I, Kelley I. Romoser, hereby submit this original work as part of the requirements for the degree of: Master of Architecture in Architecture (Master of)

It is entitled: Borrowed From the Earth: Midwest Rammed Earth Architecture

Student Signature: Kelley I. Romoser

This work and its defense approved by:

Committee Chair: George Bible, MCiv.Eng
Rebecca Williamson, PhD
Borrowed From the Earth:
Semiology of Midwest Rammed Earth Architecture

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Kelley I. Romoser

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Committee Chairs: Thomas Bible, MCiv. Eng
Rebecca Williamson, PhD
Abstract

This thesis explores the material rammed earth and its potential for application in the Midwest, specifically in Southern Ohio. Examining the specifics of rammed earth construction in this context will generate conclusions that have a broader application. Rammed earth construction has been used for hundreds of years in various locales for its many advantages including low material cost, low-energy processing, recyclability, indoor environmental quality, and uniquely beautiful aesthetic. The technique produces massive walls that can help mitigate temperature fluctuation, moderate indoor humidity levels, and dampen sound. Despite these advantages, there are numerous difficulties encountered in contemporary rammed earth construction, particularly in the United States. Rammed earth is highly susceptible to moisture and accepted codes and standards of practice in the U.S. reflect a general lack of acceptance of the method. To guide this exploration, the material has been approached from two distinct yet intertwining points of view: the technical and the experiential. It is in the union of these that a building project emerges, and, through detailing, interprets the unique characteristics of the material and its context.

“Soils, and consequently clay minerals, are the support of the most fundamental activities of mankind: agriculture, ceramics and housing. Even today about 40% of the Earth’s inhabitants live in dwellings composed in part by earth, i.e., clay assemblages with other materials. Therefore, the question of the origin of clay minerals is as important as that of the origin of humanity” (Velde and Meunier, 2008).
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**Introduction**

“Scarpa wanted to turn the act of construction into a process of communication and understanding” (37).

In the process of making rammed earth, raw earth changes with human intervention. The person, not a machine, nor chemicals, nor time, brings about the change. The change is instant, though the effort is great. There’s something poetic about the person’s ability to compress time in this role... rammed earth is like sedimentary stone only without the necessity of time. Time is shortened by the human intervention-- by the pound after pound. But rammed earth is not false. Despite the human intervention, the transformation of material, it is only temporary. The newly rammed earth, although durable, is fragile, and fundamentally unchanged. A wall, no matter how strong, can be returned to its initial state, again altered by human intervention. Once broken, the wall can return to the same function from whence it came. Here, even, human intervention is not necessary. Piece by piece, the wall could be left to slowly disintegrate back into the earth. It’s simply borrowed--serving a temporary purpose before it’s returned to the earth in its original state. Earth is by nature fragmentary--consisting of variably sized fragments of what once was rock--eroded slowly, by natural forces to constitute the amorphous body we refer to as “earth.” Even after earth has been rammed into a wall it is still possible to register its unique particulate make-up in the wall’s surface and texture.

**Sustainability**

In this era of “green,” perhaps the most promising quality rammed earth can offer is its impeccably small environmental footprint. One sustainable design goal is to minimize the embodied energy, or total energy consumed throughout the entire lifecycle of a product. Factors that contribute to embodied energy include mining, manufacturing or processing, delivery, maintenance, and disposal. Since any building site will require excavation, assuming the earth present on a site is suitable for building, excavation could provide extremely local and affordable building material. As stated by Houben, “By exploiting strata locally found on building sites, earthen construction allows a considerable savings in energy for the transportation of materials” (2004, p.339). In the event that on-site soils are not ideal for building, soils may be amended on site by adding small amounts of clay, sand, or cement, which can be transported from another site if necessary. Given the wide variety of soils in a particular region, it is likely that a suitable soil can be found within the 500-mile radius specified by the Leadership in Energy and Environmental Design (LEED) system to qualify as a locally sourced material (LEED 2009). It is likely, in fact, that a suitable soil could be located within a much smaller distance. Eliminating the need to transport building materials long distances can significantly reduce the total amount of energy used for construction, not to mention that the material can typically be used as-is, without requiring further energy input for processing. Due to the fact
that there is no chemical transformation in making rammed earth, there is very little energy (and carbon) used in initial processing and also very little energy in demolition or recovery of material.

Soil amendment, although adding to the material’s overall embodied energy, can be accomplished with a minimal environmental impact. In the U.S., where rammed earth construction is allowed, it is typically required that soils be cement stabilized to ensure durability. Cement is a high-embodied energy product, but is only necessary in very small percentages—6-10%—to achieve adequate stabilization. Therefore, a rammed earth wall with cement stabilization remains relatively low in embodied energy as compared to a similar cast concrete wall, for example, which would contain a much higher percentage of cement. According to the ASTM standard E 2392, “The manufacturing of earthen building materials that use Portland cement or some other kiln produced cement is more energy efficient per unit volume than the manufacturing of cement based concrete materials, like cast-in-place concrete and precast concrete if only because of the lower cement content of stabilized soil” (1).

Concrete and rammed earth construction both require formwork, but embodied energy of the formwork is likely to be equal in both cases. The slip forming technique in rammed earth, however, takes advantage of the material’s immediate structural capacity and can reduce the amount of formwork needed for a project. Slip forms are built in small sections and then filled with earth. Once the form has been filled and the earth tamped, the form can be shifted vertically or horizontally to the next section of the wall. By recycling the same form boards throughout wall construction, the total amount of formwork is reduced.

Since rammed earth is unfired, it also requires less energy than fired masonry products; “Manufacturing sun-dried, unfired earthen building materials, like adobe, pressed-block and straw-clay, is more energy efficient per unit volume than the manufacturing of fired-clay masonry, like brick, terra-cotta or structural clay tile” (ASTM E 2392, p.1).

**What Follows**

Part of the undeniable intrigue of the material rammed earth is its simplicity—it is made of earth. Through the ramming process, the raw material earth acquires strength, durability, and aesthetic qualities. Part one focuses on the measurable technical properties of earth as a raw material and those acquired through the transformation of raw earth into a building material. It uncovers the scientific processes at work during this material transformation, and by so doing provides a greater understanding of the nature of the material and how it might be best obtained and manipulated for optimal performance in a Midwest climate.
Going beyond the measurable characteristics of the material, Part two explores the environmental and perceptual outcome achieved by the technique. Exploring the sensory experience of occupying a rammed earth building could help to inform or augment architectural interventions. Meaning-making in a rammed earth structure is inescapable. The material earth is at once human and monumental in scale; it is the dirt we use to garden and the planet we call home. Earth, although its physical makeup varies around the world, is universal.

Of interest to this thesis are the ways architects have utilized rammed earth to address local conditions and whether culture and technology have either enhanced or limited its geographic and stylistic uses. Additionally, precedent buildings will be analyzed with particular consideration of their detailing and material expression. How are questions of culture, technology, and environment manifested in the details of construction? Furthermore, can details constitute a set of symbols, or a semiology of construction, that expresses the architect’s intent?

Chapter five attempts to expand on all of the information conveyed in previous chapters and presents a design for a visitor’s retreat at Serpent Mound in Adams County, Ohio. In this way, the design process is highly contextual, having paid focused attention to the physical and sensual characteristics of rammed earth as well as the unique climatic and site demands of southern Ohio.
Rammed Earth (Pise de Terre)

Traditionally, rammed earth is a building technique in which layers of moist earth are compacted into formwork to create walls, floors, and sometimes roofs. Soils removed to make foundation trenches were typically used and brought by the bucketful to fill formwork. Layers of approximately 6-inches were poured and then compacted using wooden tamps. Once the forms were filled they could be removed, exposing the layers of compacted earth. An application of plaster lath was then added to protect the surface of the wall from erosion or water damage.

Advances in technology have led to the incorporation of machinery into the rammed earth construction process in the form of pneumatic tamps, mechanically mixed soil, and mechanical form filling mechanisms. Advanced methods of soil analysis and testing have also influenced rammed earth construction. According to Houben, et al, recognition of the value of the earthen architectural heritage around the world led to a research initiative. “Only 32 years ago, the first international conference on the subject of the conservation of our earthen architectural heritage was organized in Yazd, Iran. For the first time, archaeologists and conservators became aware of the need to understand the earthen material they were working with in their daily professional lives. Since then, research has been active but focused essentially on the qualitative aspects of earthen materials science” (2004, p. 340).

Compression tests have confirmed the increase in the strength of a rammed earth wall with the addition of a small amount of Portland cement. Soil composition analyses have helped to identify soil conditions that are most favorable for rammed earth construction. With ideal building conditions in mind, builders can amend a soil by adding clay, sand, or water, until ideal proportions are reached. Contemporary use of rammed earth is now reflected in national codes and is defined by American Society for Testing and Materials, ASTM E 2392-05, as “A construction system that consists of walls made from moist, sandy soil, or stabilized soil, which is tamped into forms.”
Part 1: Technical

“...the modern constructor, by the means proper to his particular field of activity, brings to light not the relationship between things themselves, but the relationship between their qualities” (Van Doesburg and van Eesteren qtd. in Conrads 67).

Rammed earth construction, as with any other building method, offers distinct advantages and limitations. It is a highly sustainable building method featuring highly local materials which are widely and readily available, in addition to being extremely affordable. Similar to concrete, finished rammed earth walls are dense and thick, offering thermally beneficial mass that can mediate climate variability. A porous material, rammed earth also has the ability to absorb and desorb moisture, making it particularly suited to easing uncomfortably warm and humid Midwest summers.

Despite its many advantages, there are inherent limitations of the material that add to the difficulty of applying it in a highly variable and moist climate. Unstabilized, unfinished rammed earth is vulnerable to moisture and will rapidly degrade under continually damp conditions. Some builders, Martin Rauch (an Austrain rammed earth builder) in particular, have developed detailing strategies to combat moisture-related degradation, but in the United States it is generally accepted that a degree of soil stabilization through chemical means or use of exterior cladding is necessary. Also of concern in a Midwest climate is the low insulating value of rammed earth. Given its density, rammed earth is highly conductive and therefore requires insulation in climates that are dominated by heating needs.
Physical

Given variability of soil composition, it is difficult to pinpoint average values for the strength, density, and modulus of elasticity for rammed earth. When beginning a project using local soils, it is advisable to complete a range of soil testing to establish values that reflect the unique composition of that soil. Despite this variation, it is possible to provide ranges within which rammed earth can be evaluated.

