Towards an Affordable Rammed-Earth Dwelling

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ABSTRACT: Rammed-earth construction faded from use in the U.S. for hundreds of years and is recently being revived as an alternative for custom homes. Contemporary construction methods for rammed-earth employ the stabilizing additive of Portland cement, pneumatic backfill tampers to compact the earth mix, and expensive forms fabricated for cast-in-place concrete construction. The high cost of forms and labor take it out of the realm of affordability for most people. However, its positive thermal and environmental attributes make it an alternative that would reduce housing costs in the desert southwest if the construction methods and field practices could be made less expensive. The three case studies illustrate the first steps in refining the design of affordable incremental formwork, establishing field practices that control the quality of the earth/cement mix, and optimizing a thermal strategy for ideal energy savings.

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INTRODUCTION

Rammed-earth construction was once a technique widely practiced by the indigenous peoples of the Sonoran Desert. This load-bearing wall system was achieved by packing an earth/clay mixture between forms made of wood or cactus ribs. As with many populations dwelling in arid regions of the world, natives of Sonora built with earth because of its relative availability, ease of transport, and durability, as well as its potential for maintaining a comfortable interior environment. The earthen walls served as thermal mass, slowing down the transfer of heat from exterior to interior spaces during the day (and performing the opposite function at night). Rammed-earth construction faded from use in the U.S. for hundreds of years and is recently being revived as an alternative for custom homes. Since the mid-1990’s rammed earth construction has undergone a renaissance in the southwestern states, primarily in California and Arizona. Contemporary construction methods for rammed-earth employ the stabilizing additive of Portland cement, pneumatic backfill tampers to compact the earth mix, and forms fabricated for cast-in-place concrete construction. The high cost of forms and labor take it out of the realm of affordability for most people. However, its positive thermal and environmental attributes make it an alternative that would reduce housing costs in the desert southwest if the construction methods and field practices could be made less expensive and the field practices made more reliable.

This series of three dwellings, designed and constructed by design/build studios in the School of Architecture at the University of Arizona, chronicles the first steps in refining the design of affordable incremental formwork, establishing field practices that control the quality of the earth/cement mix, and optimizing the wall thickness and size and orientation of openings for ideal energy savings.

REGIONAL EARTH BUILDING TRADITIONS

Rammed earth was originally a building technique of Native Americans of this region, as was wattle and daub. Both have been replaced in this century by a composite wall system of wood and packed mud. Houses built with this system on the Gila/Pima reservation are referred to in English as “sandwich”
houses. Most residents of the reservation live in a sandwich house, or grew up in one. While these houses require constant patching and replacement of the mud, they are valued by tenants for their maintenance of a fairly stable interior temperature in spite of the wide diurnal temperature swings of the Sonoran desert. They also hold considerable cultural value because they are a local tradition and are built by their tenants with found materials from the landscape (cactus ribs, plant stalks, earth) that remain part of the landscape when the houses deteriorate.

![Figure 1: Traditional Gila/Pima "sandwich" house](image)

Pima communities have been located along the Gila and Salt Rivers in Arizona for as far back as their history goes. [1] The Pimas (also known as A Kimel O'otam, which means River People) were dependent upon the rivers for irrigation of their fields as well as for the materials to build dwellings and granaries. They built of arrowweed, willow and cottonwood and until the 19th century, the two most common building types were the ki and the vato. The ki was a slightly excavated, brush and mud covered structure with a domed adobe-plastered roof. This was used for shelter in cool weather. The vato was a four posted arbor covered with cactus ribs and arrowweed. This was where families cooked, ate and slept during the warmer times of the year. [2]

