BIO-MINERALISATION AND IN-SITU FABRICATION OF IN-DUNE SPACES: CASE STUDY OF THAR DESERT

MEDHA BANSAL[1] and ELIF ERDINE[2]
[1,2]*Architectural Association*
[1]*medhabansal18@gmail.com* [2]*Elif.Erdine@aaschool.ac.uk*

Abstract. Desertification has made large productive landscapes in the South-west Thar desert redundant, subjected people to migration and induced a constant influx of sand into the region (Singhvi and Amal, 2014). The abundance of sand creates an opportunity to adopt an existing technique, Bio-mineralisation, to develop a sand based composite material which, when treated with a construction binder like sodium alginate, can be used for engineering purposes. The paper sets a theoretical framework to develop a fabrication mechanism with microbial-grout injections and propose the development of in-dune/underground assembly of habitable spaces. Each of the sub-components of material system, fabrication mechanism and In-dune structures are detailed, and evaluated to devise a hierarchy between them. Their interdependencies together inform design strategies, a phasing plan and global time scale for overall terrain transformation.

Keywords. Bio-mineralisation; Bio-grouting; In-dune fabrication; Tool path algorithms; Micro-climate analysis.

1. Introduction

Desertification, being a global problem, has made large productive landscapes redundant and subjected people living in these areas to migration. Amidst the adversities, there are opportunities to procure the abundant resources in a desert and combine them with traditional and modern mitigating interventions.

The Thar desert is the easternmost extension of the vast Sahara- Arabian deserts in the horse latitudes. The desert is dominated by the south-west monsoon, which controls both the wind vector and the vegetation cover. Dearth of rain in this region is a result of configuration of atmospheric dynamics and sinking air masses which increase the surface pressure and temperature significantly (Bryson and Baerreis, 1967).Absence of any substantial vegetation cover and agricultural activities, coupled with high wind velocity has increased the vulnerability to sand movement in the region through erosion and depositional processes.

Abundance of sand can cater to the development of a material system that can be used locally by hardening the sand. While within the realm of geotechnical engineering conventional production methods are not economical, alternative biological approaches including microbial injection and by-product precipitation

PROJECTIONS, Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021, Volume 1, 493-502.

have been investigated. The presented research specifically details and adopts the application of microbial induced polymers or biopolymers as a new type of construction binder.

The material system of the research is founded on a case study conducted in TU Delft in 2009 (Van Paassen et al., 2009) The objective of the study has been to test the scalability of bio-grouting in order to verify the potential of the method in ground improvement. As an ex-situ experiment inside a laboratory, biopolymers are mixed with sand and water and cast in a mould. In another ex-situ experiment set-up bio grouts are injected to containers filled with soil of volumes 1 m3 and 100 m3 through injection wells. Progression from casting 10 cm3 of sand to injecting 1 m3 and 100 m3 of sand as single point and grid of injections has directed the research to study the flow lines of the bio grout fluids, control the forms and pattern generated along these lines, control inlet and outlet locations of injection and observe pressure difference inside the sand.

The current experiment thus in turn also focuses on controlling the uniformity and structural properties of the hardened mass. The experiment resulted in achieving unconfined compressive strength from 0-15 MPa. The increase of stiffness from precipitation of carbonate in subsurface can also be quantified as function of the volume of injected grouting agents and its dry-density. Observations and conclusions from the bio-grouting experiments done at TU Delft suggest the scalability of the technique.

Biopolymers are the most viable environment friendly option (Chang, Im and Cho, 2016). Once added to the soil, they form a stable gel matrix that synergies with ecosystem locally and does not damage it. Combined with their water retaining properties in soil, biopolymers are thought to be capable of promoting vegetation growth. Furthermore, the use of cross-linking for biopolymers may provide a more powerful soil stabilizing method. Cross-linking is a technique used to greatly improve the properties of a specific material by introducing an agent that promotes interactions between separate polymer chains, thereby enhancing their overall strength. Addition of calcium to the biopolymer and sand makes the composition gain strength and repel water solubility. About 5% Sodium Alginate and sand mixture can attain an unconfined compressive strength of 1550 KPa, 96 % of which is attained in 14 days (Zdruli,Cherlet and Zucca, 2017).

