

Part V

Application of modern earth construction:
international case studies

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Abstract: One of the most significant strides forward toward broad implementation of modern earth building is the new ability of rammed earth to perform well in very wet and very cold climates. This paper explores the nuances of heat flow in *insulated* rammed earth for very hot climates as well as the very cold climates. Techniques to gain the required strength to withstand the forces of erosion (*wet/dry* and *freeze/thaw*) are examined. Finally, practical applications of *insulated* rammed earth in a variety of natural settings are presented to show the scope of what is now possible.

Key words: Rammed earth, *insulated* rammed earth, stabilized *insulated* rammed earth, SIREWALL, thermal flywheel, humidity flywheel, thermal mass, earth blending.

21.1 Introduction

This chapter focuses on *insulated* rammed earth. Because adding insulation in a rammed earth wall creates a profound difference in performance and means of manufacture, you will notice that both '*insulated*' and '*uninsulated*' words are italicized for clarity.

Walls are the significant boundary between the indoor and outdoor experience. How well they function largely determines our level of comfort, health and safety. This chapter explores the factors that help rammed earth walls perform well.

We begin by distinguishing the philosophy that underpins the inception and development of *insulated* rammed earth. As Einstein so famously said, 'You cannot solve a problem from the same consciousness that created it. You must learn to see the world anew.' Short-term, self-interested problem solving is not the answer. Consider the world that our seventh generation descendants will inherit and what they might like to see. For them the most important shift in construction will be from toxic, disposable buildings to sustainable buildings. Because the climate is changing, the requirements for our buildings to be truly sustainable will far outstrip those at present.

Energy will play an increasing role in how we build. The level of attention to thermal detailing in rammed earth walls can result in anything from a significant ongoing energy sink to buildings that require no heating or cooling at all. Attention to detail is paramount.

1 Putting energy efficiency into action requires an understanding of how
2 heat moves in (and out of) a building. Conductive, convective and radiant
3 heat loss all affect a building's energy performance. Performance will largely
4 be determined by the most active of the three modes of heat loss. Therefore,
5 a holistic approach to heat loss is recommended.

6 The North American climate can be very demanding of wall assemblies due
7 to freeze/thaw and wet/dry cycles. Only if rammed earth is sufficiently strong
8 can it be viable in very cold and very wet climates. Compressive strength is
9 the single biggest determinant of durability. A hydrophobic admixture can
10 also be helpful. Examples of rammed earth work in extremely cold climates,
11 very wet and very dry climates show the versatility of rammed earth done
12 well.

13 Rammed earth and *insulated* rammed earth in particular, opens the door to a
14 future where our buildings are truly sustainable and a gift to our descendents.
15 First, however, rammed earth must move from a boutique cottage industry to
16 an efficient industry with greater capacity. With that capacity and efficiency,
17 rammed earth offers what could well be the most holistic and sustainable
18 building option available on the planet.

19 In Chapter 15, David Easton describes the process of building with
20 *uninsulated* rammed earth. Most of the practitioners of this style of North
21 American rammed earth, or a variation thereof, are in the American southwest
22 where the advantages of thermal mass allow for comfort in climates that are
23 moderate or where there is enough solar insolation to allow diurnal comfort.
24 Many of the components of *insulated* rammed earth are similar to North
25 American *uninsulated* rammed earth as we both blend, mix, form, ram,
26 strip and cure. This chapter will highlight the differences as well as bring to
27 light some of the concepts that have been distinguished in the unique work
28 of making rammed earth a functional, Building Code-approved technology,
29 viable in very cold and/or very wet climates.

30 The rammed earth industry in North America is very small. There are
31 approximately 50 practitioners producing rammed earth structures with half of
32 them building with *insulated* rammed earth and half building with *uninsulated*
33 rammed earth. There are very few full-time rammed earth businesses. The
34 vast majority do their rammed earth as a passionate sideline to a related
35 line of business that keeps them solvent (some do only one small job every
36 couple of years). From 1992 to 2006, we (SIREWALL) were the first and
37 only ones in North America building with *insulated* rammed earth. We tried
38 many approaches and had successes and failures. Slowly, with much trial and
39 error, we evolved a system and an approach that has generated consistent
40 quality and produces high strength walls. Through teaching courses we
41 have developed a strong team and have spread interest. To my knowledge,
42 all *insulated* rammed earth builders in North America got their start with
43 SIREWALL.

In the early 1990s I pledged my working life to making rammed earth a viable building technology that excelled in every way. My mentor was David Easton. Through him and his work I saw what was possible and that still motivates me today. Buildings that are healthy, beautiful, don't require heating or cooling, are durable, environmentally friendly and, most importantly, are a gift to our descendents are what I see as a significant contribution to our communities and to the planet.

We are only at the very beginning of realizing the potential of rammed earth building. In my second year of working with rammed earth I called David and asked him what the considerations are for ramming in the snow. He replied, 'Let me know what you find out ...' and I realized it was up to me to make rammed earth work in my cold, wet climate and high seismic zone. My work to make modern rammed earth a viable option in cold and wet climates stands on the shoulders of David Easton and his work stands on the shoulders of David and Lydia Miller. Although a tiny niche industry, we are developing a rich history and I am grateful to be part of it.

21.2 Seventh generation thinking and earth construction

The best place to start a conversation about building is to look at how we think about building. Otherwise, no change is possible (as the context is decisive). No problem can be solved by the same thinking that created it.

Chief Seattle is widely known for introducing the ancient aboriginal 'seventh generation' thinking, which is to consider the impact of current decisions and actions on seventh generation descendents. With a new generation occurring every 25 years or so, seventh generation thinking is 200 years in the future. For most people, it is difficult to imagine 20 years into the future. We have significant education and training to help imagine the past, but little for the future. We are ill-equipped for this vital task of creating a viable, long-term future. It is also something that cannot be done in isolation. It is difficult to design and build for a 200-year future when governments are only required to plan 5 years ahead. With the rezoning of land based on short-term thinking, some of the most robust buildings may be torn down in 10 years and replaced with parking lots and less durable and cheaper buildings. Buildings designed for passive solar can be blocked by future developments that deny access to the sun. It is essential that everyone believes, plans and is in action to create a sustainable future for there to be a viable, bright, long-term future.