Generally speaking, rammed earth is strong in compression and weak in tension, therefore, depending on the structural demands of a project, sometimes requires steel reinforcing. Its behavior is similar to that of lightweight structural concrete. After installation, rammed earth continues to harden and exhibits increases in compressive strength.

Density

Overall, the density of rammed earth is also similar to that of lightweight structural concrete (Fig. 1). As a result of the construction process, rammed earth walls naturally exhibit a gradient in density within each lift, or layer of soil added, where the top of the layer, closest to the ramming device, is more compacted than the lower part.

Strength

Particles of sand and larger aggregate in soil give rammed earth walls their compressive strength. The proportion of these larger particles to smaller clay particles will, in large part, determine the compressive

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Fig. 1, Density (pcf)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (pcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstabilized Rammed Earth</td>
<td>125</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
</tr>
<tr>
<td>Heavy-weight Concrete</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2, Compressive Strength (psi)

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstabilized Rammed Earth</td>
<td>10000</td>
</tr>
<tr>
<td>Stabilized Rammed Earth</td>
<td>9000</td>
</tr>
<tr>
<td>Concrete</td>
<td>3000</td>
</tr>
<tr>
<td>Heavy-weight Concrete</td>
<td>15000</td>
</tr>
</tbody>
</table>
strength that can be achieved using a given soil. Soils with significantly higher clay content may require the addition of sand or other aggregate material to improve performance. (Fig. 2)

Stabilization of rammed earth by chemical means can also improve compressive strength. Due to the increase in strength, chemically stabilized walls can be thinner than unstabilized walls (Fig). Recommendations for wall thicknesses are illustrated in Figure 3.

As with any material, rammed earth must be designed with a factor of safety that limits the percentage of total available strength that can be utilized. “King proposes an allowable compressive stress in stabilized rammed earth walls equal to 20% of material compressive strength” (Maniatidis and Walker, 2003).

**Modulus of Elasticity**

Although there is a lack of experimental data on the modulus of elasticity of rammed earth, there are recommendations given. The publication, “A Review of Rammed Earth Construction,” cites New Zealand Standard 4297: 1998 as taking the modulus of elasticity for earth wall construction as “three hundred time the characteristic compressive strength value” (Maniatidis and Walker, 2003, p. 27). Australian building codes assume a modulus of elasticity of 72,000psi, while the “permissible stress approach” used in the United States recommends a value that is 750 times compressive strength (Maniatidis and Walker, 2003, p. 27).
Fig. 4, Relationships between wall Height, Thickness, and Length

T = wall thickness, H = wall height, L = wall length

Both Ends Continuous | One End Continuous | Simply Supported | Freestanding

<table>
<thead>
<tr>
<th>H≤22T</th>
<th>T</th>
<th>L≤22T</th>
</tr>
</thead>
<tbody>
<tr>
<td>H≤21T</td>
<td>T</td>
<td>L≤21T</td>
</tr>
<tr>
<td>H≤18T</td>
<td>T</td>
<td>L≤18T</td>
</tr>
<tr>
<td>H≤10T</td>
<td>T</td>
<td></td>
</tr>
</tbody>
</table>
**Temperature**

**Thermal Conductivity**
Rammed earth has a very low R-value and would require additional insulation in a Midwest climate. Its thermal capacity gives it the ability to moderate temperature extremes and work with insulation to improve the overall energy efficiency of a structure. Based solely on energy efficiency, the best location for mass is at the interior of a building, or inside of the insulation. Rammed earth builders have, however, located insulation in between two wythes of rammed earth wall, in order to preserve its exterior appearance and capture a portion of its thermal mass.

**Thermal Storage Capacity**
Research has concluded that there is a benefit to using massive construction in a variety of climates. Under ideal conditions, with large diurnal temperature swings and minimal cloud cover, long-term energy savings would be marked.
Moisture & Related Problems

The process of rammed earth results in walls that are highly permeable and porous. According to Hall and Djerbib, “Porous materials are often permeable by air and moisture because they contain a network of open channels...” (2006, p. 270). While this makes them especially susceptible to moisture-related damage, it also means that the walls can readily absorb and desorb moisture, aiding in the reduction of interior humidity levels, thereby contributing to overall environmental comfort.

Unstabilized rammed earth is highly susceptible to moisture-related degradation from pressure-driven moisture or moisture that enters a structure via capillary action. Wide overhangs or other erosion protection is necessary as part of an overall water handling strategy. Furthermore, a foundation with a damp proof course is necessary to prevent rising vapor from damaging walls.

Pressure-Driven Moisture

Under pressure-driven moisture conditions, rammed earth behaves in a way similar to other massive masonry systems, Hall and Djerbib describe this as the ‘overcoat effect’:

“A solid (non-cavity) masonry wall naturally relies upon the ‘overcoat’ effect to resist moisture penetration... This is when the region towards the exterior facade becomes saturated (i.e., waterlogged) to a certain depth such that little or no water can further penetrate beyond this wetted region. In the case of rainfall, the volume of surface run-off increases because the incident moisture can no longer be absorbed by the already saturated wall surface layer. An alternative
theory to this approach is the ‘impervious skin’ whereby the outer surface layer of the material is made completely impervious to water penetration... However, the effectiveness of the treatment relies upon the non-deterioration of the impervious layer... Any zone of weakness in the impervious layer can result in the concentration of moisture penetration in this region. The same volume of moisture may not have presented a problem on an untreated wall where it can be dissipated across the entire wall face. Also, the impervious layer inhibits subsequent desorption of moisture held within the wall and can cause spalling at the surface due to the accumulation of confined water pressure...“ (2006, p. 376).

Through cement stabilization of rammed earth, water-related problems can be significantly minimized. Most experts recommend the addition of 6-10% cement by volume to the soil mix. The inclusion of a small amount of cement only slightly increases the environmental footprint of rammed earth construction, which is offset by the resultant increase in durability and longevity. Chemical stabilization can also effect the overall permeability of rammed earth, thereby altering its hygrothermal behavior. The effects, however, with minor soil amendment, are minute.

**Sorptivity:**

Sorptivity, as defined by Hall and Djerbib, is “... a determination of the rate of increase in water absorption due to capillary suction, in a porous solid, against the square root of elapsed time” (2006, p. 385). A range of sorptivity rates for stabilized and unstabilized rammed earth have been calculated and, in general, they compare favorably against other masonry materials (Fig).

Sorptivity data could be instrumental in the design
process when determining wall thicknesses and depth of cover for steel reinforcing, to reduce the risk of corrosion, or other materials housed within the thickness of a rammed earth wall including electrical and plumbing services.

**Capillary Suction**
Since rammed earth walls are monolithic, the capillary movement of moisture within them is a particular problem, especially since there are “no chemically dosed layers of mortar to suppress it” (Hall and Djerbib, 2006, p. 269). Research into the rate of capillary suction of rammed earth has revealed that it is lower on average than that recorded for other masonry materials including brick and concrete. Values provided by Hall and Djerbib based on a 5-min IRS ‘wick’ test for rammed earth range from 0.15-0.74% while concrete and brick values range from 0.31-1.29%, as a percentage of sample dry mass (g) to mass of absorbed water (g).

Aside from cement stabilization, designers have detailed rammed earth walls to include layers of mortar or dried clay to slow the effects of capillary suction.

**Porosity**
Rammed earth, like other masonry materials, is porous, meaning it contains a network of open pores and channels. As illustrated by Fig., there are several modes of transfer within porous materials.

**Erosion**
Rammed earth walls are thick enough that there is a factor of safety even when slight erosion occurs. That
is, even if a degree of erosion occurs, the structural integrity of the wall will not be compromised. For example, the Cemetery Extension and Chapel of Rest incorporated a process called “calculated erosion.” Master rammed earth builder Martin Rauch accounted for an amount of erosion by increasing the thickness of the wall, giving it easily a 100 year lifespan (Rael, 2009, p. 68). Unprotected vertical rammed earth surfaces will erode at a rate of approximately 1” in 20 years in locations with up to 25” of rain per year. Horizontal surfaces without erosion protection in the same environment will erode much more rapidly, at a rate of 2-3” per year (ASTM E 2392-05).

To closely examine the rates of erosion for a variety of soil mixes, researchers constructed 104 sample walls. Twenty years after construction, erosion of the walls was measured using stereo-photogrammetry. Their findings revealed that erosion is not a linear function of time for rammed earth. That is, after an initial period of surface erosion, it stabilizes. They hypothesized that the initially higher rate of erosion could be due to a “loss of compaction energy in contact with the formwork during manufacture because of friction” (Bui, et al., 2009, p. 918-919). Considering the non-linear nature of erosion, it is difficult to predict the exact lifespan of a rammed earth wall, but researchers note that there are built examples that have weathered for well over 100 years.
Soils
Due to high variability in soils, it is recommended that laboratory soil testing be completed in order to ensure high quality results. When constructing a small building, it may be acceptable to complete simple on-site tests and build sample blocks to establish the quality of site soils. Larger commercial rammed earth builders often elect to acquire soil from quarries or other known sources in order to maximize efficiency while being certain of material quality.

General information about soil make-up is available online, and for the purposes of this thesis, has been acquired for the specific project site. In addition to aesthetic concerns, the most important soil qualities to assess are clay and sand content. The ratio of clay particles to sand particles will in part determine the performance of finished rammed earth walls relative to strength and moisture, “…the particle-size distribution of the soil is critical in determining the rate at which moisture may ingress due to capillary suction (Hall and Djerbib, 2006, p. 277).

Soils on the site (pictured in fig.) are potentially suitable for use in rammed earth. The depth to bedrock is relatively shallow, and the soil clayey enough that this land is not likely to be utilized for agricultural or other purposes. At a depth of 8-24”, the soils are characteristic of the majority of soils in Ohio, high in clay content. Ideally, the proportion of clay would be at a maximum of 30%. Fortunately, on-site soils can be easily amended with the addition of sand and perhaps larger aggregate, to balance the amount of clay that is naturally present.

Although the addition of sand will increase the overall embodied energy associated with the project, it can be sourced locally and will provide ample increase in strength and durability to offset the additional initial increase in environmental footprint.
Depth to Soil Restrictive Layer:
Examples of a “soil restrictive layer” are bedrock, cemented layers, dense layers, and frozen layers.

BnB, Bratton silt loam:
89cm (35in.)

