BIO-SYNTHETIC ASSEMBLAGES

Computational Assembly of Synthetic Bio-sand Units Made from Dune Sand

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Abstract. Biomineralization is the process by which living organisms produce minerals to harden or stiffen exoskeletons and existing tissues. Mineralization is a widespread phenomenon among all taxonomic animal kingdoms. The material used in this project attempts to replicate the process of hardening and mineralizing dune sand found in the Sahara and Arabian deserts. This material is found in vast quantities but thought to be of little use in modern construction. The new bio-synthetic material used in this study is paired with the process of augmented construction and computational placement of tectonic units. The paper overlays a broad question of how organizational systems might integrate architecturally with regionally appropriate bio-material composed of dune sand and, more specifically, how this material process creates a consistent, viable architectural outcome with dune sand as a primary ingredient for architectural material. As the material agenda reaches maturity, we ask how the production of this bio-material can be combined with computation to articulate consistent architectural outcomes within a desert-specific environment. The role of this computational and material process adds to the current dialogue of designing in extreme environments and aligns with the UN Sustainable Development Goals for sustainable communities, responsible consumption and production, climate action, and life living on land.

Keywords. Performance-based design; Bio-material; Computational design; Innovative material use; Augmented Construction; SDG 11; SDG 12; SDG 13; SDG 15.

1. Introduction

Dune sand is known to be an unstable material compared to river sand and as a result it is not normally used for construction. Because of this, desert regions have grown a reliance upon imported materials. This research indicates there is a viable opportunity to leverage dune sand as an ongoing line of material inquiry, establishing that there is very little being done in architectural research that responds to the populations living

in harsh desert environments partnered with bio-sand material and computational design. The methodology begins with experiments in bio-material with sand as a compound, and then, through empirical testing, establishes an ongoing construction sequence selected from a manifold of recreations based on successful experiments. This process uses the Scientific Testing Method and Hypothesis in Action, allowing the results to inform "design by research", followed by application.

Computational parameters are used to determine a series of performative results for regionally appropriate construction based upon the characteristics of the material strength and dimension. The material demonstrates it can be used in a variety of capable configurations that make unit based, porous constructions such as those used for thick stereotomic wall types, and ventilated mashrabiya walls. These are computationally designed to be culturally appropriate to the region. Grasshopper is used to arrange the units into compositions that are also environmentally responsive and controllable. The computational patterns can be opened or closed in varying degrees to adjust for orientation and site conditions. The work illuminates possible solutions for the regional problem of building in the Arabian and Sahara Desert utilizing a surplus of dune sand to construct locally appropriate wall types that build upon vernacular traditions but offer a more performative result. Compared with other methods such as concrete or masonry, which use high degrees of imported material, this solution can be more sustainable. To meet the UN sustainability goals, we must research and discover more applications for available resources in extreme environments. This paper documents a method, a material, and an outcome with a variety of potential possibilities.

Figure 1. Bou Inania, Mashrabiya barrier, Fez, Fez-meknes, Morocco, 1350, photo, B. Hemer

2. Context

The context for this research begins in the deserts of Arabia and North Africa by looking for answers relative to how we might design in this context in current day. The vernacular traditions in these regions are limited by their material resources. Mud, arish, coral stone and rock were used traditionally when available, especially along the coasts. Fabric was used for nomadic tribes who circulated through the deserts seeking favourable weather patterns as it was light weight and offered architectural flexibility and could be transported on camel back. The question arises as to what local materials are widely available and what can be leveraged for research as a further line of inquiry relative to architecture. These regions have a massive surplus of sand, and yet very
little of it is utilized for construction. Modern cities such as Dubai, Sharjah, Abu Dhabi, and Jeddah are literally surrounded by sand yet it is mostly unused. Instead, other types of sand are imported from other countries for construction because river sand is deemed to be of higher quality for architecture and manufacturing. In these regions, imported sand is brought in from Southeast Asia and Australia by boat to manufacture concrete, glass, mortar and block which increases the carbon footprint and overall sustainability factor for every architectural project in the region. So, what is the role of the desert in modern construction? What opportunities arise from this situation?

