

Towards Functionally Graded Bio-Composites in Additive Manufacturing

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Anthropogenic greenhouse gas emissions warming up the Earth's atmosphere and triggering a climatic shift around the world evidence how the construction industry must provide a resilient built environment for an increasingly growing population, while at the same time reduce the use of cement and the demand for energy use from heating and cooling in an intensely urbanized world.

Construction using Additive Manufacturing (AM) has gained traction in recent years, promising benefits such as: reduction in waste, building time, and need for formwork; customization and fabrication of complex geometries at no extra cost; and the reduction of human labor and on-site hazards. While most implementations of AM use cement as a primary material, development of alternative technologies that use earth-abundant, low-carbon renewable materials can be seen in projects such as Gaia by WASP, as well as efforts from the Institute for Advanced Architecture of Catalonia (IAAC).

As a research framework, this project extends the efforts of building with renewable materials by developing a Functionally Graded Material (FGM) 3d Printing technology to create a bio-composite wall using lime, clay and hemp bast fiber. Unlike traditional, singular material deploying AM technologies, FGMs are a type of composite that use different materials according to where they are needed, with gradient transitioning between the materials to achieve non-discrete interphases. We work under the hypothesis that FGMs can achieve better strength-to-weight ratios than regular ceramics, and at the same time allow, through the 3d printing process, for an expression of the functional requirements of material change through form. While used in fields other than architecture, FGMs in AM have yet to be implemented in building construction.

INTRODUCTION

The construction and operation of buildings, including material extraction and manufacturing, have been responsible for up to almost forty percent of global energy-related CO₂ emissions as well as for thirty-six percent of global final energy use. When looking at materials used today in the building sector,

an increase of seventy four percent in cement-related material extraction between the years 1900 and 2005 illustrates an ongoing increase in demand. This demand is expected to double by 2050 mainly due to the urbanization process that we are currently witnessing across the globe. Today, most buildings at a global scale are built using cement, sustaining an industry that is the second largest emitter of CO₂ with 900kg of CO₂ per ton of cement produced. A global surge in population creates today an ever higher demand for energy and materials for buildings.

Additive Manufacturing (AM), a process in which material layers are deposited to accumulate three-dimensional objects, was introduced as an alternative to extant models of construction in the late 1990's with Freeform Construction, where instead of a typical assembly of parts or casting processes, sand layers would be glued using a paste made with Portland Cement. Contour Crafting followed, in which formwork was created using two layers, and smoothed during their deposition using a crane-mounted extruder with a trowel. Other early technologies include Concrete Printing where high-performance concrete was deposited from a crane-mounted extruder, and D-Shape in which a binding agent was deposited in order to solidify sand contained in a large bed.

Today, large scale Additive Manufacturing (AM), promises benefits to construction such as a reduction in the use of formwork and scaffolding, construction time, generation of construction material waste, the need for skilled labor, and potential hazards. Traditional supply chains could be replaced, potentially reducing the costs and emissions required for the transportation of end product delivery. A review by Camacho et al. shows cementitious materials as the ones most commonly implemented in the AM construction industry, mainly using Portland cement, which provides mechanical properties that are reliable and suitable at a low cost. Mechertine et al. categorize concrete extrusion processes depending on the filament size while Paolini et. al categorize the integration of reinforcement. The following examples serve as a case in point: (i) *The Office of The Future*: this is the first office building manufactured using modular prefabricated concrete; (ii) *Ynhova*: a social housing project employing filled formwork was fabricated by extruding two layers of polyurethane foam that serve as insulation and formwork for a self-compacting concrete interior.

Seeking to reduce cement use in Additive Manufacturing, sustainable materials such as clay have emerged in research as a base material ingredient that can be reinforced with other elements, as can be seen in: (i) *Gaia*, a house by WASP whose walls are made up of 25% soil from the site (made up of 30% clay, 40% silt and 30% sand), 25% rice husk, 40% from chopped rice straw, and 10% hydraulic lime; (ii) *Digital Adobe*: a clay printed wall fabricated at the IAAC that measures 2m wide and 5m high, and has a thickness of 70cm at the bottom and 20cm at the top that had the ability to modulate thermally its cross section.

