Microbially Indurated Rammed Earth: A Long Awaited Next Phase of Earthen Architecture

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ABSTRACT: Rammed earth possesses low embodied energy, high recyclability, and low toxicity while having little impact on biodiversity and virtually no depletion of biological nutrients. Although rammed earth is an inherently sustainable building material, it fails to meet the high compressive strength requirements of contemporary building standards. Attempts to rectify this shortcoming by importing advances from concrete construction have resulted in a degradation of its sustainable properties. Inspired by biomimicry, we propose to stabilize rammed earth using biomineralization through a process we are calling *microbially indurated rammed earth* (MIRE). This process offers the opportunity for earthen architecture to harmoniously reconnect to the natural world while simultaneously meeting contemporary performance demands.

The microorganism, *Sporosarcina pasteurii*, known to effectively induce calcite precipitation, was suspended in a solution containing calcium chloride ($CaCl_2$) and urea. The $CaCl_2$ is the calcium source for calcite precipitation and the urea is used as a nitrogen fertilizer to accelerate microbial growth. This microbial solution is mixed into a base soil at sufficient quantities to approximate the optimum moisture content, thereby achieving maximum bulk density of the soil material through a standard compaction process, which is common in rammed earth construction. The hyperactive ~1 μm long microorganisms are dispersed throughout the densified soil matrix and rapidly begin to modify solution chemistry to induce calcite precipitation at grain-to-grain contacts, cementing the material. In this experiment, MIRE cylinders achieved compressive strengths exceeding 2.5 times the strength of non-stabilized rammed earth. While this result is promising, related literature suggests that resistance to moisture degradation may also be substantially improved. This is significant because compressive strength and moisture resistance are the two greatest challenges in rammed earth construction. While much work is needed in order for MIRE to be a feasible alternative to cement-stabilized rammed earth, these preliminary results suggest much promise.

KEYWORDS: MIRE, MICP, rammed earth, biomineralization, *Sporosarcina pasteurii*

INTRODUCTION

The story of earthen architecture can be traced back to the mythopoeic cultural landscape of prehistoric people throughout the world. Earthen architecture once possessed a fertile legacy and was harmoniously bound to local ecologies and climates until the emergence of industrial societies, when it began to lose its status as a significant and sustainable building craft. The tragic rising action of this story is one of dislodging, abandonment, and an eventual recovery effort that imposes largely alien principles on the material and process. That is, traditional rammed earth has been altered in the most recent stage of its development to satisfy contemporary building standards using technology imported from advances in concrete construction.

Contemporary stabilized rammed earth (SRE) is often amended with Portland cement, lime, or an asphaltic emulsion, resulting in increased strength, durability, and resistance to moisture and erosion at the expense of its traditionally low embodied energy, low toxicity, inherent recyclability, and cultural significance. Our goal is to improve the material properties of contemporary rammed earth architecture by exploring the potential for natural soil microorganisms to enhance the built environment in what we are calling *microbially indurated rammed earth* (MIRE).

Natural soil microorganisms (especially the bacterium *Sporosarcina pasteurii*) are known to biomineralize calcite in soil pore spaces, aggregating mineral grains and enhancing desirable properties of earthen materials used in engineering applications. This research aims to illustrate that this technological advancement, which has accelerated within the past decade, has the potential to fundamentally transform rammed earth by strengthening the soil materials used while minimizing or even eliminating the need for highly processed industrial stabilizers such as Portland cement. This process holds the potential to advance the performance of earthen architecture while maintaining its environmental sustainability.

In this paper, we compare the compressive strength of non-stabilized rammed earth (RE) to that of MIRE and analyze the mineralogy to better understand the physical characteristics contributing to its compressive strength. We begin by mining data from existing literature on rammed earth architecture, civil engineering, and the earth sciences. We use this data to develop a model that aids in the selection of soils ideally suited to microbially induced calcite precipitation as well as to predict the optimum moisture content in order to determine the quantity of microbial solution to be added to the base soil, thereby streamlining initial research methods. We are interested in the material properties most relevant to rammed earth construction such as compressive strength, moisture resistance, and aesthetic quality. In this comparative study, however, we focus on compressive strength, a common performance criteria in earthen building codes and codes of practice.

