Mechanics and Form of Rammed Earth Construction

Joe Dahmen, Research Assistant, and John Ochsendorf, Assistant Professor; MIT

REPORT

RESEARCH

Rammed earth is an ancient building technique used in many regions of the world. However, it is generally regarded as an untried building technology in the United States. Due to the low embodied energy of the material and diminished transportation costs, rammed earth offers an economical and sustainable alternative to concrete. Moreover, existing formwork techniques used for concrete can be adapted for rammed earth construction. Mechanics and Form of Rammed Earth used funding from the BSA and other sources to conduct a three phase investigation of rammed earth as a viable building technique for New England in light of its clear environmental advantages.

The first phase of the project consisted of a literature review assessing the present state of knowledge about rammed earth. During this phase the first author also traveled to the southwestern United States and Europe to meet with a number of successful contemporary architects specifying the technique, as well as the specialized construction firms who carry out the work. In addition, the first author also visited traditional rammed earth buildings in southern France.

The addition of Portland cement appears to be the major difference between American and European rammed earth practice: American building codes generally require the addition of Portland cement, while European builders frequently leave it out altogether. From an environmental standpoint, reducing or eliminating Portland cement is advantageous because it lowers the energy embodied in the final product. Approximately seven percent of global CO_2 emissions come from the production of cement, and concrete represents nearly one half of the 136 million tons of construction waste generated each year in the United States (United States Green Building Council 2005). Virtually all of those interviewed claimed that building with rammed earth is a forgiving process tolerant of many different approaches, allowing the use of a wide range of soil types and fabrication strategies, especially when conservative design guidelines (e.g. width to height ratios) are followed.

During the second phase we identified suitable soil types and created rammed earth samples to obtain data about compaction density, compressive strength, and erosion behavior. The intent of the laboratory research was to identify a local soil that could be used for rammed earth in New England. The lack of local clay-rich soils led to utilization of an engineered soil consisting of thirty percent Boston Blue Clay mixed with commercially available sand and gravel. No Portland cement was used in the rammed earth portions of the wall; twelve tons of clay for the project was provided from a Cambridge construction site. The samples tested developed unconstrained compression of close to 300 psi, easily strong enough to build walls of up to 10m high or more. The results of initial laboratory testing were promising enough to warrant the construction of a full-scale wall on the campus of MIT.

During the final phase of the project, in the summer of 2005, a team of students and staff constructed a rammed earth wall on the campus of MIT. The publicly accessible wall, located at 275 Massachusetts Avenue in Cambridge, is seventy feet long, a foot-and-a-half wide, and six feet tall. Details on the cost of and other technical aspects construction are available from the first author.

KEY FINDINGS

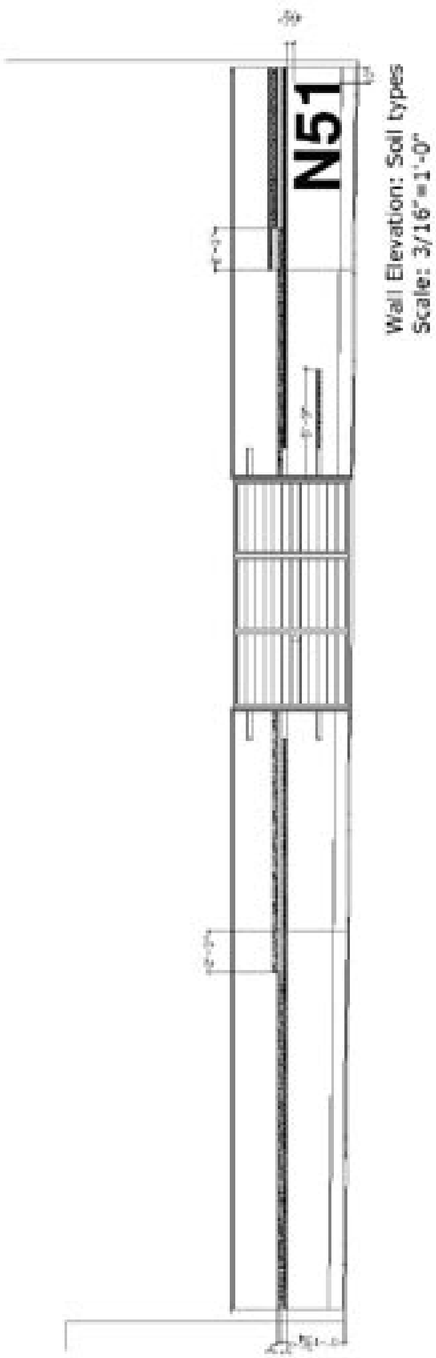
Building the prototype wall rammed earth at MIT demonstrates that the method is appropriate to New England. The principal issue to be determined is the most suitable soil for a given project. The use of marine clay, a consistent material source abundant in the region, mixed with commercially-available, locally produced aggregates allows strengths and standardization of the material without the addition of Portland cement. The method contains great promise because it offers predictable performance without the use of environmentally damaging materials. The design and fabrication of a combination soil mixing and placing apparatus is the next logical phase for rammed earth research.

