Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Stimulated Soil for Continuous Shell Structures

Roni HILLEL*[a], Tom SHAKED[b], Michael TSESARSKY[c] Aaron SPRECHER[a]

* [a] Material Topology Research Lab, Faculty of Architecture & Town Planning, Technion – Israel Institute of Technology, Haifa, Israel
[b]Architectural Robotics & Construction Automation Lab, School of Architecture, Ariel University, Ariel, Israel
[c]Department of Civil and Environmental Engineering, Ben-Gurion University of the Negev, Beer Sheva, Israel
ronihillel@campus.technion.ac.il
tomsha@ariel.ac.il
michatse@bgu.ac.il
asprecher@technion.ac.il

Abstract
Historically, local soil has been a primary construction material. Buildings featuring thick walls, vaulted roofs, and domes were designed and built for local communities. However, this practice is labor-intensive and inefficient. Addressing these challenges, the study explores the potential of Microbially Induced Calcium Carbonate Precipitation (MICP), a technique that utilizes bacteria to harden soil, as a solution to enhance the structural integrity of soil-based construction materials. This initial research focuses on biostimulating existing bacteria in locally sourced soil, thus simplifying the MICP process and facilitating on-site applications. It extends this approach by examining the construction of continuous shell structures using local soil, with cutting-edge material methods in creating vaults and domes. The research employs robotic fabrication to experimentally investigate the application of MICP by stimulation in shell structures subjected to compressive forces. It evaluates the performance and stability of these structures, employing an additive manufacturing process. Two distinct materials are tested: 1) local loess soil mixed with water as a control method, and 2) local loess soil treated with MICP for the experimental method. Two identical shell structures are 3D printed for each material using a custom robotic end-effector. This study suggests that applying MICP by stimulation can potentially enable the use of soil in the construction of continuous shell structures, provided their design is optimized for such forces. Ultimately, this research initiates the integration of traditional construction materials with innovative biotechnological methods to produce more sustainable construction practices.

Keywords: MICP; sustainable materials; locally sourced soil; shell structures; robotic fabrication

1. Introduction

1.1. Local Materials for Sustainable Construction

Given the environmental toll of concrete production, evidenced by substantial CO2 emissions and resource depletion [1], [2], the construction field is turning towards local materials for more sustainable practices. This revival of traditional construction techniques, which make use of local materials and are designed to adapt to climate conditions, underscores the importance of thermal mass in regulating temperature and the architectural significance of specific suitable geometries [3]. Despite historical challenges associated with these traditional methods, such as inefficiency and higher maintenance, contemporary advances in construction technology, notably additive manufacturing, offer innovative solutions to overcome these obstacles [4].

1.2. Earthen Construction Geometries

Throughout history, the use of local materials for construction was common and necessary. Architects Hassan Fathy [5] and Bernard Rudofsky [6] exemplify this trend by using mud in construction to highlight the significant relationship between materials, climate, and architectural form. Both emphasize distinctive shapes like domes and vaults to enhance structural and aesthetic qualities. In more recent research, Bradley et al. [7] explore using steep catenary vaults with earth bricks for affordable housing, emphasizing the structure's effective compression capacity and the material cost benefits. The study also addresses challenges like the material vulnerability to tension, bending, and potential cracking due to wind, thermal expansion, and shrinkage. This indicates the material and geometric potential but also reveals the limitations.

1.3. Soil Stabilization Through Stimulation

The Microbially Induced Calcium Carbonate Precipitation (MICP) technique emerged as a method for soil stabilization to enhance its properties. This method utilizes bacteria-produced urease to degrade urea into carbonate and ammonium, which, with the presence of calcium ions, forms solid calcium carbonate cement, and thus strengthening the soil. Traditionally, the method involves introducing cultivated bacteria into the soil with a reagent solution used for stimulation [8]. However, the traditional MICP approach, often faces challenges with bacterial adaptation to natural soil environments, consuming significant time and resources. Gat et al. [9] and later Raveh-Amit et al. [10] demonstrated the effectiveness of stimulating native bacteria for similar benefits. Their approach was successfully tested to mitigate dust emissions and reduce soil erodibility, while MICP's potential in construction requires further research to enhance local soil's structural properties.