Our current disposable building paradigm ensures continued and expanding erosion of the natural environment through resource extraction and land filling. We cannot continue much longer on this path. We are already experiencing the impacts of the disposable paradigm in our energy costs, our health, species

1 extinction and environmental degradation. We also have a responsibility
2 to our descendents to pass on durable and comfortable buildings, not toxic
3 waste.

4 Buildings are typically designed and constructed to meet the programmatic,
5 financial and technical requirements and demands of today. With the current
6 design, funding and approval processes, this renders them out of date prior to
7 tender and before construction is complete. If we apply seventh generation
8 thinking to how we design and build, then we create buildings that last 200
9 years and those buildings are conceived of as meeting the needs at 100 years.
10 They are then ahead of their time for the first 100 years and becoming out
11 of date for the last 100 years. This will be a big stretch for most people
12 and projects. However, the dysfunction of the current practice and process
13 requires that we begin to seriously anticipate the world as it will be in the
14 future. How much longer will we be willing *and able* to embrace the toxic,
15 disposable building paradigm?

16 So, what does the future look like? It is anticipated that there will be
17 more extreme weather events. Ocean levels and overall global temperatures
18 are expected to rise accompanied by large-scale winds in some areas. Other
19 areas will experience extreme rains. Some places will get much hotter and
20 others much colder. Raw materials will become more expensive as more
21 people consume resources that are sourced in more difficult places. Labor will
22 be much cheaper than commodities, which will need to be reused/recycled
23 for economic reasons. The disposable economy will lose its inertia. Energy
24 resources will dominate decision-making. Are any of these prognostications
25 certain to come into being? No, they are like a weather forecast. If the forecast
26 is for heavy rain, one carries an umbrella or raincoat. It would be foolish
27 not to, even though rain is not inevitable. We act on our best information
28 or (likely) suffer the consequences.

29 For some, seventh generation thinking is an ethereal exercise. It is trying
30 to care for the unborn, way into the future. That is well and good, but the
31 real value in seventh generation thinking is applying it to all decisions in
32 the building process, from design through material selection. It is above all,
33 a practical tool.

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21.3 The interplay of indoor and outdoor weather

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When we see an eagle flying on thermals above a cliff, we know that warm
air is rising. As the warm air rises, a lower pressure area is created beneath
it and the cooler air in the valley moves to the bottom of the cliff. Nature
is constantly trying to equalize air pressures.

The dew on the morning grass evaporates as the air heats up and then
condenses in the evening. The existence of dew implies 100% relative humidity
(RH) between the grass blades. In the morning the temperature increases

and the capability of that warmer air to hold moisture also increases so the dew evaporates. We see nature equalizing water vapor pressure as well. We park our car and the engine is hot but it doesn't take long for it to lose its heat and reach the temperature of its surroundings. This can be seen as the second law of thermodynamics at work (one consequence of the *second law of thermodynamics* is that differences of temperature, pressure and chemical potential equilibrate over time in an isolated physical system). The 'weather' in the context of building walls is a force imposed on the building by the surrounding environmental conditions, mediated by the interplay of three pulls of nature (equalizing air temperature, air pressure and vapor pressure). The physical conditions inside a building may be quite different to those outside but the same dynamics of equalization are at play. The greater the variation between inside and outside conditions, the greater the demands on the building envelope.

Let's look at extreme temperatures and what rammed earth (or other) walls might be required to cope with. If the temperature is a record low of -62.2°C (-80°F) in Mayo, Yukon and the desired indoor temperature is 20°C (68°F), then there is a very large temperature difference or **DT** (82.2°C or 148°F) across the thickness of the wall. There is a very large pull (tendency to equilibrium, or entropy) for the interior heat to pass across the wall to the outside. If the temperature is a record high of 56.7°C (134°F) in Death Valley, CA, and the desired indoor temperature is 22°C (72°F), the **DT** is 34.7°C (62°F). The **DT** is positively correlated with the strength of the pull of nature to equalize temperature. The greater the pull, the greater the demand on the ability of the wall to resist heat flows. The dynamic is the same whether desert heat flows into a building or the building's heat leaves to warm the Arctic. Heat is travelling across the wall material's resistance to heat flow (expressed as R, U or k values). Larger **DT** exists in cold climates and hence technology for managing heat flows across walls is more developed in colder climates. Ironically, more energy and money is spent cooling buildings in warmer climates where they don't begin to take advantage of the cold climate technologies. It is difficult to keep walls dry because water vapor is pulled across wall assemblies. If, for example, the ambient humidity in Miami is 100% and the interior humidity is 40% due to air conditioning (AC), water vapor is pulled across the wall from outside to inside (people are most comfortable at 40–60% RH). If the humidity in Winnipeg or Albuquerque is 10% and the interior humidity is 40% there is a pull in the opposite direction, but only half as strong. Note that the magnitude of the pull will determine the demand on the resistance to water vapor flow across the wall. The mechanism that resists the water vapor transport across the envelope is the vapor barrier (or a combination of materials that has sufficient vapor resistivity), and in areas where the pull is great and the detailing is poor, the walls will always be susceptible to dampness (unless

1 the drying capability is greater). This is a problem for wall assemblies that
2 include organic materials because organic materials are designed by nature
3 to decompose (due to mold, rot, insects, rodents, etc.). For modern earth
4 buildings if they are well built, this should not be a problem as there are
5 usually no organic materials in the wall to decay.