BrC2, Bratton-Opequon complex:
84cm (33in.)

OpD2, E2, Opequon silty clay loam:
48cm (19in.)

Percent Clay:
Depth = 8” to 24”

BnB, Bratton silt loam:
40.2%

BrC2, Bratton-Opequon complex:
45%

OpD2, E2, Opequon silty clay loam:
55%

Percent Sand:
Depth = 8” to 24”

BnB, Bratton silt loam:
23.1%

BrC2, Bratton-Opequon complex:
26.1%

OpD2, E2, Opequon silty clay loam:
13.3%
Conclusion

In order to become intimately familiar with a material, it is useful to learn about its measurable, physical characteristics in order to design the most appropriate solutions based on the properties of the material and the context in which it is expected to perform. Emerging from this research are several important characteristics that must be accounted for in design and detailing strategies.

Generally speaking, unstabilized rammed earth is:

--Strong in compression, weak in tension.
--Subject to rapid moisture-related degradation
--Highly conductive, will require strategies to improve environmental performance

With a minimal amount of cement stabilization (6-10%), many of rammed earth’s weaknesses can be significantly negated. Stabilized rammed earth is much less susceptible to moisture-related degradation and is stronger than unstabilized rammed earth. There are drawbacks to stabilization, mostly concerning the increased environmental footprint associated with the use of cement. These drawbacks, however, must be weighed against the benefit of increased durability and longevity resulting from stabilization.

By examining the strengths and weaknesses of rammed earth, design opportunities and limitations surface. Also, the potential to incorporate a broader material pallet emerges in the ability of other materials to complement rammed earth’s inherent strengths and mitigate its weaknesses.

Design Implications

Rammed earth construction will not comprise a building in its entirety. It is always rely on the properties of other materials to enable its construction and detailing in a way that highlights its positive qualities and compensates for its weaknesses. Frascari points to the detail as the storyteller in architecture. A detail, in his definition, is always a joint, be it at the scale of the material joint or the room, “...any architectural element defined as detail is always a joint. Details can be ‘material joints,’ as in the case of a capital, which is the connection between a column shaft and an architrave, or they can be ‘formal joinings,’ as in the case of a porch, which is the connection between an interior and exterior space” (Frascari).

In the same sense, a detail could be thought of as a diagram that illustrates the different functions of each component or component material. A lintel above an opening, for example, is a diagram that discusses the relative strength of each material present. Each material is placed adjacent to other materials in a way that describes the properties and purpose of that material. A detail is a diagram that talks about the nature of each material present as well as the architectural agenda in play. The way materials are juxtaposed and the interface between them can describe at once their shared and disparate attributes as well as the environment in which they must perform.

In Peter Zumthor’s design for thermal baths at Vals,
Switzerland, material considerations and architectural agenda unite in the skylight detail used throughout the project.

The design originated in the decision to utilize structural concrete piers. In them, concrete bases support cantilevering concrete roofs. At the junctures between these roofs, space was left where skylights could be incorporated. The series of interior units that are created by the concrete bases organize program and circulation, further reinforcing the overall narrative that unites the architecture.

Examining the skylight detail, then, reveals much more about the design than technical information. Edges of the concrete roofs appear in the detail separated by a narrow gap that is capped with layers of glass to permit light while preventing water infiltration. The spacing and number of gaps present in a space refers to program requirements, which dictated the size of each concrete base. Overall, the result is a series of spaces that are unique, yet united by the distinct and dramatic light quality that results from the manifestation of all of these architectural strategies into a detail.

Behind the success of Zumthor’s design lies the idea that there is an underlying logic or logics at work in various scales throughout the design. Studying a complete building as a diagram, logic can be uncovered. One can similarly read the language of the details (or semiology of the architecture) to understand this logic as well as the nature of materials present and the context in which they were crafted.
Comparing a historic example of rammed earth construction to a contemporary one illustrates this point. During the 1940’s the U.S. government built several rammed earth homes in Gardendale, AL through the Works Project Administration. Designed by Architect Thomas Hibben, these homes incorporated only one conventional window “because of the material,” (Mud Houses Pass the Test of Time) referring to the relative inability of rammed earth to span. Other openings were full-height in consideration of the limitations of the material. The outward appearance of these openings, however was altered when “some residents added partitions at the top and bottom of window areas to give the houses a more conventional appearance” (Mud Houses...), thereby obscuring the aesthetic that resulted directly out of material consideration.

In comparison to a home designed by Austrian rammed earth builder Martin Rauch, the difference in architectural agenda is clear. Rauch approached the material in a similar way, creating full-height openings, however his design intent clearly emerged out of a desire to express these physical constraints. Openings in this case are sized to match interior spaces and enhance the massive appearance of the walls by incorporating a wood frame that appears to be an extrusion of interior volume. According to an article in Werk Bauen Mohnen, “As clay construction cannot tolerate arbitrary fragmentation of the walls, the openings are precisely matched to the size of the rooms. The spatial quality of the windows allows the thickness of the walls to be experienced” (2008 n.3).
Differences in approaches to rammed earth are apparent in other comparisons between the Gardendale designs and Martin Rauch’s design. For instance, the Gardendale homes incorporated wide eaves and stucco cladding on the interior and exterior wall surfaces. Martin Rauch, on the other hand, expresses the fragility of rammed earth in the walls themselves, incorporating layers of baked clay to help shed water away from and slow capillary action within rammed earth walls.

Early forms of architecture in a variety of materials, perhaps, follow similar formal evolutionary patterns. Semper discusses the evolution of architectural style in wood and stone. He points to the Romans, for example, as the first significant stone masons, “…the transformation of parts of an original timber construction into those of a monumental stone building was a normal development common to all people of the past, the Romans alone excepted. He called them “the inventors of true stone construction,” who introduced the joints of an ashlar walling as a decorative element and thus achieved Roman style…” (Herrmann 167). For Vitruvius, Romans were the first stone constructors because they approached the material with a sensitivity to its unique properties.

The evolution of rammed earth architecture in the U.S. in this regard, is stunted. Compared to the advanced development of rammed earth architecture in other parts of the world (Austria, Germany, Australia), it is largely undeveloped here—the exception to this being, of course, in the southwestern United States, which
has a more favorable climate for earth construction in general. As evidenced by advances in rammed earth architecture in other parts of the world, however, it is clear that with careful detailing and knowledge of the material, rammed earth has the potential to flourish in a variety of climates.

Continued research into the physical properties of rammed earth will help to elucidate its strengths and weaknesses. This information, in turn, can find its way into design and detailing solutions that address the particulars of rammed earth and advance its architectural development. Design, if framed around Frascari’s ideas of detailing and narrative, can also serve to advance the investigation of rammed earth. By approaching architectural design in rammed earth with intimate knowledge of the material, designers can develop detailing strategies that more successfully capture the nature of the material and communicate their design intent.
Part 2: Experiential

“It’s quiet; the house feels solid and sturdy, calming, comfortable, timeless... we are hardwired to be at home in the earth” -David Easton

The most moving characteristics of rammed earth lie, perhaps, in its sensual aspects. It possesses a unique texture, weight, color, and coolness that can only be achieved using this method. In its role as a wall, earth is brought out of its typical context, creating a unique and unexpected relationship between a building/material and its occupants. The level of transformation of material is minor. Whereas materials like concrete and drywall might have originated in the earth, they have been markedly altered by human intervention in order to suit necessities of cost and efficiency. Rammed earth, on the other hand, although it brings earth out of its standard context, is readily recognizable as consisting of earth.

According to Pallassmaa, “The flatness of today’s standard construction is strengthened by a weakened sense of materiality. Natural materials--stone, brick, and wood--allow our vision to penetrate their surfaces and enable us to become convinced of the veracity of matter. Natural materials express their age and history, as well as the story of their origins and their history of human use.”

In a rammed earth wall, compacted layers of soil illustrate the story of construction and achieve a dynamic and variable texture that captures light and shadow. Rammed earth is like man-made sedimentary stone, where the necessity of time has been removed. Time is shortened by human intervention, by the pound after pound that compresses both time and material.

Like sedimentary stone, rammed earth is by nature fragmentary, consisting of variably sized fragments of what once was rock, eroded slowly, by natural forces to constitute the amorphous body we refer to as “earth.”
Texture

Even after earth has been rammed into a wall it is still possible to register its unique particulate make-up in the wall’s surface and texture, at least those that can be registered by the naked eye. In the same way the particle matrix in rammed earth can be modified to suit the technical demands of a building, it can be altered to enhance its textural character as well. In the Chapel of Reconciliation, for example, fragments of a church once present on the site were embedded in rammed earth walls to accentuate their texture and memorialize the destroyed church.

Without adding other material, the texture of finished rammed earth walls can be modified by adjusting component ratios in the mix. The images to the right capture three different textures that were created utilizing the same soil base, but altering the type and/or quantity of sand added. Finer grained sand produces a smoother finished surface (fig), whereas more coarse sand lends a coarser finish (fig). Each surface finish traps light in a slightly different way, the coarser textures create deeper pockets of shadow and generate a more diffuse light quality. Captured by light, each texture invites touch, encouraging the user to experience the material through multiple senses.
**Mass**

Monolithic rammed earth construction is unlike contemporary layered construction in many ways, not the least of which lies in how materials are experienced. Architecture can be used to highlight the massivity of rammed earth and further enrich the experience of occupying a rammed earth building.

Openings present an opportunity to capture mass, since they must puncture the thickness of walls and can allow users to pass through it, visually and physically. The inset windows in Gallo Consortium’s design are detailed to be minimally present, allowing an unobstructed view through the massive walls and creation of a tunnel-like effect. On the interior and exterior of the house, the overall weight of the structure is highlighted by the small, punched openings.

Massive construction provides the added benefit of mitigating temperature fluctuation. Those experienced with rammed earth construction have often noted that it remains cool in the summer and warm in the winter.
Color

The aesthetic of local soils are captured in rammed earth walls. If local soils are suitable for construction, they can be used to generate a highly unique and contextual design. In some places, where there are several soils suitable for construction, each can be used in successive layers, to enhance the layered appearance of walls. Soils can also be tinted using oxides or concrete dye to achieve this effect in locales with limited soil selection. The Nk’mip desert cultural center uses color additives in soil to “evoke geological sedimentation” (Rael, 2009, p. 104).
Light

Light in a rammed earth structure captures all of the other qualities of the material and can be used to orchestrate particular effects that take advantage of them. Through careful detailing, material deployment, and consideration of the relationship between glazing and rammed earth, dramatic light qualities can be achieved in combination with passive design strategies to moderate the thermal character of a space.