Sand is a resource heavily in demand. It is the most widely used resource in the world besides air and water. It is in everything we use in modern society, cell phones, glass, concrete, roads, computers. Yet the largest concentration of sand is not used. The importance of understanding how desert sand can be used is a critical environmental concern especially for the regions living closest to it.

![Figure 2. Satellite image of Sahara & Arabian Deserts and Dubai.](image)

3. Properties and Necessity

“Natural sands are eroded or weathered particles of rocks. Sand is made by simply grinding up rocks into increasingly smaller pieces. Sand can also be made out of living creatures, from shells and other organisms of the living world, and many beaches are composed of pulverized animal shells. Sand grains can originate from catastrophic geologic phenomena, as when molten lava erupts from volcanoes and shatters in the air, scattering particles across the oceans to land as tiny grains.” (Rael and San Fratello, 2018). Sand is different depending on its origin and the potential uses are different as well compared to origin. Desert sand has a different set of physical characteristics compared to river sand. River sand is sharp and angular as the grains were conditioned by water rather than air, it contains higher concentrations of quartz, and as a result it compacts successfully as a mixture for concrete. Desert dune sand is round and does not self-organize in the same way river sand does. Because it was conditioned by air, the grains are round in shape, so it organizes like a bag of marbles. The grains have a smooth surface finish and the particle size of desert sand is very fine, it is slightly alkaline in nature, and it is very dense, similar to dirt, all of which make it less useful for modern construction. Sand is a self-organizing material, as are all aggregates, and adheres to a consistent behavior when poured. As the architect Frei Otto noted with extensive studies of spoil piles and sand, these materials have “a funnel that is formed within the granule mass with a natural angle of repose” (Otto, 1992). Measuring a material angle of repose produces slightly different results. (Nichols and
Franklin, 1898), however in sand it is normally a 34 degree angle, which limits it (Glover, 1995), and asks for additional binders to be involved in this material research.

Sand is a global necessity and UN reports suggest his will continue, for example the UN 2060 projections indicate that sand is most widely consumed construction resource, and past UN studies in both 2011 and 2017 have accurately predicted the future of sand and aggregate to advance beyond other materials, (Torres and Simoni, 2021) and even though research through sustainability is allowing some material mining to slow down, sand and aggregates will remain massively mined and used well into the future. It is estimated to be a widely used material even in 2060 projections which also illuminate the further environmental problems that will follow with mining, habitat loss and global importation.

Because this is a problem that has both regional and global implications, it was deemed appropriate to study as a further line of inquiry. In the UAE, almost all materials are imported or made from imported resources so the importance of employing regional resources and finding new ways of building and designing with local sand as an option for regional materiality can lead to productive solutions for architecture and the UN Sustainable Development Goal for life on land. In order to move forward with this research, the project re-considered what regional architecture is in this location, how computational approaches can intervene with new material options, and how an advent of bio-technology/bio-engineering can alter our current understanding.

4. Methodologies

For this project, the methodology manifests in two parts. The first being a material study for the creation of a bio-sand unit that can be used architecturally. The second being an overlay of computational technology to begin understanding what can be construed from this bio-material performatively. Experiments using bio-material with sand are very complicated and often unsuccessful due to the nature of the material. Previous precedents have been successful in making structurally stable units using resins and binders that are unsustainable and toxic. This study called for an approach that was not using resins or toxic binders. We began with recreations of experiments using scientific testing method (STM) that implemented a workflow for a hypothesis in action, design by research and application. The project followed this method using desert dune sand sourced from the wild in the desert of the UAE paired with three biological substances that could act as a sustainable binder, Sporosarcina Pasteurii, sodium thiosulphate, and urea.

