a digital model for the formwork;

(5) Fabricate using CNC or 3D printing;

(6) Cast and assess;

(7) Optimize the digital design and refabricate the formwork;

(8) Optimize the mix;

(9) Develop the final prototype

In the different experiments in concrete conducted over the years, three main trajectories or lines of inquiry emerged, each one approaching materiality, digital fabrication and enhanced environmental characteristics from a different position. The first trajectory relies on fluid material experiments and flexible formwork as a design process. The second focuses on hybrid integration of organic or inert materials to produce design products with bio-performance. The third involves using the fabrication process itself as a design generator for more sustainable processes and applications.

6.1 Flexible formwork and light weight composites

The first trajectory involved the use of concrete lightweight composites, through form-finding techniques and fluid material properties, bringing in flexible formwork into the digital fabrication process. Student groups explored concrete plasticity and behaviors, as they worked on the design of an exterior urban seating using digitally produced molds. Two main projects formulated two main approaches within this trajectory.

In project 1, the students worked on an elastic concrete mix and a tensile stretched fabric mold to produce a thin concrete seating surface, with centralized zones of depressions and mounts, directed by functional and ergonomic requirements. They experimented with fabric casting at various scales, using tension, gravity and materiality to develop their designed surface. Their design shifted between digital analysis and modeling, and physical tensile experiments. In parallel, they tested concrete and plaster composites, using gypsum, acrylic polymers and cement mix (based on an initial material research on Jesmonite) to produce various material tests ranging in strengths and plasticity. Their objective was to create a more versatile and elastic concrete mix that can respond to the flexible fabric formwork. As such, different compositions of the concrete acrylic mix were tested to reach the most optimal results. Their material studies allowed them to move up to a real-scale installation, using the fabric formwork casting method, with wire mesh and a carbon fiber sheet to support the cast. The fabric-formed process enabled using the force of gravity to cast the surface's form inversely and also to cast it as a thin cross section of 7 cm, helped reduce its weight further (Figure 1).

In project 2, the students utilized light aggregate substitutes and foam formwork to cast a topographic modular seating, starting from the turtle shell analysis as a hexagonal structure, where material, form and structural integrity are interlinked. After their analysis, they formed a modular hexagonal system of their own, where variations in the top surface of the unit created varied seating positions. In their material mixes, the students worked with foam spheres and inflated balloons to hollow the body of the concrete seating and decrease its weight. Their material experiments further focused on variations of textures and elasticity of

Figure 1.
Fabric formed concrete with acrylic composites (Henri Asmar, Tina Najia, Fayssal Yatim)

their concrete mix, using stronger mixes for lower parts of the mold and more elastic mixes, enabled by the use of acrylic, for top layers. The design was developed digitally to produce the cast formwork, which was then CNC milled in foam and wood panels. The formwork was further lined with acrylic sheets to form the hexagonal sides, with the seating surface milled in extruded polystyrene to provide a textured finish. The resulting seating system was formed out of stacking the different hexagonal modules (Figure 2).

6.2 Bio-performance materials

The second trajectory focused on bio-composites and material experiments, working with hybrid concrete mixes and using digital fabrication to create performative cladding systems that actively respond to air pollution. The interest was mainly in addressing critical urban and environmental issues through these materials and to bring awareness to the imminent problems of air pollutants in Beirut. Following the research methodology, the students researched local pollution and material case studies, experimented with concrete composites, relying on digital and hands-on trials to develop their cladding prototypes.

Project 3 focused on the use of photocatalytic concrete to design adaptable façade louver systems that directly absorb air pollution. The students built upon locally available louver products to develop more efficient and novel applications that can adapt to new or existing constructions. They became thus interested in photocatalytic concrete and its ability to absorb N02 in the air and reduce debris through a unique chemical reaction induced by titanium dioxide and the sun's incidence (Sopov *et al.*, 2020). The students developed their formwork through digital modeling and integrated the process of physical testing to optimize the performance of their louver system. Their system was designed as an L-shaped module that creates various façade patterns through different combinations, positioned in a diagonal direction to cater for various shading needs. The system can be adapted to existing or new constructions and helps create effective shading in front of large glazed facades. Through the use of photocatalytic concrete, the resulting cementitious material maintains a clean surface and further captures nitrogen dioxide pollutants from the surrounding air. To enhance the performance of their system, the students focused their design efforts on creating the most

