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Terrene 1.0 : Innovative, Earth-Based Material for the Construction of Compression-Dominant Shell Structures

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Abstract:
With the construction industry being one of the leading contributors to annual carbon dioxide (CO_2) emissions and to excess of waste, the utilization of sustainable materials is critical for the future of the built environment. Therefore, this research explores using the abundant resource of sand as a primary support by combining structural and material optimization methods. On one hand, to provide this compressive material with a tensile capacity, a composite is designed enhancing sand with natural fibers, plasticizers, and binding agents. This creates a biodegradable material system that can be reintegrated back into the environment without ecologically damaging effects. On the other hand, funicular form finding through polyhedral graphic statics is deployed to optimize the structural capacity, provide geometric efficiency, and use minimal material thickness in the designed geometry. Fabrication is executed via a networked enclosure that provides tensile capacity and contains pneumatic formwork as the foundation for a sand-based shell. The result of this research is a tension-compression system with performative geometry and material.

Keywords: Earthen Construction, Biodegradable Systems, Polyhedral Graphic Statics, Sustainable Material Composites, Reusable Pneumatic Formwork, Tension-Compression Shell

1. Introduction
Within our current climate context, the buildings and construction account for almost 40% of the global energy-related CO_2 emissions, 11% of which is tied to the construction material manufacturing of glass, steel, and cement [1, 2]. Although these materials are revolutionary in the development of the contemporary city, we have developed a learned dependency for these unsustainable material practices [3]. With global urbanization rapidly increasing, it is critical that we turn towards renewable site specific material solutions to guide the design process and construction methods of our built environments.

Using locally sourced soils as a primary building material has been utilized by humans for thousands of years in the form of modular bricks, rammed earth, adobe construction, etc [4]. Each of these methods were specific to the environmental conditions that they had to withstand and in turn this would spawn means and methods specific architectural typologies. Through material experimentation, construction methods utilizing these locally abundant resources were developed and have given us buildings that are still standing thousands of years later, such as the Ziggurat at Ur that was constructed in 4,000 BCE in Taos Pueblo, New Mexico [4]. Although having a strong history of earthen construction, earthen materiality is not often thought of having a role within an urban context in contemporary times. Concrete, metals, wood, and various polymers have been given primacy in our construction standards, while minimally processed earthen materials have fallen to the wayside. Although recent research is starting to think about how we might take advantage of these material properties through other means of construction.

For instance, Jammed Architectural Structures by Gramazio Kohler Research at the ETH Zurich [5] and Rock Printing by Self-Assembly Lab at MIT in collaboration with Gramazio Kohler Research [6]. These two installations took advantage of the basic material properties of rocks and string to develop a load-bearing structural system. This occurs through an automated process of laying rocks and placing coiled string between each layer of these rocks [5–7]. While the rocks want to crumble downward, the string is able to hold the compressive material system together in tension. This enables a tension-compression material network to occur through this intelligently designed system. This is a low cost alternative to traditional load bearing construction materials and methods with little to no material waste. Through a built-in design intelligence, we have the capability to replace the less sustainable methods that currently dominate the market.

While one side of material waste occurs through an excess of construction material itself, additional waste is generated from single-use formworks. Much of our construction industry is dominated by wood or metal formworks that have their pros and cons, but neither are long term sustainable solutions for the construction industry. In 1942, Wallace Neff founded a technique of using pneumatic formworks to develop shellular concrete domes [8]. This typology that was directly informed by the construction method produced what became known as bubble houses [9]. These homes used a rubber balloon inflatable that was tied down to a series of metal hooks that were embedded within a poured concrete foundation to help prevent substantial uplift from occurring upon inflation [9]. This would then provide a surface in which insulation and concrete could all be sprayed onto. While this formwork solution didn't replace other methods per se, it did show the potentials of this construction methods application across a variety of scales and programs. At the time, the geometric possibilities were limited but now has the potential to expand upon its established vocabulary.

