Bio-digital Sand Logics: Dune Sand Material and Computational Design

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Abstract. This paper discusses the creation of a new sand-based material, performative testing, and the computational logic involved in the design of a prototypical architectural system. Dune sand is known to be an unstable material compared to river or marine sand and as a result it is not normally used for construction. Because of this, desert regions have grown a reliance upon imported materials creating massive sustainability issues due to large scale global shipping, importation and resource extraction. This research indicates there is a viable opportunity to leverage dune sand as an ongoing line of inquiry for material science and design in local desert regions. It establishes that there is very little architectural research being done in this particular area. The methodology begins with experiments in bio-material using dune sand as a compound, and then establishes a construction system based upon a manifold of experiments. Along with material investigations, the process uses a Scientific Testing Method (STM) and Hypothesis in Action (HIA) as part of the testing methodology.

Keywords: Technology · Desert environments · Bio-materials · Bio-digital design

1 Introduction

The research project asks how a regionally appropriate architectural system might integrate with computational process to allow for the use of a new material agenda using dune sand from local deserts. Sand is a global necessity. The UN 2060 projections indicate that sand is the most widely consumed construction resource [5], and past UN studies in both 2011 and 2017 have accurately predicted the future need of sand and small aggregate to advance beyond other materials and will remain massively mined and utilized well into the future creating environmental problems due to mining, habitat loss and global importation. To facilitate this line of inquiry, the research followed a hypothesis using sodium and sodium mixtures to create bio-synthetic material from local dune sand. Cities in the Middle East and North Africa (MENA) import massive quantities of river sand from Southeast Asia and Australia to fuel the need for concrete and masonry products [13]. This thesis tested sodium and sand together as a superheated mixture and concluded that in certain situations it has characteristics that rivals concrete or traditional masonry.

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The research points to the fact that local sand material can be used to create typological prototypes such as *mashrabiya* and *jalis* or other facade units for spaces requiring breezes, which can create better situations for humans in harsh desert environments. With this in mind, an algorithmic design workflow was generated using computation to articulate specific architectural outcomes that have regional relevance. Units that emulate breeze blocks are employed to create a variety of performance-based compositions that can be highly programmed to accommodate site specific conditions. Using Grasshopper Ladybug we can determine additional performance-based logic for the compositions on a given site based upon sun and wind data.

The project responds to pressing global issues as identified by the UN Sustainable Development Goal SDG11, "Sustainable Cities and Communities" [16] 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. It also responds to UN Sustainable Development SDG13, "Climate Action" by reducing greenhouse gases due to transportation and importation on a global scale. Because dune sand is known to be an unstable material, desert regions have grown a reliance upon imported materials. This work 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* and *jali* walls. A jail, meaning "net", is the term for a perforated stone or latticed screen, usually with an ornamental articulation based upon geometry or natural patterns. This form of architectural decoration is common in Indo-Islamic architecture [14]. These are computationally designed to be culturally appropriate to this 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 Sahara and Arabian 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 (Fig. 1).

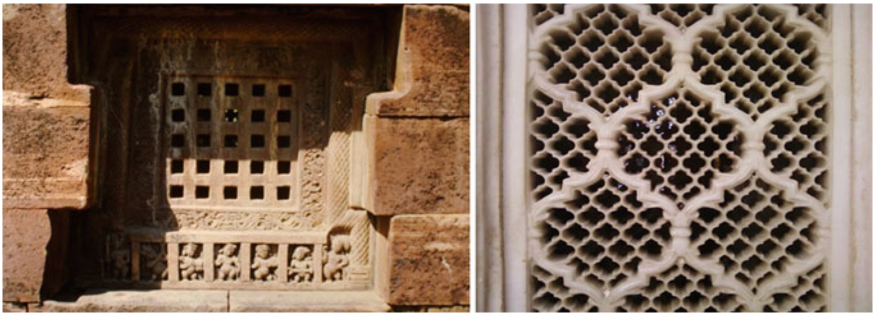

Fig. 1. Nachna Parvati, Temple Jali, India, Gupta Period, and Jali at Bibi Ka Maqbara, Aurangabad, India.

2 Location, Properties and Need

To place the project in a regional environment, the Arabian desert was used as a context. The vernacular traditions in this region are limited by their material resources. Mud, arish, coral stone and rock were used traditionally when available, especially along the coasts [8]. Fabric was used by nomadic tribes who circulated through the deserts seeking favorable weather patterns as it was lightweight and offered architectural flexibility and could be transported on camel back [9]. The question arises as to what local materials are widely available now, 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 [3] 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 [2]. It is in most 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 (Fig. 2).