2. Research and Development

This research is founded upon existing applied research in the field, with existing machine definitions / limitations, as well as applied research on material composite studies. The innovation of this research is how it brings together research on material composites and large-scale fabrication with environmental and climatic considerations.The material system discussed in the previous section has the potential to be adapted and coupled with a fabrication mechanism to propose a new morphology of habitation spaces in Thar Desert. The current section details several components of the fabrication mechanism and evaluates them for their environmental performance.

2.1. SCALING UP FABRICATION MECHANISM

2.1.1. Single Point Injections and Matrix Jnjections

In order to harden a vast dunal land mass, bio-grouting should be carried out such that large sections of the terrain are hardened at once with some local variations. Single point injection has shown its industrial success and ability to stabilise ground, however the impact of its application is local and limited to a small area. By building on the observations and conclusions from the TU Delft experiment discussed in the previous section (Van Paassen et al., 2009), the limitations of single point injection are aimed to be resolved by proposing an extension to this technique. The proposal comprises replacement of a single point injection with a matrix of injections, which can harden a larger portion of subsurface at once (figure 1).

The customised injection grid can be mounted onto a grouting machine which can freely run over the dunal fields. It is beyond the scope of this work to digitally simulate the grout spread of individual injections, and the density of the injections in the matrix can only be determined on site by observing the net grout spread. For the following experiments, it is assumed that the grout spread by each injection is uniform so that the net grout spread from all the injections can collectively cover the entire surface homogeneously without leaving any traces of loose unhardened portions or overly injected portions within that patch.

2.1.2. Machine Specifications

The selected machine should be able to withstand the load of the injections, manoeuvre over the undulating field and inject into varying depths and at different angles. In order to meet these objectives, the mobile injection grouting drill KR 807-7G by Klemm- Bohrtechnik is selected. Long and heavy drilling masts are mountable so that the maximum depth the mast can travel is up to 15000mm and can attain stability while taking challenging drilling positions. The machine is designed with enhanced inherent stability such that its manoeuvring and setting up times are significantly less. Machine's crawler base's oscillating ability (from +12.5° to -7°) and the mast's automated positioning within ±5° from the vertical in all directions (K Bohrtechnik, 2018) maximise its area of impact (figure 1).

The jig/extension that can be attached to hold the injections has a dimensional constraint of 3m X 3m, indicating that the machine can harden patches in multiples of 9 m2. These start to define the physical constraints of fabrication and have a direct impact on the profile of in-dune habitable units, which will be further discussed in the following sections.

2.1.3. Machine Positions

Having the ability to rotate the mast, the machine can inject in all the planes between two orthogonal planes. Injecting in orthogonal planes enables the machine to develop a vertical, horizontal and inclined injection system(figure 1), each having a different area of impact.

2.2. MACHINE TOOL PATHS

While the machine allows injection in 3 orthogonal planes and increases the scope of developing multiple tool paths, by injecting horizontally a large portion of vertical surface remains unhardened (figure 1). On the contrary, while injecting vertically, the machine can harden the entire 15m depth uniformly. This narrows down the focus to development of vertical injection systems and compel further development of tool path algorithms in the global x-y plane.

The propagation path of the machine can define the hardening pattern of the surface. During the injection process, there is a possibility that the hardened patches can either overlap or be separated by a distance. Either of these cases make the resulting hardened surface inefficient, for there is wastage of material in overlapping, and weakening and erosion of sub-surface in separation. Considering the prime objective of a compact packing of 3m X 3m patches, tool path algorithms are developed in two stages. The first stage formulates the trajectory type for machine's propagation based on mathematically defined 1°, 2° or 3° curves. Stage 01 rules out the possibility of the innumerable tool paths that can be developed by the machine's unconstrained ability to manoeuvre in x-y plane. In additional to the compact packing of hardened patches, it is essential that the time to harden multiple patches is also reduced. Due to the crawler base's turning capability, more than one patch can be injected from the same machine position (figure 2). This could reduce the time lost in moving and parking the machine for next injection position. The second stage leads to computational form-finding of specific tool paths based on machine's turning radii, injection positions and the selected trajectory type from Stage 01.