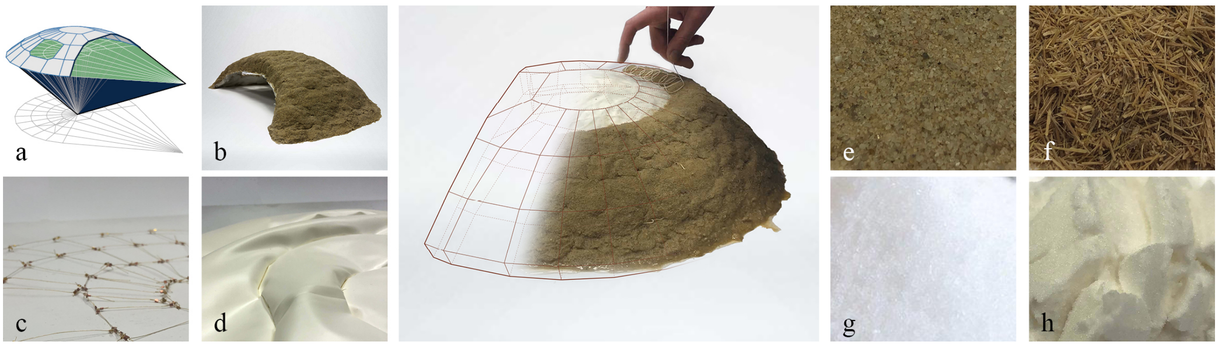

Figure 1: Geometric Design: (a) form's polyhedral force diagram, (b) completed compression-only half dome model, (c) tension wireframe network, (d) pneumatic bladder; Material Design: (e) sand base, (f) short natural fibers, (g) natural plasticizer, (h) natural binder.