6 Air enters and leaves buildings through the building envelope. Differences in
7 air pressure across a wall are dynamic or static. Static differential air pressure
8 in buildings is known as the 'stack effect' and is an expression of the building
9 acting as a chimney. Taller buildings have more stack effect than shorter
10 buildings. Given that warm air rises, there is a higher air pressure at the top
11 of a building than there is at the bottom. Let's look at this pressure gradient
12 in detail. Say that the air pressure outside is 1.0 Atmospheres (all around
13 the building) and inside at the top of the building it is 1.1 Atmospheres. At
14 the bottom of the building it is 0.9 Atmospheres. There is a pull from inside
15 to outside at the top of the building and at the bottom of the building, the
16 pull is from outside to inside. Somewhere between the top and the bottom
17 of the building, there is a neutral plane where the indoor air pressure is 1.0
18 Atmospheres and there is no pull across the wall. If the air tightness of the
19 building was uniform, then that neutral plane would be halfway up, but that
20 seldom happens. The mechanism that resists air flow across the envelope is
21 the air barrier and it is both difficult and critical to maintain integrity and
22 continuity of the air barrier. The quality of the air barrier is tested with a
23 blower door and the difference between a tight wood house and a leaky
24 wood house can be 100-fold. What happens in a leaky wood house is most
25 air comes into the building at the lowest elevation (crawl space or basement)
26 and exits at the top. Occupants breathe poorer quality air from the crawlspace,
27 or other lowest entry point, throughout the house. Moisture and heat can
28 be carried on the airstream into the wall cavity upon entry or exit from the
29 building, potentially causing rot and compromising the thermal envelope.
30 Rammed earth buildings have walls that are impermeable to passage of an
31 airstream and if the detailing is well done around the windows and doors,
32 the building is well on its way to being airtight. There is broad agreement
33 in building science that a tight building is essential to managing temperature
34 and humidity. As the building gets tighter it becomes essential to include an
35 air-to-air heat exchanger to supply a continuous stream of fresh air. Typical
36 systems used in air-tight buildings are heat recovery ventilation systems
37 (HRV) or energy recovery ventilations systems (ERV).

38 Dynamic forces such as hurricanes or cyclones create a large demand on
39 structures. A wood frame structure might have 30 tons of mass above ground
40 level and a similar size rammed earth structure could well have 200 tons
41 of mass above ground level. It is well known that the weight of a structure
42 will oppose the high wind forces but the geometry and composition is also
43 important. A tall heavy wall at right angles to a strong wind can be blown

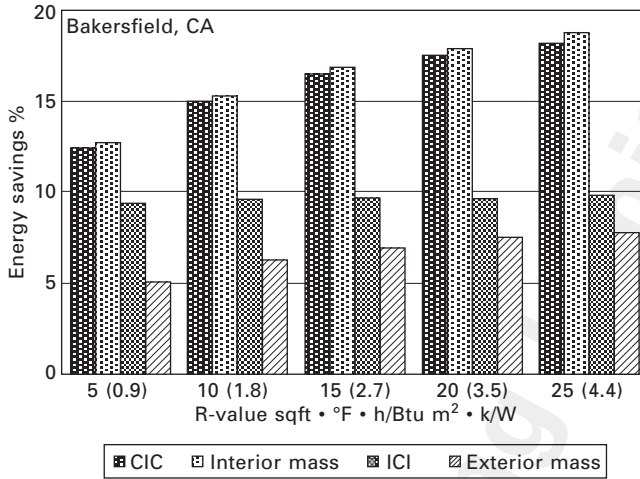
over fairly easily. Buttressing and shear walls need to be part of the design. It is much easier for a tornado to lift or tear apart a 30-ton multiple material building assembly (e.g. wood) than a consolidated 200-ton assembly (e.g. rammed earth). How the roof is secured to the rammed earth and limiting the overhang uplift are also key design considerations.

The requirements of a building envelope will correlate with the differences between the indoor and outdoor weather. The more extreme the differences in temperature, humidity or air pressure, the more robust the response required from the building envelope. The correlation need not be exact and it is best to err on the side of a higher performance response when using seventh generation thinking. Too little response, with insufficient insulation and non-airtight detailing, will cause the building to be uncomfortable and expensive to operate, whereas too much response will have the impact of an added incremental initial cost and the benefit of reduced operating costs over time.

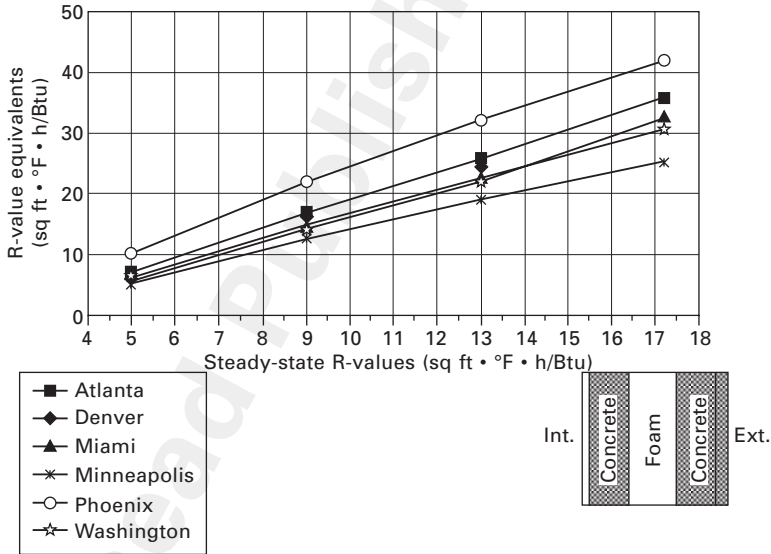
21.3.1 Thermal Mass

Passive solar design makes reference to the necessity of extra mass in the building to moderate temperature swings associated with sunshade transitions at windows. Too often the mass is insufficient to absorb the incoming solar energy and the tight passive solar house overheats while the sun's out and then slowly cools down when the sun stops shining in through the windows. Part of the difficulty of designing passive solar in the northern hemisphere is that the hottest day of the year is not when the angle of the sun is the highest. The hottest day is often several weeks after the longest day and by that time the angle of the sun is already 20–30% of its way to its lowest angle of incidence. Further, the hottest time of the day is often a few hours after noon, at which time the sun is no longer at its peak elevation. This compromises the effectiveness of the carefully calculated overhangs, which are intended to allow solar entry in winter but not in summer. Alternative designs and additional thermal mass help guard against overheating in late summer.