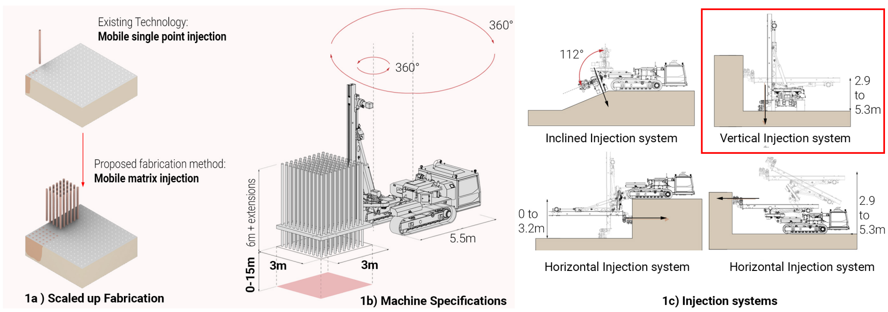

Figure 1. Scaling-up Fabrication Mechanism.

Stage 01- Tool Path Trajectory type and Direction of Propagation

If the machine were to run in the trajectories as demonstrated in figure 2 and inject at the intervals of 3m, only the trajectories based on mathematically defined 1° curves (polynomial equations with highest power as 1) meet the objective of compact packing. Hence, a series of tool paths are further developed based on 1° curves. Furthermore, running of the machine or other heavy equipment over pre-hardened patches can cause cracking due to differential settlement of sand. The tool paths are therefore developed as unidirectional so that there is no cross-routing for machine.

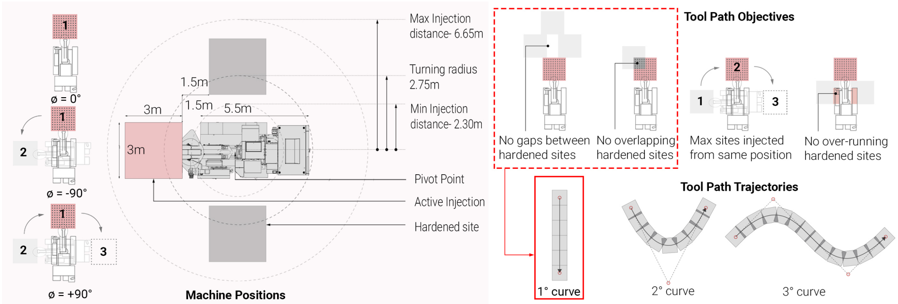

Figure 2. Machine Position and Tool Path Objectives.

Stage 02- Tool Path algorithms

Mathematically there are three variables involved in defining the tool paths of the machine- the local co-ordinates (x and y) of the machine's pivot position and the turning radii of the machine, ø (figure 2). Combinations of rotation and pivot positions can computationally generate a series of tool paths. For the experiments, a test area of 12m X 24m has been selected.

For hardening the selected site of 12 m along x-axis and 24m along y-axis, machine trajectory is defined such that it first completes hardening one row along x direction before shifting to next position in y-direction at steps of 3m and repeating the hardening pattern. For a given y co-ordinate we consider the machine to inject in increments of 1.5 m along x-axis. Total number of variables along x-axis = 5 (-6.0 to +6.0). Similarly, as trajectories based on 1° curves are opted for, ø can only vary in multiple of 90°(ranging between -90° and +90°). Total number of variables for rotation = 3.

Total number of variables in injecting 12m width (1st row) = 8.

Total number of combinations that can be formed= $\Sigma\ {}^{n}_{r}C$ (here n=8 and r= 1 to 8)= 246

A total of 246 tool paths are developed. Some of them are shown in figure 03.