FUNCTIONALLY GRADED ADDITIVE MANUFACTURING (FGAM)

In this paper we propose a design-to-construction research framework that incorporates Functionally Gradient Materials (FGMs) (An FGM material is a kind of composite where material composition is determined locally based on the performative requirements at a given position in space within a monolithic piece, while the material transitions occur through a compositional gradient.) as a newly developing Additive Manufacturing (AM) technology for building. With FGAM the capacity of AM to produce structures without assembly is extended to include local variation of material composition. Contrary to conventional composites, in FGMs the interface where two materials meet is replaced by a gradient, a quality that increases the piece's ability to withstand extreme conditions without delaminating; this presents a significant advantage over traditional composite materials. Examples of propositions for FGM in architectural applications include: (i) Tsamis' Chunk, a building skin prototype designed in VSpace, that exhibits qualities of structure, insulation and transparency within a monolithic building skin; (ii) The Aguahoja Pavilion: a water-based, 16-feet tall flexible bio-composite structure made of cellulose, chitosan, water, and pectin that can dissolve in water at the end of its life; (iii) Material Blending Simulation Using Particle Systems: Grigoriadis demonstrates a design approach for FGMs in which material properties are assigned to particles, simulating gradient blending within the architectural element. While these projects present compelling ideas, none of them seem to be viable as building technologies for construction.

Our framework precisely articulates this proposition. How can FGAM become a viable alternative to current methods of construction? What are the necessary steps and areas of inquiry that need to be developed in order for this new material method to be transferred to mainstream building technology? This framework consists of three distinct areas of inquiry that although presented independently and in many ways still under development, are mutually informed and interrelated. These areas are: 1. Design of an FGM building construction system, 2. Design of an FGM additive manufacturing technology and 3. Design of an FGM mixable material palette.

DESIGN OF AN FGM BUILDING CONSTRUCTION SYSTEM

A cursory glance at any "fundamentals of construction" publication (For example, see: Allen, Edward and Joseph Iano. *Fundamentals of Building Construction: Materials and Methods*. (New York: Wiley, 1999).) taught in architecture schools today reveals a plethora of constructions details and building systems addressing typical materials such as wood, concrete, masonry units or steel. Although large scale Additive Manufacturing has not reached the school manuals yet, a pattern seems to be forming. Current high-performance cement based AM details consider a wall section as having an outer and an inner layer of continuous material while its thickness is usually infilled with a variant of a hatch pattern made from the same material (figure 1. left). This general typology varies, sometimes having as additional infill a second insulation material or rebar for reinforcement - in most cases added as a separate construction process. It seems to us that this pattern is a direct relic of the additive technology developed for smaller scale printing (printing of plastic objects on desktop printers). Forced to become "architectural", this general building system typology does not address adequately the complex performative characteristics of contemporary building structures.

A PRELIMINARY FGAM BUILDING SYSTEM

In order to demonstrate principles for design, we chose two fundamental building elements, structure and insulation, as the beginning point. What would typically be an assembly of distinct parts or materials, here becomes a gradient distribution of heterogeneous material whose properties vary within the thickness of a wall section according to structural and environmental parameters (figure 1. right). Initially, lines of compression stresses where "sketched" (These lines could be designed, optimized, calculated and so on... depending on the specificity of the structural condition.) as continuous 3-dimensional vectors that carry loads (figure 2. top left). We assume here a structure similar to a continuous "liquid" space frame. These vectors were designed with continuity in mind. Insulation on the other hand is calculated as a material "offset" from structure. We developed an algorithm that offsets in space incremental layers of insulation. The purpose of this algorithm is to ensure material continuity in space for both structure as well as insulation. Depending on the specific thermal requirements, insulation would be present in the form of smaller or larger material pockets, whose arrangement, size and thermal characteristics could vary either vertically or horizontally along the wall. At the same time, structural thickness could also vary, not only in a homogeneous way, but also discretely, as well as could the overall wall section, becoming thicker to provide for higher structural or thermal needs whenever needed.