The relationship between thermal mass and insulation is often not well understood. That is further complicated by the varying effectiveness of that thermal mass due to climate and latitude. Conductive heat loss is a simple evaluation of a steady-state condition, whereas the dynamic thermal performance of high mass walls is often not considered because the analysis is so complicated and site specific. That does not mean there isn't significant benefit to high mass walls. Jan Kosny of Oak Ridge National Laboratory (ORNL) has done a lot of very valuable work of relevance to the *insulated* rammed earth industry. He has quantified the effects of mass and insulation in different configurations in a wall assembly (see Fig. 21.1) and he has



21.1 Different configurations of mass and insulation.



21.2 Dynamic R-value equivalents.

graphed the Dynamic R-value equivalents to steady-state R-values for six different American cities (see Fig. 21.2).

It is interesting to note (from Fig. 21.2) that the dynamic R-value equivalents range from ~1.5 to 2.25 times the steady-state R-values for mass-insulation mass assemblies.

Probably the easiest way to understand the difference between insulation and thermal mass is that insulation slows down heat loss and mass acts to

minimize temperature swings. At times mass may appear to be doing the job of insulating by minimizing the temperature swings from sunny day to cold night. However, an *uninsulated* massive house in a cold climate like Winnipeg in the winter will be extremely cold and difficult to heat. It will be most affected by the average daily outdoor temperatures (combined with other contributing factors such as the temperature of the earth under the building, the effects of solar gain, thermal characteristics of the rest of the building envelope and occupant contributions). In Winnipeg the outdoor winter temperatures trump all the other contributing factors. However in San Francisco, where the climate is mild, *uninsulated* rammed earth is dependent on the other contributing factors. For example, a passive solar *uninsulated* rammed earth house may be very comfortable, but an identical house in the same general location on the north side of a hill, having no solar access, would provide a decidedly different thermal experience. When the average outdoor temperature combined with the other contributing factors results in an uncomfortable interior space, *insulated* rammed earth can almost always be a solution if the projected discomfort is identified beforehand through energy analysis.

By far the most popular configuration of *insulated* rammed earth is the 24 in. wall. While it is possible to make *insulated* rammed earth walls as thin as 18 in., the extra cost for the extra mass (usually placed on the inside of the thermal envelope) is good value. Eighteen-inch walls have 7 in. wythes on either side of 4 in. insulation. Most 24 in. walls have 12 in. of earth inside the envelope (over 70% more mass than the 18 in. configuration). The added bonus to the thicker interior wythe configuration is that one can fairly easily create window seating (or window beds) by having the bottom of the window at 14 in. to 16 in. elevation (Fig. 21.3).

Can there be too much mass? In most circumstances the answer would be no. There are many studies that calculate the optimal balance between storage and passage of heat through an *uninsulated* massive wall. These studies are not useful for the well-*insulated* rammed earth wall where the function of the mass is purely storage. We once built a large home in coastal British Columbia (BC) with over 300 tons of thermal mass (in addition to the 100 tons for its normal construction), enhanced insulation (up to R-60 in the walls), low 'e' glazing and airtight detailing. Our hope was that we would be able to move from diurnal heat storage to seasonal heat storage. In other words, the heat from the summer sun could be stored and slowly released to delay the beginning of the heating season to well after Christmas, instead of September. What we didn't account for were the impacts of comfort on lifestyle. The occupants would leave doors open in November without apparent penalty (the house did not cool down uncomfortably as most houses would) and it was certainly a nice indoor/outdoor experience, but the heating season did begin before Christmas. Moving from diurnal



21.3 Inner wythe window seat.

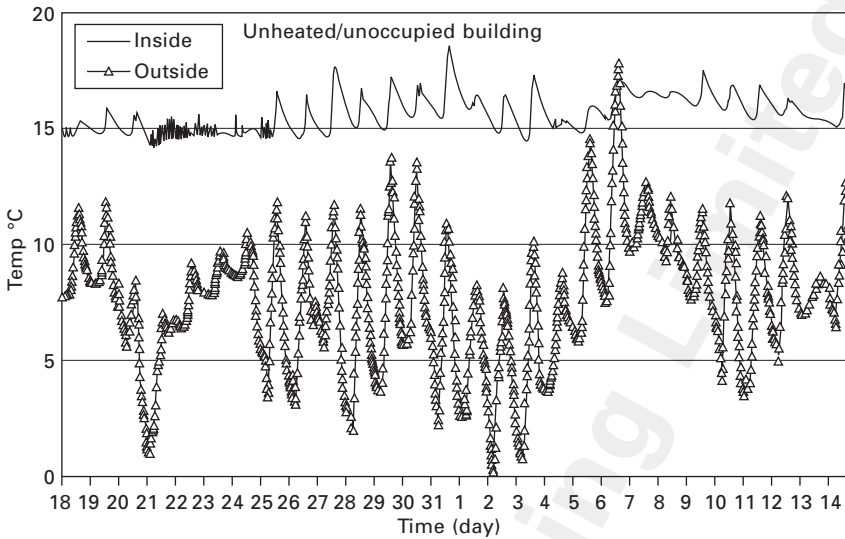
heat storage (gathering the day's heat for release at night) to weekly heat storage allows for periods of cloudy weather. More mass allows for this. In the end the amount of thermal mass is usually an architectural decision. Certainly the exterior of the walls should all be *insulated* rammed earth, but beyond that there are diminishing thermal benefits to adding interior rammed earth walls (though there are acoustic benefits) and the architecture typically takes precedence. It is a value in design decision – net zero energy usage vs. additional square footage in a tight floorplan.