Figure 2.
Hexagonal prototypes with foam formwork and inflated balloons (Tracy Bou Zakhem, Ghida Chehab, Nour Hajj, Ismail Hutet)

efficient louver form that has its surfaces directed toward the direct sunrays. They integrated small surface undulations that increase this surface area of contact by 70%, similar to solar vacuum tubes. This was achieved through the fabrication process itself by using CNC milling to generate the rough striations in the mold through the milling bits size. Their mix further included fiberglass for reinforcement and Styrofoam pellets to reduce its relative weight (Figure 3).

Project 4 was developed as a system of modular urban cladding that can reduce air pollution at the urban street level and focused on the Beirut Corniche area with its heavy car-generated pollution and active pedestrian activities. Their research expanded on work done by Biota Lab (Cruz and Beckett, 2016) and referenced the latter's experiments in composites of concrete and moss; the moss actively helps by absorbing CO_2 concentration in its vicinity in addition to releasing oxygen. The students further looked at aerated concrete techniques and experimented with additives to create lightweight pockets in the pour while adding phosphate magnesium to lower the pH level of the concrete mixture, and thus allow for better moss growth. Their design approach was informed by the naturally occurring geometry of the Voronoi cell to create pockets and cavities of varying sizes in their cladding system. After analyzing sun and shade incidence on their select urban wall, the students defined parameters of cavities size and depth to allow for better moss growth. The top part of their system, with the highest exposure to direct sunlight, was made of small cavities to reduce sun incidence and optimize shade and moisture for moss growth. The cavities at the base were larger allowing higher water capture and enhancing the growth of the moss. Their design was iteratively developed and tested digitally, then transferred through CNC into a foam mold. The resulting cast formed a portion of the cladding system (Figure 4).

6.3 Fabrication as a design generator

In the third trajectory, the process of fabrication and the formal design method were the main instigators for the design solutions. The form was not entirely premodeled but rather relied on the actual fabrication process and physical prototyping to produce the shape. Within the process, clay 3-D printing was integrated to simulate the behavior of concrete in an additive fluid deposition process.

Project 5 focused on porous concrete pavers as a system that allows water infiltration into the ground, reduces water run-off in urban streets and includes rainwater collection for irrigation needs of green surfaces. The design was developed as a smart urban paving system that integrates seating, greenery and walkways along a widened pavement area in Beirut. It was developed as a smooth surface with varying dips and hills, subdivided into a modular triangular grid that is prefabricated and assembled together on site, replacing existing urban pavers. The students first experimented with various mixtures of porous concrete, using lightweight and foam-based aggregates of various sizes, and tested their water infiltration rate. However, as they progressed to clay 3-D printing, they realized that porosity can be achieved through the material extrusion itself as varying material viscosities and printing speeds can generate voids and cavities in the resulting print. The clay 3-D printing process was thus used to simulate real-scale concrete fabrication and to generate varying degrees of porosities and surface qualities (Figure 5). The design of their system, therefore, integrated this porosity to enhance the water infiltration performance of their urban paving system. The resulting triangular modules had varying degrees of porosity that were controlled by the speed and the thickness of the printed layer of clay. The modules were then stacked together to form the urban sidewalk system, with water collection and irrigation systems integrated within, helping maintain the incorporated greenery.

Project 6 was concerned with the Syrian refugees' crisis in the Bekaa Valley and the need for immediate protective shelters that can withstand the harsh weather conditions in the area.