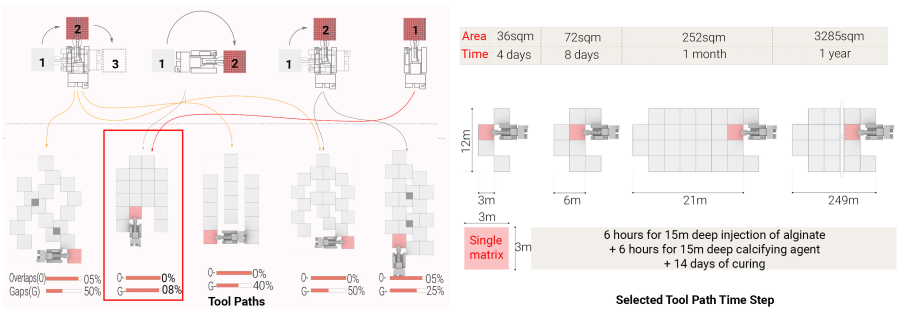

Figure 3. Tool Paths and Time Step.

2.3. TOOL PATH TIME SCALE

The selected tool path has no overlaps and gaps within the hardened patches. The selected tool path has a width constraint of 12 m and hardens 36 m2 area in first cycle of complete injecting before moving to the next row (figure 3). Multiple machines injecting with the same rate and at the same time need to be deployed on different parts and steps of the dunal section to escalate the stabilisation procedure for the entire terrain. Development of the site starts with identification of dune valley to be developed to accommodate 2250 people. Based on selected tool/path and rate of injection, it is estimated that it would take 25 years to develop the entire terrain. The continual procedure of injection for over 2 decades demands for construction of pathways for machines' circulation around the dune profile and establishment of a machine maintenance area at the centre(figure 4).

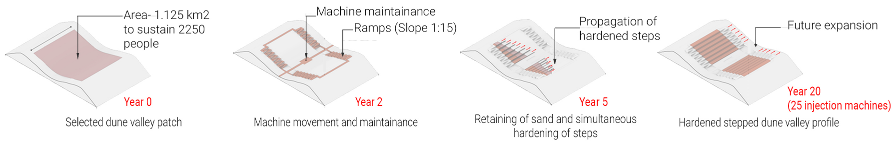

Figure 4. Multiple injections on site and Global Time Scale.

3. In-Dune Structures

The development of the material system and fabrication system is followed by the elaboration of an assembly of in-dune habitable spaces. The ability of the injections to inject at different depths can create volumetric enclosures within the dune. Occupying the interiors of a dune can demonstrate several environmental and functional benefits which can enhance living conditions in relation to the arid biome. The adaptation can facilitate heat exchange between the structure and dunal sub-soil, which in turn can significantly lower the temperature of inhabited spaces. In-dune habitation minimises the area exposed to the hot winds and sedimentation caused by their dropping velocity.

3.1. COMPONENTS OF IN-DUNE HABITABLE UNITS

In the adopted matrix injection system, injecting at different levels within the 3m X 3m grid is proposed. The construction of foundations and walls comprises the application of multiple injections and single point injections at different depths respectively (figure 5). Locally procured secondary material is used to stack additional floor slabs and roof over the pits.

3.2. LIVEABILITY IN IN-DUNE STRUCTURES: MICRO-CLIMATE ANALYSIS

A shoe-box microclimate analysis is conducted to simulate the liveability of excavated habitable spaces in terms of thermal comfort based on the relationship between parameters such as depth of excavation, peripheral wall thickness, soil temperature and value of sub-soil's thermal conductivity. Openings on the pits influence the convective capacity of the space's air volume due to its exposure to direct solar radiation. Thermal mass and opaque conductivity regulate the nature and degree of heat transmission through the peripheral wall assemblies. The same wall properties of the hardened sand (in figure 06) work with low U-values to inhibit high degrees of thermal exchange and permit more regulated living conditions for the occupants.