21.3.2 Humidity flywheel

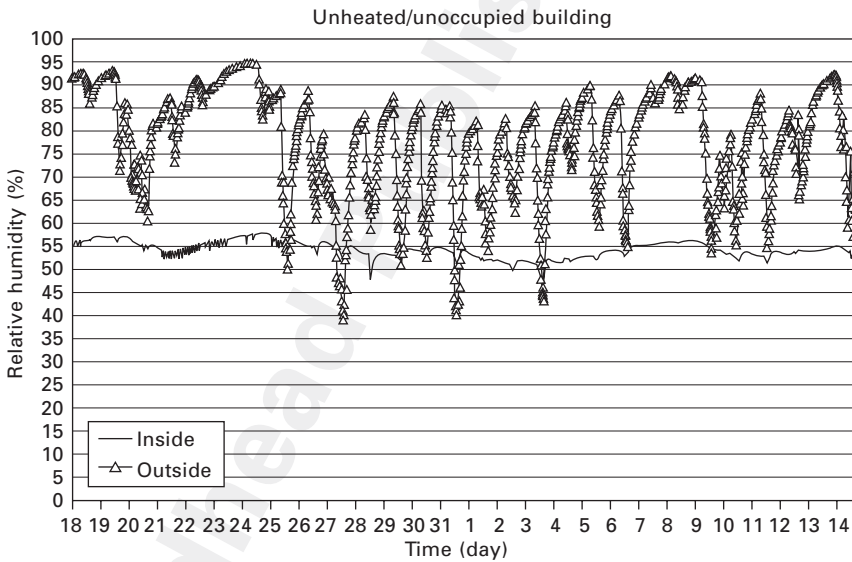
In the same way that the stabilizing effects of mass on temperature are sometimes described as a thermal flywheel, the humidity flywheel describes the inertia created by having mass that absorbs and releases humidity contained inside the vapor barrier of a building. The hygroscopic ability of rammed earth to moderate the changes in relative humidity of the surrounding air can clearly be seen in the British Columbia Institute of Technology (BCIT) study done of three SIREWALL buildings. Temperature, humidity and dew point were monitored over a one-month period on Salt Spring Island near Vancouver, BC. One of the buildings was unoccupied for that period, the windows and doors were shut and the power was shut off. Figure 21.4

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21.4 BCIT study of temperature across the north wall of an unoccupied SIREWALL home.



21.5 BCIT study of humidity across the north wall of an unoccupied SIREWALL home.

shows a graph of exterior and interior conditions of that house, with the rammed earth walls of the building doing the work. Notice that the exterior temperature is fluctuating widely and having only a minor effect on the temperature inside the building.



21.6 Unoccupied SIREWALL home.

Note also that the solar heat gain is around 9°C (16°F) of free stable heat. The widely vacillating exterior humidity is dramatically moderated by the stabilized *insulated* rammed earth to a very stable 50–57% RH. As discussed earlier, people are most comfortable when the RH is 40–60%. It is important and useful to know that no mold can grow when the RH is under 65%. Therefore the ability of rammed earth to moderate humidity can be an excellent tool against mould in construction. As can be seen in the graph, the RH never approaches 65% when no people are in the house and no Heat Recovery Ventilator (HRV) is operating. When people occupy buildings they contribute humidity through breathing (1 liter of water per person per day). Other contributions include pets, cooking, showering, laundry, etc. The HRV tends to counteract this effect by having a drying effect on the building's internal air quality. The volume of the space per occupant can make humidity control easy or difficult. The final factor is the rate with which the moisture passes through the rammed earth. If the mean exterior moisture content, when raised to the interior temperature, creates a desirable RH, then the perm rating of the envelope (and the insulation is the biggest variable) need not be too high. For example, fabric-coated polyisocyanurate foam, could be used without penalty. If there is an undesirable exterior mean moisture content, an aluminum-coated polyisocyanurate is the best choice to manage humidity by balancing the occupants' respiration and activity inputs with the HRV drying effect and the volume of contained space per occupant. In summary, *insulated* rammed earth is very effective at moderating interior RH, and the overall humidity regimen can be influenced by the selection of

a climate-specific insulating material. Further information on this behavior is also provided in Chapter 3.

21.3.3 Heat in modern earth buildings

Heat moves by conduction, convection and radiation. Understanding heat flows in rammed earth buildings is essential in the design phase as a poorly designed building can lose or gain many times the heat of a well-designed one. There are many common misunderstandings about thermal detailing in rammed earth construction.

Conductive heat loss

Conduction is the ability of a material to transfer heat. A highly conductive material is copper (i.e. 401 W/m K) and the worst conductor is no material at all, i.e. a perfect vacuum. We evaluate the ability of materials to conduct heat and ascribe R-values or U-values to different materials. Table 21.1 lists R-values and U-values per inch for common materials used in earth building:

To determine the (Imperial) R-value of 4 in. of polyisocyanurate foam, for example, one simply multiplies the 7.0 per inch R-value by 4 in. to get R-28. For a 24 in. *insulated* rammed earth wall there are 20 in. of rammed earth (excluding the 4 in. of rigid foam) so one simply multiplies the 0.25 per inch to get R-5 for the rammed earth. To determine the steady state R-value of a 24 in. *insulated* rammed earth wall (that uses polyisocyanurate foam) we add the R-28 of the foam to the R-5 of the rammed earth to get R-33.

Table 21.1 R-values and U-values for common rammed earth building components

	R (h*sq ft*°F/BTU)	U (1/R)	RSI (m²K/W)	U (W/m²K)
Concrete	0.11	9.09	0.077	12.987
Steel/rebar	0.0032	312.5	0.0225	44.444
Rammed Earth (CSIRO)	0.25	4.0	0.1761	5.679
Roxul insulation	4.0	0.25	2.818	0.355
Fiberglass insulation	3.5	0.286	2.465	0.406
Expanded polystyrene	3.5	0.286	2.465	0.406
Extruded polystyrene	5.0	0.2	3.522	0.284
Polyisocyanurate foam	7.0	0.143	4.931	0.203
Trex recycled sawdust/plastic lumber	0.5*	2.0	0.3522	2.839
Framing lumber	1.0	1.0	0.7044	1.42

*approximate, actual value not found.
 The Imperial values are per inch thickness
 The metric values are per 100 mm thickness