1.0 THEORY

1.1. How microbially induced calcite precipitation works

To our knowledge, this experiment is the first to explore the phenomenon of microbially induced calcite precipitation as applied to rammed earth construction. Within recent years, this specialized area of research, however, has been applied to reducing the moisture absorption of bricks (Sarda et al. 2009), reducing the moisture absorption of concrete (Achal et al. 2011a), increasing the strength of concrete (Bang et al. 2001), stabilizing sandy soils that tend toward liquefaction (DeJong et al. 2006), improving security of wellbores during injection of super critical CO_2 into subsurface reservoirs (Ebigbo et al. 2012), and repairing cracks in concrete (Ramakrishnan et al. 2005). At a conceptual level, this technique has been proposed as a solution in halting the desertification of the African Sahel through the creation of a 6,000 km long biocemented sand wall (Larsson 2009). Microbially induced calcite precipitation (Fig. 1) is a new and growing area of research (Achal et al. 2011a; Dhami et al. 2012).

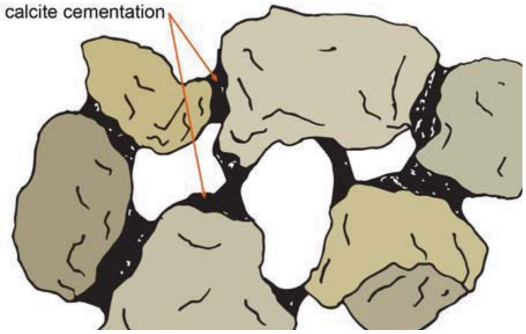

Figure 1: Diagram of calcite cementation occurring at grain-to-grain contacts.

Microorganisms mediate calcite precipitation through a number of different metabolic processes that supersaturate solutions with respect to calcite, most commonly by converting organic carbon to inorganic carbon and increasing solution pH (e.g. Warren et al. 2001). Ureolysis (hydrolysis of urea by microorganisms) is common in indigenous microorganisms in soils and sediments and has been used as a means of plugging or cementing geologic porous media with carbonate minerals (Ferris and Stehmeier 1992; Ferris et al. 1996; Stocks-Fisher et al. 1999). Microorganisms convert urea to ammonium, bicarbonate, and hydroxide, which drives calcite supersaturation through increased bicarbonate and pH in the presence of Ca^{2+} (e.g., Eq. 1; Ferris et al. 1996).

$$NH_2CONH_2 + 2H_2O + Ca^{2+} \rightarrow 2NH_4^+ + CaCO_3 \qquad \text{(Eq. 1)}$$

The kinetics of this reaction are fast (~10^{14} times faster than the uncatalyzed rate; Benini et al. 1996), are largely temperature dependent (Dupraz et al. 2009), and have been established in both aerobic and anaerobic environments (Tobler et al. 2011).

In particular, *Sporosarcina pasteurii* has been found to be a very effective producer of urease and an effective inducer of calcite deposition (Sarda et al. 2009). *Sporosarcina pasteurii* is ideally suited for larger scale activities, such as rammed earth construction, because of its ability to survive desiccation through spore-forming (Smith et al. 1952). In addition, *Sporosarcina pasteurii* has proven to be a good candidate for microbially induced calcite precipitation of sandy soils due to its tendency not to aggregate, thereby allowing for thorough dispersion throughout the soil structure. Furthermore, the size of these microbes allows them to move freely through granular sandy and silty material (DeJong et al. 2006), an important attribute if the soil medium is to be compacted. *Sporosarcina pasteurii* is conveniently ubiquitous in subsurface soil, where source material for rammed earth is gathered (DeJong et al. 2006). Sandy soils cemented using *Sporosarcina pasteurii* have performed similarly to specimens cemented using more traditional soil stabilizers such as gypsum (DeJong et al. 2006). Recent research has shown that microbial deposition of calcite has not only increased the compressive strength of concrete, it has significantly improved its moisture resistance as well (Achal et al. 2011b; Chahal et al. 2012; Dhami et al. 2012).