Daylighting can be used in combination with mass to harness heat during the winter. Utilizing south and west facing glazing to permit heat gain during winter months could be used to take advantage of rammed earth’s thermal storage capacity. The mass would be gradually warm in sunlight and dissipate stored heat to interior spaces.

Conversely, shading can be used to contrast the aesthetic of light, creating deep shadows to emphasize the massive, cave-like quality of rammed earth. Shading can also be used to prevent interior spaces from over heating. By guarding massive walls from heat gain, they are able to remain cool longer and equilibrate interior temperature fluctuations.
Chapel of Reconciliation
Reitermann & Sassenroth
Berlin, Germany, 2000

Description / Intent
In 1985 the Church of Reconciliation was destroyed by the German Democratic Republic (GDR). Its unfortunate location within the “death strip” that divided East and West Berlin put it in the way of patrol routes and ultimately led to its demolition. After the fall of the Berlin Wall, community members sought a new chapel to replace and commemorate the one that they had lost.

The Chapel of Reconciliation is a small oval structure that lies within the footprint of the former church. It has inner and outer layers, one of wood and one of rammed earth, that align to different axes, on in the traditional East/West orientation, and one that marks an alcove where remnants of the recovered church altar are stored.

Although originally slated to be constructed from concrete and steel, rammed earth and wood were selected as materials for the new chapel. When presented with the initial proposal, community members felt that concrete and steel were too reminiscent of the oppressive wall that had once stood prominently in their neighborhoods. Clay was a natural choice for the site, which was at one time adjacent to a historic clay mine.

The Chapel is presented to visitors in layers, each one...
distancing the outside world from the inner sanctuary. First they pass through a wood screen, which, although it is translucent and allows the passage of air and light, is a marker of their first step toward a separate experience.

Two-foot thick rammed earth walls form the next boundary that surrounds the sanctuary. Once inside, visitors are surrounded by monolithic rammed earth walls. Mass quiets noise and heightens the experience of separation from the outside. Since only opening is in the roof, visitors do not have a visual connection beyond the rammed earth core. Although visually restricted, visitors connect to the passage of time, light, and climate through other senses, directly experiencing outside conditions in the entirely unconditioned space.
Chapel of Reconciliation, front

Chapel of Reconciliation, walkway and wood screen

Chapel of Reconciliation, salvaged cross and skylight

Chapel of Reconciliation, altar
Analysis

The Chapel of Reconciliation addresses the strengths and weaknesses of rammed earth in a number of ways. A covered walkway that results from wide overhangs and the use of a wood screen protects the vulnerable rammed earth core from moisture while providing shade to prevent overheating. Wood is used as “screen” and fragments the monolithic texture of rammed earth--opaque is contrasted with translucent, a unit is contrasted against a monolith.

An inset in the wall frames a reclaimed cross from the former church. Above the inset, a light well permits a wash of natural light, augmented by artificial light at night, to drape the cross and enhance the apparent depth of the inset.

Concrete is used as a lintel, to span openings, and a bond beam, for lateral stability.

The roof structure appears to creep over the top of the rammed earth walls, forming a shell that is distinct from the rammed earth core.

Details in wood screen are highly articulated, whereas rammed earth is detailed to appear as though it is seamless. This is especially apparent in the base details of both walls. Rammed earth appears to disappear into the earth floor through a minimally articulated seam. Wood slats, on the other hand, are individually braced with metal components, and clipped to the structures foundation.
The organ level floor pierces through the rammed earth walls, taking advantage of their compressive strength. Inside the wall, metal anchors grip the rammed earth for added stability.

There are very few openings in the rammed earth walls. Aside from openings for entry and to display the salvaged cross, there are only two, both at the organ level. The only other opening into the interior chapel space is through the roof. There are several advantages to minimizing openings for both experiential and technical reasons. It is much simpler to exclude openings from rammed earth walls due to the reduction in formwork needed as well as the necessity of using alternative materials for lintels or frames. Experientially, visitors to the chapel can observe the passage of light and time in a way that separates them from their everyday experience. By restricting outward views, their visual connection to the outside world is restricted, but their ability to experience light through other senses is enhanced.
Organ level

Concrete lintel

Metal anchor

Organ-level floor

Rammed earth wall

Concrete bond beam

Concrete lintel

Rammed earth wall

Bearing detail conjecture by Author

Lintel detail conjecture by Author
Cemetery Extension and Chapel of Rest
Marte. Marte
Batschuns, Vorarlberg, Austria, 2001

Description / Intent
The Cemetery Extension and Chapel of Rest were aimed at expanding existing burial grounds and creating a mortuary chapel for an existing church. Using soil from on-site excavation, rammed earth walls were raised to form a cube-shaped mortuary and walls that extend to form boundaries for the cemetery.

Analysis
In the Chapel of Rest, strength and deficiency of rammed earth are highlighted by architecture and detailing. Rammed earth is used to express solidity and heavy mass enclosure. Enabled by the strength of metal supports and careful detailing, light becomes a material
expression.

From the outside openings are indistinguishable, giving the volume a solid, impermeable quality. The heavy, asymmetric wooden door adds to the overall weight of the composition. Wide wood trim accentuates the thickness of rammed earth walls, and the minimally articulated door appears impenetrable. A thin roof profile is barely distinguishable from the walls, and it is easy to imagine that the structure is simply a cube of earth.

Once inside, slivers of light seem to cut through the walls, pushing apart the volume of earth. One of the massive rammed earth walls, enabled by the strength of a thin metal beam, lifts from the ground to give the illusion of weightlessness. This detail calls to attention the inability of rammed earth to perform in tension, a limit that is accounted for by the significant tensile strength available in the metal support. By inserting metal in place of rammed earth, a precise edge is made available to anchor glass.

To a even greater degree than the Chapel of Reconciliation, the Chapel of Rest incorporates earthen materials to completely enclose the interior experience of the space. Earth in the floor, walls, and ceiling is detailed to create a seamless, unarticulated...
appearance, which allows light to emerge as a primary means of articulation. Aside from light, the only detail articulated with another material is the vertical strip of wood inserted into the rear wall, which, in tandem with horizontal layers of earth, forms a cross.

The idea of minimal articulation is carried through in the structural design of the chapel. Metal reinforcing is incorporated into the thickness of the wall above the door to act as a lintel, and wraps the corner to provide additional lateral bracing. Expression of the metal support is suppressed in favor of the appearance of solid rammed earth.
Opening at the bottom of the wall

Lintel / Lateral Brace

Metal Beam

Wood Inset

rammed earth wall

metal beam

glass

Slot detail Conjecture by Author
Part 3: Design

Details emerge as the quintessential union of technical and experiential. Daylighting in the case of this project captures this union and provides an opportunity to address site considerations as well.

Experiences of rammed earth can be enhanced by architectural intervention—orchestrating the play of light against its surface. Light and shadow reveal the character of a space, capture material texture, connect occupants to the passage of the day, and give depth to a space in the same way charcoal can give volume to an otherwise shallow sheet of paper. An architect modulates these experiences through careful detailing and ensures technical performance by selecting and exploiting complementary material properties. Similar to the diagrammatic role of Serpent Mound, careful daylighting has the potential to highlight the diagrammatic character of a building and the interplay of its materials as well as connect a building’s occupants to terrestrial cycles.

In sum, I aim to convey the mass, thickness, weight, and permanence of rammed earth played upon by the passage of each day’s light across its surface. Returning to the idea of an architectural semiology, the set of details that emerge from this study will at once describe the physical properties of the material rammed earth as well as the context in which it resides. In other words, I seek to explore how meanings can be communicated through materiality and detailing.

“…the detail expresses the process of signification; that is, the attaching of meanings to man-produced objects. The details are then the loci where knowledge is of an order in which the mind finds its own working, that is, logos” (Frascari, p.23).
Sentiments From the Field

A summer spent working hands-on with rammed earth was challenging and rewarding, and gave me insight into the trials of working with a non-industrialized building material. This section contains excerpts from the journal I kept while communing very intimately with dirt.

07/17/09

Continued transcribing interview with Joe Dahmen and put in more foam for testing. Talked with Therese about the interview and how the ASTM process works for authoring standards. She pointed out that they only have meetings for new standards twice a year. To get a new standard started you have to get an editorial committee together and start the process for writing. Can take a very long time to get one published. We checked on ASTM’s website to look at who was responsible for the standards about rammed earth (EO 6.71 task group) and discovered that there’s another standard in the works: WK 16155, Revision to Earthen Wall Design Standard. ASTM Technical Contact for task group: Bruce King.

Apparently for rammed earth to move forward as far as testing and standards, there would have to be a material standard which would require test standards to be developed.

Called a couple of places to see about getting dirt to build samples with and came across Earl Dunn (dirdunnright) and he agreed to take me to his family property to get dirt. Drove out toward Strawberry Plains and got a trunk load of dirt!
07/24/09
Emailed Dan Naus to ask about compression and freeze/thaw testing and he suggested some other contacts, one of which was S&ME lab in Knoxville. Called and was told to contact Randy Rainwater, will call back on Monday. Would like to know if they’d be willing to do my testing for free or reduced rate and also let me come visit the lab during the testing to watch the procedures or assist. Haven’t explored the other contacts Dan mentioned, but will do so on Monday.

07/28/09
After working with the soil a bit I’m concerned it’s too silty/clayey, but will give it a try nonetheless. Also I think the addition of sand will make it much more usable. The shake test is a little hard for me to read. The water is still a bit cloudy, which is slightly disconcerting, and it’s difficult to tell if the particles on the bottom are sand or clay. If the particles at the bottom are sand, then I think I’m in pretty good shape. If not, however, it seems like the soil has much too much clay. The other question I’m struggling with is how much does the soil need to be broken up. It’s fairly easy to get it into approximately 1/8" or so pieces, but smaller than that requires some serious grinding. I’ll try to ram one with the soil only partly broken up and see what kind of a result I get. Yesterday I heard back from Randy Rainwater at S&ME with a quote of a minimum of $2,000 to do all of the tests I requested on one soil/cement mix, so I’ll have to put that off or wait to see if I can get those tests done at UC.
Spent the morning putting together my first sample block made from the unmodified soil. Will leave the sample in the form until Friday since I’ll be out of the office Wed-Thurs for the AIA TN convention. Hopefully by then it will have cured sufficiently to remove it from the form. I also mixed a bucket of a soil/sand mixture at the ratio of 2 parts soil to 1 part sand. I brought it inside to dry out a bit and will ram it into the form on Friday. I also would like to re-do the tests I did for the unmodified soil with the sand-added version to see what differences emerge. I decided to take the first sample out of the form and perhaps should have waited. The sticky clay stuck to the form and made dents in the sample.