2. Background

2.1. Robotic Fabrication and Locally Sourced Materials

Robotic manufacturing using natural materials marks an advancement toward innovative, sustainable construction. Perrot et al. [4] explored the use of extrusion-based 3D printing with earthen materials to overcome the limitations of traditional building methods. Similarly, Shaked et al. [11] introduced middleware that combines subtractive and additive manufacturing for intricate robotic stonework, enhancing digital fabrication on-site. Bar-Sinai et al. [12] further explored this theme by applying various robotic fabrication techniques for converting local desert soil into soil into viable construction elements. Aiming to enhance similar production processes, Asaf et al. [13], propose a method to optimize clayey soil mixtures for 3D printing, emphasizing the design and utilization of local materials for eco-friendly construction. Collectively, these explorations highlight a shift towards merging historical building practices with cutting-edge technology to achieve more sustainable construction solutions.

2.2. Shell Structures Using Earthen Materials

Traditional construction practices have historically utilized locally sourced materials and designs adapted to the local climate [3]. Architect Hassan Fathy [5] explores mud construction, highlighting the influence of material and climate on design. This approach employs thermal mass for temperature regulation and utilizes specific geometries like domes and vaults to create relatively large spaces from materials such as mud. Additionally, architect Bernard Rudofsky's [6] examines carved rock dwellings, underground loess structures, and the use of mud bricks for vaults and domes, demonstrating the diverse application of local materials in architecture. Catenary domes and vaults are considered efficient geometries for earth brick shell structures, as described by Bradley et al. [7]. They note the advantages of such compression structures due to the material availability and its low cost, but also highlight their disadvantages due to tension forces. The material’s weakness is expressed in its inability to resist horizontal forces such as wind and its tendency to bend and crack, thereby limiting the dimensions and the geometry of such structures.

Current studies by Curth et al. [14] and Moretti [15] delve into the potential of 3D-printed earth architecture for constructing domes and vaults, leveraging the sustainable attributes of local materials. The former implements innovative printing strategies, such as angled deposition, to address the challenge of building compression-dominant architectural forms without traditional formwork. The latter presents the TECLA project which marks a significant advancement in using earthen materials for sustainable habitat construction. Both reaffirm the structural viability of ancient construction techniques in a modern context and highlight the environmental benefits of utilizing earthen materials in contemporary architectural practices.

Furthermore, enhancing the material properties is a parallel strategy for creating sustainable architectural solutions with earth-based materials. Lasting et al. [16] introduce Terrene 1.0, a biodegradable composite material conducive to compression-dominant shell structures by innovatively combining sand with natural fibers and binders. Employing polyhedral graphic statics, the research achieves structural optimization and material efficiency, showcased through a construction methodology that leverages pneumatic formwork for creating performative geometries. These studies pursue sustainable construction practices aiming to reduce the environmental impact associated with conventional building materials and techniques.

2.3. Stabilizing Soil Utilizing MICP

In 2010, van Paassen et al. [17] conducted pivotal research on biogrouting, demonstrating its effectiveness in soil improvement through microbial-induced carbonate precipitation, presenting a sustainable option to traditional methods. This technique, confirmed by injecting bacteria and solutions into the soil, underscores the practicality of biogrouting for enhancing soil mechanical properties in real applications.

Biogrouting and microbial-induced calcium carbonate precipitation (MICP) are innovative methods to stabilize soil, improving its strength, durability, and resistance [8]. These processes utilize bacteria to catalyze carbonate formation, solidifying calcium carbonate within soil structures. The prevalent laboratory approach involves introducing exogenous bacteria and a reagent solution into the soil, promoting this transformative mechanism.

Exploring MICP's broader applicability, Gat et al. [9] highlighted the efficacy of leveraging local bacteria for soil stabilization, avoiding the complexities of using non-native microbes. Furthering this application, Raveh-Amit et al. [10] successfully applied MICP to combat soil erosion, optimizing the solution concentration activating of indigenous bacteria, and showcasing significant erosion and crack reduction. With further research, this approach can be used as a method to stabilize local soil for construction.

3. Research Objective

This study is a part of an introductory research that examines the potential of using the MICP process through preliminary small-scale experiments of stimulating local soil bacteria for sustainable construction [18]. The study aims to promote the production of a protocol for manufacturing and testing the properties of a material based on soil and a reagent solution and comparing it to a material based on the same soil and water. A domed shell structure is ideal for examining the properties of a soil-based material, as the geometry is suited to compressive forces and allows for optimal testing of the material's durability and strength for construction purposes. Additionally, the research explores using this material in a 3D printing process, which is a more efficient method than traditional soil construction techniques.