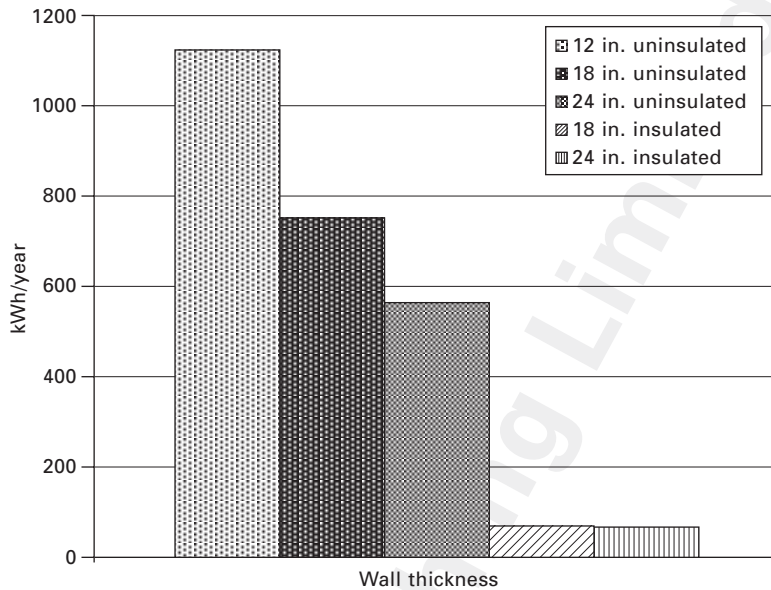
1 However, we know there are significant benefits to R-values provided by
 2 thermal mass (see earlier section on thermal mass), which are quantified as
 3 dynamic R-values. From Jan Kosny's work at Oakridge National Laboratory
 4 we see that thermal mass increases the dynamic R-value by 1.5 \times to 2.25 \times
 5 dependent on location. We will use the most conservative multiplier of 1.5
 6 \times and apply it to the R-33 of the *insulated* rammed earth to get a dynamic
 7 R-value of R-50.

8 Every so often we encounter someone who adamantly believes that earth
 9 is warm in and of itself and proceeds to build a rammed earth house in a
 10 northerly climate (6000 DD) without insulation. Degree days (DD) are a
 11 measure of how much heat is required to achieve comfort in different climates.
 12 For example, Vancouver has 5660 DD and colder Toronto has 6756 DD.
 13 Looking at the heat loss characteristics of *uninsulated* rammed earth in a
 14 6000 DD climate vs. *insulated* (with 4 in. of polyisocyanurate) we find for
 15 an 8 ft \times 10 ft wall, using $H = 24$ h/day \times DD \times 1/R \times area:

- 16 1 12 in. of *uninsulated* RE; $H = 24 \times 6000 \text{ DD} \times 0.3333 \times 80 \text{ sq ft} =$
 17 3,840,000 BTU/year or 1125 kWh/year for 12 in. *uninsulated*
- 18 2 18 in. of *uninsulated* RE; $H = 24 \times 6000 \text{ DD} \times 0.222 \times 80 \text{ sq ft} =$
 19 2,560,000 BTU/year or 750 kWh/year for 18 in. *uninsulated*
- 20 3 24 in. of *uninsulated* RE; $H = 24 \times 6000 \text{ DD} \times 0.1666 \times 80 \text{ sq ft} =$
 21 1,920,000 BTU/year or 562 kWh/year for 24 in. *uninsulated*
- 22 4 18 in. of *insulated* RE; $H = 24 \times 6000 \text{ DD} \times 0.0206 \times 80 \text{ sq ft} = 237,312$
 23 BTU/year or 70 kWh/year for 18 in. *insulated*
- 24 5. 24 in. of *insulated* RE; $H = 24 \times 6000 \text{ DD} \times 0.0200 \times 80 \text{ sq ft} = 230,400$
 25 BTU/year or 68 kWh/year for 24 in. *insulated*

26
 27 One can see in Fig. 24.7, the dramatic reduction in heat loss from *uninsulated*
 28 to *insulated* rammed earth. Inevitably and unfortunately, the result of
 29 *uninsulated* rammed earth building in a northerly climate is a very cold
 30 and difficult-to-heat home during the first winter, followed by a summer
 31 application of insulation and stucco to the exterior and subsequently a less-
 32 than-comfortable second winter due to difficulties in properly upgrading the
 33 thermal envelope post-construction (e.g. the detailing).

34 According to the National Building Code of Canada, the minimum
 35 insulation level in a wall assembly is to be no less than R 20. Most wood
 36 houses are *insulated* with fiber glass insulation fitted between 2 \times 6 framing
 37 studs. The 2 \times 6 studs measure 5.5 in. \times 1.5 in.. Therefore the insulation is
 38 5.5 in. thick, or $5.5 \times 3.5 = R19.25$, which when added to the drywall and
 39 sheathing totals at least R20. However, there is thermal bridging across the
 40 studs. If we look at the short length of 8 ft tall wall that has a 30 in. wide
 41 \times 42 in. tall window shown in Fig. 21.8, we can begin to get an idea of the
 42 impacts of thermal bridging. For further details on thermal bridging theory
 43 refer to Chapter 3.

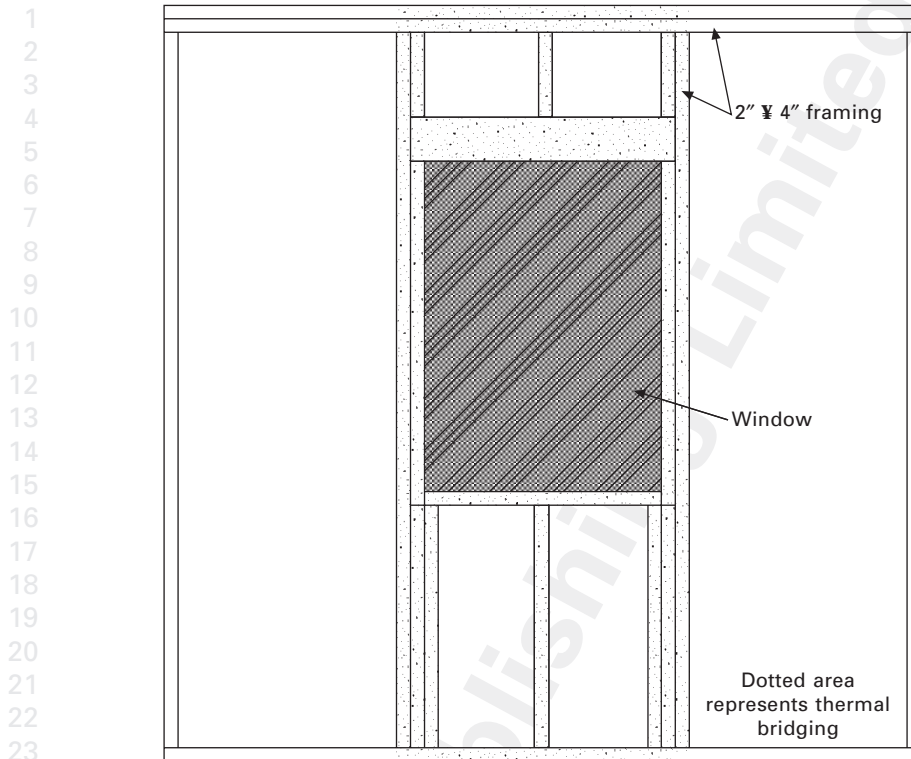


21.7 Insulated and uninsulated rammed earth conductive heat loss.

The diagram compares the heat loss through a 30 in. \times 42 in. window with the heat loss of the surrounding structure in a 6000 DD climate;