Experiment: The experiment aims to record the range of temperatures inside an excavated pit for varying wall thickness and depth. Controlling these parameters alter the thermal transmittance or u-value of the subsoil and bring significant changes to micro-climate. The evaluation is based on the combination of depth and wall thickness (figure 6) that modify the air temperature such that it falls under the comfort band of Jaisalmer for respective seasons (with reference to ASHRAE 55). The machine constrainting injecting depth to 15 m marks the limit to test these variations (ranging 0.1m-15m). The wall thickness is ranging 0.3m-1.5m. The study is conducted separately for summer and winter.To record the temperature variations, the surface temperature of the surrounding soil are calibrated based on precedent data (Gupta, 1986) for both the seasons. (figure 6)

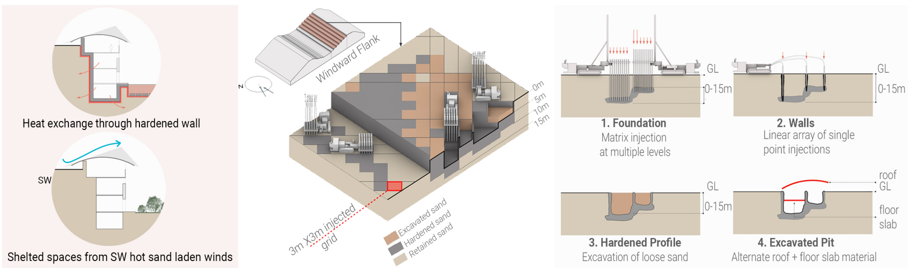

Figure 5. Fabrication strategy and components of in-dune structure.

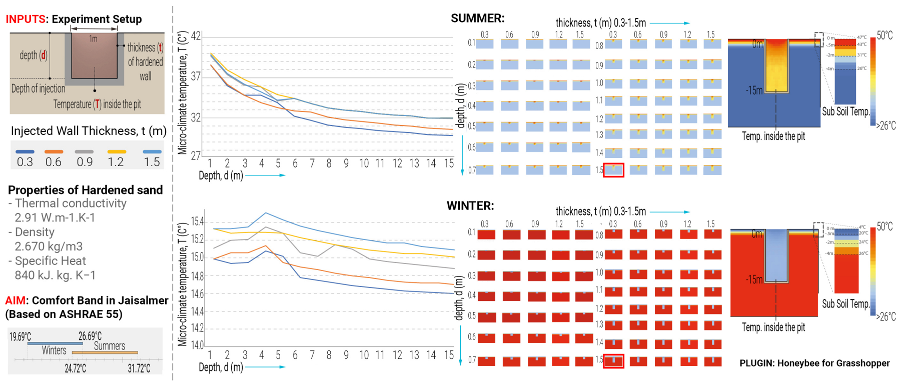

Figure 6. Shoe-box Micro-climate analysis.

Observations & Conclusions: Ground coupling serves as a proficient thermal comfort enduring technique. The technique shows significant difference for summer, for there is a flow of heat from interiors of the pit to subsoil. When the temperature outside during harsh summers is 50°C, a drop of 20°C can be achieved inside the pit. As shown in the graphs above, the temperature is observed to start equalising after a depth of 9-12m . Hence, despite having injecting capability up to 15m, the injection depth of the machine can be limited to 12m to save time and material. For winters, there is a reverse flow of heat from subsoil to the interiors of the pit. This increases the temperature of the pit instantaneously to about 10-12°C (figure 6)when the outside temperature is 4°C but shows no significant variation across different depths. The temperature variations brings the micro-climate of the excavated pit within the comfort band for both the seasons.