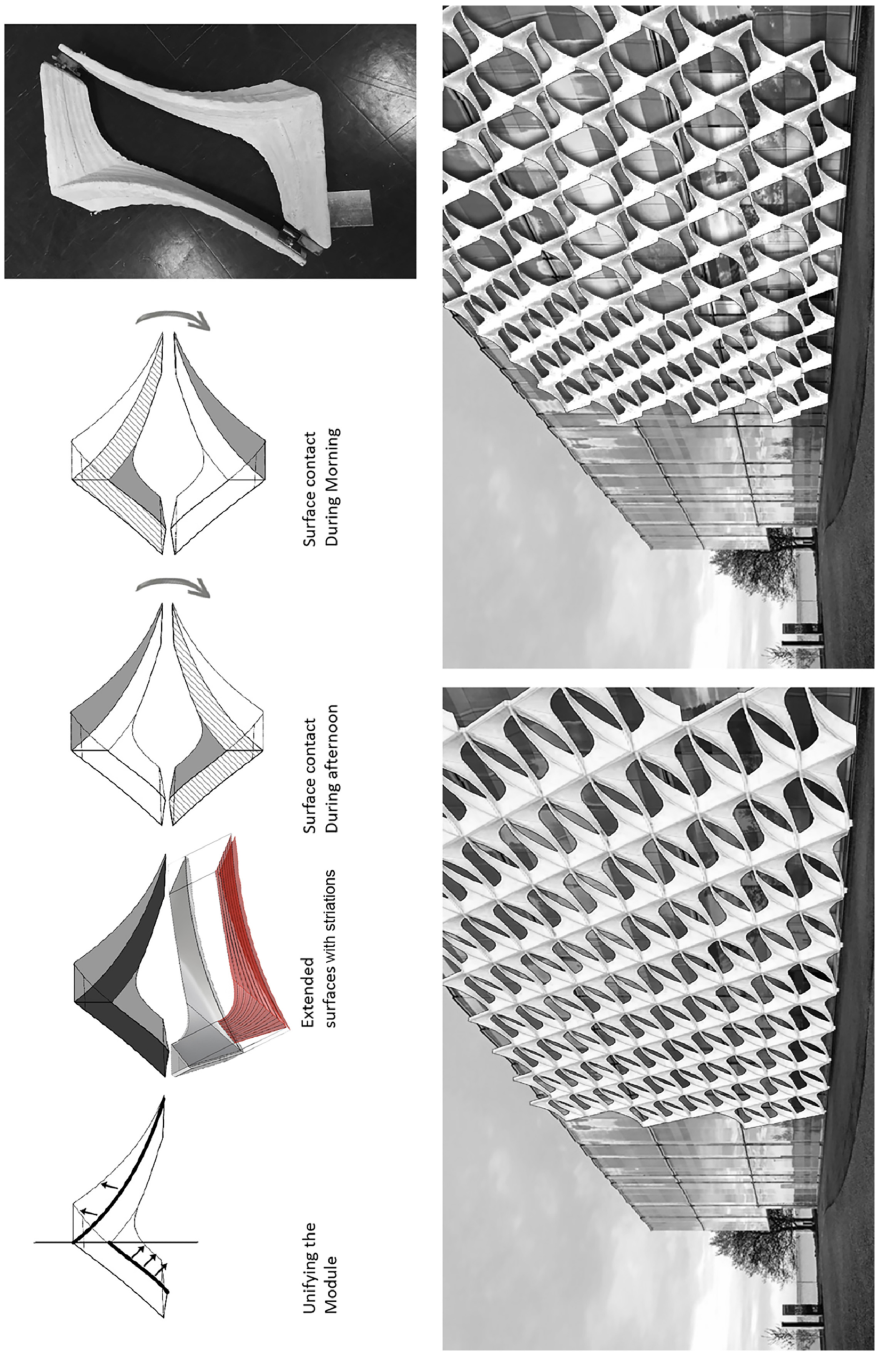


Figure 3.
Photocatalytic concrete louver system (Christelle Ayle, Christelle Hallak, Najla Hassanie, Joseph Jadam)