1.2. Predicting the physical characteristics of soil ideally suited to biostabilization

Existing research has shown that predictive models using benchmark performance criteria can be useful for selecting soils with appropriate properties (Burroughs 2008). Using soils from 219 stabilization experiments in New South Wales, Australia, Burroughs (2008) demonstrates that soils will consistently meet a benchmark compressive strength if they possess a gravel content ≥ 13%, sand content < 64%, combined clay and silt content between 21 and 35%, a linear shrinkage < 11, and a plasticity index < 30.[1] These figures were used as a guide in selecting an appropriate local soil as the base material for both test mixtures: non-stabilized RE and MIRE.

1.3. Predicting the optimum moisture content to aid biostabilization

Building upon this research, we combine a series of equations from the literature to predict the optimum moisture content for compaction of soil for biostabilization during the rammed earth process as follows. Maximum bulk density of the fine-earth fraction (MBD_{fe}) from the standard Proctor compaction test can be estimated following Zhao et al. (2008):

$$MBD_{fe} = 2.07 - 2.11\,LL + 0.0006\,clay \qquad \text{(Eq. 2)}$$

where MBD_{fe} is given in Mg m^{-3}, LL is the liquid limit of the material in kg kg^{-1}, and clay (i.e., <0.002 mm) is the clay percentage of the fine-earth fraction (i.e., <2 mm). Liquid limit can be expressed empirically as a function of clay content (Keller and Dexter, 2012):

$$LL = (17.52 + 0.86\,clay) / 100 \qquad \text{(Eq. 3)}$$

The porosity of the fine-earth fraction (ϕ_{fe}) after compaction can be found as follows:

$$\phi_{fe} = 1 - MBD_{fe} / \rho_s \qquad \text{(Eq. 4)}$$

where ρ_s is the density of the solid fraction assumed to be 2.65 Mg m^{-3}. The void ratio (e_T) of the total sample including gravel can be written as:

$$e_T = \left[\frac{\phi_{fe}}{1-\phi_{fe}}\right]\left[1-\frac{gr}{100}\right] \qquad \text{(Eq. 5)}$$

where gr is gravel content expressed as percentage of the total. The porosity of the total (ϕ_T) is found as:

$$\phi_T = e_T / (1 + e_T) \qquad \text{(Eq. 6)}$$

and maximum bulk density of the total (MBD) is found as:

$$MBD = (1 - \phi_T)\,\rho_s \qquad \text{(Eq. 7)}$$

Finally, maximum bulk density can be expressed as a function of optimum moisture content (OMC) for a given degree of saturation following Ishibashi and Hazarika (2011) as:

$$MBD = \frac{G_s \rho_w}{1+\frac{G_s OMC}{S}} \qquad \text{(Eq. 8)}$$

which we rearrange to solve for OMC:

$$\mathrm{OMC} = \frac{S}{G_s}\left[\frac{G_s\rho_w}{\mathrm{MBD}} - 1\right] \qquad \text{(Eq. 9)}$$

where OMC is in kg kg^{-1}, G_s is the specific gravity of the solid fraction assumed to be 2.65, ρ_w is the density of water (approximately 1 Mg m^{-3}), and S is degree of saturation assumed to 80% following Hillel (1998).

2.0. METHOD

Typical rammed earth laboratory methods for compressive strength determination are illustrated in Fig. 2 along with the process for microbially precipitating calcite. This combination of conventional rammed earth and microbially induced calcite precipitation results in MIRE.