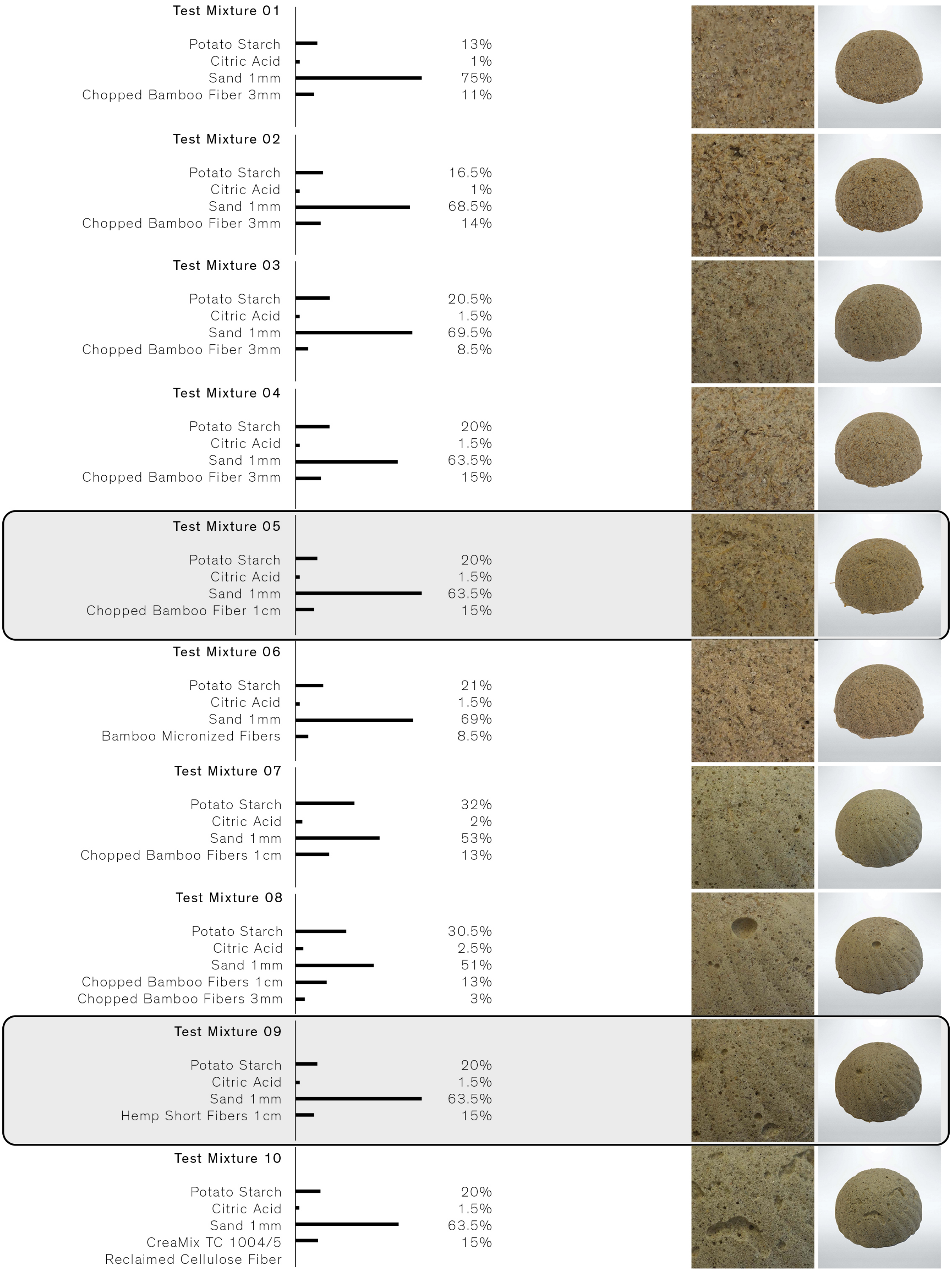

Figure 2: Preliminary Terrene mixture material studies and composition ratios

2. Methodology

Quikrete's all-purpose silica sand mixture with a granularity of 0.5 - 1mm was purchased from Home Depot; bamboo short fiber +/- 1cm, bamboo short fiber +/- 3mm, bamboo short fiber micronized filler, hemp short fiber +/- 1cm were all purchased from Sunstrand LLC; CreaMix TC 1004/5 - reclaimed cellulose fiber was purchased from CreaFill Fibers Corporation; VintageLineStyle's natural flax fiber and Mohair & More's bamboo spinning fiber was purchased from Etsy; Earthborn Element's powdered potato starch, Roots Circle's citric acid, CandleScience's all natural soy candle wax, and Silk City Fiber's 100% bamboo yarn were purchased from Amazon.com Services LLC. The Terrene mixtures components were measured using a SurmountWay high precision digital laboratory scale with a 10kg x 0.1g accuracy. The material study compression testing was measured using an Instron model 4206 universal testing machine with a 2267.962kg load cell.

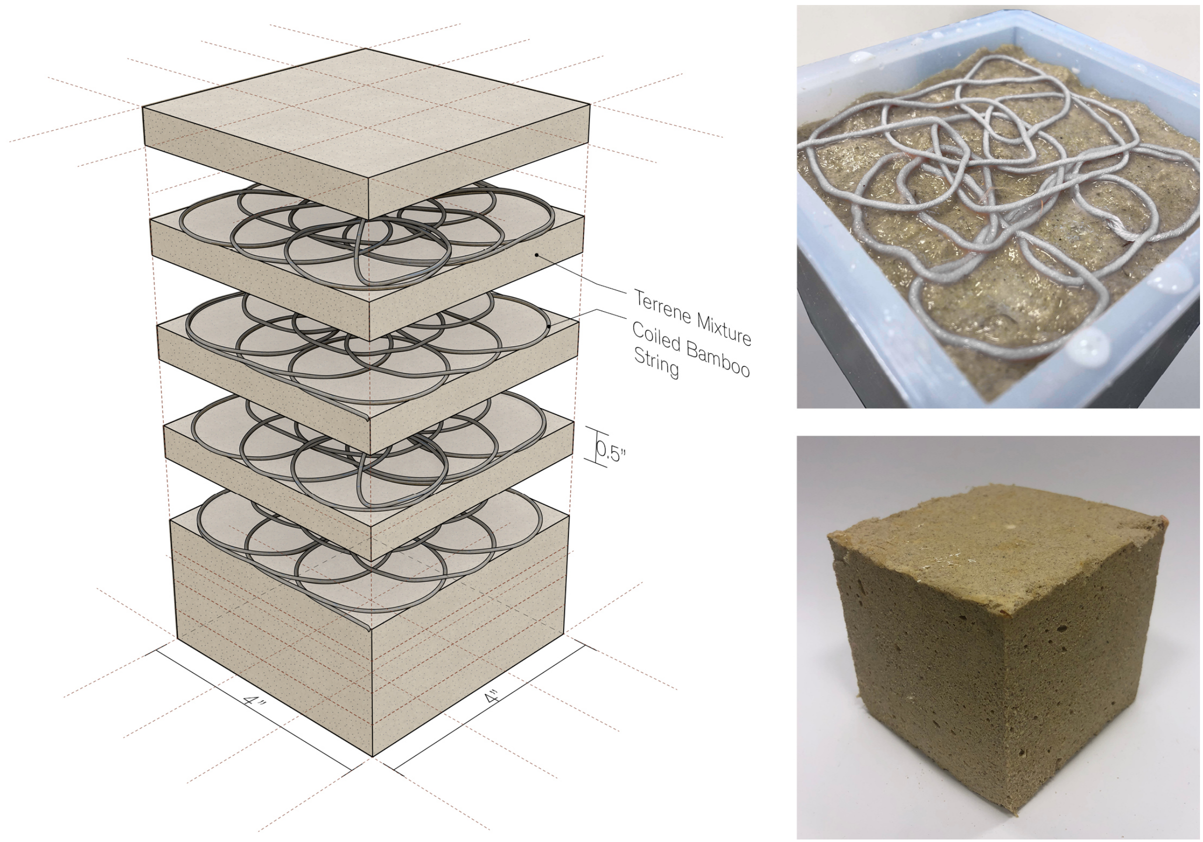

Figure 3: Cube material sample scale and assembly.