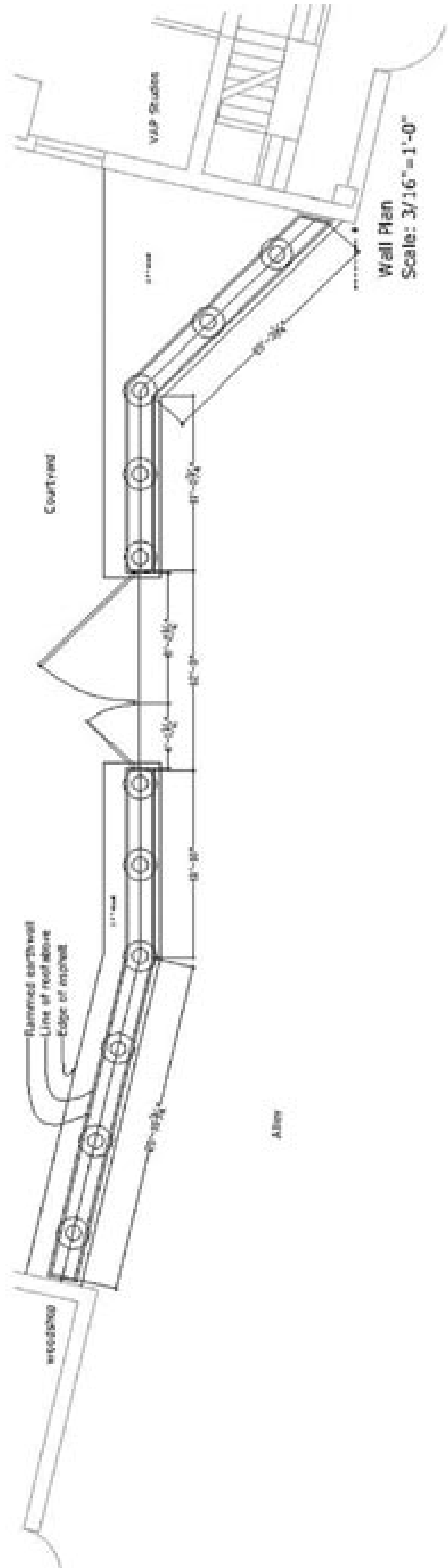
CONCLUSION

Prior to this project, rammed earth had yet to be investigated satisfactorily as a viable building technique for New England, despite its clear environmental advantages and similarity to present construction practices. By replacing even a small part of concrete with rammed earth, a significant reduction would be made in the environmental impact of construction activities. We are thankful for the generous funding from the BSA that allowed us to complete this project.

WORKS CITED

The most useful reference works were *Adobe and Rammed Earth Buildings*, by Paul Graham McHenry, Jr., *The Rammed Earth House*, by David Easton, and *Rammed Earth: Design and Construction Guidelines*, by Rowland Keable, et al. *Buildings of Earth and Straw*, by Bruce King, P.E.., and studies on rammed earth by the University of Arizona.


N51
Wall Elevation: Soil types
Scale: 3/16"=1'-0"