3.3. FABRICATION OF DIFFERENT PROFILES BASED ON FUNCTIONS

While the material and fabrication mechanism enable the construction of in-dune spaces, the shoe-box thermal analysis indicates liveability. It also limits the depth of these pits to 12 m and peripheral wall thickness to 0.3 m. Constraint of machine width and injection depths start defining the sizes of the spaces that can be created and determine the functions they could transform into (figure 7). The shapes and sizes of these components play a critical role in developing sand stabilisation and deflection mechanism and will be further elaborated in another publication.The fabrication of these different profiles begin with piling and flattening of the sloped dune face. First the slope is retained by sheet piles or fences before cutting. Injection on these loose stepped profiles are carried simultaneously near the sheet piles on each step to maintain the homogeneity of the retaining wall. Once the surfaces have attained strength (after 14 days of injection), the loose sand is excavated and the hardened mass is either shaped or filled with fertile soil based on the profile's purpose.

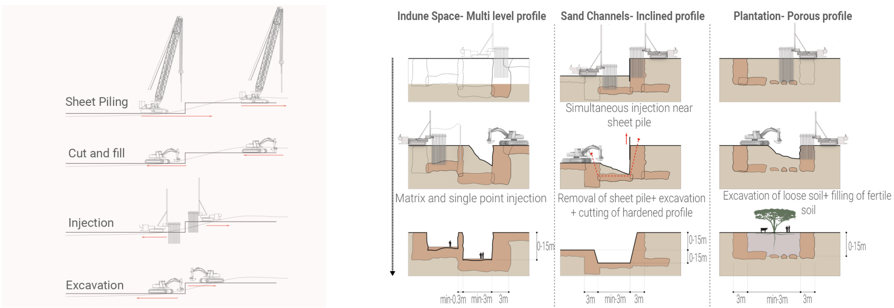

Figure 7. Fabrication of different profiles.

3.4. EVALUATION OF FABRICATION METHODOLOGY AT CLUSTER SCALE

The shoe-box micro-climate experiment done in Section 3.2 suggest favourable temperature variations in summers and winters inside these pits and set the parameters/physical constraints for the fabrication of in-dune spaces. The following experiment is another micro-climate analysis carried on the design proposal of a cluster of open, semi-open and closed spaces inside a dunal stretch (figure 08). These spaces are an output of a series of multi-objective optimisation experiments carried out previously and will be further expanded in another publication. The results from this micro-climate analysis will evaluate liveability for the in-dune inhabitants in open and closed spaces.

Experiment Setup: A smaller portion from the cluster is extracted and it is assumed that the spaces within this portion are separated from the rest of the cluster by an adiabatic wall so that there is no heat loss or gain within this selected portion from the entire dunal stretch. Considering that the foundation slab and walls are made of bio-mineralised sand and stacked floors of wood, temperature variations are stratified for outdoor and indoor spaces during summers and winters. We input the same material properties as defined in previous experiment.

Observations & Conclusions: It is observed that in summers when temperature peaks to 50°C there is a significant drop of 10-12°C at both indoor and outdoor spaces. In winters however no significant rise in the temperature is observed. The outdoor spaces rather witness a minor temperature drop, making them less favourable to use. In comparison to the shoe-box experiment of section 3.2, the cluster here has greater surface area exposed to the sun versus the volume of the pit , facilitating faster dissipation of heat. There is greater thermal mass within the cluster. It can be concluded that while the proposed material system having a high thermal mass regulates the temperature of a given space to human comfort, the high surface area to volume ratio does not allow the heat to be trapped within the pit. The dimensional constraints from the proposed fabrication methodology supports the usability of in-dune spaces for mainly in summers.

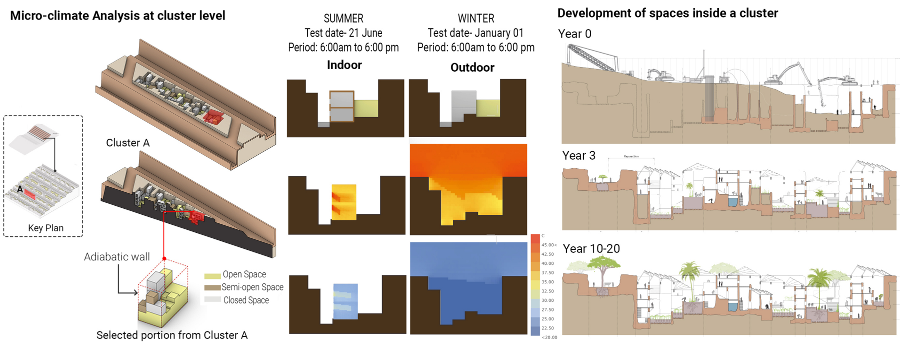

Figure 8. Cluster Scale Micro-Climate Analysis.