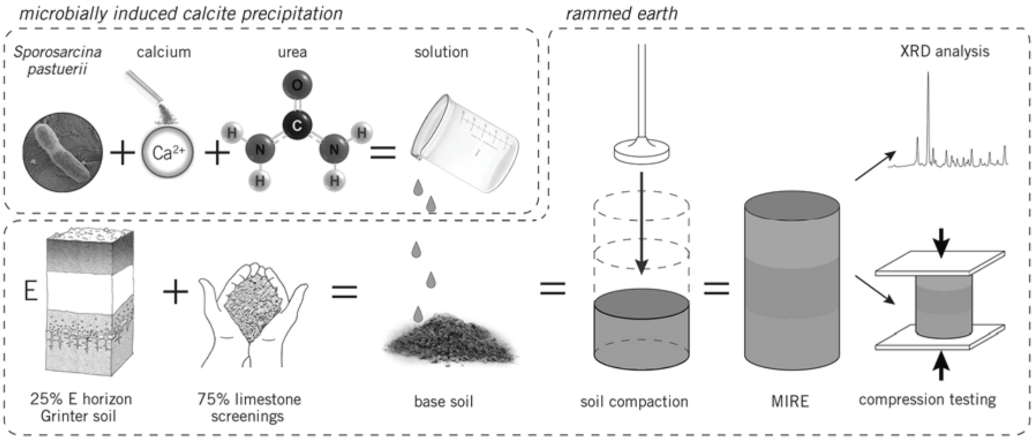

Figure 2: Diagram of the MIRE method used in this study; microbially induced calcite precipitation + rammed earth.

2.1. Culturing *Sporosarcina pasteurii*

Our experiments with MIRE began by cultivating cultures of *Sporosarcina pasteurii* (Fig. 3). This bacterium, formerly known as *Bacillus pasteurii*, was acquired from Robin Gerlach at Montana State University and maintained in the Roberts Laboratory at the University of Kansas.

Growth curves and yields for *Sporosarcina pasteurii* were established using commercial growth media (BBL; Brain Heart Infusion supplemented with 20 g L^{-1} urea) at 20°C. For experiments, cells were grown to mid-exponential phase then harvested under vacuum filtration and resuspended in artificial groundwater (AGW; based on that of Ferris et al. 2004) amended with 500 mM of Ca^{2+} and urea to an optical density (600 nm) of 0.07 (~10^6 cells mL^{-1}; e.g., Tobler et al. 2011). Control experiments were performed with uninoculated AGW.

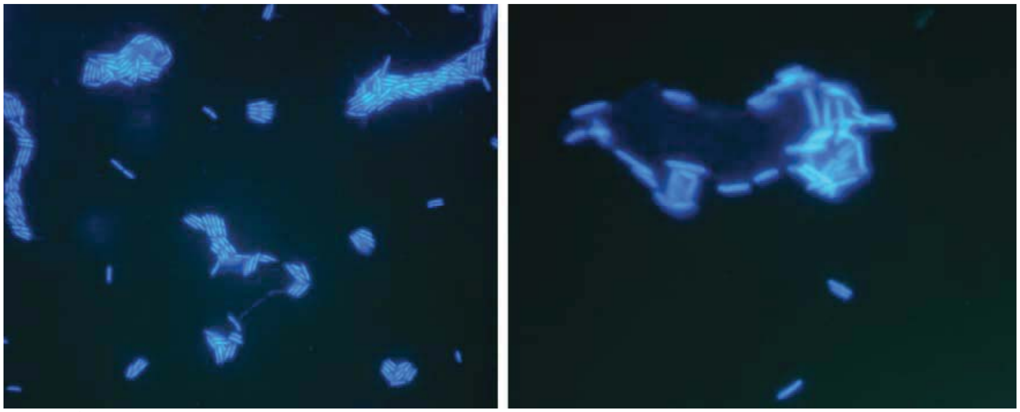

Figure 3: Photomicrographs of *Sporosarcina pasteurii* at 60x (left) and 100x (right) using UV epifluorescent microscope after staining with DAPI (4,5-diamidino-2-phenylindol). *S. pasteurii* are ~1 µm in length.

2.2. Preparing the soil

Based on our predictive models, a blend of 75% limestone screenings from a local quarry (comprised of 70% gravel, 14% sand, 11% silt and 5% clay) and 25% Grinter soil sampled from the University of Kansas Field Station (comprised of 80% sand, 16% silt and 4% clay), with a blended particle distribution of 52% gravel, 27% sand, and 21% of silt/clay, was selected as the base material for further experimentation.