4. Methodology

The methodology is divided into three main parts: material, geometry and analysis, and fabrication experiments.

4.1. Material

The examination of the material's viability involved multifaceted testing, initially focusing on detecting bacterial activity within local loess soil samples collected from the Israel-Egypt border region, whose mineralogical characterization results are described in Table 1. This investigation into bacterial activity was conducted under three distinct conditions: dry soil, moist soil, and soil that had been moistened and subsequently dried. For each condition, a 10 g (gram) soil sample was combined with yeast extract, urea, and 100 mL (milliliter) of water to facilitate bacterial growth and urea decomposition, indicating bacterial activity through pH shifts toward basic levels [9]. Despite the addition of 0.1 g of yeast extract on the seventh day to potentially spike pH levels, a continued decline was observed. The composition and pH levels of each mixture are systematically presented in Table 2 and Table 3, respectively. Notably, the mixture involving pre-moistened soil demonstrated the most significant pH increase on the fifth day (as depicted in Figure 1). A subsequent experiment with this mixture, using a doubled soil and solution quantity, revealed an even higher pH peak on the second day, suggesting variable bacterial activity based on soil condition and mixture composition (Figure 2).

Table 1: Mineralogical characterization results for local loess soil

Phase	**Quartz**	**Calcite**	**Motmorillonite**	**Illite**	**Albite**	**Koalinite**	**sum**
Weight (%)	53.4	19.6	11.5	8.3	5.5	1.7	100

Table 2: Soil status and solution ingredients

Soil					**Solution**		
Mix	Status	Gross weight (g)	Water (%)	Net weight (g)	Ingredients (per liter)		Weight (g)
Mix A	Raw	10	0	10	Urea	20 g	100
Mix B	Wet	13.89	28	10	Yeast extract	1.5 g	96.11
Mix C	Dried	10	0	10			100

Table 3: pH measurements due to bacteria stimulation

Days	**0**	**1**	**3**	**5**	**6**	**7**	**8**	**12**
Mix A	6.8	7.05	8.71	8.58	8.49	8.3	8.07	8.07
Mix B	6.8	6.88	8.75	8.66	8.56	8.4	8.13	8.01
Mix C	7.1	7.5	8.73	8.81	8.73	8.6	8.27	8.19

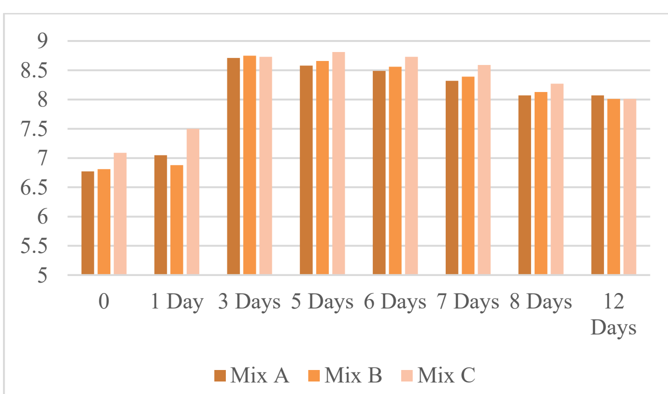


Figure 1: pH measurements due to bacteria stimulation

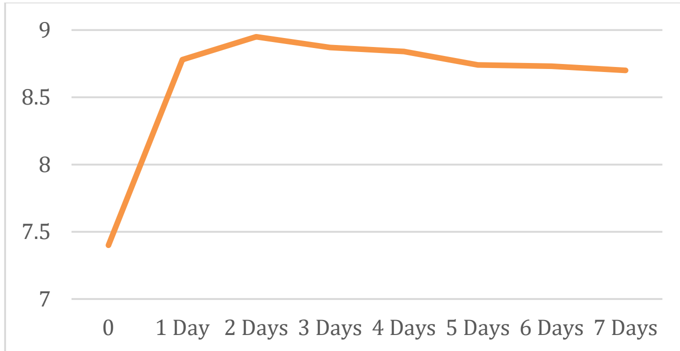


Figure 2: pH measurements due to bacteria stimulation of the subsequent experiment with Mix C