08/03/09
After going to the library and ordering some books from UT, I spent the afternoon making a sample from my 3 parts clay to 1 part sand mix. After I finished tamping, I mixed a new batch to test that’s 1 part clay to 3 parts sand. There are noticeable color differences between the unadulterated soil and the 1:3 mix, which is much more brown in color, definitely less red, and produced a much smoother mixture without so many clumps of clay. Since it’s not supposed to rain this week I decided to leave my 3:1 sample outside to dry and see if the more slow drying time results in less cracking/stronger edges.

08/05/09
Last night I left my dirt and samples uncovered thinking that the weather was supposed to be dry, but storms popped up last night with torrential rain, so my dirt pile is soaked this morning, and the samples have suffered very noticeable erosion. Rain is proving to be one
of the most difficult things to deal with relative to rammed earth. Since the soil can’t be too wet when you put it into the form, and direct water contact has to be avoided, rain makes this very difficult. On the other hand, without some moisture, the rammed earth can cure too quickly, and would have to be sprayed with water to avoid cracking due to rapid curing.

08/11/09
Jerry finished making my 2’x2’x4” form yesterday, so I’m now trying to get my dirt dried out enough to move along with building a sample to put in the 605 machine. In order to get all of this to work, we had to put the two pieces of plywood in the machine and test their conductivity alone, then sandwich the plywood with foam in between the pieces and then retest the two pieces of plywood by themselves in order to get an accurate enough reading of the conductivity of the plywood so that we can then subtract that value from the reading we get with the rammed earth.

08/13/09
Since I bought sand and concrete dye last night, I decided to go ahead and try to make a tinted sample and get started on the bigger sample that’s going into the 605 machine. I found a sledgehammer in the shop, so I’m using that as a compactor instead of the smaller one Jerry made. So far I think I’m achieving better compaction using the sledgehammer, even though it’s only an 8lb-er. I made one layered small sample using alternating layers of tinted and un-tinted dirt. I’m quite happy with the result and am eager to see how the strength of this sample compares to the strength of the other samples. For the small sample today and the first part of the bigger sample I decided to use a mix of 1.5 parts sand to 1 part clay, since I hadn’t yet tried that mix. The sand I bought from Ace has far more fines than the sand I picked up from Earl Dunn, and that appears to be affecting the texture of the mix. I seem to be getting more small clumps with the fines since they are essentially increasing my silt content, so I’ll be curious to see how the resulting block turns out. Aesthetically speaking, I like the smooth finish I got from the Earl Dunn sand, but also the more roughly textured surface achieved with the Ace sand. I’m still curious to test out mixes with larger aggregate and mixes with a small percentage of Portland cement. Also, I’d like to test out a variety of aggregates to see if I can achieve any variety in strength or finish. I finally wore myself out and decided to put off finishing the larger sample until tomorrow morning—also it will be cooler than. Another problem I’ve encountered is bowing in the form. I didn’t have that problem with the smaller sample, but since I have the same thickness of plywood spanning the larger sample, I’m noticing some bulging. This will only prove problematic if the 605 can’t make adequate contact with the sample.

08/17/09
Today Jerry helped me scrape down the big sample to fix the bowing on the sides. We used a
dull hand saw, and since the sample was left in its form over the weekend it was still damp enough that it was relatively easy to scrape off the surface. Therese came over to see it and wanted to check with the lab equipment company before putting it in the machine to make sure it wasn’t too heavy—

**we’ve estimated that it weighs between 100-150lbs.**

08/20/09

**A disclaimer to this last entry... having just ended an argument with one of the ORNL researchers about the role of sustainability in architecture, I discovered that rammed earth represented much more than a simple building method. In my opinion, it symbolizes an approach to design and environmentalism that seeks to minimize technological strong arm solutions in favor of low-tech. options. I learned that what seemed to me to be a harmless building method was actually counter to the very nature of much of present-day sustainability research and engineering. Rammed earth finds itself in the angry waters of a much larger social and political discourse. The problem with many high-tech fixes for sustainability is that they still fall back on existing design ideas and models. Can sustainability really be achieved using exactly the same design and development models with simply a shift in the level of technology that’s applied? Rammed earth falls more into the category of grass-roots environmentalism and subversive political action.**
Site Concepts

The site is adjacent to Serpent Mound in Adams Co., Ohio, which was created by the Ft. Ancient culture (AD 1000-1550). The 1,300-foot long serpent made of earth is the largest effigy mound in the U.S., possibly in the world (Ohio Historical Society website).

Serpent Mound is at once a diagram and an instrument. The mound is carefully tuned to align with important solar and lunar events throughout the year—the nose of the serpent aligns directly with the setting sun on the summer solstice. In this way, it is possible to interpret the passage of the sun and moon by reading the diagram laid out in the mound. Furthermore, it follows that its makers might have used the mound as an instrument to measure the passage of time, perhaps for agricultural or ceremonial purposes.

It is likely that the Ft. Ancient culture used Serpent Mound as an instrument that connected them with yearly terrestrial cycles. By tracking the rising and setting sun they would have been able to trace the seasons and prepare agricultural lands or perform other tasks related to seasonal variation.

The positioning of the mound is also critical to understanding the site. It rests on top of a promontory at the edge of a massive crater that formed 250 million years ago when it was struck by a meteorite. Until recently the cause of the crater was uncertain—meteorite or volcano. The uncertainty led to the term cryptoexplosion, alluding to the uncertain circumstances of its creation that continue to mystify.

Serpent Mound plays the dual role of diagramming conditions of the site and functioning as an instrument of time. Lessons borrowed from Serpent Mound (the way ancient people shaped and used the earth on the site) might inform the design and detailing of a building.
Bedrock geology maps showing the boundary of the cryptoexplosion
Climate Considerations

According to Lechner, my site resides in Climate Region 3, the Midwest. In this region, cold winter winds are of concern, but summer winds can be utilized to advantage. During the summer, however, high temperature and humidity lead to increased cooling loads. Some of the design strategies suggested by Lechner and Climate Consultant for this region are as follows:

Lechner:
-- Keep heat in and cold temperatures out in the winter
-- Protect from the cold winter winds
-- Let the winter sun in
-- Keep hot temperatures out during the summer
-- Protect from the summer sun
-- Use natural ventilation for summer cooling

Climate Consultant:
-- Extra insulation might prove cost effective, and will help to steady indoor temperature
-- Tiles or slate or a stone-faced fireplace can help store winter daytime solar gain and summer nighttime ‘coolth’
-- Window overhangs or operable sunshades can reduce or eliminate air conditioning
-- Organize floorplan so winter sun penetrates into daytime use spaces with specific functions that coincide with solar orientation

Based on fig., a diagram of the temperature range in my climate zone, it is clear that some intervention--passive
or active—is necessary in order to increase occupant comfort for more months of the year. I propose that rammed earth could be a good option to mitigate some of these temperature fluctuations because of its high thermal mass. When the interior/exterior temperature differential is great enough, the mass will alone help to mediate the gap. When there is less of a temperature differential, mass can be utilized along with natural ventilation or solar heat gain to steady temperature swings.

The diagrams in Fig. illustrate the effect of humidity on dry bulb temperature, and consequently on the thermal comfort of building occupants. Since rammed earth is a porous material, it readily absorbs and desorbs moisture, almost like it is breathing. In effect, this serves to mediate internal humidity levels. It has been noted that the interior humidity level in a rammed earth structure remains around 50% throughout the year.

Both Lechner and Climate Consultant strongly recommend utilizing passive solar shading in this region of the country. Lechner states that the region has 5,650 heating degree days and 988 cooling degree days. Clearly, careful planning of shading will be important to insure that adequate shade is provided during warm months, while as much solar gain as possible is permitted during cool months. Not necessarily related to indoor environmental quality, but pertinent to my site is the alignment of the serpent at Serpent Mound with the sun and moon. On the summer solstice, the nose of the serpent aligns directly with the setting sun—a spectacle that draws hordes of onlookers to the
site. Capitalizing on the alignment of the sun and moon while avoiding mimicry and respecting the integrity of the ancient monument will be important design considerations.

Cold winter winds are also mentioned in both Lechner and Climate Consultant as being vital to making informed design decisions in this region. The mean daily wind speed listed in Lechner ranges from about 7-12 mph, more than enough to achieve successful natural ventilation.

Climate Consultant charts *gray bar indicates comfort zone
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Details
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Appendices
Barriers to Greater Use of Rammed Earth in the U.S.

“In the modern era, earth architecture has undergone some curious developments. During the Second World War the Nazis set up special units under Hitler’s chief architect Albert Speer to investigate how to make buildings without using steel, as it was needed by the war effort. By this quirk of history, Germany is now highly advanced in the practice of building with earth. Scandinavia and Austria are not far behind and France can point to CRATerre, a Grenoble-based institute founded in 1979 which undertakes surveys of building types and trains architects in the techniques of earth architecture” (Slessor, 2009, p. 94).

Looking at barriers to the use of rammed earth in the U.S. is useful for this thesis because it could help form a design agenda that is specific to this context. Outside of physical and climatic limitations, there are cultural conditions that exist that may have an impact on the use of this form of construction here. For example, rammed earth construction is labor intensive. When designing a rammed earth structure in the U.S., then it would be instrumental to the success of the project to design for the most cost-effective and efficient means possible.

Given the simplicity and numerous advantages to the rammed earth method, why has it not been more widely utilized in the United States? Research into this question does not provide a concise answer. In three publications about rammed earth, separated by decades, authors asked similar questions in their introductions. The first excerpt is from Karl Ellington’s 1924 publication, “Modern Pise Building”:

“The fact that the pise method is not known everywhere is by many taken as indicating or proving that pise must have been tried and found wanting… But anyone who will give a little more attention to the subject will find, that in some parts of the world the pise method has been in use for several thousand years. And in countries where the pise method has not been practiced it has never been tried because of the presence of wood or brick or other materials—and tradition has cared for the continued use of methods once established, just as pise has kept its ground from times remote and until the present day in localities where everyone knows the merits of the method and is familiar with the requirements in utilizing it. If only it was as easy to remove prejudice as to build with pise, the method would be in use everywhere today” (Ellington, 1924, p. 9).