The predicted optimum moisture content of the blended base soil, 11%, was compared with common field practices to determine approximate appropriate moisture content. Because the predicted values and the values estimated from field practices were strongly correlated, the field-based technique was used in the experiment to approximate optimum moisture content. Due to antecedent moisture in the soil prior to the addition of the microbial solution, the actual moisture content of the MIRE samples was slightly higher than that of the RE samples.

2.3. Preparing and testing cylindrical MIRE samples

Using our base soil material, a control mixture and our experimental MIRE mixture were prepared as follows:

- Control (RE): Unamended blended soil + uninoculated AGW
- Treatment (MIRE): Blended soil + *Sporosarcina pasteurii* inoculated AGW (refer to section 2.1)

For each of the mixtures, six 4” x 8” compression test cylinders were prepared. Two cylinders per mixture were tested for compressive strength at three days, seven days, and finally at fourteen days. For each test sample, soil was manually tamped into forms with an approximate 2 2/3” lift height. Compression test samples were removed from their forms 24 hours prior to testing to allow for additional drying and to cap the test specimen. Compressive strengths were tested using the ASTM Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM C39/C39M).

2.4. Examining mineralogy

X-ray diffraction (XRD) was performed on post compression samples taken from control and MIRE treated cylinders using a Bruker SMART APEX single-crystal diffractometer equipped with a Bruker MicroSTAR high-brilliance microfocus Cu rotating anode X-ray generator, a graphite monchromator, MonoCap collimator and a SMART APEX charge-coupled device area detector in the KU Small-Molecule X-Ray Crystallography Laboratory. XRD was used to examine mineralogy of the samples and distinguish calcite and dolomite in the carbonate fraction. As expected, the mineralogy of the blended limestone screening and Grinter soil reveal the presence of calcite and dolomite in the carbonate fraction as well as the presence of quartz and mica in the sample (Fig. 4).

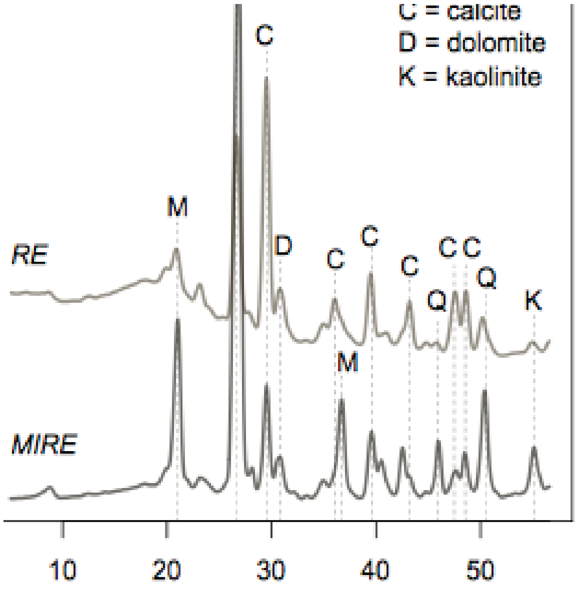

Figure 4: X-ray diffraction (XRD) of RE and MIRE samples indicating mineralogy.

3.0. RESULTS AND DISCUSSION

3.1. Compressive strength test results compared to controls

Results of the compressive strength test are shown in Fig. 5. After three days, the compressive strength of the control RE cylinders exceeded the performance of the MIRE cylinders. Although this discrepancy was unexpected, it may be due to the greater moisture content of the MIRE sample (9.9 compared to 12.0%). After seven days, the compressive strength of the MIRE cylinders surpassed that of the RE cylinders, suggesting that the activity of the microorganisms did not significantly alter the composition of the soil until sometime after three days. The final compressive tests, occurring at fourteen days after the initial cylinder preparation, resulted in a compressive strength ~2.5 times stronger than the RE control. We anticipate a continued increase in the compressive strength of the MIRE sample at the conventional 28-day benchmark due to the effects of *Sporosarcina pasteurii* activity persisting throughout most of the drying process. It is likely that the presence of carbonate from the limestone screenings is buffering the solution pH and creating an obstacle for further calcite precipitation. We speculate that the increase in compressive strength of MIRE over the control would be even greater in base soil where carbonate is minimal.