- A Through R-3 window; $H = 24 \times 6000 \text{ DD} \times 0.3333 \times 8.75 \text{ sq ft} = 420,000 \text{ BTU/year}$ or 123 kWh/year through the window
- B Through the wood framing around the window; $H = 24 \times 6000 \text{ DD} \times 0.143 \times 7.125 \text{ sq ft} = 146,718 \text{ BTU/year}$ or 43 kWh/year through the framing
- C Through SIREWALL detail 3 in. around window; $H = 24 \times 6000 \text{ DD} \times 0.0333 \times 3.0 \text{ sq ft} = 14,400 \text{ BTU/year}$ or 4 kWh/year through SIREWALL opening detail.
- D Through RE detail with 3 in. solid RE around window; $H = 24 \times 6000 \text{ DD} \times 1.0 \times 3.0 \text{ sq ft} = 432,000 \text{ BTU/year}$ or 127 kWh/year through non-SIREWALL opening detail
- E Through 30 in. length of concrete bond beam above window; $H = 24 \times 6000 \text{ DD} \times 0.5555 \times 2.5 \text{ sq ft} = 176,000 \text{ BTU/year}$ or 52 kWh/year though 12 in. tall by 18 in. deep concrete bond beam.

One can see from this example that more heat can be lost (or gained) through a poor window opening detail than through the window itself. Note also the heat loss through a very short length of bond beam. The bond beam typically goes around the circumference of the house or building and thereby creates a 12 in. thermal bridge that typically loses (or gains) more heat than



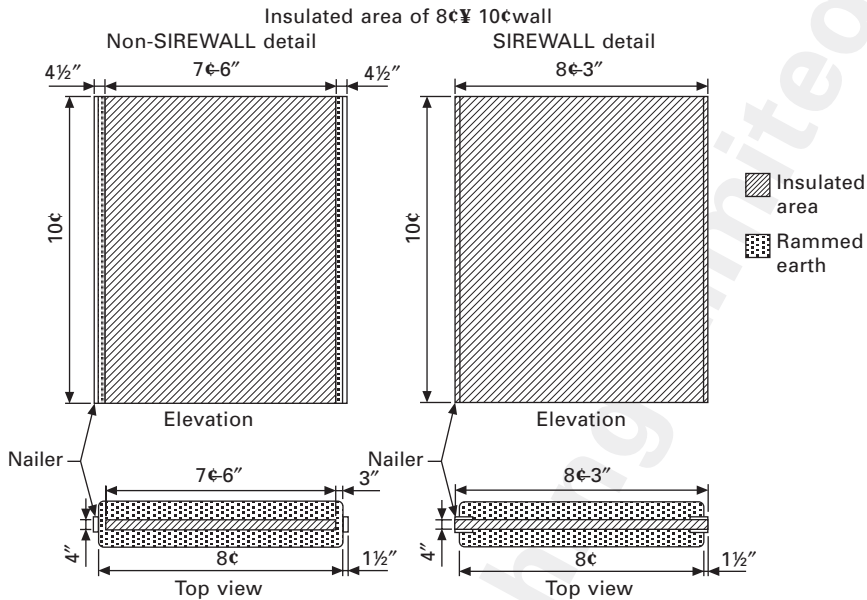
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21.8 Thermal bridging around window.

the total of all the windows beneath it. Bond beams and poor window and door details can undermine an otherwise well-*insulated* building. A well-*insulated* cooler with a lid that doesn't close completely is a good analogy. *Continuity of a thermal envelope is more important than the R-value of the insulation.* What does that mean for a rammed earth building? Replacing a non-SIREWALL window detail with a SIREWALL detail cuts wall heat loss in half, or it allows for the doubling of the window area, with a similar overall conductive heat loss.

Another way to look at it is, if an 8 ft \times 10 ft *insulated* wall was built with the SIREWALL detail of uninterrupted insulation edge to edge all around and that wall is compared with a identical size *insulated* wall with a 3 in. thermal bridge of solid rammed earth on two sides (perhaps for full height windows), the overall heat loss of the wall goes from 68 kWh/year to 314 kWh/year. See Figure 21.9. That seemingly innocuous detail increases the heat loss of the 8 ft \times 10 ft *insulated* rammed earth wall more than four-fold (462%)! Once again, continuity of the thermal envelope is more important than the R-value of the insulation.