2.1. Material Composition & Mechanical Properties

The Terrene material mixture aims at using simple and sustainable material building blocks with diverse functional contributions [3] and is comprised of; a compressive sand matrix, various natural fibers to provide an increase in tensile capacity, potato starch to function as a natural adhesive, and citric acid as a natural plasticizer [10]. Preliminary material tests were developed through the casting of 7.62cm in diameter and 3.556cm tall half-dome structures. The dried material ratios of these tests can be found within Figure 2. Based on the outcome of these preliminary studies, an additional six material blends were each cast three times within 10.16cm3 silicone cube molds. Some of the cube compositions included a coiled

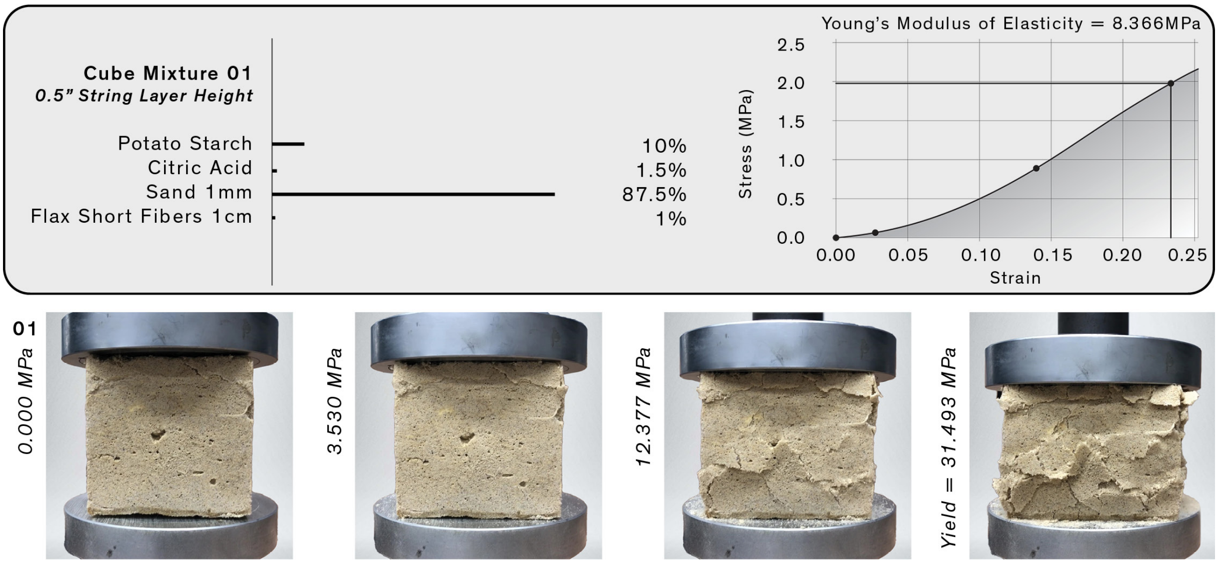

Figure 4: Cube material test 01 composition, stress strain graph, and instron compression testing results.

bamboo fiber string that is laid at various layer heights throughout, as illustrated within Figure 3. One cube of each material blend was cast within each of the three groups. Each group was left to dry in ambient conditions within their respective silicone molds for 10 days. After being demolded, each group was left to dry within ambient air for an additional 30 (group 1), 21 (group 2), and 12 days (group 3); prior to being compression tested. The selected cube's material composition and Instron compression results can be found within Figures 4. These compression results revealed that Terrene Blend 01 has the highest stress capacity of 1.97MPa and a Young's Modulus of Elasticity of 8.366MPa. Therefore, based on these quantitative results from the load testing, material Blend 01 was selected for its application in the fabrication of the 0.5m2 crescent dome model.

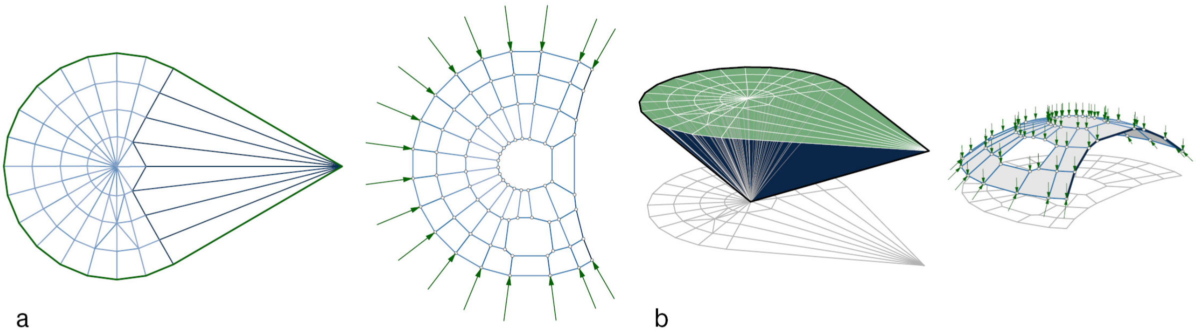

Figure 5: Polyhedral Graphic Statics Model: (a) a subdivided global force polygon and its reciprocal compression-only crescent dome form, (b) the 3D equivalent of the same network extruded to a point below the network and its reciprocal crescent dome form.

