Who’s afraid of raw earth? Experimental wall in New England and the environmental cost of stabilization

J. Dahmen
University of British Columbia School of Architecture and Landscape Architecture

The use of rammed earth has grown considerably in the past half-century in the developed world, where perceptions about its environmental sustainability account for its popularity. Significant changes to materials and installation techniques have accompanied its transition to the mainstream. These changes include the use of chemical stabilizers, engineered soil blends, and mechanical placement and compaction, which provide reliable performance at a reasonable cost in the context of the developed world. This paper assesses the effect of these changes on the embodied energy of rammed earth through a review of pertinent literature, which suggests that chemical stabilizers have the greatest effect on the embodied energy of rammed earth. The construction of a rammed earth test wall on the campus of the Massachusetts Institute of Technology built without the use of cement stabilizers to evaluate its suitability in temperate climates is documented. The paper offers recommendations for future research to develop a more nuanced understanding of the environmental effects of stabilized and unstabilized rammed earth in the developed world context.

1 THE COSTS OF MAINSTREAM APPEAL

1.1 Rammed earth, cement stabilization and embodied energy

Rammed earth has experienced an upsurge in popularity over the past five decades in the developed world, where it commonly incorporates cement stabilizers to address soil variability and provide reliable performance (McHenry, 1984; Easton, 1996; Hall & Swaney, 2012). Embodied energy measures the total amount of energy required to produce product, including raw material acquisition, manufacturing, and installation (Cohen, 2011). Studies indicate that the embodied energy of stabilized rammed earth corresponds closely with the use of cement stabilizers, and that they account for the greatest share of embodied energy of rammed earth due to the energy required to produce cement (Treloar et al, 2001; Lax 2010, Reddy & Kumar, 2010).

These findings suggest that there could be considerable environmental benefits to building with unstabilized rammed earth, referred to hereafter as “raw” rammed earth. Building with raw earth requires uses naturally occurring non-expansive clays as binders, in keeping with historical practices, and presents architects, engineers, and builders in the developed world with unique challenges. In this context, engineering practices demand predictable material performance, delays due to material variability can be costly, and erosion due to weathering can be unacceptable. Finally, as in the developing world, care must be taken to provide adequate structural performance, especially in seismically active regions. Assuming these challenges can be met, raw rammed earth can offer significant environmental benefits.

1.2 Changing rammed earth practices

The growing popularity of rammed earth in developed countries over the past half-century has resulted in changes to traditional practices. Providing predictable material performance capable of meeting the building code requirements has resulted in the addition of chemical stabilizing agents, most commonly ordinary Portland cement (OPC), which a study indicates is responsible for 6-7% of global carbon emissions (Chaturvedi & Ochsendorf, 2004). Where codes governing the use of rammed earth in construction have been established, such as the of New Mexico (US) Building Code, they favour the use of cement stabilization, and require the use of 6% OPC if rammed earth walls are left exposed (New Mexico Earth Building Code, 2009).

The widespread incorporation of stabilizers is not the only change to rammed earth materials. Increasingly, engineered soil blends such as aggregate base course (a common roadbuilding material) replace naturally occurring soils. These engineered soil blends offer more reliable structural performance than site soils. These changes to the materials of rammed earth have been accompanied by alterations to installation procedures of rammed earth. Mixing and placement of soils, once done manually, is now handled with diesel-powered equipment, and pneumatic compaction utilizing powerful air compressors (Easton, 1996). Generally speaking, these new approaches to rammed earth materials and installation reduce labour and increase structural reliability at a cost of increased environmental impacts, due the
greater amount of energy they require (Hall and Swaney, 2012). Understanding their relative effects requires a more in depth look at the embodied energy of rammed earth.

2 EMBODIED ENERGY OF RAW VERSUS STABILIZED RAMMED EARTH

2.1 Embodied energy of rammed earth

Three studies have attempt to account for the embodied energy of rammed earth. (Treloar, 2001), (Reddy & Kumar, 2012), and (Lax, 2010). Significantly, all three state that OPC stabilizers are the strongest determinant of embodied energy of rammed earth. This finding across studies suggests that utilizing raw rammed earth offers significant reductions to embodied energy.