The later-period Pima and Papago houses were rectangular, flat-roofed structures with a post and beam frame covered with arrowweed and mud. Changes in housing practices since the 1880s have largely resulted from constant pressure by church and government groups; but the sandwich houses are not part of any government sponsored development plan and retain Pima characteristics. [3] They include locally available materials and employ locally known techniques while evolving to reflect the arrival of milled lumber. The walls are built of mud and straw which is packed into a frame of heavy vertical posts and lighter horizontal cross pieces that are spaced a few inches apart or staggered. The mud fills the frame cavity and squeezes out between the cross pieces, forming a composite wall. Most sandwich houses are plastered inside and out with a coat of mud, which must be repaired frequently. The packed mud must also be repacked frequently, especially after monsoon rains wash out areas of the walls. The roofs are framed with mesquite posts, crosshatched with saguaro ribs, and thatched with arrowweed and mud. Sandwich houses are still the most common dwelling type found on the Gila River reservation and new ones are still constructed as a matter of preference and also economy.

Contemporary rammed earth techniques differ due to available technology and requirements of building codes, but the genealogy remains obvious. The reliance on the earth from the site, the intensity of the labor required, and the uncomplicated techniques involved make it an easy fit in the arid regions of the southwest, with their housing shortages and ready supply of unskilled labor.

The load-bearing system requires wall thicknesses of 12 to 24 inches that may taper in section from base to top. Having almost no insulation value, rammed earth walls serve instead as thermal mass, which slows down the transfer of heat from exterior to interior spaces during the day (and performs the opposite function at night). The rate of heat transfer through a rammed earth wall is about one inch per hour. In the desert climate, this means that the sun’s heat works its way towards the interior spaces, but due to the wall thickness, does not complete the transfer before nightfall. The substantial drop in air temperature at night causes the walls to cool off again before sunrise. The possibility of gleaning most of the construction material from the site also makes rammed earth an economical and environmentally conscious choice of building construction.

THREE PROJECTS

In 1996, the Design/Build Studio of College of Architecture at The University of Arizona collaborated with the Campus Recreation Department, to design and construct a rammed earth classroom facility for skills course instruction that would be located on the edge of the practice soccer fields. A stand-alone facility with sporadic use times, the classroom building could take advantage of thermal mass walls to stabilize its interior temperature.

In 1999, the Design/Build Studio was supported by a grant from the Kellogg Foundation to design and construct a rammed earth dwelling as a prototype residence for a family on the Gila River Indian reservation. The construction was done in partnership with three members of the Gila River Community’s construction crew, in order that the methodology could be transferred to them for use in constructing their own dwellings rather than relying on outside contractors.

In 2001, the Design/Build Studio designed and constructed a rammed earth residence for the Tucson affiliate of Habitat for Humanity. The non-profit housing provider was interested in the potential of the volunteer-friendly, unskilled labor required, as well as the low cost of maintenance of rammed earth and the relatively lower energy requirements to heat and cool a house with thermal mass walls.
EVOLUTION OF A CONTEMPORARY LOW-TECH FORMING TECHNIQUE

First Iteration

As the professors and the shop master in the College of Architecture’s Design/Build studio worked to develop a forming system that would allow their students to accomplish the classroom building without the capital investment required by concrete forms, the universality of the need became apparent. Rammed earth construction is currently a fairly expensive choice for wall systems, as the necessary formwork constitutes a major investment and the labor is specialized. Contractors who focus on rammed earth construction form the entire building at once with the steel reinforced forms, and tamp the earth/cement mixture in a brief, intensive period. An alternative method of forming walls incrementally, with formwork that could be managed by two or three people and then reused, was necessary for low cost efforts. The efficiency of the large scale forming could be traded for the manageable system, if labor was plentiful and cheap. The problem of developing a low cost forming system for the Design/Build studio was the same as the challenge of bringing rammed earth into the affordable housing arena.