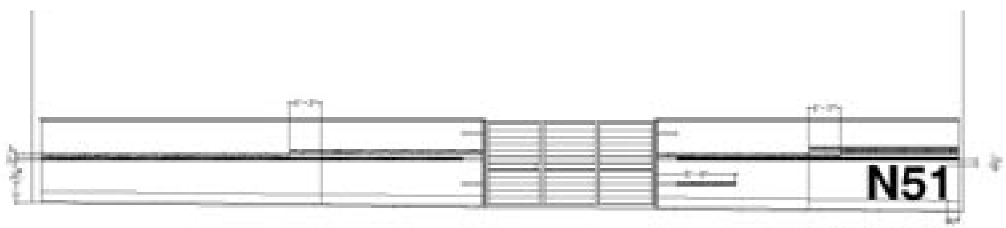

Wall Plan
Scale: 3/16"=1'-0"
Courtyard
Alley

Rammed Earth N51

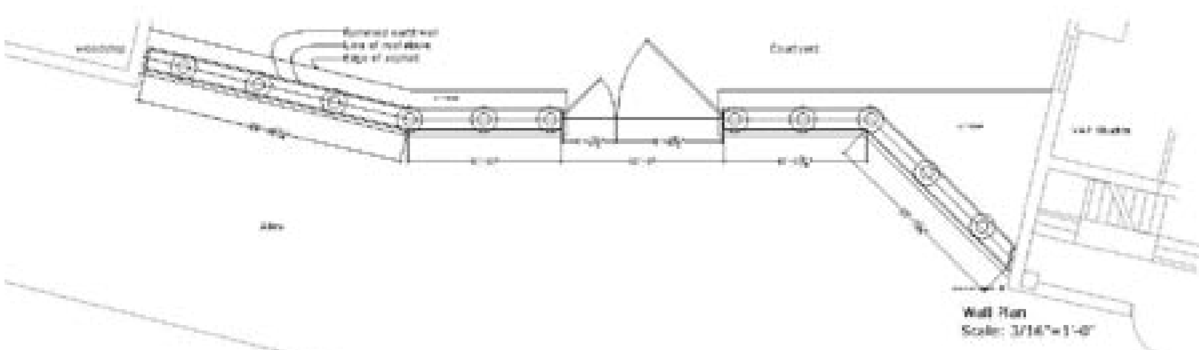
Overview
The rammed earth wall along the alley at the side of MIT Building N51 (275 Massachusetts Avenue) was constructed in 2005 by an independent team of students drawn from the Departments of Architecture and Civil and Environmental Engineering. The wall is intended to enclose the courtyard formed by on three sides by building N51, while simultaneously serving as a research project on rammed earth construction techniques and performance.

Rammed earth is an ancient building technique used in many regions of the world. Although it has been employed to construct sections of the Great Wall of China and buildings around Europe prior to the 20th century, it is generally regarded as an untried building technology in the United States. Due to the low embodied energy of the material and diminished transportation costs, it offers an economical and sustainable low-strength alternative to concrete.

A limited number of contractors build with rammed earth in the Southwest United States
The rammed earth wall at N51 was constructed in order to investigate rammed earth as a potential construction element in contemporary architectural practice in New England. This investigation covers methods of fabrication, as well as the long-term performance of the wall, in particular its resistance to erosion in the New England climate.



Wall Elevation: Soil types


Wall Plan
Scale: 3/16"=1'-0"

Method

Rammed earth is a construction process in which layers of moist soil are compacted within formwork to create solid load-bearing walls. The simplest method of compaction is by hand with a soil tamper, which is an 8”x8” steel plate mounted on a handle. Other methods of mechanized compaction include backfill tampers powered by compressed air. Both of these methods were tested in the wall.

Laboratory tests prove that maximum compaction occurs when the moisture content of the soil is 12-15%. Field studies have shown that a maximum of 97% compaction is possible at these levels. The field test for this is to form the soil in a ball and drop it from waist height. If the ball shatters into 4-5 distinct pieces, the soil is at the proper moisture content for ramming. This moisture guideline should also be followed for any repairs made to the wall. Laboratory testing indicates strengths of 250psi for the soil used in the construction of the wall.

The wall was created from an engineered soil composed of 30% Boston Blue Clay and 55% Coarse Mason sand and 15% 3/4”- crushed stone. Four bands exist in the wall which were rammed from other soil compositions in order to test the performance of these blends. The bands are identified by the steel identification blocks at the entrance and the wall ends on the outside (alley side) of the wall. No portland cement was used in any portion of the wall, in accordance with European rammed earth construction practices.

The wall is covered with a cap of Core 10 Weathering steel, which is intended to corrode to a rust-red patina as part of its natural course. This corrosion should be considered as a part of the aesthetic effect of the wall and attempts should not be made to stop corrosion through painting or other means. Weathering steel is composed of an alloy which is designed to allow a limited amount of corrosion, stopping it before it compromises the structural performance of the material.

Precipitation poses the greatest danger to the wall. The design is intended to prevent water from above and below through the use of a steel cap and a concrete grade beam. Either direct precipitation or rising damp can have deleterious effects on the wall. However, the soil used should exhibit reasonable resistance to wind blown precipitation.

The resistance of the earthen portions of the wall to weathering, particularly erosion due to precipitation and spalling, is one of the main effects being studied. We expect there to be approximately one inch of erosion in 20 years. The amount of erosion will be measurable at the steel blocks at the entrance, which will not erode. Erosion at the aforementioned scale should be considered a part of the material testing of the wall, and left without repair. In the event of severe erosion (more than 2” at any point from the surface of the wall, some maintenance may be required.