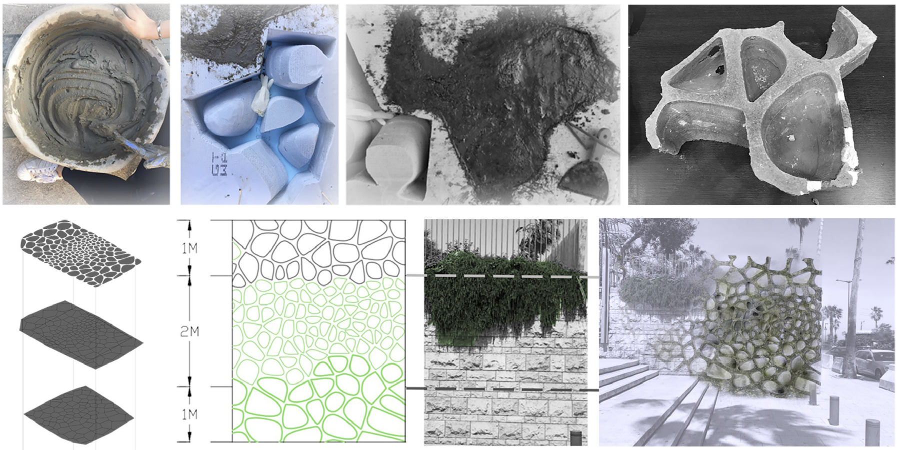
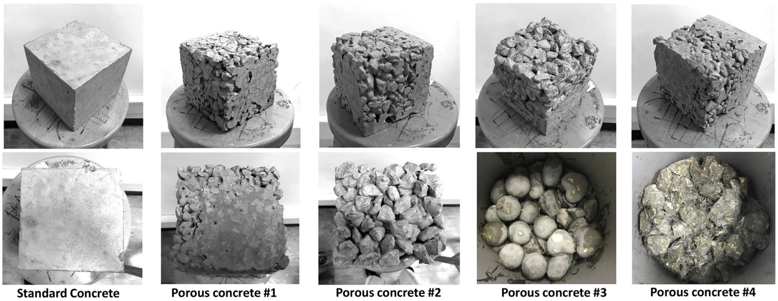


Figure 4.
Bio-moss cladding system (Faisal Annab, Taha Barazy, Hiba Hage, Manar Khatib)



	Sand	Medium Gravel	Small Gravel	Cement	Water	Styrofoam	Fiber Glass & white glue
Standard concrete	I	-	-	II	-	-	-
Porous concrete #1	-	-	I	I	I	-	-
Porous concrete #2	-	I	I	I	I	-	-
Porous concrete #3	-	II	-	I	I	-	-
Porous concrete #4	-	I	I	I	I	I	I

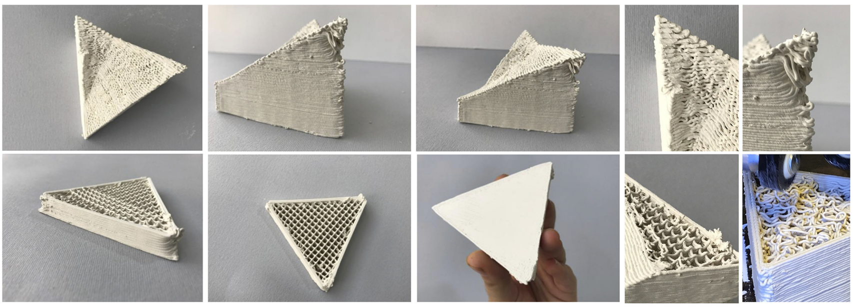


Figure 5.
Porous concrete tests with clay 3-D printing (Sarah Abiad, Reem Al-Awar, Yasmine Atoui, Soraya Hachem)

The students set out to design easy-to-assemble shelters through innovative concrete blocks that can be stacked together to form quick shelters while addressing issues of durability, comfort, security, sustainability and cost efficiency. Their investigations began by looking at examples of modular lightweight cement blocks with the objective to invent a new block type that can directly generate the shelter's form and provide high efficiency in its construction. To enhance the sustainability of the blocks, the students looked at aggregate and fiber replacements in their mix, through locally available waste materials.