Research into ancient forming methods, soil composition, and wall dimensions led to speculation about a contemporary construction system that could once again be employed in the vernacular architecture of the region. The specific challenge of designing formwork for the University classroom facility had implications for further, and ultimately more significant research. Several rounds of formwork design and test walls prefaced the actual construction. Before construction began on the classroom facility, formwork designs focused on the goals of mobility and reassembly. Early prototypes used plywood walls stiffened with steel sections, which were later replaced by aluminum in order to lighten the weight of the form. Aluminum angles allowed the plywood pieces to bolt together easily and doubled as handles for lifting and moving the forms. However, the pressure built up by the tamping made it very difficult to disassemble the forms, the sides bowed in spite of the stiffeners, the assembled forms were cumbersome to move around, and they could not be stacked one upon the other. This forced a working sequence of ramming walls in horizontal courses, which had the drawback of a small amount of horizontal form creep in the direction of the wall progress. Looking at precedent for ramming walls in vertical piers (ancient and contemporary Chinese, Moroccan, Australian, Californian [4] methods), plywood walls, pipe clamps, and stiffening boards were used in a simpler configuration. After a few test runs with the revised formwork, fine tuning of pipe spacing and placement allowed the actual building construction to begin. As the walls rose, the forming system was rethought, revised, and constantly improved until results became consistent.

Developing a working method with the rammed earth forms and earth mixing equipment required moving through a steep learning curve. Initial setting of forms and squaring, plumbing, and clamping was tedious until a logical sequence became obvious. Incorporation of small chamfer strips to create reveals between the rammed earth and concrete was very time consuming and caused logistics problems. The earth mixing had to be done by hand, as no earth moving equipment was available, and this slowed down the tamping progress and caused some wall sections to be over-tamped. But, as the construction proceeded, the students developed a rhythm for the work and synchronized the mixing of earth batches, the moving of scaffolding and forms, and the tamping. Eventually, they were able to understand the process and make suggestions for revised formwork, details, and earth mixing techniques. The two-person system of incremental forming became a reliable system with an investment of about $300 in plywood. As the students honed their expertise with this system, they also identified the main challenges of working with rammed earth: formwork design and reliability of field practices of mixing earth with cement and water.

Figure 2: Plywood forms clamped to window boxes of classroom facility

Figure 3: Fully tamped walls with chamfer strips, window boxes and electric conduit visible

Second Iteration

As one faculty member and the next generation of students began to work on the design of a dwelling for a Gila family on the Gila River Indian Reservation, new considerations arose. The soil mixture had to be re-designed in order to make best use of the soil found on the site, and the family had preferences for integrating other traditional materials, such as cactus
ribs and arrowweed thatch, into the house. Also, the faculty member wanted to revise the formwork to make fewer breakdown and set-up periods necessary, as those took more time and labor than the tamping. A period of design and testing followed, until the 1999 Design/Build Studio felt prepared to begin new construction.

The experiences of the classroom facility construction led to changes in the forming system that included doubling the height of the forms, reducing the number of pipe clamps and walers, using the PVC sleeves left within the walls as conduits for the bond beam formwork. The walls of the Gila residence were built in nine days with the participation of members of the Gila River Community construction crew. The revised rammed earth formwork proved to be manageable by two people, although a third person was useful in tightening the clamps and checking for level and plumb. The new problem revealed in this iteration of building was the difficulty of rebuilding "flying" formwork at the top of the walls in order to pour the concrete bond beam required by the building code. The tops of the rammed earth walls were not level, and it was challenging to find a method of leveling and securing the formwork for the concrete pour. Plywood strips were cut from wall formwork and clamped to the rammed earth walls with snap ties used in concrete construction. 2x4 braces were used to keep the forms a uniform distance from the wall footings, but the system was cumbersome and tedious to construct. Holes left in walls where pipe clamps had passed through turned out to be the most useful points for supporting the forms. This discovery led to the further refinement of the form design for the third iteration of building.

The cost of the earth materials imported to the site (sand and gravel admixture) was approximately $400, and the formwork cost $300 not including the pipe clamps which were already on hand. The formwork is re-usable, although it does suffer from contact with the tampers over time and the edges get rough. Some of the formwork was used in forming the bond beam; most was saved for the next house. As designed, the system works well for the single, low cost house. To build houses in greater quantities might involve staggering the phases of construction so that one component of the small Gila construction crew was always pouring footings while another followed and tamped walls, for example. The cost of plywood for new forms would have to be figured in for about every third house.