The second stage of the experiment involved larger soil mixtures, each with 5.2 kg of soil, focusing on achieving a 10% calcium carbonate precipitation to enhance soil properties in a printable mixture. Initial water content varied across mixtures, and the targeted calcium carbonate precipitation was based on a 0.5M (molar) concentration solution [10]. However, the required high water-to-soil ratio either resulted in overly dilute mixtures for 3D printing [13] or necessitated prolonged drying times. The soil's composition further complicated the process by impeding water drainage and accurate pH measurement. Consequently, the experiment was adjusted to aim for a 3% calcium carbonate precipitation in the mixture, which, after two days of drying at approximately 38°C, was subject to a moisture test and a flow table test, to achieve the optimal window as Asaf et al. [13] describe, to determine its printability. Due to the initial high moisture content (31%), 8 kg of 2 mm quartz sand aggregate was added to the mixture to achieve a consistency suitable for 3D printing. Table 4 presents the results of the flow table test before and after adding the sand. To ensure consistency between experiments, the preparation of the second mixture mirrored that of the first, utilizing the same amount of soil (5.2 kg net) with a 31% moisture level. An additional 8 kg of 2 mm quartz sand aggregate was incorporated to adjust the mixture's consistency for 3D printing capabilities.

Table 4: Flow table spread measurements to identify the "window" for 3D printing

Flow table spread						
Number of jolts	0		15		25	
Before adding sand (mm)	105	110	170	170	185	180
After adding send (mm)	101	100	133	138	146	145

4.2. Geometry and Analysis

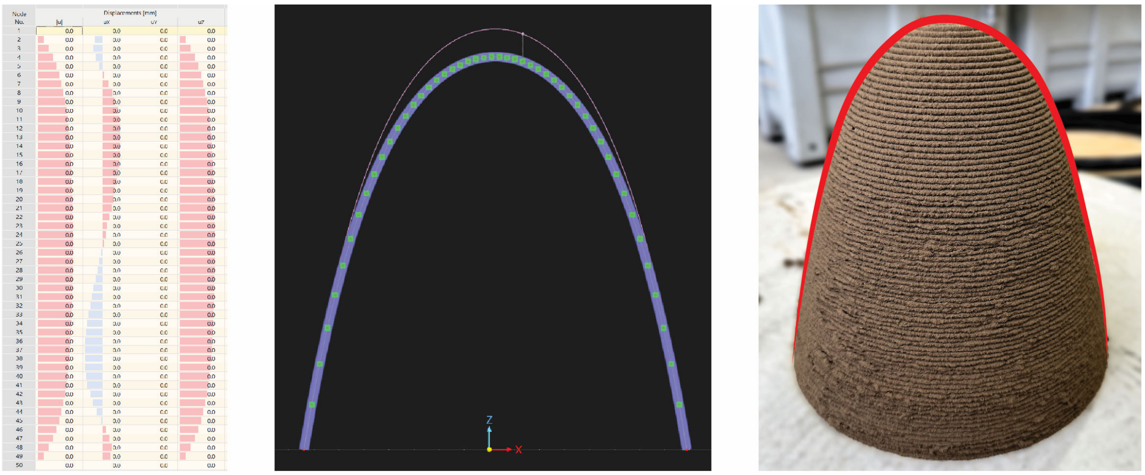
The selected structure for printing is a catenoid dome, valued for its compression efficiency, to facilitate a comparative analysis between the mixtures. This dome was precisely modeled to have a base diameter and height of 20 cm each conforming to the catenary curve equation (1) with a parameter of a=4 and x=10.

$$y = a\,cosh\left(\frac{x}{a}\right) \tag{1}$$

To evaluate the behavior of the material, an analysis was performed to predict the possible deformations on a two-dimensional model, using RFEM software by Dlubal. The analysis was conducted on a layer section of 5mm×15mm and is based on data from a prior material examination performed by the authors and existing literature on earthen materials properties [19] detailed in Table 5. When dry, the analysis of the dome indicates it should support its own weight with minimal to no deformation, as shown in Figure 3.

Table 5: Analysis parameters

Layer height (mm)	Layer width (mm)	Modulus of elasticity (N/mm²)	Shear modulus (N/mm²)	Poisson's ratio	Mass density (kN/m³)
5	15	3	1.1	0.375	1806



(a) (b) (c)

Figure 3: Deformation Analysis: (a) Displacements chart, (b) Analysis visualization (c) Printed catenary dome

4.3. Fabrication Experiments

The 3D printing experiments were conducted at the Technion National Building Research Institute utilizing a KUKA KR50 robotic arm with a custom 3D Potter extruder using an 8mm nozzle (Figure 4). Four experiments were conducted in total. In the first experiment, the layer height was set to 5mm, the speed to 60 mm/s, and the expected layer width was 15mm, but the resulting width was 10mm. In the other experiments, the layer height was set to 2.5mm and the resulting width was 15mm. The parameters of these experiments are detailed in Table 6.