An early comparison of the environmental impacts of rammed earth stabilized at 8% to two other forms of masonry construction in Australia by Treloar et al (2001) finds that OPC stabilizers are the largest contributor to embodied carbon of rammed earth, although the method of deriving the embodied energy is so approximate as to be of limited value. A key finding is that large foundations and substructure required on rammed earth projects can mitigate or eliminate the effects on embodied energy when the impacts of the entire building are taken into account. A typical masonry wall is 200mm wide; a typical rammed earth wall begins at 300mm, and many are considerably thicker than that. This research also suggests that environmental comparisons of rammed earth to other construction materials should account for the greater volume of rammed earth required to enclose a given space, a quality that is not always accounted for in comparisons of embodied energy when it is calculated per unit volume of materials.

A widely cited study on the embodied energy of stabilized rammed earth by Reddy & Kumar (2010), also finds that embodied energy of stabilized rammed earth varies linearly with OPC content. While this study is considerably more detailed than the 2001 study by Treloar et al, Reddy & Kumar’s investigation is based on manual compaction, which is rare in developed world contexts, so its findings are of limited accuracy for the developed world.

In contrast to the approximate methods and limited contextual relevance of the previous two studies, Lax (2010) performed a rigorous Life Cycle Assessment (LCA) study with data collected from three rammed earth construction sites in Great Britain where placement and compaction was done mechanically, reflecting current practices in the developed world. Like the first two studies, her research suggests that OPC stabilizers have the greatest effect on the embodied carbon of rammed earth and that the environmental impacts of mechanically compacted rammed earth correspond directly to the amount of OPC used for stabilization. Her research suggests that at levels of stabilization of 8% (common in North America and Australia), the embodied carbon of rammed earth installed and compacted mechanically is within 20% to that of conventional cavity wall masonry construction. The embodied carbon of rammed earth stabilized with 9% OPC is roughly equivalent to that of cavity wall construction. This should be a sobering statement for those interested in rammed earth as an environmentally sustainable alternative to conventional cement-based materials.

2.2 Breaking down the embodied energy

It is instructive to look at the breakdown of the energy required for rammed earth according to Lax’ study. In keeping with Reddy & Kumar’s 2010 study, Lax’ analysis finds that there is a linear relationship between the amount of cement and the environmental impact of rammed earth. “There is an increase of 5.5kg of embodied carbon for every 1% cement increase” for a one square meter area of wall 300mm thick, and the embodied carbon of rammed earth stabilized at 8% OPC is 2.5 times higher than that of raw earth (Lax, 2010). This suggests that engineered soils might offer a reasonable alternative to cement-based binders. While they may not develop the strength of stabilized rammed earth, they can address concerns about site-soil variability. Mechanical compaction requires the greatest amount of energy for installation, but amounts to between 6-16% of the energy required the wall overall, suggesting that mechanical compaction is an environmental tradeoff worth making.

Figure 1. Raw rammed earth wall constructed on MIT campus (photo taken just after completion in 2005).

3 UNSTABILIZED RAMMED EARTH DEMONSTRATION IN NEW ENGLAND

3.1 Motivation

A raw rammed earth demonstration wall was constructed on the campus of Massachusetts Institute of Technology in 2005 to evaluate whether rammed earth could be constructed with local soils without the use of OPC stabilizers in the climate of the Northeast United States, and to gauge the effect of
the climate on the resulting construction. The wall utilized engineered soil and mechanical compaction to accommodate the demands for predictable performance and to minimize the labour required, which the embodied energy analysis cited above suggests does not add significantly to the embodied energy.

3.2 Soil selection and mix designs

In keeping with authorities on raw rammed earth construction (McHenry 1984, Houben & Guillaud, 1994; Easton, 1996), a mineral subsoil consisting of thirty percent clay and seventy percent sand, gravel and fine particles was sought. Investigations of mineral subsoils within a 25 km mile radius of the site showed no easily accessible, naturally occurring soils with the necessary clay content. However, geological research indicated that a layer of non-expansive marine clay deposited during Holocene period (roughly 10,000 years ago) now lies at a depth of 10 meters throughout the majority of the metropolitan Boston area (Terzaghi & Peck, 1996). This clay is commonly encountered in excavation for large building foundations and generally presents a disposal problem for excavation contractors. It was decided to engineer a soil consisting of thirty percent marine clay mixed with commercially available sand and gravel. Different mix designs were used during construction and identified through the use of identifying steel blocks placed in the wall (Fig. 2).