Figure 2 shows increments of material change from structure to insulation at various intervals. Percentages (100% - 0%) indicate the amount of structural capacity within the material mix at the given areas in space. It should be noted here that the specific design is without context. It is one possible generic building system detail. In order for it to be further developed,

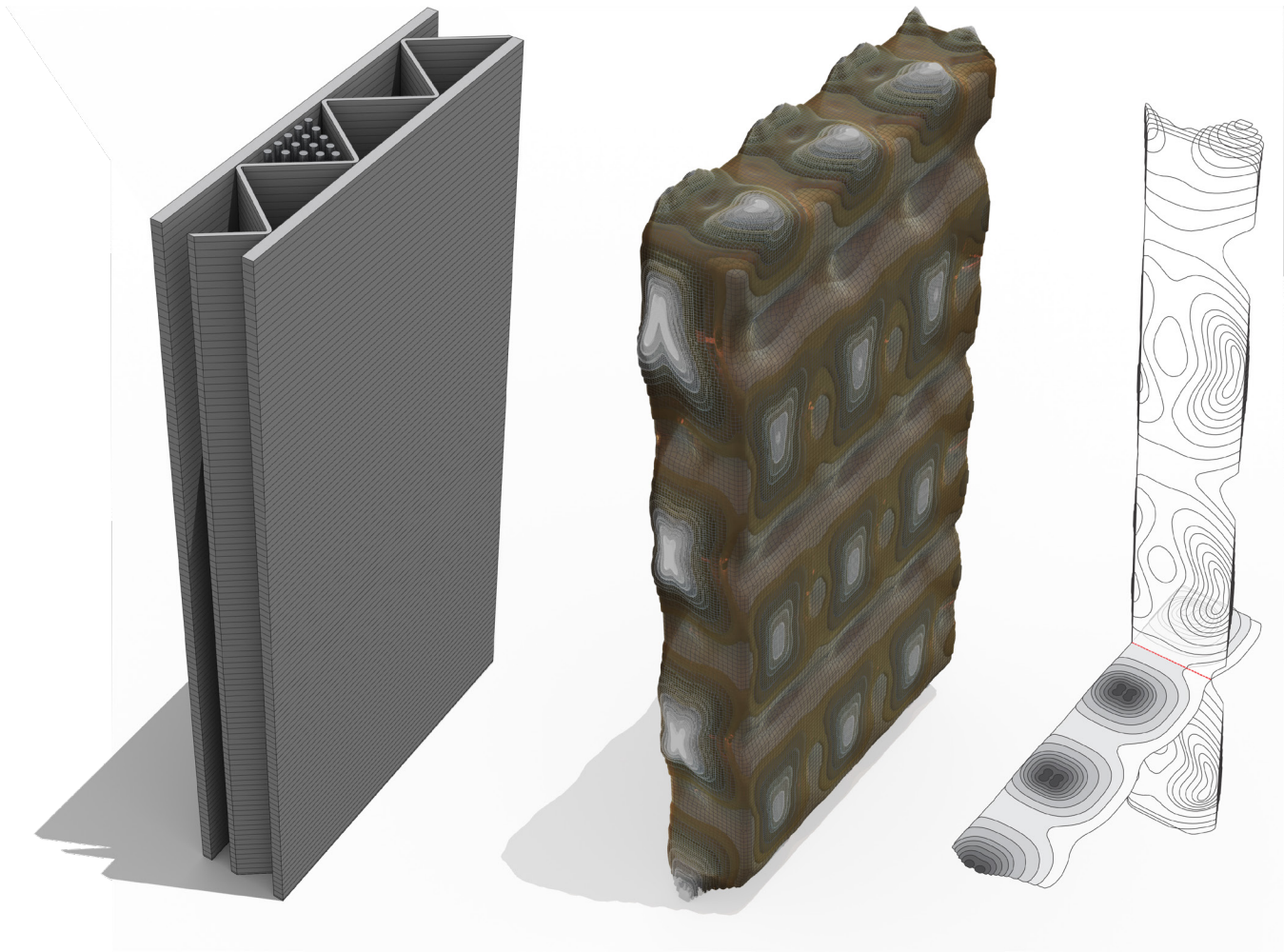


Figure 1. Generic conventional AM building system (left), and generic FGAM building system (right).

a multi-objective design process could be implemented, so that a responsive climatic design, structural needs, material optimization, and form could be concurrently addressed. At the moment this is only a “scaffold”. Key questions like how to “turn the corner” or “how to integrate an opening” are still open. Furthermore, specific material “offset” characteristics would have to be determined according to the specific printing technology used or physical characteristics of the specific materials to be deployed as we will see in the following sections.