2.2. Polyhedral Graphic Statics Application

The geometrically efficient form finding technique of Polyhedral Graphic Statics was deployed to develop the compression-only funicular crescent dome geometry [11]. As shown in Figure 5, the form-finding process starts by making a network of convex polygons on a 2D plane. This network is then extruded to a single point underneath the network's geometry to construct a polyhedral force diagram. A reciprocal form of a compression-only shell is then extracted from the force diagram using the PolyFrame software [12]. This compression-only form is a single-layered shell structure that will be used as a compression-dominant geometry for the rest of this research [11]. Because the top faces of the force diagram are all parallel to the $xy-$ plane, the direction of the applied loads on the reciprocal form of the shell will be perpendicular to the ground which may represent the self-weight of the shell [13]. The method of polyhedral graphic statics yields a geometry that is made entirely of planar surfaces, making it easy to translate the geometry back and forth between 2D and 3D.

2.3. Construction Method

Derived from the polyhedral graphic statics crescent dome model (section 2.2), the planar surfaces were unrolled and seamed for the construction of a reusable pneumatic formwork. This formwork was fabricated using a vinyl coated fabric and seamed with a combination of liquid stitch and hot glue. The formwork was constrained by a wireframe network that was developed based on the exact lengths of each member from the polyhedral graphic statics computational model. With the pneumatic formwork inserted underneath the anchored wireframe network, it can be inflated with the wireframe resisting the outward forces to keep the physical geometry precise to the digital formulation. With the pneumatic formwork inflated, bamboo spinning fiber is cut to lengths of six inches, soaked in melted soy wax, and then applied to the surface of the pneumatic structure. This process ultimately yields the wireframe network embedding itself within the wax-fiber composite with the inflatables removal.

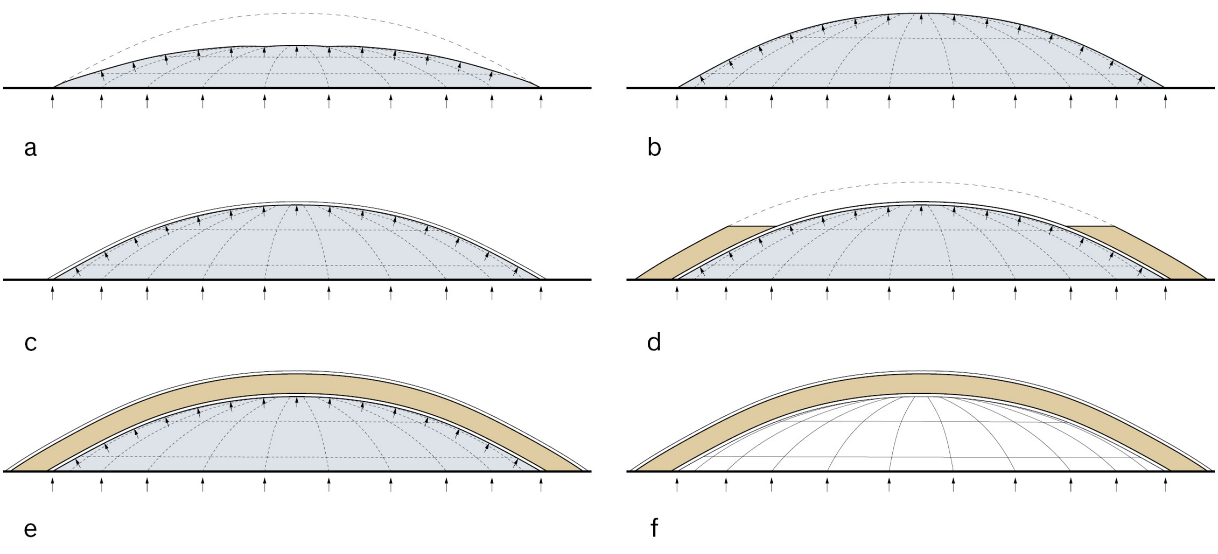

Figure 6: Construction Process: (a) pneumatic formwork inflation, (b) pneumatic formwork constrained by wireframe network, (c) interior wax-fiber composite placed on pneumatic formwork, (d) Terrene composite placed with coiled string interstitially laid, (e) exterior wax-fiber composite placed onto Terrene composite, (f) inflatable formwork deflated and removed.