Twenty-three years later, in 1947, Anthony F. Merrill published the book, “The Rammed-Earth Home,” with an introduction by former Secretary of Agriculture, Clinton P. Anderson. Anderson expressed similar sentiments:

“…For all my intimacy with this building method, I confess a little bewilderment at the fact that after so many years of modern availability, rammed earth still remains relatively unpublished. Though the Department of Agriculture has answered thousands of queries on the subject since long before the publication of its first rammed earth
pamphlet in 1926, there has been nothing as yet which could be described as a rammed earth building boom” (Merrill, 1947, p. X).

In 2009, 62 years after the publication of Merrill’s text and 85 years after Ellington’s, Ronald Rael, author of, “Earth Architecture” again addressed this dilemma:

“The perceived hegemony of the industrialized world has for decades been directly responsible for causing an inferiority complex among earth-building cultures. Today, the most common building material on the planet is classified as ‘alternative’ or worse—‘primitive.’ At the dawn of every country’s transition to an industrialized society, it makes a concerted effort to abandon its earth-building traditions at the risk of depleting natural resources such as wood; investing in construction projects using expensive industrially produced materials such as concrete, which often perform poorly in developing nations; and losing traditional cultural knowledge. The perception that industrial materials are better is often coupled with society’s embarrassment about its highly developed, contextually responsive, and deeply meaningful traditions” (Rael, 2009, p.15).

These excerpts demonstrate some of the barriers faced by rammed earth architects and builders in perhaps the most popular or well-known rammed earth texts. Their sentiments are echoed, however, many times in various media.

Virtually every rammed earth aficionado that is posed with these questions provides a different explanation.

Lack of Standardization / Building Experience

Some rammed earth architects point to the standardization process used in the United States as a barrier to greater use of the method. During an interview, Joe Dahmen, an Architect and rammed earth consultant in Massachusetts, pointed out this issue, “…standards are what govern construction…and if you’re trying to write a specification for durability of rammed earth…you know it actually makes it pretty difficult for Architects, say, to specify the rammed earth because they can’t refer to a reliable standard” (7/16/2009). Researching and writing standards for rammed earth, or any other material, is made still more difficult by the lengthy and sometimes expensive process involved. According to Therese Stovall, a Professional Engineer with Oak Ridge National Laboratory, in order to begin the process of authoring a standard, a diverse board of contributors must be assembled that can help evaluate and edit the standard. Once the new standard is written, it must be brought to a new standards meeting of the American Society for Testing and Materials (which happen twice a year) for a final vote before it can be considered an active standard. Standards must be written to guide selection and installation of the material, as well as provide guidelines for testing the material itself (07/17/09). That is, standards address how tests will be performed on the material and what outcome can be generated by the proposed tests. Considering the low material cost of rammed earth and that it is frequently owner-built, there has
been little money or lobby available to advance the standardization of rammed earth.

Given that the majority of new construction was completed in wood or metal, builders gained little if any experience with alternative methods, including rammed earth. Public exposure, as a result, to rammed earth has been extremely limited in the United States. Without the benefits of familiarity, rammed earth remains largely unexplored here, with the exception of the western U.S., where adobe and rammed earth have been in use for much longer, granting them a degree of acceptance.

**Low-Cost Alternatives**

Other factors that could have influenced the use of rammed earth in the U.S. are related to labor and economics. Although it was never used extensively in the U.S., there is evidence that, prior to WWII, rammed earth enjoyed a degree of popularity; the use of rammed earth to construct several depression-era houses in Alabama is one example, as well as experiments done by Ralph L. Patty in South Dakota on rammed earth for agricultural buildings. Following WWII, there was an enormous housing shortage. Weapons manufacturing plants were quickly converted into automotive and building component manufacturing. Materials that were readily available, inexpensive, and that could be readily integrated into mechanized processes and modularization were common. The mechanization of building component manufacturing reduced the relative labor costs associated with these types of building (namely wood frame), which is evident in subsequent available housing stock. Though other materials underwent mechanization that effectively reduced costs, rammed earth was not, until recently, easily mechanized. Installing rammed earth is quite labor intensive, especially without the assistance of modern machinery, and therefore makes little sense in regions, like the U.S., where labor costs are high. In developing nations, on the other hand, where there is a ready supply of inexpensive labor, earth building constitutes a much larger percentage of the building stock.

**Availability of Quality Material**

Although there are sites in the United States with soils that are ideal for rammed earth construction (mostly in the southwest), most soils here would require a degree of amendment in order to achieve optimal performance. That said, many soils are suitable for small construction projects, and with careful detailing a range of soil types become more usable. Also, many soils are amenable to cement stabilization, which makes them significantly more suited to construction.

**Perception of Inferior Materials**

Lacking direct experience with rammed earth structures, many may be left to assume that it is an inferior building method, otherwise, why has it not been used more heavily? Also, earth building is prevalent in developing countries, where locally-sourced materials are the only ones available for
construction. It is possible that the perception of earth materials in developed countries is that they are inferior and only to be used when there is no other alternative.

Since rammed earth has been much more heavily used in the western and southwestern U.S., much of the architectural design reflects elements of Southwest regionalism. It is possible, perhaps, that the material has suffered from perceptions of it as being limited to this style, or as having limited design potential. Architects outside of the U.S., however, have proven this to be quite untrue. Martin Rauch, an Austrian rammed earth builder, for example, has used the material to create architectural works that unite the careful construction and detailing of a craftsman with modern formal elements and explorations that capture the unique qualities of the material.

**Incompatibility With Climate**

Finally, there is the problem of climate, especially in the United States where there is a wide variety of climate conditions. After learning about the properties of rammed earth and its successful application in other countries, some of them European with similar climate conditions, it has become apparent that rammed earth can perform under a variety of conditions. In order to meet the heating demands of colder climates, insulation must be used, and in damp areas moisture shedding strategies are key to ensure the durability of rammed earth.

In my experience, when people are approached with rammed earth for the first time, they question its ability to perform in moist areas. It is possible that many of the fears associated with performance could be quelled through education and publication of research regarding rammed earth. Also, the method would benefit immensely from increased exposure in the U.S. If people could observe rammed earth buildings successfully performing in a variety of locales, acceptance would be more likely.
Standard Guide for Design of Earthen Wall Building Systems

This standard is issued under the fixed designation E 2392; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This standard provides guidance for earthen building systems that address both technical requirements and considerations for sustainable development. Earthen building systems include adobe, rammed earth, cob, cast earth and other earthen technologies used as structural and non-structural wall systems.

1.1.1 There are many decisions in the design and construction of a building that can contribute to the maintenance of ecosystem components and functions for future generations, that is, sustainability. One such decision is the selection of products for use in the building. This standard addresses sustainability issues related to the use of earthen wall building systems.

1.1.2 The considerations for sustainable development relative to earthen wall building systems are categorized as follows: materials (product feedstock); manufacturing process; operational performance (product installed); and indoor environmental quality (IEQ).

1.1.3 The technical requirements for earthen building systems are categorized as follows: design criteria, structural and non-structural systems, and structural and non-structural components.

1.2 This standard does not provide guidance for structural support of roofs made of earthen material.

1.3 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:


D 559 Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures
D 560 Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures
D 698 Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft³ (600 kN-m/m³))
E 631 Terminology of Building Constructions
E 2114 Terminology for Sustainability Relative to the Performance of Buildings

2.2 ASCE Standards:

ANSI/ASCE 7 Minimum Design Loads for Buildings and Other Structures

3. Terminology

3.1 Definitions:

3.1.1 For terms related to building construction, refer to Terminology E 631.

3.1.2 For terms related to sustainability relative to the performance of buildings, refer to Terminology E 2114. Some of these terms are reprinted here for ease of use.

3.1.3 alternative agricultural products, n—bio-based industrial products (non-food, non-feed) manufactured from agricultural materials and animal by-products.

3.1.4 biodegradable, adj—capable of decomposing under natural conditions into elements found in nature.

3.1.5 biodiversity, n—the variability among living organisms from all sources including: terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems.

3.1.6 ecosystem, n—a community of plants, animals (including humans), and their physical environment, functioning together as an interdependent unit within a defined area.

3.1.7 embodied energy, n—the energy used through the life cycle of a material or product to extract, refine, process, fabricate, transport, install, commission, utilize, maintain, remove, and ultimately recycle or dispose of the substances comprising the item.
3.1.7.1 Discussion—The total energy which a product may be said to "contain" including all energy used in, inter alia, growing, extracting, transporting and manufacturing. The embodied energy of a structure or system includes the embodied energy of its components plus the energy used in construction.

3.1.8 renewable resource, n—a resource that is grown, naturally replenished, or cleansed, at a rate which exceeds depletion of the usable supply of that resource.

3.1.8 Discussion—A renewable resource can be exhausted if improperly managed. However, a renewable resource can last indefinitely with proper stewardship. Examples include: trees in forests, grasses in grasslands, and fertile soil.

3.1.9 sustainability, n—the maintenance of ecosystem components and functions for future generations.

3.1.10 sustainable development, n—development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

3.1.11 toxicity, n—the property of a material, or combination of materials, to adversely affect organisms.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 adobe, n—(1) unfired masonry units made of soil, water, and straw with or without various admixtures; (2) the soil/straw or soil/staw/admixtures mix that is used to make them; (3) the mud plaster used for covering walls or ceilings, or both; (4) the building that is built of adobe and; (5) the architectural style.

3.2.1 Discussion—The word itself is believed to come from an Arabic word atob, which means muck or sticky glob or atubah "the brick." The adobe style of architecture migrated from North Africa to Spain, so the name adobe is likely to have come with it. In many other countries, the word adobe is meaningless, and it is more accurate to say "earthen-brick." Other forms of the same material with different details and names, such as rammed earth, Pise, Jaccal, Barjareque, cob, or puddled mud are sometimes referred to as adobe.

3.2.2 adobe construction, n—construction in which the exterior load-bearing and the non-load-bearing walls and partitions are of unfired clay masonry units while the floors, roofs and interior framing may be wholly or partly of wood or other approved materials.

3.2.3 adobe, stabilized, n—unfired clay masonry units to which admixtures, such as emulsified asphalt or cement, are added during the manufacturing process to help limit water absorption and increase durability.