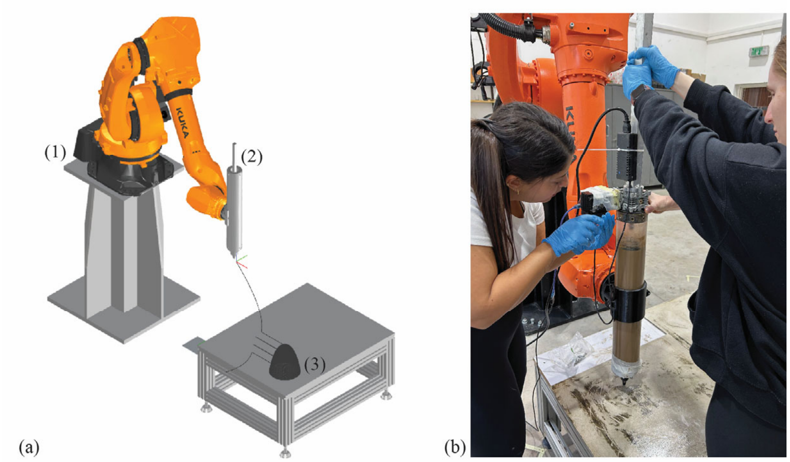


Figure 4: The experimental set up: (a) Illustration of the robotic cell comprising of the (1) Kuka KR50 robotic arm, (2) 3D Potter extruder, and (3) printing toolpath; (b) The set up preparation

Table 6: The parameters of the experiments

Experiment	Nozzle size (mm)	Velocity (mm/s)	Layer height (mm)	Expected layer width (mm)	Resulting Layer width
1	8	60	5	15	10
2-4	8	60	2.5	15	15

5. Results

The following section details the results of the fabrication experiments, focusing on the buildability of the shell structures in relation to the printing and material parameters according to the two examined mixtures.

5.1. Mixture 1: Loess Soil, Sand, and Reagent Solution

The initial printing of the dome failed due to inadequate layer width, leading to collapse (Figure 5). Subsequent adjustments included halving the layer height and adding sand as internal support, which ultimately resulted in misalignment and cracking perpendicularly to the layers (Figure 6) due to internal pressure from the sand. Without additional support and maintaining the revised layer height, a third attempt, successfully produced the dome, alongside a half-dome and eight 50mm³ cubes for subsequent strength and water resistance evaluations (Figure 7).