DESIGN OF AN FGM ADDITIVE MANUFACTURING TECHNOLOGY

Typically, large scale Additive Manufacturing is based on a **single material** extruding technology. Other more experimental, multi - material extrusion processes are currently being investigated. For example, the Aguahoja project, utilizes an extruder that is comprised of 6 different containers of materials, each controlled by a pump. In this case, one of six variants of the chitosan based bio-composite is deposited when functional requirements demand it. Although this specific technology

can deposit multiple materials within the same model, it can only print one consistent material variant at a time (per line segment). For example, in the case of the six distinct materials (M1, M2, M3, M4, M5, M6), the Aguahoja technology deposits one of them (ie.M1) while travelling from a point A to a point B. Hence, from point A to point B, the mixture remains consistent and therefore a gradient transition is not possible.

A principle characteristic of FGM composites is that two or more materials are continuously blended in order for gradient transitions to be achieved between them. For this reason, we have developed a new type of mixing technology extending a more experimental process that was outlined in 2010 by Tsamis with his project Cast_it.

Our Building System employs two performance characteristics, structure and insulation. For this reason, we have developed a print head that is comprised of two numerically controlled extrusion containers that merge their respective materials into a third mixing chamber. (figure 3. Bottom right). Typically, in 3d

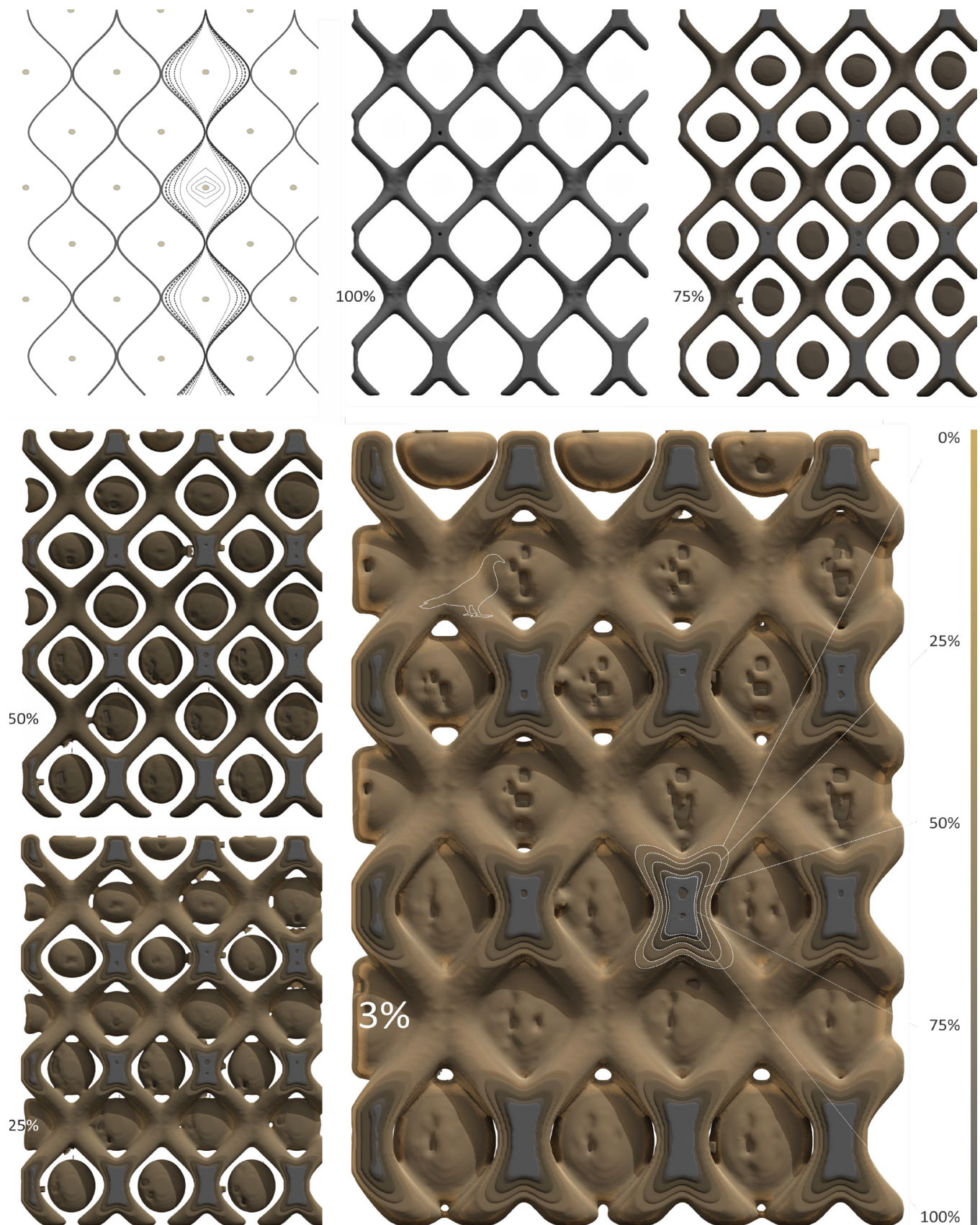


Figure 2. Material offsets from structural and thermal diagram.