3.2.4 adobe, unstabilized, n—unfired clay masonry units that do not meet the definition of stabilized adobe.

3.2.5 carbon sink, n—a reservoir that absorbs or takes up released carbon from another part of the carbon cycle.

3.2.5.1 Discussion—For example, if the net exchange between the biosphere and the atmosphere is toward the atmosphere, the biosphere is the source, and the atmosphere is the sink

3.2.6 cast earth, n—a construction system utilizing a slurry containing soil, calcined gypsum and water, which is poured into forms similar to those used for cast-in-place concrete.

3.2.7 clay, n—inorganic soil with particle sizes less than 0.005 mm (0.0002 in.) having the characteristics of high to very high dry strength, medium to high plasticity and slow to no dilatancy.

3.2.8 cob, n—a construction system utilizing moist earthen material balls stacked on top of one another and lightly tapped into place to form monolithic walls. Reinforcing is often provided with organic fibrous materials such as straw and twigs.

3.2.9 earthen building systems, n—building systems that utilize soil as the principal structural material.

3.2.10 energy efficient, adj—refers to a product that requires less energy to manufacture or uses less energy when operating in comparison with a benchmark for energy use, or both.

3.2.10.1 Discussion—For example, the product may meet a recognized benchmark, such as the EPA’s Energy Star Program standards.

3.2.11 gravel, n—inorganic soil with particle sizes greater than 2 mm (0.079 in.).

3.2.12 horizon, n—distinctive layer of in situ soil having uniform qualities of color, texture, organic material, obliteration of original rock material, and more.

3.2.12.1 Discussion—In World Reference Base for Soil Resources, by the Food and Agriculture Organization of the United Nations, seven master horizons are recognized – Ho, A, E, B, C, and R.

3.2.13 indoor environmental quality (IEQ), n—refers to the condition or state of the indoor built environment in which the building product is installed. Aspects of IEQ include: light quality, acoustic quality, and air quality.

3.2.14 loam, n—soil with a high percentage of organic material, particles are predominately silt size but range from clay size to sand size.

3.2.14.1 Discussion—Loams are usually good agricultural soils due to their nutritional organic content and their ability to hold water.

3.2.15 manufacturing process, n—refers to the process of creating a building product and includes manufacturing, fabrication and distribution procedures.

3.2.16 materials (product feedstock), n—refers to the material resources that are required for the manufacture or fabrication, or both, of a building product.

3.2.16.1 Discussion—Material resources include raw materials and recycled content materials.

3.2.17 moisture wicking—the capillary uptake of water from foundation soil, ambient humidity or precipitation. Moisture wicking can result in saturation of adobe with accompanying decrease in strength and durability.

3.2.18 operational performance (product installed), n—refers to the functioning of a product during its service life. Specific measures of operational performance will vary depending upon the product. Aspects of operational performance include: durability, maintainability, energy efficiency, and water efficiency.

3.2.19 pressed-block, n—a construction system that consists of walls made from earthen materials formed in a block mold by the compacting of lightly moistened earth into a hardened mass.
3.2.20 **rammed earth**, *n*—a construction system that consists of walls made from moist, sandy soil, or stabilized soil, which is tamped into forms.

3.2.20.1 **Discussion**—Walls of unstabilized soil are usually a minimum of 300 mm (12 in.) thick for load bearing purposes. Soils for rammed earth construction usually contain about 30% clay and 70% sand.

3.2.21 **sand**, *n*—inorganic soil with particle sizes ranging from 0.05 to 2.0 mm (0.002 to 0.079 in.).

3.2.22 **silt**, *n*—inorganic soil with particle sizes ranging from 0.005 to 0.05 mm (0.0002 to 0.002 in.) having the characteristics of low dry strength, low plasticity, and rapid dilatancy.

3.2.23 **straw**, *n*—an agricultural waste product that is the dry stems of cereal grains after the seed heads have been removed.

3.2.24 **straw-clay**, *n*—a construction system that consists of clay slip and straw, of which straw makes up a high percentage by volume.

3.2.24.1 **Discussion**—This system is well suited for manufacturing bricks, floor blocks, and insulating panels.

4. **Summary of Practice**

4.1 This guide identifies the principles of sustainability associated with earthen building systems. Additionally, it outlines technical issues associated with earthen building systems, identifying those that are similar to construction that is commonly used in the marketplace.

4.2 This guide is intended for use in framing decisions for individual projects.

4.3 This guide is intended for use in framing decisions for development of standards and building codes for earthen building systems.

5. **Significance and Use**

5.1 **Historical Overview**: Earthen building systems have been used throughout the world for thousands of years. Adobe construction dates back to the walls of Jericho (now located in Israel) which was built around 8300 B.C. Many other earthen structures have been functioning for hundreds of years. However, with the development of newer building materials, earthen building systems have been largely abandoned in part of the world where they were once commonly used.

5.2 **Sustainability**: As world population continues to rise and people continue to address basic shelter requirements, it becomes increasingly necessary to promote construction techniques with less life cycle impact on the earth. Earthen building systems are one type of technique that may have a favorable life cycle impact.

5.3 **Building Code Impact**: Earthen building systems have historically not been engineered. The first written standards for adobe were developed in the United States in the 1930s and were based on common construction practices. Only during the last 20 years have architects and engineers attempted to engineer adobe and rammed earth for use and compliance with contemporary building codes. Standards for the use of adobe were initially limited to local and state codes, predominantly in the southwestern United States. However, over time regional and national model building codes adopted provisions for adobe construction. For example, the International Building Code (IBC) provides empirical requirements allowing the use of adobe when the applicant follows specific procedures. New Mexico building code provides empirical requirements for the use of both adobe and rammed earth building systems. Where the building code does not specifically address earthen building systems, governing agencies frequently classify the construction as an alternative material, design, or method of construction. An alternative material, design, or method of construction will be approved when the code official finds that the proposed design is satisfactory and complies with the intent of the provisions of the code and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in the code in quality, strength, effectiveness, fire resistance, durability and safety. However, development of standards such as this can aid in the appropriate recognition and adoption of earthen building systems materials and methods by building codes and code enforcement agencies.

5.4 **Audience**: There are existing markets in the United States and internationally using adobe, rammed earth, and other earthen building systems. It is estimated that 40% of the world’s population lives in earthen dwellings. Safety, functionality, and sustainability of earthen building systems can greatly be improved through establishment of an international design standard. Intended users of this standard guide include: planners, developers, architects, engineers, interior designers, general contractors, subcontractors, owners, financial organizations related to building industry, building materials and product manufacturers, government agencies including building officials, and other building professionals.

6. **Considerations for Sustainable Development**

6.1 **Materials (Product Feedstock)**: Materials of earthen building systems include a binder soil, typically clay, clay-silt mixture or loam; and inorganic or organic tempering materials, or both. Sand and gravel are commonly used inorganic tempers and straw, hair, and chalk are commonly used organic tempers. Soils may be stabilized, using such materials as cement, asphalt emulsion, calcined gypsum or cactus juice, or may be unstabilized. Adobe bricks may be held together by a variety of mortars. Systems may be finished with plaster or pigments, or both, or left unfinished.

6.1.1 **Soil**: Soils for earthen building systems are a mixture of a binder soil, for example, clay, silt, clay-silt combination or loam, and temper soils of sand and gravel. These mixtures may be naturally occurring local soils or engineered by mixing different soils. Sources for the soils include on-site horizons, by-products of sand and gravel quarrying, and alluvial deposits.

Care should be taken to avoid adverse affects on the capacity for food production when considering the use of loams and other soils that are suitable for agricultural purposes.

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6.1.2 **Straw**: Straw, being dry and having no seed heads is more durable in earthen building systems than hay — which is a green, typically shorter, grass animal feed product containing stems and seed heads. Straw is an agricultural waste product that is typically not used for productive end use; therefore, it is considered an alternative agricultural product and a renewable resource when used in earthen building systems.

6.1.3 **Plaster**: A material applied to the exposed surfaces of earthen building systems to improve durability, water resistance or modify its appearance, or both. Commonly used on adobe, pressed block, and straw clay systems to protect or conceal, or both, the joints between the units.

6.1.3.1 **Clay Plaster**: Clay plaster is a mixture of clay, sand and water. Tempering materials, such as straw, and pigments may be added.

6.1.3.2 **Cement-stabilized Clay Plaster**: Cement-stabilized clay plaster is similar to clay plaster except for the addition of Portland cement or some other hydraulic cement, which is added to improve durability or reduce dusting, or both. Tempering materials, other admixtures and pigments may also be added.

6.1.3.3 **Cement Plaster**: Cement plaster is a mixture of cement, sand and water; the mixture may also include pozzolans, lime, pigments, glass fibers and proprietary admixtures. Cement plaster, which is often less permeable than many of the structural materials used in earthen building systems, can be used to encapsulate the tops and bottoms of walls and around openings to prevent moisture wicking which can result in saturation and deterioration of unstabilized systems.

6.2 **Manufacturing Process**:

6.2.1 **Manufacturing**: Manufacturing sun-dried, unfired earthen building materials, like adobe, pressed-block and straw-clay, is more energy efficient per unit volume than the manufacturing of fired-clay masonry, like brick, terra-cotta or structural clay tile. The manufacturing of earthen building materials that use Portland cement or some other kiln produced cement is more energy efficient per unit volume than the manufacturing of cement based concrete materials, like cast-in-place concrete and precast concrete if only because of the lower cement content of stabilized soil. Stabilized materials that use Portland cement, asphalt emulsion or calcined gypsum are less energy efficient to manufacture per unit volume than similar unstabilized materials. Asphalt emulsion is made by combining asphalt, a by-product of crude oil distillation, with water and proprietary surfactants.

6.2.2 **Fabrication**: In fabrication of adobe a binder soil, typically clay, is tempered with inorganic or organic materials, or both, to reduce shrinkage and cracking, and to increase strength and workability. Soils may be unstabilized or may be stabilized. Stabilizing is done to increase durability and strength. Placement of the material is done by forming units, such as adobe brick, pressed-block or straw-clay, which are then stacked to form the structure; or the material is placed directly into its final position using forms, for example, the rammed earth and cast earth methods; or without using forms, for example, the cob method. Placement of adobe, pressed block and straw-clay systems is similar to the placement of fired-clay and concrete masonry units systems in that manufactured units are hand stacked upon one another to produce structures. Where the fabrication of these systems differs is in the material used to bond the manufactured units or the firing of the units or both. Fired-clay and concrete masonry systems use mortars containing Portland cement, proprietary masonry cements, and mortar cements, and lime putties which use more energy in their manufacturing processes than unstabilized earthen building mortars and, to a lesser degree, stabilized earthen building mortars.