Third Iteration

The third project, a rammed earth house for Habitat for Humanity Tucson, allowed another round of formwork refinement. Extra pipe clamps were purposefully run through the top of each wall to establish a set of holes at the save level relative to the wall footings. Once the walls were completed, pipe clamps could be reinserted into the holes, establishing an armature for the placement of the bond beam formwork. The forms could be rested on the pipe clamps, then fitted with snap ties and carefully leveled as they were tightened. This eliminated the need for 2x4 bracing below, and made the leveling a fine-tuning procedure rather than a struggle.

Even though this refinement proved clear and logical, another refinement became obvious. If a method of pouring an incremental bond beam could be developed, the need for separate "flying" forms for the bond beam would be wholly unnecessary. The required four-inch bond beam could be poured into the top of each eight-foot wall section while the rammed earth forms were still erect. The building
code requires a continuous bond beam for lateral support of the walls, but does allow for separate concrete pours if the reinforcing steel is continuous. The next trial will attempt to reconsider the forms to allow the passage of continuous steel through the end boards of the forms and to control the aesthetic detailing of the inevitable cold joints of the consecutive concrete pours.

Then, given clamps holes are visible

The configuration of the dwelling was a simple rectangular plan (similar to the typical sandwich house) on an eight-foot module to correspond with the form dimensions; adapted to the family’s preferences for orientation, view, and outdoor living practices. The appearance of the traditional mud and saguaro rib walls is a desirable attribute for this family, who asked for a similar appearance in some location of their new home. The challenge to incorporate saguaro ribs into the formwork and earth tamping system of rammed earth led to several experiments with strips of milled lumber and cactus ribs and different methods of embedding them into the earth or attaching them to the formwork.

Third iteration

A third collaboration was formed between the professor of Architecture, a professor of Civil Engineering, and the local affiliate of Habitat for Humanity. The two professors realized that there is a lack of transferable knowledge about the consistency of the soil-water-cement mix or the amount of compaction necessary to achieve a specific compressive strength. There is also no accessible body of knowledge about other material properties of rammed earth mixtures, including stiffness and shrinkage potential. The composition of a mixture and the compaction is arbitrary and based on experience of the work force. The professors worked together (with a third crop of Design/Build students and a research assistant in Civil Engineering) to engineer a consistent earth and cement mix with consistent water content and sufficient compaction. This involved creating tests and testing equipment in the University’s Soils Lab to evaluate the relationship between the compacted dry density, water content, compaction energy, cement content, and compressive strength of the product. For the soil used in this study, the ideal mixture was compacted at 6% cement and a water content of 9.5%-10.25% based on dry weight of the soil. The ideal compaction energy was found to be 250 KN-m/m³. The minimum unconfined compressive strength was 5000 kPa which gave a safety factor of two with respect to the USB code requirements for structural stability. [5] The next goal is to find ways of controlling the field practices of rammed earth construction in order to parallel the ideal practices established in the laboratory setting. Upcoming experiments will include translating the energy input to the miniature test lab cylinders to a time and area equation for ramming earth with pneumatic tampers in the field, as well as

EVOLUTION OF A CONSISTENT EARTH MIXTURE

First iteration

Composition of the earth mix was another variable in the design process that had to be tested and revised in several iterations. Generally, earth from the given site is tested by sieve and settlement to determine its composition in terms of particle sizes. Then, admixtures are designed to bring about the result of a well-graded mix. This mix is then combined with cement and water, and tamped into test cylinders for curing and compressive strength trials. The percentage of cement to total mix is the subject of much testing, and a number of versions must be tried to achieve the compressive strength required by building code. Color pigments are another variable that affect the final strength of the mix due to their fine particulate nature. In the case of the classroom building, scores of test cylinders were tamped and crushed before a reliable mix was discovered. In that project, 5% cement and .1% concrete pigment was used (based on the weight of the soil).