The mix designs evaluated were as follows:
- 3 parts marine clay, 7 parts structural road base (blend of stone dust and crushed stone)
- 1.5 parts marine clay, 1 part sand, 3 parts gravel (crushed granite less than 75mm)
- 3 parts marine clay, 7 parts bank run gravel (unwashed naturally smooth stones less than 75mm mixed with sand and fine particles)

3.3 Material testing

Proctor tests established the appropriate moisture content and compressive strength of 2 MPa (300 PSI) was established according to ASTM standards for unconfined compression. The results of initial laboratory testing were promising enough to proceed with the construction of a full-scale wall. The wall is 305mm thick and is covered with a steel cap that overhangs the rammed earth construction by 35mm on either side.

3.4 Foundation

The rammed earth wall is supported on a pier and beam foundation of reinforced concrete. This method differs from the typical spread footing characteristic of most rammed earth construction, which results in the use of a considerable amount of concrete and steel below grade given the thickness of rammed earth wall sections. In contrast to the continuous footing, 300mm diameter posts of reinforced concrete approximately two meters apart support the wall. The posts have flared bottoms to distribute the weight of the wall and rest on undisturbed soil below the frost line. The layers of earth were then rammed on top of the continuous beam. This approach saved approximately eighty percent of the concrete that would be used in a conventional spread footing.

![Figure 2. Weathering steel blocks identify mix designs in the prototype wall (photo taken in 2014)](image)

3.5 Processing soil blends

Mixing the clay with sand and aggregates to final consistency proved to be the most challenging aspect of constructing the wall. The soil was batch mixed in a gasoline powered plaster mixer. A variety of mix designs were incorporated in the wall for research purposes, each marked by an embedded steel plaque identifying it. The mixing method limited the size of aggregate used in construction; crushed stone larger than three-quarters of an inch caused problems for the machine.

In all instances the sand was washed coarse masonry sand provided by a local masonry yard. The same company delivered crushed granite. The road base came from a nearby site of road repair. The marine clay was delivered in the same hydrated state in which it was excavated one to two days prior to delivery and was kept covered at all times to maintain it in a plastic state for maximum workability. It was found that the mixing the plastic clay with the various admixtures did not generally require the addition of supplementary water as the moisture in the clay provided sufficient moisture required for compaction. Appropriate moisture content of the final mix was verified by the ball drop field test identified by Easton (1996).
3.6 Compaction

The wall is divided into two equal lengths of approximately 7m each, separated by a gate in the middle (Figs. 1 & 3). The first side of the wall was constructed by hand. The soil was placed in the formwork using five-gallon-buckets in an assembly-line fashion, and compacted with hand tampers made from a 150x150mm steel plate 6mm thick attached to the end of a wooden handle. The soil was placed in the formwork in layers 20cm deep, which was compacted to a final depth of approximately 13cm. The second half of the wall was placed and compacted mechanically. Soil was placed with of a hydraulic loader (“Bobcat”) and a pneumatic backfill tamper driven by a diesel compressor. Although no data exists to document the final compaction densities produced by the two methods, it was observed that the pneumatically compacted section looked denser than the section that was compacted by hand, particularly at the bottom of the lifts, where compacting by hand failed to consolidate all of the material. Predictably, constructing the mechanically placed and compacted side went considerably faster, taking approximately one quarter of the time required for the first half.

![Figure 3. Rammed earth wall after 9 years of weathering (photo taken in 2014)](image)

4 DETERIORATION DUE TO WEATHER

4.1 New England climate

New England is located on the Northeastern seaboard of the United States. The region is characterized by a temperate climate that ranges between an average of 2.1 degrees Celsius in January to 26 degrees Celsius in August. Some form of precipitation falls on an average of 137 days annually. Total annual precipitation averages 1067 mm. Approximately 1118 mm of snow falls between December and March, when freezing temperatures are common. Following large snowfalls, passing plows often pushed snow against the bottom third of the wall, where it might stay for a period of a week or more. The wall was evaluated after 9 years of exposure to the elements, during which time it was unprotected from the weather except by the steel cap described above. The method used to measure deterioration here relies on direct observation and averaging of measurements of material taken along reference lines established by the concrete foundation and steel elements embedded in the wall described above.