Once the wax-fiber composite is dried by the ambient air, Blend 01 of the Terrene mixtures is laid with a 2.5cm width and 2.5cm layer height. Interstitially placed between each Terrene mixture layer is a starch soaked coiled bamboo yarn where each loop has a rough diameter of 1.5cm and overlaps two thirds onto the previous loop as illustrated by Figure 1. With the structure complete, it is left to dry in ambient air for 12 hours before the pneumatic formwork is deflated and removed. An additional layer of the wax fiber composite is then placed overtop, onto the exterior of the Terrene mixture.

3. Results

We believe that the intersection between intelligent material design [18] and innovative structural design will lead to more sustainable construction methods that yield a minimal amount of waste [14]. The material intelligence that is presented within this paper provides a low-cost alternative to other environmentally damaging composites such as concrete for homogeneous compression-only funicular structures. The lack of required complex machinery and its use of abundantly accessible materials makes this structure adaptable to many different environments using either locally sourced materials or already existing material transportation routes.

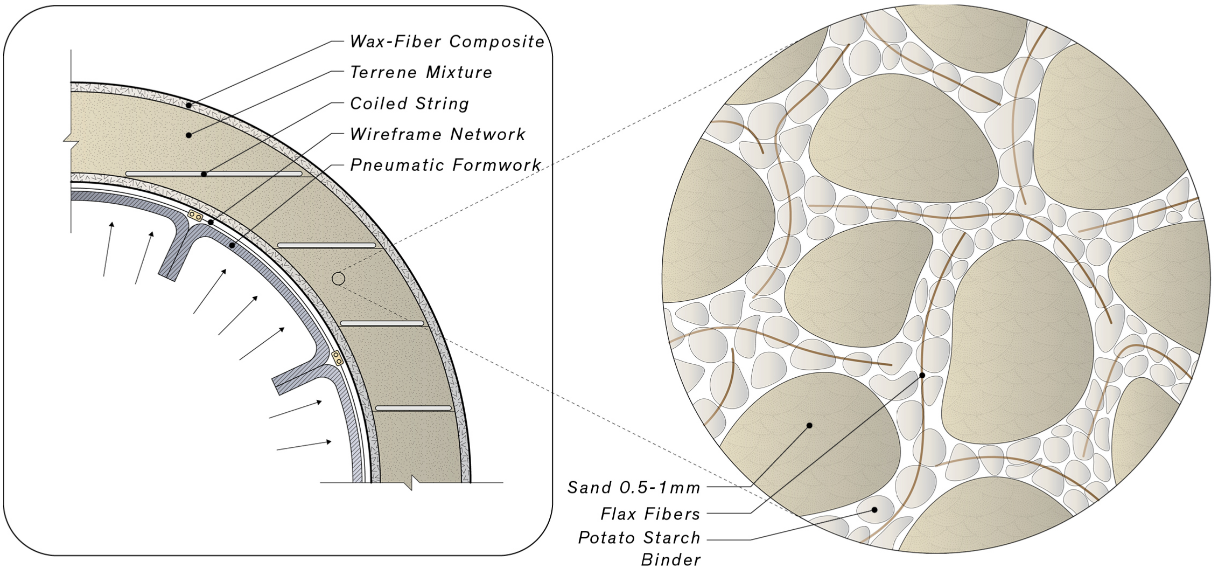

Figure 7: Construction detail and illustration of material organization.

3.1. Terrene Material Benefits

Taking inspiration from the traditional rammed earth construction method, Terrene looks to expand upon this technique through removing the need of wasteful formwork during the construction process and through tuning the materials properties to provide additional formal typologies. Due to the multi-regional abundance and accessibility of sand, this was selected as the composites base. While sand has its strength in compression, it lacks any tensegrity and requires some form of adherence for the granules to hold themselves together. The built-in intelligence of this material mixture begins with the introduction of short chopped bamboo, hemp, or flax fibers. The introduction of these fibers provides the sand mixture with tensile strength. Additionally, when the renewable potato starch binder is added to the mixture, the sand grains and short fibers are capable of producing a homogeneous tension-compression material system. While this material system's compressive strength resulted in being eight times weaker than concrete [15], it has the potential for smaller scale applications in which the use of concrete would be unnecessary and wasteful. Due to their natural composition, all of the materials can break down and reintegrate themselves back into the natural environment without having ecologically damaging effects.

Another key advantage is the material systems ability to solidify naturally over time within ambient conditions. This eliminates the discharge of any air pollutants that are released into the atmosphere during the typical firing process of other earth-based materials such as bricks, ceramics, or cement and also avoids the use of curing agents in concrete which highly contribute to its carbon dioxide emissions [16–18].

Further material intelligence is built into the system through the application of the wax-fiber composite finish, that provides additional tensile support, embeds the wireframe tension network within itself, waterproofs the Terrene mixture, and reinforces against any material erosion. In creating a barrier between the pneumatic formwork and the Terrene mixture, the wax-fiber composite is able to eliminate risk of unwanted material adherence between the two.