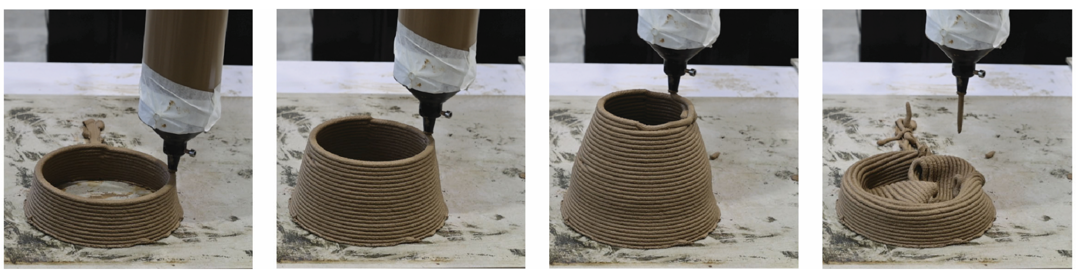


Figure 5: First experiment of 3D printing the catenary dome with stimulated soil

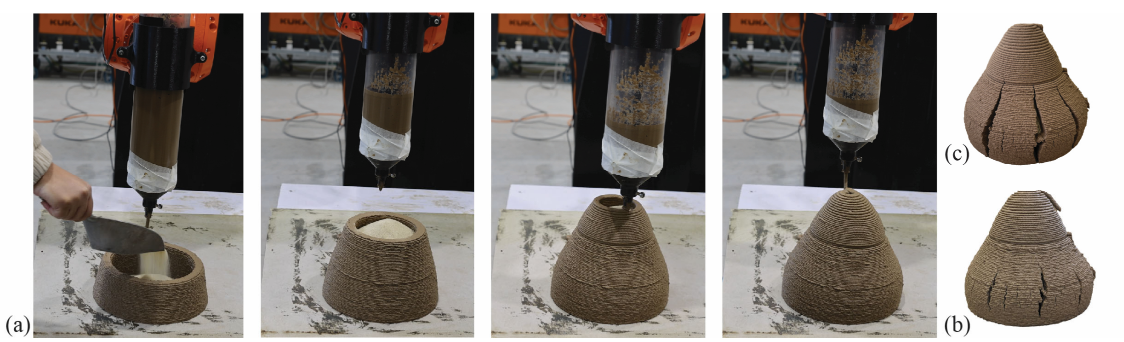


Figure 6: Second experiment of 3D printing the catenary dome with sand used for support: (a) printing process, (b) perpendicular cracks developed a short time after printing, and (c) perpendicular cracks developed after one week

(a) (b) (c) (d)

Figure 7: The 3D printed catenary domes: (a) a catenary dome 3D printed with stimulated soil, (b) 8 cast 50mm³ stimulated soil cubes, (c) a catenary dome 3D printed with non-stimulated soil, and (d) 8 cast 50mm³ non-stimulated soil cubes.

5.2. Mixture 2: Soil, Sand, and Water

Leveraging insights from the successful trial using Mixture 1, the dome printing with this mixture was accomplished. Similar to the first mixture, a half-dome, and eight 50mm³ cubes were also created for further testing.

5.3. Mixtures Comparison

The dome created with the reagent solution mixture remained stable over time, while the one made without solution developed cracks perpendicular to its layers at the base a week after its production (as depicted in Figure 8). A similar cracking pattern was observed in the base of the half-dome. This distinction highlights the impact of mixture composition on the structural integrity of printed forms. In this context, future research will include standard point and uniform load tests, as the current mixtures did not reach the required strength for load tests.

(a) (b) (c) (d)

Figure 8: The 3D printed catenary domes: (a) the non-stimulated mixture dome with a crack at its base, (b) a top view of the non-stimulated mixture dome, (c) the stimulated mixture dome with no cracks, and (d) a top view of the stimulated mixture dome

6. Conclusions, Limitations, and Future Work

The research delves into the innovative application of Microbially Induced Calcium Carbonate Precipitation (MICP) by stimulating local soil bacteria, aiming to enhance the structural integrity of soil for sustainable construction materials. It extends the potential of MICP by focusing on creating continuous shell structures such as vaults and domes, employing robotic fabrication for experimental investigation. This approach is posited to integrate traditional construction techniques with advanced biotechnological methods, contributing towards more sustainable construction practices.

The study acknowledges certain limitations and avenues for future research:

1. Challenges in accurately measuring pH levels within mixtures due to uneven water distribution highlight the need for developing sensors capable of precise measurements in solid and post-printed soil contexts.
2. While recognizing the environmental concerns associated with large-scale urea production, initial research into sustainable production methods is noted, suggesting a potential area for further exploration.
3. Addressing the by-product of ammonium during the MICP process, the research suggests future work to capture this gas for agricultural or other uses, pointing towards a holistic approach to sustainability.
4. Future research includes analysis and tests on stimulated soil using sample cubes and custom shell structures, specifically by performing standard load tests under point and uniformly distributed loads, water resistance, and quantifying calcium carbonate deposition, aiming to scale up printed objects for architectural applications.

In conclusion, the research marks a significant step towards leveraging MICP by stimulation in construction, demonstrating the viability of soil as a construction material for shell structures, optimized for compressive forces. It paves the way for integrating traditional and innovative construction methods, promoting sustainability in the construction industry.

Acknowledgments

The authors gratefully acknowledge the support of the National Building Research Institute (Israel) staff, especially Pavel Larianovsky. Their dedication and cooperation are greatly acknowledged. Along with much appreciation to Prof. Arnon Bentur from the Technion Advanced Construction Center and Prof. Avraham Dancygier from the Structural Engineering and Construction Management for their consultation. Also, we value the cooperation with Dr. Yoram Mass, who kindly performed the deformation analysis. Additionally, we would like to thank our research assistants, Maria Katzman and Sivan Shafrir, for their assistance during the experiments. Finally, we express our gratitude to Arch. Etan Kimmel and Arch. David Robins for their guidance in the final project that preceded this research.