printing the main mode of communication is through G-Code. (An ordered set of points that describes the print-head's trajectory (like in Contour Crafting) are fed into the machine sequentially. Generally, G-Code tells the print head to move from point A to point B at a fixed speed while depositing a fixed material at a constant flow rate.) As an extension of G-Code, we have developed a file format that stores, along with point coordinates for movement, corresponding concentrations for each material to be used. While the print head is moving from one point to the next, the flow of each material is accelerated or decelerated respectively to achieve the desired concentration at the target point. For example, for two materials M1, M2 and two points A and B, the information that is fed to the printer looks like this:

Point A (Xa,Ya,Za, 30% M1, 70% M2)

Point B (Xb,Yb,Zb, 10% M1, 90% M2)

Essentially, this translates to instructions that say: "go from point A to Point B at a constant speed in a linear or circular motion and while doing so decelerate the speed of extrusion of material M1 and accelerate the extrusion of material M2". A geometric representation on how the dynamic material mixing could be achieved through G-Code and the calculation process that would need to occur while processing the file is presented in (figure 3. top right). The acceleration and deceleration of each material can be precisely controlled to meet the desired volume amounts at each point in space.

For our first test we chose to use two clay materials of different colors in order to test the functionality of our hardware and software. In figure 3. (bottom left), we have identified a correct speed relationship between the extrusion motors and mixing motor in order to achieve homogeneously mixed material at the nozzle. On the top and mid left we have tested how "fast" and how "slow" a material mix can change from one to the other. These parameters would affect the way material "offsets" would be determined in the design above as well as lead the way to design actual performative materials for construction.

DESIGN OF AN FGM MIXABLE MATERIAL PALETTE

Unlike traditional materials research in large scale additive manufacturing which seeks to develop an Ultra-High Performance Cement or a clay equivalent, with FGAM the quest is not to develop a single material. Instead, we are looking to define chemically compatible material ingredients that, when mixed at different ratios, the resulting material can range in physical properties. For this project we chose Hydraulic Lime, Clay and Cement as materials that would serve as a matrix in a composite and Hemp Fibers and Hurd that would constitute the reinforcement or aggregate. (Clay and Lime were chosen as earth abundant and environmentally benign materials already used in construction, while Hemp was chosen for being the strongest natural fiber as well as for its well documented

in literature carbon sequestering abilities. Hemp in the form of Hempcrete is also used in construction.) Our material is a hemp-based bio-ceramic composite that is best represented as a range of possible combinations rather than a singular material. We call this a "Differential Material". (figure 5. Top left) In order to understand how physical characteristics of a Differential Material change along a gradient, we established a material matrix containing thirty discrete instances. Twenty-seven were made of a lime-clay binder, while the remaining three were made of a cement-clay binder. The gradient varied in: (i) binder composition in percentage of lime/clay: 20/80%, 50/50%, and 80/20%, and in percentage of clay/cement: 80/20% and 60/40%; (ii) hemp aggregate content: 20%, 30% and 40%; (iii) hemp gradation: fine (retained at screen #30), coarse (retained at screen #8), and graded (using a mix of fine, coarse and medium (retained at screen #16)). (Figure 4).

Since our initial design called for a "differential material" that grades between structure and insulation, our experimental procedure involved two different sets of experiments in order to characterize the hemp based composites both structurally and thermally. For the structural compressive strength tests, three 2-inch cubes were cast for each mix, to be tested in 7, 14 and 28 days of curing. A total of nine cubes per mix were required for Uniaxial Compressive Testing resulting in 180 distinct material samples tested (Figure 5). Tests were conducted with an MTS 810 Material Test System, using a 5,000lb capacity load transducer. Preliminary results showed that the amount of aggregate content has an impact on the compressive strength of the mixes, with 30% aggregate mixes being the ones with highest compressive strength proportional to the compressive strength provided by their matrix composition. Furthermore, from the range of material mixes, the strongest in compression showed a value of 118 psi – if this material would be used in the form of bricks, two parallel walls at 60 feet apart would be able to hold a typical wood frame floor and truss roof of a two story high building with a safety factor of 2.57 (per code a minimum of two is required) – while the weakest of materials showed compressive strength of 20 psi – able to hold its own weight.