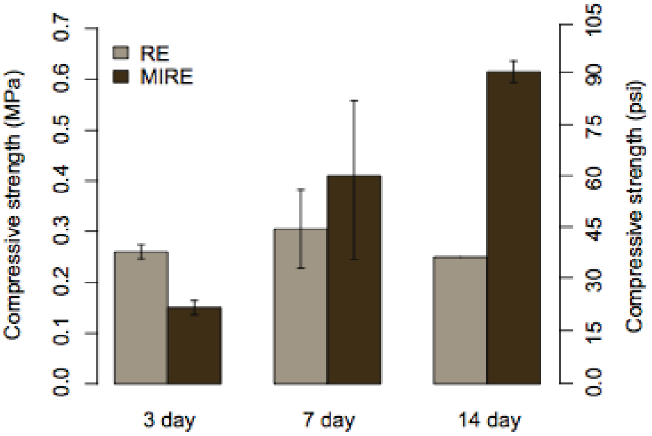

Figure 5: Comparison of compressive strength of non-stabilized rammed earth to microbially indurated rammed earth.

3.2. Key Challenges to Successful Microbially Indurated Rammed Earth

A significant challenge to successfully implementing MIRE in this study was related to the concentration and distribution of the *Sporosarcina pasteurii* microorganism and the dissolved $CaCl_2$. Antecedent moisture content in the soil limited the addition of microbial solution by approximately half of the expected quantity. While this had no effect on the resulting strength of the RE control, it likely had adverse effects on the MIRE sample.

In addition, the microbial solution was added to the MIRE soil mixture by pouring the solution in a fine stream over the spread of soil. This method was used to approximate the procedure used for the uninoculated AGW as it was added to the control RE soil mixture. While this reduced potential sources of experimental error, adding the solution to the samples in this way may have created concentrated domains of microbial activity resulting in a heterogeneous distribution of calcite. A more uniform delivery of the solution to the soil sample may further improve the resulting strength.

CONCLUSION

While further research is necessary, the preliminary results of this research illustrate the efficacy of microbially induced calcite precipitation in increasing the compressive strength of rammed earth material. Furthermore, existing literature in this nascent field of inquiry has shown significant increases in moisture resistance in a variety of materials utilizing these techniques, including concrete and sand cores. Although this was not a focus of our study, it is likely that equally significant increases in the moisture resistance of MIRE are possible. The critical challenges of rammed earth are directly linked to compressive strength and moisture resistance. MIRE, therefore, holds the promise of advancing this long dormant building craft into the twenty-first century.

Ancient rammed earth builders are known to have added organic substances such as pig's urine or ox blood to aid in stabilizing the soil. The precise reasons why ancient builders used these substances are not known;

like much vernacular architecture, the proof of the eating is in the pudding: what works is passed down to later generations. Today we know that mammal urine contains nitrogen-rich urea. We know that blood meal, a nitrogen-rich powdered substance made from animal blood, is an effective fertilizer. We also know that billions of microorganisms, including *Sporosarcina pasteurii* and others like it, exist in most soils. It is certainly possible that, unbeknownst to these ancient builders, they had already discovered the potential of MIRE. In that case, MIRE may be one of the oldest methods of construction on earth, as well as a clue to a more sustainable future. As architect Louis Kahn wrote, "What will be has always been."

ACKNOWLEDGEMENTS

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ENDNOTES

[1] Burroughs uses the following soil classification using only sieve analysis: gravel > 2.36mm; sand between 0.075 and 2.36mm; clay + silt <0.075mm. We, however, are using the United States Department of Agriculture’s soil classification, i.e. gravel > 2mm; sand between 0.05 and 2mm; and clay + silt <0.05mm. This is also the classification system used by the North American Rammed Earth Builder’s Association.