Through research, the students became inspired by the traditional Musgum mud huts from Cameroon, which are conical shaped dwellings with an inherent structural capacity and an insulating thick wall, similar to shell structures found in nature. Their design elaborated on this conical form and resulted in a dome-like shelter with a central top opening for ventilation. A tessellated pattern was projected on the dome and formed the base grid for the modular block system. The new "hut" would be fabricated from the resulting diamond shaped blocks, stacked above one another with a locking compressive joint. To produce these blocks, the students experimented with various mixes and composites of concrete, trying to reduce the heavy aggregates in the mix and to replace them by lightweight alternatives. To make the mix more sustainable, they researched different types of local waste byproducts, such as chip wood, sawdust, wood bark and plastic fibers, as potential aggregates replacement. Their aim was to integrate waste in an up-cycling strategy, reducing cost and increasing the efficiency of their modular blocks. Their different material experiments produced a variety of potential composites with different block weights and consistencies. Their final variation relied on plastic waste fibers, locally sourced from grocery bags and Styrofoam pellets (Figure 6).

7. Findings and outcomes: potential applications

The resulting work over the years has been grouped under the aforementioned three lines of inquiry to depict the different resulting approaches to concrete applications in the course. The outcomes generated through this work can be divided into two main outcomes:

(1) Findings related to the design and making process;

(2) Outcomes and potential applications for the designed products

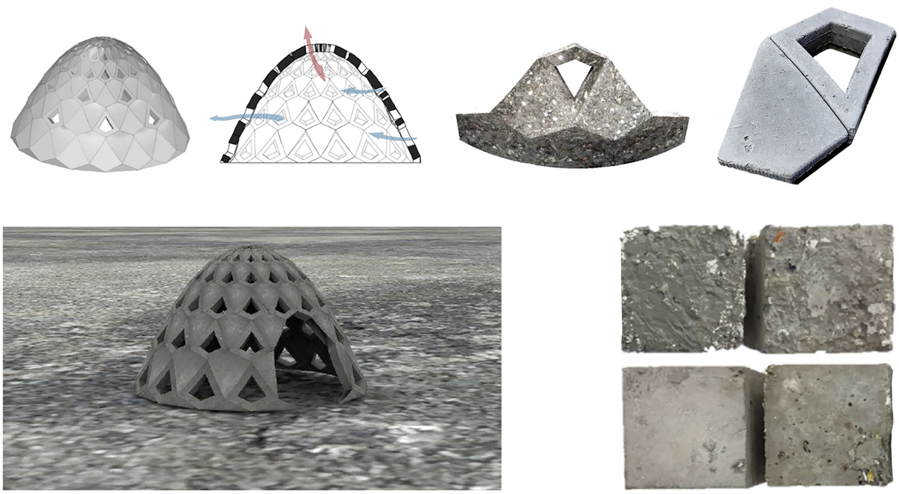


Figure 6. Shelter assembly with composite concrete blocks (Karen Asmar, Lana Barakeh, Souha Bou Matar, Omar Darwiche)

The design process itself brought forth findings and learnings that impact the design outcome. One key finding is the understanding of the knowledge shift that happens between the digital model and physical prototype; this includes noting the material constraints and behavior of concrete while re-embedding these constraints in an optimized version of the 3D model. This also includes understanding the constraints and limitations of the machine used for fabrication and how it affects the resulting product in order to integrate this limitation in the design. Going back and forth between digital modeling and physical prototyping thus results in a more precise and optimized outcome. This is illustrated in project 3 where the CNC milling constraints, the size of the milling bit and resulting first prototypes dictated the final design of the louvers, their shape and size of the striations to reach an optimal surface area for N02 absorption.

Another important learning is that in such an open-ended process, errors are typically good; the errors that might occur in the prototype such as material defects or changes in formal alignments can result in unexpected and often more performative outcomes. It is important to understand these “errors” and to use them to feed back into the design process. Project 5 utilized the emerging formal errors that resulted from 3-D printing with clay to rethink their design completely. As their interest was to develop porous concrete, the gaps and voids that emerged in their prototype from the clay printing process and material behavior, led them to pivot their design. Their previous iteration relied on creating a concrete mix that allowed porosity through the foam aggregates in it. This change toward using the 3-D printing process itself through varying the speed of the material deposition and the viscosity of the clay resulted in porous three-dimensional pavers. This was only simulated in clay; however, more testing is necessary in the future in composite concrete mixes.