Figure 8: Physical Model Construction: (a) pneumatic formwork constrained by wireframe network, (b) wax-fiber composite placed on pneumatic formwork, (c) wireframe network embedded within wax-fiber composite.

3.2. Digital to Physical Translations

The benefit of using polyhedral graphic statics in the application of this funicular form is that it is able to achieve a maximum mechanical strength with a minimal material thickness [11]. This translation between the digital to the physical begins with the development of the wireframe network (Section 2.3). As shown in Figure 5, the crescent dome geometry that was generated based on the reciprocal polyhedral force diagram provides a series of edges that are calculated to specified lengths. Therefore, moving from the digital to the physical, the lengths of each tension member of the wireframe network is exactly the specific length that is calculated within the digital model. This translation also occurs between the planar surfaces that exist between these closed edge lengths and the assembled inflatable structure. Through an unrolling of the planar geometry, tangential surfaces are able to be combined to simplify the manufacturing process and reduce the number of seams that occur. The benefit of reducing the seams in this instance is that there are less opportunities for the pneumatic system to leak and therefore depressurize. While the form finding technique of polyhedral graphic statics is extremely beneficial to structural and material efficiencies, it provides this tangible adaptation from a conceptual form to a clear means and methods for accurately constructing geometry based on the calculated constraints.

3.3. Construction Sustainability

The fabrication process of this structure is built off of the constraints enforced by the materials mechanical properties and geometric formulation (Sections 2.1 and 2.2). In enabling these principles to develop the construction process, a series of low-impact environmental solutions are achieved, starting with the pneumatic formwork. This design solution provides a foundation for the material system to be laid upon without the need of wooden formwork that must be discarded after the construction is completed or metal formwork that is cumbersome and costly [19]. This enables the development of a modular formwork system that can be applied repeatedly to the construction of like structures. This lightweight formwork solution also minimizes transportation needs and costs since this system can begin compact and then expand to size on site when internal air pressure is increased.

In addition to the utilization of the reusable pneumatic formwork, the material system also benefits from the minimal amount of energy that is needed during the processing of the structure. Since the Terrene mixture dries within ambient air (Section 3.1), the only energy that is put into the fabrication process is maintaining the pneumatic structures' air pressure and the melting of the soy wax. Through this ambient curing, all construction can take place in-situ with minimal material transportation. When constructed in the right context, the sand matrix and natural fibers could be harvested locally on site. Therefore the only material that would have to be transported is potato starch, citric acid, the pneumatic formwork, and the tensile wireframe network. With all aspects being spatially efficient and lightweight, this system can provide a more accessible material system and construction method.

4. Conclusion

As we look forward to developing a more sustainable future for the construction industry that minimizes the amount of waste we produce during the construction and demolition of our buildings, we must turn to further exploring the application of renewable resources and smarter methods of construction. In the United States in 2018, 145 million tons of construction and demolition debris was sent to landfills [20]. With the proper material composition, this material does not need to be sent to landfills but rather reintegrate itself into its surrounding environment. While this material is not as performative as concrete, it can provide a low environmental impact alternative when applicable to various design constraints and architectural typologies. Further research is currently underway in the use of different binders to provide the material system with additional mechanical strength, for a wider range of applications beyond funicular forms [21, 22]. Our continuing research goal is to branch into explorations of anticlastic shellular geometry [23] through this further refined material blend and a more polished construction process.

Figure 9: Physical Model Construction: (a) terrene mixture solidified into crescent dome structure, (b, c) wax-fiber composite placed on exterior of terrene mixture.

While the construction method was guided by the developed Terrene mixture, it is a method that can be deployed with various other materials to help reduce or completely eliminate any formwork waste. Current industry standards revolve around the utilization of wood, steel, or aluminum as concrete construction formwork, but each of these have their disadvantages either due to cost, constrained geometric typologies, labor intensive fabrication, or single-use applications [24]. Through the proper manufacturing channels, complex geometric pneumatic formworks can be produced for little cost and re-deployed numerous times for the construction of different structures of the same geometry.

Additionally, the accessibility of this system, as demonstrated in the construction of the crescent dome model, is a process that can all occur through a manual application of the material to the formwork. Although, at larger scales, this manual process might not be desired. Therefore, additional tooling is being explored such as the mixtures application with shotcrete spraying technologies and a prefabricated tension system that replaces the need for coiled string to be interstitially placed between each layer of the Terrene mixture. Along with these new explorations, we look towards the potential of the construction process being executed through the use of programmed autonomous technologies.

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References

[1] IEA, "Global status report for buildings and construction 2019," 2019.

[2] B. Dean, J. Dulac, K. Petrichenko, and P. Graham, "Towards zero-emission efficient and resilient buildings.: Global status report," 2016.