As a second step in the characterization process we initiated a set of experiments to test the thermal diffusivity (an indicator of insulation performance) for 6 of the 30 mixes (We chose mixes that had higher levels of hurd content assuming these would be better insulators.) (figure 5. right). Two plates of ten-inch by ten-inch by one-inch were tested for each of the 6 mixes at sixteen and twenty-eight days of curing. The test was conducted by placing two plates parallel to each other and sealed from their environment inside an oven. After heat was applied on one side for a given time, the change in temperature in between the plates, or across the material, was recorded through 4 heat sensors positioned on each side of the plate. Preliminary results for thermal diffusivity of our 6 samples range between $a = 2 \cdot 10^{-7} \text{ m}^2/\text{s}$ and $a = 0.7 \cdot 10^{-7} \text{ m}^2/\text{s}$ with the lowest values representing a more insulative material. As a comparison, these

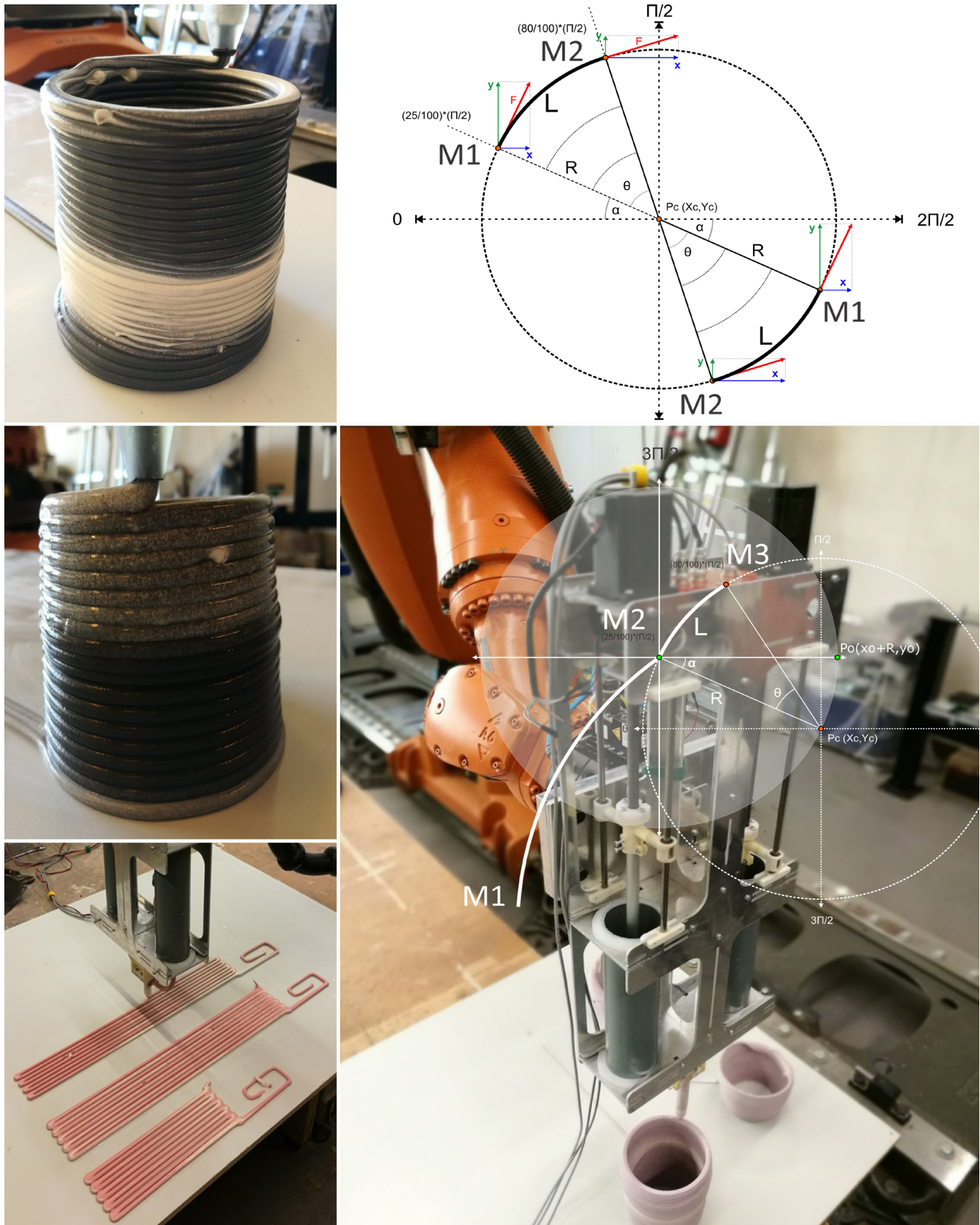


Figure 3. Machine design and tests for FGAM.



Figure 4. Matrix of 180 different material samples.

values range between those of Wood and insulation Cork. Some of the mixes could be used as Insulation, while others could be used in places where thermal mass is required but structure is not needed.

CONCLUSION

A process of characterization can include many more aspects of a material's performance. In the case of our differential hemp ceramic composite material, the ultimate goal is not to choose the perfect one. Instead our goal is to understand how each mix behaves in order to be able to determine its place in the wall section. All mixes within a range are candidates for a specific application within a wall section. As future work, we aim to make enough tests so that for the specific differential material we are able to produce a mathematical model that predicts its characteristics