Second iteration

The earth from the Gila family’s site was high in silt and clay due to their location in the flood plain between the mostly dry Santa Cruz and Gila Rivers. A sand and gravel company on the reservation had the necessary admixtures - natural clean sand material mined from the riverbeds and small pieces of granite leftover from a crushing operation (known as crusher fines). Together with the sand and silt, a suitable mixture was found.

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the use of a field kit for measuring water content of a dirt pile by noting the reaction of earth and water with a bicarbonate powder in a closed container equipped with an pressure gauge.

From trial walls built for the third project, the professors noted that the compactive energy of the pneumatic tamper appears to be less than that of the standard Proctor. This observation must be tested and evaluated in order to establish the amount of tamper time needed for a given volume of soil distributed in eight-inch lifts. The strength of the soil-cement mixture must be tested for immediate performance as well as the 28 day performance in order to develop guidelines for working adjacent to newly tamped walls. Also, additional testing must be done on various soil types.

**EVOLUTION OF A THERMAL STRATEGY**

**First Iteration**

In the extreme summer heat of the Sonoran Desert, earthen walls are used primarily for their ability to delay the transmission of heat from exterior to interior space, rather than as thermal storage walls. The lag time for conductivity serves to eliminate daily indoor temperature fluctuations. Rammed earth walls are generally constructed with 18 to 24 inches of thickness, resulting in a lag time of 12 to 16 hours, and an indoor temperature fluctuation of 7°F to 8°F. [6]

The design of the classroom facility placed the rammed earth walls on the north and south exposures of the building, with shaded glazing on the east and an insulated storage building on the west. There were glazed openings in the north and south walls as well. In retrospect, it seems that the rammed earth on the north plays an insignificant role in the passive energy strategy. Although the building functions well in terms of stable indoor temperature, the cost of rammed earth may not be justified on a north wall, especially when that is the premier exposure for glazing in this climate. The cost of rammed earth construction grows when concrete lintels are added to span openings.

**Second Iteration**

The design of the Gila River dwelling employed a different strategy for the placement of the thermal mass walls. Uninterrupted rammed earth walls were built on the east and west exposures, with corners that turned north and south. The continuous bond beam spanned between the rammed earth walls with large areas of glazing below it, and a deep porch shaded most of the south and west exposures. The long unsupported bond beams required large amounts of reinforcing steel and greater depth, however, adding to the construction costs. In this project, the east, southeast, and west walls perform as thermal mass walls, while the north and south walls are insulated frame and glass construction.

**Third Iteration**

The third project followed the same strategy as the second, to use the rammed earth primarily on the east and west, with small corners of it on the north and south. Most glazing was concentrated into insulated frame construction facing due north and south. A carport was used to shade the south exposure during the warm months. While none of these designs have been modeled with thermal simulation software or monitored for actual energy usage, the strategy of using the rammed earth is supported by anecdotal evidence. This is an area of research that needs attention, in order to determine the most judicious uses of a labor-intensive construction system.

**POTENTIAL AS AN AFFORDABLE BUILDING SYSTEM**

Professional rammed earth contractors in the Phoenix/Tucson metro areas charge $26 per square foot of wall area for rammed earth construction (including concrete footings and bond beams). With the evolution of an incremental form system, the cost of the rammed earth construction for the third project was $9.30 per square foot of wall area (including concrete footings and bond beams). With the hours of student labor factored in at minimum wage, the total cost per square foot came to $10.80. This points to the potential of rammed earth used as a construction material for affordable housing, especially if the long term reduced costs of utilities and maintenance are figured in. When viewed as an evolution of a long cultural tradition in this place, the incentive for further research and development of this construction methodology gains momentum.

**REFERENCES**