![Figure 3. Material tests using sand and sodium to create bio-synthetic sandstone](image-url)
Sodium thiosulphate was the material that worked most consistently with the project trials and subsequently became the dominant material additive with the sand for the project. This material was used to create a series of additive molding trials based on thick casts and thin casts. Sodium thiosulfate is a colorless crystal of sodium, sulfur, hydrogen, and oxygen. Both the Environmental Protection Agency (EPA) and Federal Food and Drug Administration (FDA) in the United States consider it a safe substance and permit its inclusion in human foods such as table salt. (World Health Organization, 2019). It is often present at therapeutic bath spas or thermal spas in contact with the human body, and other uses include waste water treatment plants where it is used to clean water before releasing it back to a river. In principal it is more un-toxic than table salt. It is on the World Health Organization’s List of Essential Medicines as one of the safest and most effective medicines needed in a health system.

This additive is affective because it changes states with temperature variation allowing the sand and salt to bind in a superheated mixture and upon cooling this process forms a composite unit. The strength varies based upon the amount of sodium and sand added together. It works by creating a monolayer of sodium around the sand, binding it at the same time, and resulting in the production of multiple layers of hardened sand material solidified by the sodium as it dries into a hardened state.

This material combination ultimately was used to create a series of bio-synthetic units made from sand that simulated standard masonry sizes. Rhino and Grasshopper were then used to demonstrate the material in a series of compositional arrangements, essentially by creating a surface in the X-Z directions, adding an ability to move freely and create twisted openings while stacking the units, and orienting the bricks in various positions so as to become performative in a variety of different positions. This in turn is being used in a second set of tests which involve Fologram and augmented construction processes, to be discussed in a separate paper.

5. Results

During the course of research for this project, four distinct and separate processes were tested all using varying concentrations of dune sand and sodium as a mixture. The natural self-organizing behaviours of sand were observed and also researched. One can observe the behaviour of sand as a self-organizing material especially with pourings
and pilings. Although pourings and pilings were studied initially, molds and casting became the primary vehicle for making the architectural units in this study. Different thicknesses were tested with these processes to understand the material behavior in a solid state ranging from thin (6.35 mm) to thick (76.2 mm).

Out of the tests conducted, Experiment 3 entitled “Solid State Sand as Thick Material” performed with the most consistency and the most strength. This material was generated by combining one part dune sand to one part Sodium Thiosulphate (sand & sodium equal by percentage), which created a unit of 76 mm in thickness. This was achieved by heating solid state sodium to a melting point, superheating to reach boiling temperature, removing from burner, creating a "Solid State" to "Liquid State". The super-heated bath of liquid state sodium thiosulphate was poured into a sand-filled mold 3” / 76 mm deep. Solidification was achieved through stirring the mixture as the sand particles were allowed to bind with sodium and the mixture cooled. The solid-state Sodium Thiosulphate is now effectively combined with sand as a hardened material, proving the hypothesis that when melted Sodium Thiosulphate comes into contact with sand, they form a bond (a biological cementation), creating a sandstone-like biomaterial.

The creation of the bio material was a significant component to this research project, however the second phase was to test how this material can be used in an architectural scenario. In the Middle East, mashrabiya is commonly used architectural features. Their existence dates back hundreds of years and were originally used as water storage areas in houses so that the ventilated openings could cool the water (Ashour, 2018). The continued use of the mashrabiya allowed for its evolution from water storage to devices that protruded or cantilevered over irregular plots in dense urban areas to correct the language of the architecture and increase the sizes of spaces on the upper floors of stacked housing without changing the size of the ground floor or moving past the plot limit. They were also used for privacy which is an important concern in Middle Eastern architecture. They are found in both historical and contemporary architecture as a commonly used feature for regional architecture. For this reason, it was used as an initial typological reference. In Grasshopper, a definition was made that arranges stacks of sandstone units. These stacks were given
inputs the same size as the units made from the final sandstone test mold. With grasshopper, the units were then allowed to rotate from one unit to the next so as to create a ventilated façade. The control of the openings can be calibrated to be fully open or fully closed.

The strength of the sand brick was tested for compression using a calibrated Form+Test M1 3000 kN machine. The material proved to be very durable and held up well under continuous compression with 1750 kg/m³ being used for Bulk Density, and 1511.6 kN being applied for Normalized Compression, and 51.4 MPa for Strength, where one MPa is equal to one million pascals (Pa); a pascal is one newton of force per square meter, a megapascal is one million newtons per square meter. As a rule, the higher the MPa of a material, the stronger the material will be, and the less likely it is to fail. For example a 32 MPa (at 4,600 psi) for concrete is often used in the region (Giancoli, 2000). However, important to note that Load was not calculated as it was not an ASTM test.