Fabrication of rammed earth and cast earth systems is similar to the fabrication of cast-in-place concrete systems in that formwork is required. Formwork is usually temporary wood, steel, fiberglass or earth construction built to give the desired shape and size to the completed structure. The formwork is removed before full curing of the material and can be reused or recycled depending upon the material used. There are now some plastic formwork systems which, rather than being removed, are incorporated into the final structure. Where the systems differ is in the amount of labor required to place the materials in the formwork. Cast-in-place concrete and cast earth, which are continuously poured into place until the desired height or thickness is obtained, require less labor than rammed earth, which is placed into the form in short layers called lifts and compacted after each lift.

6.2.2.1 **Energy Use**: Because of the additional steps required for fabrication, fired-clay, concrete masonry, wood or steel systems use more embodied energy in their manufacturing processes than unstabilized earthen building systems. Stabilized earthen building systems use slightly more embodied energy because of the use of small amounts of cement or other admixtures in their fabrication. Embodied energy involved in the formwork is equal for all methods requiring temporary formwork. While the energy required to place the rammed earthen material into the formwork is higher per unit volume, the differences are minimal in comparison to the quantity of energy used in the manufacturing and distribution procedures for cast or placed concrete or concrete/plastic systems. Important considerations for sustainable development in the fabrication of earthen building wall systems versus fired masonry, concrete, wood or steel systems are the quantities of energy consumed and carbon transferred from the biosphere to the atmosphere during manufacturing and fabrication per cross-sectional unit length of the entire system, including the foundation, bond beams, lintels, and so forth. Materials that are more energy intensive to manufacture than earthen building materials, such as concrete, are often used for foundations, bond beams and other components of earthen building systems. This results in the earthen building systems being more energy intensive than just the earthen building materials used in the systems. Quantities of energy consumption and carbon transfer associated with earthen building systems increase as wall thicknesses increase to match structural load capacities of thinner fired-clay masonry, concrete masonry, cast-in-place and precast concrete wall systems. In earthen building systems, where wall thicknesses are increased and more energy intensive materials are used for components, the quantities of energy...
consumed and carbon transferred can exceed quantities associated with fired-clay masonry, concrete masonry, cast-in-place and precast concrete wall systems.

6.2.3 Distribution Procedures: Distribution procedures for earthen building systems range from on-site extraction, manufacturing and fabrication of individual buildings by their owners to regional multi-corporation systems involving off-site quarries, masonry manufacturers, and building contractors.

6.3 Operational Performance (Product Installed): It is commonly held in Europe and other parts of the world that stabilization is not necessary. In the United States, many builders have used stabilization to prevent dusting or to increase strength, or both, depending on soil characteristics. The need for stabilization will vary from project to project and professional judgment is required.

6.3.1 Durability: Moisture will disintegrate earthen building systems; therefore, earthen building systems should be protected with foundations, protective coating such as cement plaster or overhangs, or both. Vertical surfaces in areas with rain up to 640 mm (25 in.) per year will likely erode at the rate of approximately 25 mm (1 in.) in 20 years. Horizontal surfaces such as the top of a wall, on the other hand, will likely erode much more rapidly (50-75 mm (2-3 in.) per year). Various factors may affect durability and rate of erosion; therefore, specific site and climate conditions should be carefully evaluated. Demolished, unstabilized adobe can disintegrate and return to the soil without negative impact on the ecosystem. Materials used to stabilize earthen building systems, such as asphalt emulsion and cement, can alter soils and their suitability for agricultural uses.

There are currently ASTM standards for freeze-thaw testing of soil-cement (Test Methods D 560), concrete (Test Method C 666/C 666M) and hydraulic cement mortar (Test Method D 5860) and wet-dry testing of soil-cement (Test Methods D 559) but not for unstabilized adobe.

6.3.1.1 Standard construction materials tests such as dry compressive strength, wet compressive strength, modulus of rupture, percent absorption, moisture content, field density and dry density can be used to assess the probable durability of earthen building systems. In many areas of relatively high adobe usage, some criteria, based on these tests but modified to reflect the unique characteristics of adobe materials, are already in place for determining moisture susceptibility and load resistance. Examples of these criteria follow:

6.3.1.1.1 Moisture susceptibility can be assessed using criteria of either an average wet compressive strength of 2068 kPa (300 psi) after submersion of a 76 mm (3-in.) cube for 24 hours or an absorption rate of no more than 2.5 percent of the initial dry weight of a 76 mm (3-in.) cube after 7 days on a constantly saturated porous surface.

6.3.1.1.2 Load resistance for dried adobe units can be addressed using current criteria for an adobe unit dried to a constant mass of having an average dry compressive strength of 2068 kPa (300 psi) and an average modulus of rupture of 345 kPa (50 psi). According to these criteria, a cured adobe unit should have a moisture content of less than 4%. For rammed earth construction, a common criteria is that it have a field density greater than or equal to 95% of maximum dry density, determined in accordance with Test Method D 698, for the material being used. For cement-stabilized rammed earth one criteria currently in use is a 14-day compressive strength greater than 2068 kPa (300 psi).

6.3.2 Maintainability: While proper testing for durability will also aid in maintaining the earthen building system, some tests such as random sampling of adobe units for shrinkage cracks will increase maintainability by decreasing the likelihood of significant breaches in the materials, which may allow moisture to the interior of the building. One criteria already in use requires that randomly sampled adobe units have no more than 3 shrinkage cracks and that no single shrinkage crack be longer than 76 mm (3 in.) or wider than 3.2 mm (1/8 in.).

6.3.3 Energy Efficiency: Earthen building systems provide thermal storage capacity. The specific heat and U-factor of earthen building systems are high in comparison to insulated wood or steel stud frame construction making it suitable for thermal storage and unsuitable for thermal insulation.

In climates where the desired indoor temperature is between the maximum and minimum daily outdoor temperatures, exterior walls of earthen building systems can dampen thermal transfer and help stabilize indoor temperatures.

In climates where both the maximum and minimum daily temperatures are above or below the desired indoor temperature for several consecutive days, weeks or months exterior walls of earthen building systems will reduce thermal comfort by increasing conducted heat transfer, due to the high U-factor; and increasing radiant heat transfer, due to high mean radiant temperatures (MRT) during hot weather and low MRT's during cold weather. Since both the specific heat and U-factor of earthen building systems is high, it is difficult to alter the surface temperature of walls. In these climates, earthen building systems can improve energy efficiency by isolating the earthen building systems from outdoor temperature with insulation on the exterior surface or limiting earthen building systems to interior walls.

6.4 Indoor Environmental Quality (IEQ): IEQ for earthen building systems is generally considered good. Possible causes for poor IEQ are; VOC outgassing associated with asphalt emulsion, dusting from unstabilized systems, and radon gas production from certain soils.

7. Technical Requirements

7.1 Earthen Building Systems: Earthen building systems include adobe, rammed earth, cast earth, and pressed block.

7.2 Design Criteria:

7.2.1 Earthen buildings, structures, and parts thereof should be designed and constructed in accordance with internationally recognized design standards such as IBC or ANSI/ASCE 7 for strength design, load and resistance factor design, allowable stress design, empirical design, or conventional construction methods.

7.2.2 Earthen buildings, structures, and parts thereof, should be designed and constructed to support safely the factored loads in load combinations defined in ANSI/ASCE 7 without exceeding the appropriate strength limit states for the materials of construction. Alternatively, earthen buildings, structures, and parts thereof, shall be designed and constructed to support safely the nominal loads in load combinations defined in
ANSI/ASCE 7 without exceeding the appropriate specified allowable stresses for the materials of the earthen building systems.

7.2.3 Earthquake Loads: Consider lateral forces on earthen structures and structural components from seismic events. Consider in terms of the effects of earth movement, soil conditions, building occupancy, and location of the earthen component within the structure.

7.2.4 Wind Loads: Consider lateral forces on earthen structures and structural components from wind forces.

7.2.5 Rain and Snow Loads: Comply with design loads based upon rain as required for conventional construction. Care should be taken during construction to protect work from rain or snow since moisture uptake during construction can be extremely detrimental.

7.2.6 Dead Loads: Consider the impacts, both negative and positive, of gravity and dead loads as they affect earthen building systems.

7.2.7 Flood Loads: Earthen materials are not considered suitable for flood prone areas.

7.2.8 Load Combinations: Consider the effects of various load combinations and develop recommendations for design requirements consistent with conventional construction.

7.2.9 Impact Loads: Consider the stability of earthen wall systems to resist impact loads.

7.2.10 Bending Loads: Earthen materials do not perform well in bending conditions. Limit use of earthen materials as bending elements.

7.2.11 Compressive Loads: Develop safe and practical compressive loads stress formulas for earthen materials of different strengths and for the various uses in earthen building systems.

7.2.12 Tensile Loads: Earthen materials are limited in tensile strength. Limit use of earthen materials as under tensile loads.


7.3 Structural Systems:

7.3.1 Load-bearing wall braced: This system utilizes bond beams as lateral force resisting elements. This system utilizes shear resistant earthen walls.

7.3.2 Diaphragm Braced Load-Bearing Wall: This system utilizes conventional diaphragms such as roofs or floors to transfer loads to shear resistant earthen walls.

7.3.3 Post and beam: This system utilizes wood, concrete, or steel as the vertical and lateral load resisting system. This system utilizes earth as an infill material only.

7.4 Structural Components: Earthen building systems should especially consider the appropriate design for the following structural components:

7.4.1 Bearing walls.

7.4.2 Non-bearing walls, and

7.4.3 Inverted cantilever walls and elements.

7.4.4 Bond Beams: Consider materials and attachment to walls.

7.4.5 Bolting and attachments.

7.5 Non-Structural Systems:

7.5.1 Veneer: This system uses earthen materials as non-load bearing veneer.

7.5.1.1 Adobe brick

7.5.1.2 Adobe plaster

8. Keywords

8.1 adobe; alternative agricultural products; alternative building materials; energy efficiency; indoor environmental quality (IEQ); rammed earth construction; sustainability; sustainable development; thermal mass