Additionally, learning from the material mixes and types of formwork used in the process can also result in more performative designs. Aspects such as elasticity and surface texture of the cast concrete composite can lead to more applicable design outcomes. Projects 1 and 2 both explored these variations of surface results through their different material trials and formwork. Project 1 focused on elasticity and the fabric used for the formwork to manipulate the resulting form, seating positions and surface textures. Project 2 used different formwork materials from smooth plywood for the side surfaces, to foam and stepped wooden top, in order to vary the resulting surface finish from glossy to matte to ribbed for sitting locations.

In addition to the above findings that impacted the design process, each of the projects presents different design and performative outcomes with potential for local applications.

Project 1 results in a versatile surface-shaped design that can adapt to different contexts, seating and types of gathering requirements following ergonomic guidelines. This is optimized by the method of design used by manipulating a fabric formwork using gravity. Furthermore, the project offers cement content reduction through the thin surface cast it generated and through the concrete composition that relied on an acrylic, gypsum and cement mixture while using wire mesh for strengthening.

Project 2 creates a modular seating system that has the flexibility to be multiplied and adapted to different contexts. It uses a straightforward casting method with cheap formwork that enables variations of surface textures. To reduce the volume of this cast, the inflated balloons, strategically positioned within the mold, radically reduce the concrete volume, cutting it by almost half while maintaining the module’s structural consistency.

The louver system developed in project 3 has the potential to be applied to different existing glass facades as an add-on system that optimizes both shading needs and urban pollution extraction. The design itself can be positioned and grouped in different arrangements to better respond to sun shading or visual needs. Furthermore, the embedded striations developed as part of the louver surface through casting also show a design aspect that allows a higher surface area of 70% and corresponding pollution absorption rate by the louver.

Project 4's design raises the potential for urban cladding at the street level to become environmentally efficient and to reduce CO2 concentration by the optimized shape of the designed cavities that enhance moss growth. The concrete bio-moss module can be applied to any street level façade in areas with critical pedestrian activities and high vehicular emissions and can enhance the street experience through an oxygen-generating green aesthetic.

The paving system of project 5 creates a 3-D urban pavement that allows various activities to take place, and to collect water for urban irrigation needs. The *in situ* potential of the concrete 3-D printing process can result in more customized options rather than repetitive prototypes, adapting to the specifications of the urban context. The innovative application is further observed in using the process of 3-D printing to produce the porosity in the design outcome, reducing the reliance on aggregates.

Project 6 creates a dynamic modular Concrete Masonry Units (CMU) block that enables rapid and cheaper construction with the direct integration of joints and openings. The design also helps in locally upcycling waste by-products and to reduce concrete reinforcement and cement content by replacing aggregates with waste materials.

The different project outcomes thus remain as experimental design solutions, which are assessed through research and initial testing; however, more scientifically proven testing in future phases to verify the results and exact environmental performance capability is still required. Further testing in coordination with experts and engineers would be key to reach verifiable products. Potential testing includes the exact reduction of cement content, measuring precisely the pollutants' absorption rate, and verifying compactness, strength and water absorption of the resulting concrete modules. The design experiments presented here however do offer a potential to link such academic work to industrial applications, which through further development can be turned into market-ready building products.

8. Conclusion

The applied research and design process pushed the students to consider an environmental and design problematic in an open-ended fashion, to approach it as an opportunity for experimentation rather than as a problem-solving endeavor. The gained know-how in both digital and physical methods of making, with all the associated constraints and results, was more significant through the process itself rather than the final outcome alone. The research presented the students with the opportunity to gain innovative and thorough understanding of the correlation between environment, materials, technology and design.

The design objective also positioned the need to rethink local concrete applications and to apply new knowledge production at the level of innovations in building systems and their design to enforce more sustainable changes for the built environment. The research and design methodology tried to show the persisting importance of material knowledge while engaging with advanced digital fabrication, and the significance of learning from natural systems and biological properties to embed an active performance in today's design process. Through the coursework, the process further projects an essential responsibility on the new generation of designers to address critical, environmental and local issues through design and to benefit from advancements in technology and the design field at large to push the boundaries of making.

With the proliferation of digital fabrication techniques, a continuous awareness of the tactility of material and the necessity for environmentally innovative applications remain crucial for an informed, locally relevant and critical design process.

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