To design with this unit in mind, the step by step Grasshopper definition starts by defining the Output Parameters for P (Plane) and World XZ (Plane) to reference a planar surface. It then moves to Input Parameters for the P (Plane) component and Surface base plane in the X (Domain) for dimensions in the X direction, and Y (Domain) for the dimensions in the Y direction. The Output parameters of the surface connect to a panel for custom values which was plugged into the parameters for the surface. The next part of the definition works to explode the referenced curves into smaller segments. The Output parameters: S (Curve) was connected to Item L (Generic Data) to retrieve specific item data from a list. This was connected to a Cull Index along with a Divide component. This effectively allows for an offset to be created in the direction of the Z. The Cull was connected to Sub List which extracts a subset from the list. Elements in the list are identified by their index. The subset allows for a continuous range of elements to be copied as a new list.

The next part of the definition divides the referenced curves into equal points and a Domain Box was defined by XYZ in order to orient the units. This transformation is critical as it allows for the remapping of geometry from one axis-system to another, and allows the units to be transformed more systematically. With this process, the
Grasshopper definition allows for a flexible mashrabiya to be modeled along with the synthetic bio-material. This acts as the primary design tool that facilitates a workflow for a bio-synthetic mashrabiya. The mashrabiya can move from a closed wall surface to a system with various openings and closing in a very systematic way. This design workflow can benefit regional architecture and can be custom controlled to allow for different lighting situations, privacy requirements, ventilation needs and can accommodate the breeze patterns for a particular area in a city.

Figure 7. Grasshopper definition for Bio-synthetic mashrabiya compositions

6. Conclusion

The research project asks how a regionally appropriate architectural system might integrate with a computational process to allow for the use of a new material agenda using dune sand from local deserts. To facilitate this line of inquiry, the research
followed a hypothesis using salt and salt mixtures such as Sodium Thiosulphate to create bio-synthetic material from local dune sand. This was important due to the fact that desert dune sand is rarely used in modern construction. Cities in the Middle East and North Africa import massive quantities of river sand from Southeast Asia and Australia to fuel the need for concrete and masonry products. Based upon previous scientific evidence, the project research found that Sodium Thiosulphate and bacteria using Microbial Induced Calcite Precipitation could successfully help to create sand based material systems. This thesis tested Sodium Thiosulphate and concluded that in certain situations it is a viable material outcome that can have the strength needed for material assemblages. It is relatively safe and easy to mold. Concerns however are the amount of Sodium required to create the material and the durability of the material if exposed to weather and water. The referenced test in this paper (Experiment Three) concludes that with a dimension of 76 mm or more, it is a stable unit capable of being stacked and arranged in compositions similar to masonry construction, lending additional viability due to the skillsets of local craftsmen and their familiarity with brick.

A design workflow incorporating this bio-material can be combined with computation to articulate specific architectural outcomes that have regional relevance. The research points to the fact that local sand material can create typological prototypes such as mashrabiyas and façade units requiring breezes, offering a method for viable human scale architectural prototypes to be further explored and designed. Further research can be done on the material responses to weather and the structure limitations of the material. This is needed to continue conversations regarding how designers can replace current proprietary media such as mass-produced masonry and concrete created from unsustainable methods using imported sand. The project responds to pressing global issues as identified by the following UN Sustainable Development Goals: SDG11, "Sustainable Cities and Communities" by helping to design resilient, and sustainable cities and human settlements, and designing material that aids in
the reduction of environmental impacts of cities and city building by fostering resource efficiency in sustainable and resilient building processes. SDG12 by fostering responsible consumption and production in order to ensure sustainable consumption and production patterns, and to ensure good use of resources. SDG13, "Climate Action" by reducing greenhouse gases due to transportation and importation on a global scale. (Fagan, 2020).

Figure 9. Bio-masonry mashrabiya prototype

References