References

[1] A. Horvath, "Construction materials and the environment," *Annu. Rev. Environ. Resour.*, vol. 29, pp. 181–204, 2004.

[2] N. Mohamad, K. Muthusamy, R. Embong, A. Kusbiantoro, and M. H. Hashim, "Environmental impact of cement production and Solutions: A review," *Mater Today Proc*, vol. 48, pp. 741–746, 2022.

[3] V. Olgyay, *Design with climate: bioclimatic approach to architectural regionalism*. Princeton university press, 2015.

[4] A. Perrot, D. Rangeard, and E. Courteille, "3D printing of earth-based materials: Processing aspects," *Constr Build Mater*, vol. 172, pp. 670–676, 2018.

[5] H. Fathy, *Architecture for the poor: an experiment in rural Egypt*. University of Chicago press, 2010.

[6] B. Rudofsky, *Architecture without architects: a short introduction to non-pedigreed architecture*. UNM Press, 1987.

[7] R. A. Bradley, M. Gohnert, I. Bulovic, A. M. Goliger, and D. B. Surat, "Steep catenary earth-brick shells as a low-cost housing solution," *Journal of Architectural Engineering*, vol. 23, no. 2, p. 4016018, 2017.

[8] D. Mujah, M. A. Shahin, and L. Cheng, “State-of-the-art review of biocementation by microbially induced calcite precipitation (MICP) for soil stabilization,” *Geomicrobiol J*, vol. 34, no. 6, pp. 524–537, 2017.

[9] D. Gat, Z. Ronen, and M. Tsesarsky, “Soil bacteria population dynamics following stimulation for ureolytic microbial-induced CaCO3 precipitation,” *Environ Sci Technol*, vol. 50, no. 2, pp. 616–624, 2016.

[10] H. Raveh-Amit, A. Gruber, K. Abramov, and M. Tsesarsky, “Mitigation of aeolian erosion of loess soil by Bio-Stimulated microbial induced calcite precipitation,” *Catena (Amst)*, vol. 237, p. 107808, 2024.

[11] T. Shaked, K. L. Bar-Sinai, and A. Sprecher, “Craft to site: Middleware for in situ robotic stonework,” *Construction Robotics*, vol. 4, pp. 141–150, 2020.

[12] K. L. Bar-Sinai, T. Shaked, and A. Sprecher, “Robotic tools, native matter: workflow and methods for geomaterial reconstitution using additive manufacturing,” *Archit Sci Rev*, vol. 64, no. 6, pp. 490–503, 2021.

[13] O. Asaf, A. Bentur, P. Larianovsky, and A. Sprecher, “From soil to printed structures: A systematic approach to designing clay-based materials for 3D printing in construction and architecture,” *Constr Build Mater*, vol. 408, p. 133783, 2023.

[14] A. Curth, B. Darweesh, L. Arja, and R. Rael, “Advances in 3D printed earth architecture: On-site prototyping with local materials,” *BE-AM| Building Environment Additive Manufacturing*, pp. 105–110, 2020.

[15] M. Moretti, “WASP in the Edge of 3D Printing,” in *3D Printing for Construction with Alternative Materials*, Springer, 2023, pp. 57–65.

[16] L. N. Lasting, I. Lee, L. Mogas-Soldevila, and M. Akbarzadeh, “Terrene 1.0: Innovative, earth-based material for the construction of compression-dominant shell structures,” in *Proceedings of IASS Annual Symposia*, 2022, pp. 1–12.

[17] L. A. van Paassen, R. Ghose, T. J. M. van der Linden, W. R. L. van der Star, and M. C. M. van Loosdrecht, “Quantifying biomediated ground improvement by ureolysis: large-scale biogrout experiment,” *Journal of geotechnical and geoenvironmental engineering*, vol. 136, no. 12, pp. 1721–1728, 2010.

[18] R. Hillel, T. Shaked, M. Tsesarsky, and A. Sprecher, “Exploring Robotic Fabrication Using Stimulated Soil,” in *Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe*, 2024.

[19] M. Moevus, R. Anger, and L. Fontaine, “Hygro-thermo-mechanical properties of earthen materials for construction: a literature review,” in *Terra 2012, XIth International Conference on the Study and Conservation of Earthen Architectural Heritage*, 2012.