4.2 Deterioration due to weather

The wall has survived with no major failures since its completion during the summer of 2004. Although local areas of degradation in excess of 35mm can be observed, the majority of the areas of the face have lost approximately 5-7mm per side over the course of the 9 year observation period. This represents approximately 2% of the total volume of the wall, more than twice the amount of deterioration than the 6.4 mm of erosion of raw earth recorded over 20 years by a previous study using a stereo photogrammetric method of measurement (Bui et al., 2008). The difference could be attributable partly to the measurement method employed. One area of approximately 2m² has experienced increased degradation, demonstrating a depth of material loss of approximately 35mm. This local erosion appears to be due to large amounts of precipitation collected on the roof of the wall and running down the wall in one concentrated area. Two small areas where degradation has occurred due to repeated exposure to water due to faulty roof approach 55mm deep over approximately .3m². The outside corners are another area of significant weathering, having lost on average approximately 30mm of material. The relationship of different mix designs to weathering was generally inconclusive owing to variations in compaction regimens (by hand versus pneumatic) and different exposure to weather because of adjacent buildings. It was observed that higher sand contents produced smoother initial surface finishes. In some cases these sections appeared to lose less material, although this could be due to the fact that they were sheltered from the direction of the most inclement weather by adjacent buildings. Setting aside these areas of local degradation due to increased stresses and exposure to weather, the wall might be expected to lose approximately 25-50mm of material per side over the course of 50 years if the current trends continue. This would constitute roughly 16-32% of the total mass of the wall. However, other areas of the wall protected from direct wind-blown precipitation by adjacent buildings have experienced virtually no material loss at all. This suggests that with appropriate detailing protecting it from direct precipitation, raw earth construction could last almost indefinitely in the New England climate. This observation is supported by the significant number of extant raw rammed earth buildings in the Rhone Valley of France (CRATerre, 2006) and the Fujian province of China (Aaberg-
Jørgensen, 2000), which have persisted for hundred of years despite climates with ample of rainfall and freezing temperatures.

4.3 Future Directions

Building with raw rammed earth in the developed world is possible and can offer significant environmental advantages over stabilized rammed earth. Capitalizing on these advantages requires further study in a number of areas outlined below.

A rigorous LCA study should be done that compares the embodied energy of raw and stabilized rammed earth between 0% OPC and 8% OPC versus concrete masonry versus wood frame construction. Following Lax (2010), such a study should base the comparison on a functional unit determined by the assembly or amount of material required to provide a given U-factor for 1m² of residential wall construction to account for the additional thickness of rammed earth relative to rammed earth.

A second LCA study should be conducted to compare the total energy of a residential rammed earth structure versus the same size structure constructed with concrete masonry and wood frame construction. In this study the functional unit should be a house of a given volume over a thirty-year period for a range of climates. Such a study would put the initial embodied energy of construction into perspective with the operating energy that a study has found have found accounts for as much as 85% of total energy consumption over a thirty year period (Cole & Kernan, 1996).

Probably the most significant obstacle facing raw rammed earth construction is structural. The lower compressive strength of raw rammed earth makes it a special concern in seismic regions. One solution to this problem could be to utilize raw rammed earth with a moment frame of reinforced concrete. Comparing the environmental effects of these two approaches would require an LCA study comparing stabilized load bearing rammed earth to raw earth used as infill with supplementary structure of reinforced concrete or steel.

Finally, a comprehensive library of soils, amendments and minimum amount of stabilizers necessary to produce desired strengths should be developed to reduce uncertainty about soil performance, along the lines of the assessment criteria offered by Ciancio et al (2013).

5 CONCLUSION

Rammed earth is a minimally processed material that can be sustainable. However, rammed earth in the developed world is typically is stabilized with energy intensive ordinary Portland cement. Three studies have suggested that embodied energy of rammed earth varies with cement content, and cement content of 8% is comparable to concrete construction.

In contrast to stabilized rammed earth, raw earth can be used to create durable buildings in the developed world without the use of chemical stabilizers. The use of engineered soils and mechanical compaction can increase reliability and reduce labor, making the use of rammed earth in the developed context possible without sacrificing the environmental advantages that often serve as its primary justification. Using raw earth presents challenges in meeting structural stability requirements, and additional research will be required realize accurate comparisons of raw rammed earth construction to stabilized rammed earth and other construction methods.

REFERENCES