based on amounts of ingredients mixed. This would allow us to connect the specific differential material to our design process described above. However, perhaps the most important characteristic to be evaluated for this hemp-based composite is neither its ability to perform as part of a building nor its ability to be processed from the AM machine. Instead it is its ability to perform on a broader larger context: the planet.

A rigorous environmental evaluation requires specific system boundaries and context-based parameters to be established such as electricity generation methods, local manufacturing practices, transportation means, and the distances that the materials must travel to reach the construction site. Although we would need to take many more steps to be able to determine with certainty how this building system would perform, the results from the embodied energy calculations for the 30 material mixes show that, in comparison to other insulative materials such as mineral wool (16 MJ/Kg) or EPS foam insulation (111.6 MJ/kg), and to structural materials such as hollow concrete block (1.1 MJ/kg), cement (3.7-5.8 MJ/Kg), the sample in our differential material with the highest embodied energy has a very low embodied energy value of 0.742MJ. Furthermore, in order to estimate the difference in embodied energy between a conventional AM and the proposed FGAM building system, the two wall sections considered to have a volume footprint of 1.0m x 2.0m x 0.20m (figure 1): (i) the conventional AM type consisted of two 0.03m thick layers, connected to each other through a diagonal infill of the same thickness; (ii) the FGAM bio-composite wall consisted of a space frame, that grades in a stepped way into a series of ellipsoidal insulation mix pockets, with a total of five different mixes. The result of the embodied energy calculation for the FGAM wall was 267.98 MJ, including the energy required for processing