4. Conclusion and Analysis

The paper marks a clear hierarchy between the material system, fabrication process, and habitable spatial organisation to propose a highly sophisticated and interdependent complex methodology. Their interdependencies together inform design strategies, a phasing plan and global time scale for overall terrain transformation. Heavy ground manipulation needs a radical shift in adapting to fabrication mechanism and habitation of in-dune spaces. Every subsystem has its own limitation in the scope of application and some deprecated impact on the neighbouring terrain. Scaling up their applicability across the dunal field would also mean scaling up the limitations. Inclusive of all the advantages and disadvantages, these systems can build an ecosystem which has the potential to be resilient to desertification in western Thar.

Microbial injecting into sand to develop habitable spaces and other components in different profiles has been proposed based on the compressive strength that homogeneously cast composite brick attains. While it is assumed that the grout spread is uniform inside the sand, the actual spread should be tested physically. The results from the tests would start defining the attainable surface textures, wall thicknesses, undulations, permeability and load bearing capacity. The arrangement of spaces has been directed by micro-climate analysis only, the strategy should be coupled with structural tests. For the difference in hardening time of different components for varying injection depths, profiles and volume of required grout, the fabrication strategy and time estimations for development of each phase should be revisited. Monolithically casted each wall would behave like a load bearing structure. While core-cutting is proficient to make small openings in such structures, its ability to make bigger openings for doors and windows need to be practically tested. The developed climate conscious architecture finds its applicability in dunal regions which are severely affected by desertification and shifting sands. The schemes can be adopted and adapted based on the effected regions' dune morphology, wind pattern, demographics, ground fabric, availability of resources like water and other infrastructural support.

Acknowledgement

This work is a part of the graduate thesis completed at AA, London in 2019-20 by Medha Bansal, Saumil Nagar and Kai Yeh, under the supervision of Dr. Michael Weinstock and Dr. Elif Erdine. Special thanks to Patrick Lawrence Monfort for conducting the environmental performance simulations.

References

Bohrtechnik, K.: 2018, "Drill Rigs: KLEMM Bohrtechnik GmbH" . Available from <https://www.ecanet.com/uploads/files/Resources/KR-807-7G_7GP.pdf> (accessed 10th May 2019).

Bryson, R.A. and Baerreis, D.A.: 1967, Possibilities of Major Climatic Modification and their Implications: Northwest India a Case for Study, *American Meterological Society*, **48**, 136-142.

Chang, I., Im, J. and Cho, G.C.: 2016, Introduction of Microbial Biopolymers in Soil Treatment for Future Environmentally-Friendly and Sustainable Geotechnical Engineering, *Sustainability*, **8**, 251.

Gupta, J.P.: 1986, Moisture and thermal regimes of the desert soils of Rajasthan, India, and their management for higher plant production, *Hydrological Sciences Journal*, **31**, 347-359.

Van Paassen, L.A., Harkes, M.P., Van Zwieten, G.A., Van Der Zon, W.H., Van Der Star, W.R.L. and Van Loosdrecht, M.C.M.: 2009, Scale up of BioGrout: A biological ground reinforcement method, *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*, Alexandria.

Singhvi, A.K. and Amal, K.: 2014, The aeolian sedimentation record of the Thar desert, *Journal of Earth System and Science*, **113**, 371–401.

Zdruli, P., Cherlet, M. and Zucca, C. 2017, Mapping Desertification: Constraints and Challenges, *in* R. Lal (ed.), *Encyclopedia of Soil Science*, CRC Press.