[3] M. F. Ashby, *Materials and the environment: eco-informed material choice*. Elsevier, 2012.

[4] R. Rael, *Earth Architecture*. Princeton Architectural Press, 2010.

[5] P. Aejmelaeus-Lindström, G. Rusenova, A. Mirjan, F. Gramazio, and M. Kohler, "Direct deposition of jammed architectural structures," in *Robotic Fabrication in Architecture, Art and Design*, pp. 270–281, Springer, 2018.

[6] Z. Cohen, N. Elberfeld, A. Moorman, J. Laucks, S. Kernizan, D. Holmes, and S. Tibbits, "Superjammed: Tunable and morphable spanning structures through granular jamming," *Technology— Architecture+ Design*, vol. 4, no. 2, pp. 211–220, 2020.

[7] P. Aejmelaeus-Lindström, J. Willmann, S. Tibbits, F. Gramazio, and M. Kohler, "Jammed architectural structures: towards large-scale reversible construction," *Granular Matter*, vol. 18, no. 2, pp. 1–12, 2016.

[8] D. Veenendaal, M. West, and P. Block, "History and overview of fabric formwork: using fabrics for concrete casting," *Structural Concrete*, vol. 12, no. 3, pp. 164–177, 2011.

[9] J. Head, *No nails, no lumber: The bubble houses of Wallace Neff*. Chronicle Books, 2011.

[10] P. Jia, H. Xia, K. Tang, and Y. Zhou, "Plasticizers derived from biomass resources: A short review," *Polymers*, vol. 10, no. 12, p. 1303, 2018.

[11] M. Akbarzadeh, *3D Graphical Statics Using Reciprocal Polyhedral Diagrams*. PhD thesis, ETH Zurich, 2016.

[12] A. Nejur and M. Akbarzadeh, "Polyframe, efficient computation for 3d graphic statics," *Computer-Aided Design*, vol. 134, p. 103003, 2021.

[13] M. Akbarzadeh, T. Van Mele, and P. Block, "On the equilibrium of funicular polyhedral frames and convex polyhedral force diagrams," *Computer-Aided Design*, vol. 63, pp. 118–128, 2015.

[14] M. Bolhassani, A. T. Ghomi, A. Nejur, M. O. Furkan, I. Bartoli, and M. Akbarzadeh, "Structural behavior of a cast-in-place funicular polyhedral concrete: Applied 3d graphic statics," in *Proceedings of IASS Annual Symposia*, vol. 2018, pp. 1–8, International Association for Shell and Spatial Structures (IASS), 2018.

[15] M. Bechthold and J. C. Weaver, "Materials science and architecture," *Nature Reviews Materials*, vol. 2, no. 12, pp. 1–19, 2017.

[16] B. M. Skinder, A. K. Pandit, A. Sheikh, and B. Ganai, "Brick kilns: cause of atmospheric pollution," *J Pollut Eff Cont*, vol. 2, no. 112, p. 3, 2014.

[17] M. Muthukannan and A. S. C. Ganesh, "The environmental impact caused by the ceramic industries and assessment methodologies.," *International Journal for Quality Research*, vol. 13, no. 2, 2019.

[18] M. Schuhmacher, J. L. Domingo, and J. Garreta, "Pollutants emitted by a cement plant: health risks for the population living in the neighborhood," *Environmental research*, vol. 95, no. 2, pp. 198–206, 2004.

[19] M. K. Hurd, "Formwork for concrete," American Concrete Institute, 2005.

[20] EPA, "Sustainable management of construction and demolition materials," 2018.

[21] L. Mogas-Soldevila, J. Duro-Royo, D. Lizardo, M. Kayser, W. Patrick, S. Sharma, S. Keating, J. Klein, C. Inamura, and N. Oxman, "Designing the ocean pavilion: Biomaterial templating of structural, manufacturing, and environmental performance," in *Proceedings of IASS Annual Symposia*, vol. 2015, pp. 1–13, International Association for Shell and Spatial Structures (IASS), 2015.

[22] J. Duro-Royo, J. Van Zak, Y. Tai, A. Ling, and N. Oxman, "Parametric chemistry reverse engineering biomaterial composites for additive manufacturing of bio-cement structures across scales," *Innov*, vol. 217, no. 223, pp. 217–223, 2017.

[23] M. Akbari, A. Mirabolghasemi, H. Akbarzadeh, and M. Akbarzadeh, "Geometry-based structural form-finding to design architected cellular solids," in *Symposium on Computational Fabrication*, pp. 1–11, 2020.

[24] W. Li, X. Lin, D. W. Bao, and Y. M. Xie, "A review of formwork systems for modern concrete construction," in *Structures*, vol. 38, pp. 52–63, Elsevier, 2022.