"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" [7]. 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

Fig. 2. Dubai with UAE desert in foreground, and satellite image of Rub' al Khali desert (the Empty Quarter), Getty Images.

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" [11]. Measuring a material angle of repose produces slightly different results [10], however in sand it is normally a 34° angle, which limits it [7], 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 [15], 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.

3 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 constructed 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. It 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.

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 [17]. 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 [18] (Fig. 3).

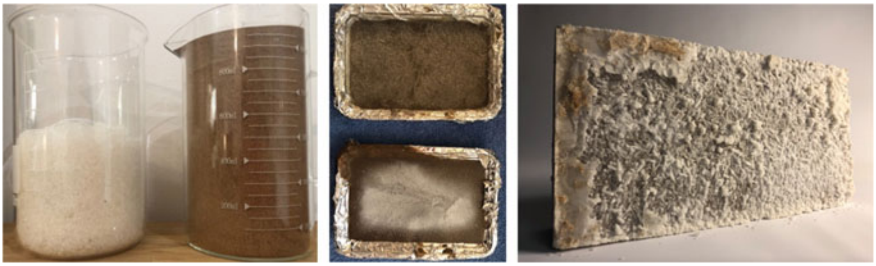

Fig. 3. Sodium Thiosulphate, Dune sand brick "growing", final sodium sand brick.

This additive is effective 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 results 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 situations.

4 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 behaviors 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* and *jalis* are 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 [1]. The continued use of the *mashrabiya* and *jalis* allowed for its evolution from these water storage areas 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, with a vast array of potentials between (Fig. 4).

Fig. 4. Salt brick, compression test & resultant brick.

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/m^3 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 [3]. However, it is important to note that "Load" was not directly calculated as it was not an ASTM test.

The use of Grasshopper 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* and *jalis* 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* and *jalis*. The system 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 (Figs. 5 and 6).

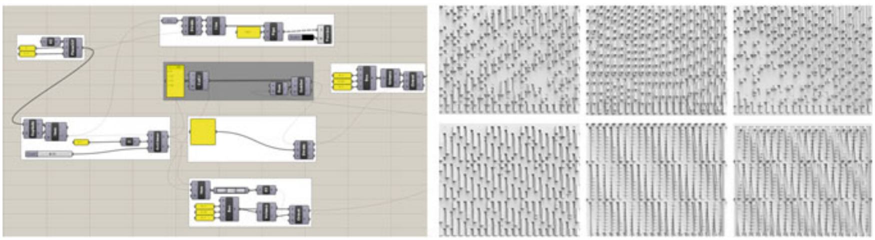

Fig. 5. Grasshopper jail/mashribiya arrangements

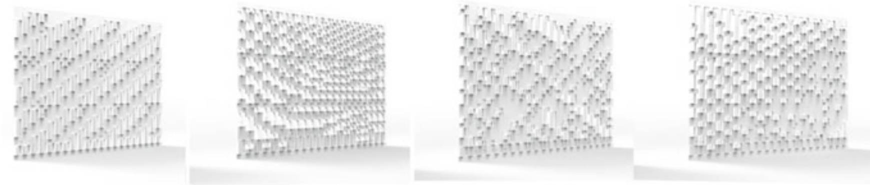

Fig. 6. Jali/mashrabiya compositional arrangements

5 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 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 mashrabiya and jalis or 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 (Figs. 7 and 8).

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 [2].

Fig. 7. The result of the grasshopper defined bio-synthetic masonry material composition

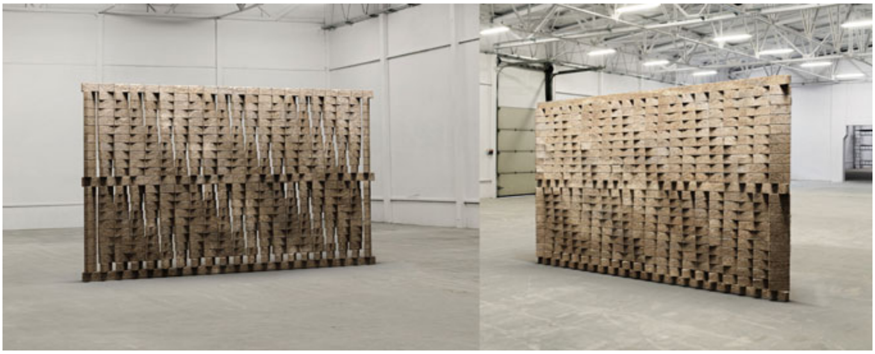

Fig. 8. Bio-masonry mashrabiy/jali prototype

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