The earthen portions of the wall rest upon a reinforced concrete grade beam, which in turn is connected to reinforced concrete piers located at approximately six foot intervals. The piers have flared bottoms and are located 4-6’ below grade to resist heaving and settling of the finished wall. The intent of the cap at the top and the concrete beam at the bottom is to protect the wall from precipitation from above and from rising damp from below.

Maintenance

The rammed earth wall was constructed to evaluate the resistance of rammed earth to erosion in the New England climate. Accordingly, some change in the surface characteristics of the wall should be considered normal and left alone. In no cases should surface treatment be applied (including paint or other topical treatments) , because they will interfere with evaluating the resistance of the rammed earth to the weather. Moreover, research shows that the performance of such treatments on rammed earth is mixed at best.

The wall is built with a conservative ratio of height to width (1:4) to allow a reasonable amount of material loss (three inches per side) without jeopardizing structural safety. If the wall evidences weathering in excess of two-and-a-half inches, repairs to the surface should be considered. The mode of failure most likely to cause excessive weathering of the wall would be a failure of the steel roof. While the wall is designed to resist a reasonable amount of wind-blown moisture, large quantities of direct precipitation from above (particularly in the case of a roof leak collecting water and concentrating it in the area of the leak) can have catastrophic effects. The most important aspect of maintenance is ensuring that the welded steel roof does not leak onto any portion of the wall. Guidelines for local and total surface repair follow below.

Localized surface repairs

In the event of deep local erosion (over 2" measured from the surface of the wall) a soil mixture approximating that used in the main body of the wall can be compacted into place to fill the void. The easiest way to do this is to place the soil of a type comparable to that used in the construction of the wall (see preceding section) into the gap by hand until it is slightly proud of the wall surface. Wall should be dampened at the place of repair with a sponge before new material is added. The new soil can then be compacted into place using an ordinary hammer and a piece of steel 1/8" thick. A mason's trowel works well for this. Repair person locates the trowel on hand-placed soil in the area to be repaired, and hits the trowel with the hammer. The steel has the effect of distributing the blow while compacting the new soil into place. Continue hitting the steel until the new soil is flush with the surface of the wall. The area of the repair can then be blended in with a wood float or dry sponge.

More serious local damage: In the event that the wall is damaged severely in a local area, e.g. by a vehicle in the alley, every attempt should be made to repair the area with an earthen mix approximating that of the original composition of the wall. The use of concrete in such a situation is likely to result in separation of the repaired area from the rest of the wall. New areas can be compacted in place through the use of backing plates in the event of severe damage.

Severe erosion across entire surface

In the event that the wall erodes more than two inches and a half inches across a significant portion of its surface, global repairs may be needed. There are several alternatives in this situation.

1. New earth approximately matching composition used in the original construction of the wall (see preceding section for ratios) can be compacted onto the surface of the wall as required. After initial placement by hand, use of a pneumatic bench-rammer, of type commonly used

for forming sand castings will greatly speed this process. Areas receiving new earth should be dampened before the soil is applied.

2. Lime plaster. A traditional lime plaster is also an effective technique for returning material to the face of the wall. Numerous books exist on the use of lime plaster and should be consulted for technical instruction.

3. Traditional portland cement-based stucco can be applied to the wall. This method is the least advantageous as the stucco will behave differently than the earth according to changes in temperature and may impede the natural ability of the earth wall to regulate its moisture content. If this method is desired, battens to attach stucco netting should be installed at the top of the wall with screws after removal of the steel cap. The stucco netting can then be attached to furring strips along the concrete beam at the bottom of the wall, providing a well-secured net to which to apply the stucco. Screws have been used with limited success in rammed earth construction. Surface of the stucco should be left unpainted to allow maximum circulation of moisture out of the wall.

Cracking

The wall was constructed in sections and some cracking has been observed at the location of the cold joints between the sections. The cold joints were staggered in order to avoid large planes of weakness across them. The staggered joints, in conjunction with the conservative ratio of width to height, ensure that some localized cracking should not pose a structural problem in the wall. If cracks develop from top to bottom of the wall this might indicate differential settlement at the foundation. This is a more serious problem which would need to be addressed. The best method of repairing these type of top-to bottom cracks is by packing earth in to the crack. Using conrete to fill the gap will have little effect at mitigating the cracking and is likely to force the two sides apart further.

Funding

Financial Contributors to the Rammed Earth Wall as of Sept. 28, 2005 are as follows:

Dean’s Office, School of Architecture and Planning
Department of Civil and Environmental Engineering
MIT Council for the Arts
MIT Police
Boston Society of Architects
Sasaki Associates, Inc.