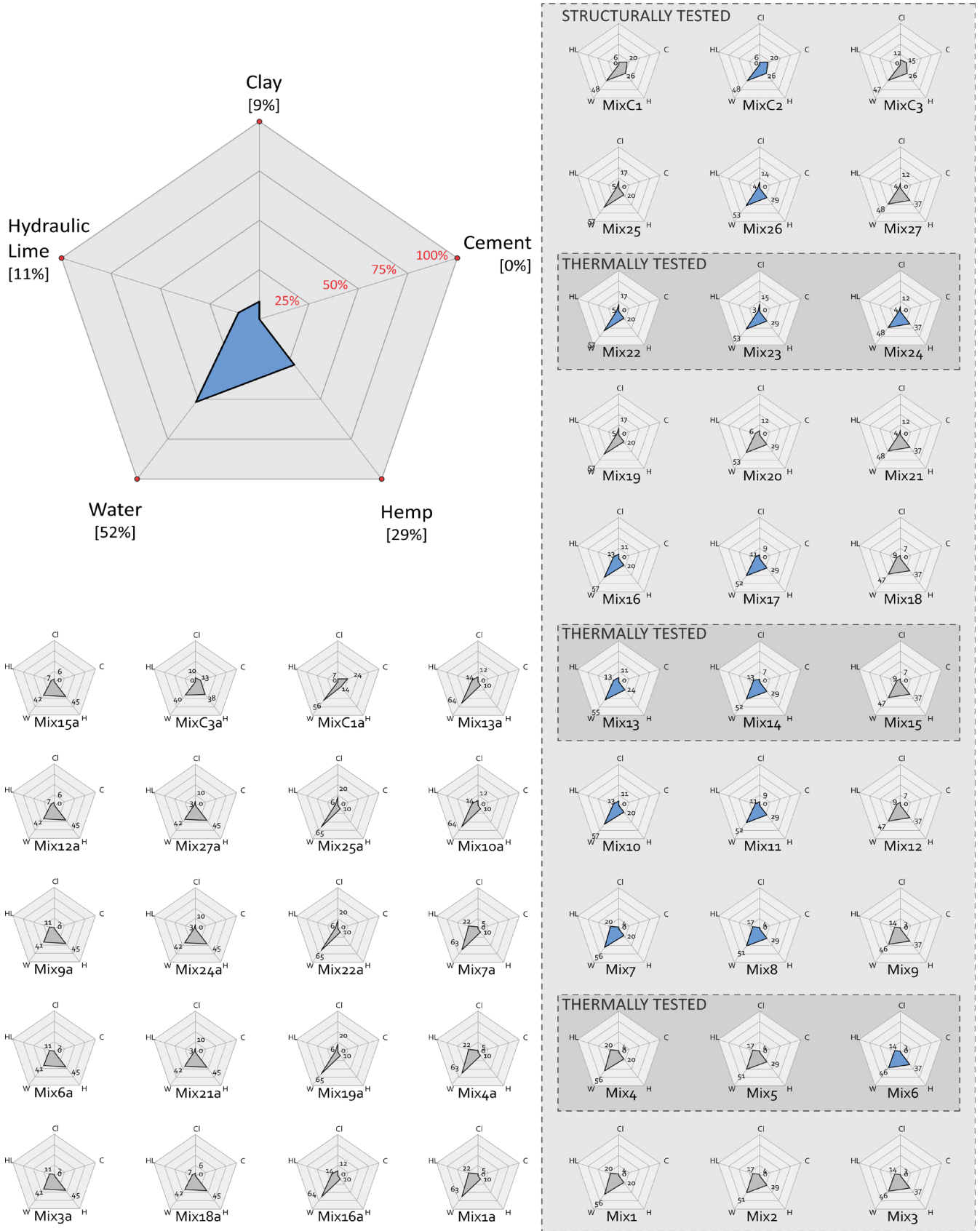


Figure 5. Differential Material. Thermal and structural performance.

the material. While the Embodied energy of a typical AM wall section using Portland Type I cement and without any consideration for insulation or other additives would be around 2024 MJ. In other words, a Functionally Graded building system could have eight times less the amount of Embodied energy than conventional AM would.

Beyond its technical characteristics, with Functionally Graded Material Additive Manufacturing there is also a potential for change in the paradigm of construction. Instead of an assembly of district construction parts or a homogeneous monolithic building section, FGAM opens up the possibility of a building system in which, for example, structure insulation and skin can become an integrated entity³⁵. This merging allows for the articulation of multi-purpose building systems in which structural, thermal, environmental performance characteristics and material/logistical efficiency can be co-designed and embedded into an integrated building envelope. The implementation of FGM in large scale AM opens up the space to reconsider what the tectonics of 3d printing are. What is currently understood as a mono-material extrusion can become an intricate articulation of performative material “parts” in a continuous integrated building envelope.

Mix #	Clay	Lime	Cement	Aggr./ Matrix	EE [MJ/kg]	Aggr. Type	Hemp [kg]	Sieving Energy Req'd. [kg]	EEint for Processing 1Kg [MJkg]	Total EEint [MJ]
1	0.2	0.8	0	0.369	44.82	Graded	29.42	0.0702	N/A	44.89
2	0.5	0.5	0	0.286	35.30	Graded	30.13	0.2517	0.6236	36.18
3	0.8	0.2	0	0.200	17.02	Fine	13.82	0.1649	0.6217	17.80
4	0.4	0	0.6	0.200	44.82	Fine	6.66	0.0794	0.2995	10.48
5	0.2	0	0.8	0.200	35.30	Fine	133.08	1.5884	5.9884	158.64
Total EEint										267.98

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