42
43



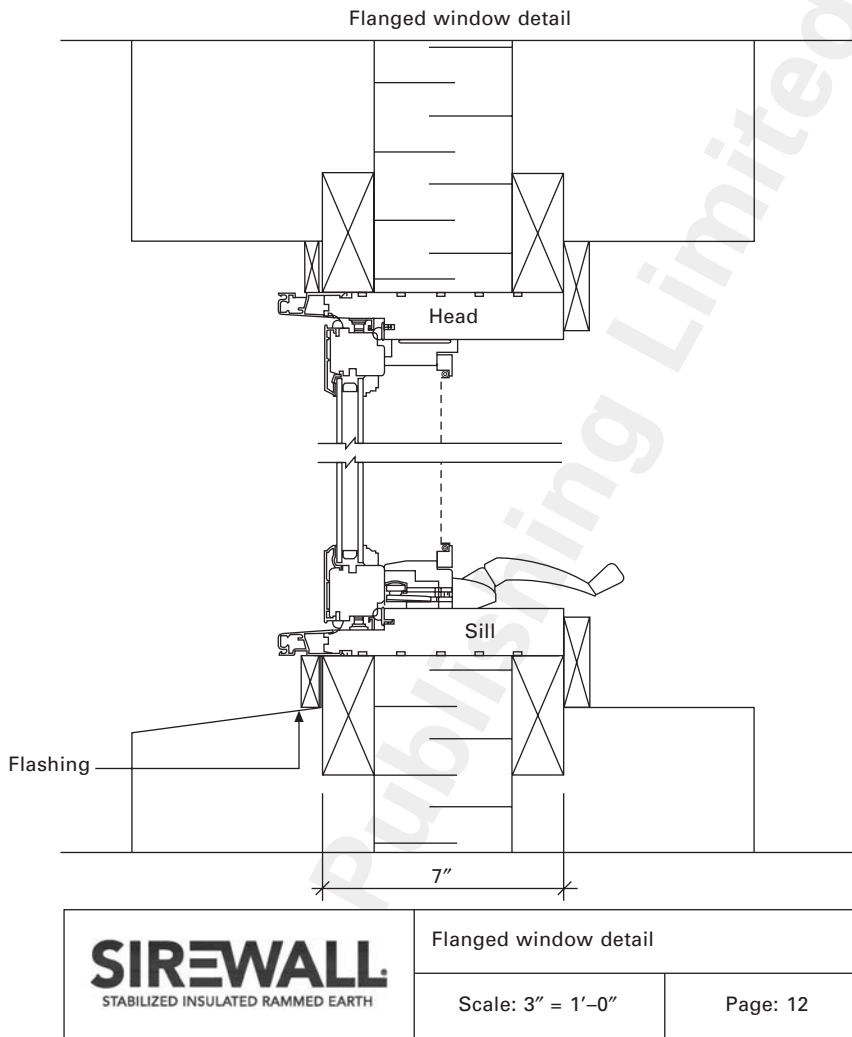
21.9 Rammed earth wall edge thermal bridging.

The previous two examples highlight some of the opportunities and impacts of decision-making around thermal envelopes. In the wood frame construction industry, conversations center on efficiency gains of 10–20%, whereas the above two examples demonstrate that 500–1000% improvements are available in *insulated* rammed earth. Every building offers multiple opportunities to make significant heat loss reductions. There is an enormous difference between *insulated* rammed earth done well and done poorly.

A review of the conductive heat loss characteristics of different wall assemblies in a 2100 sq ft bungalow allows us to assess the relative impacts of wall and window choices. For wood frame housing we use R-11.7 as the whole-wall R-value for a 2 ft 6 ft wall with typical installation (ORNL). Assuming a 20% glazed area and 10 ft tall walls in a 30 ft 70 ft rectangle (resulting in 400 sq ft of window and 1600 sq ft of wall) we find (still in our 6000 DD climate) that:

- A Wood frame + R-1 windows; 5767 kWh/year + 16,869 kWh/year = 22,636 kWh/year
- B Wood frame + R-2 windows; 5767 kWh/year + 8435 kWh/year = 14,202 kWh/year
- C Wood frame + R-5 windows; 5767 kWh/year + 3374 kWh/year = 9141 kWh/year
- D 18 in. of *uninsulated* rammed earth + R-1 windows; 14,994 kWh/year + 16,869 kWh/year = 31,863 kWh/year

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21.10 Typical SIREWALL window and door sections.

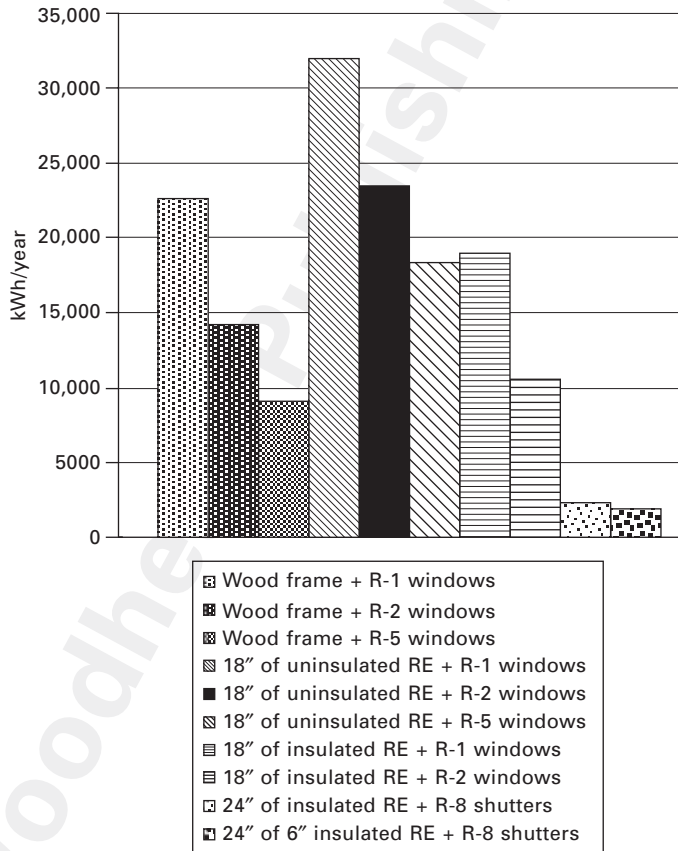
- E 18 in. of *uninsulated* rammed earth + R-2 windows; 14,994 kWh/year + 8435 kWh/year = 23,429 kWh/year
- F 18 in. of *uninsulated* rammed earth + R-5 windows; 14,994 kWh/year + 3374 kWh/year = 18,368 kWh/year
- G 18 in. of *insulated* rammed earth + R-2 windows; 1400 kWh/year + 8435 kWh/year = 9835 kWh/year
- J 18 in. of *insulated* rammed earth + R-5 windows; 1400 kWh/year + 3374 kWh/year = 4774 kWh/year
- K 24 in. of *insulated* rammed earth + R-8 + shutters; 1360 kWh/year + 937 kWh/year = 2297 kWh/year

L 24 in. of 6 in. *insulated* rammed earth + R-8 + shutters; 975 kWh/year + 937 kWh/year = 1,912 kWh/year

This is a very simple analysis and only considers conductive heat loss. It does not factor in solar heat gain, convective heat gains and losses, moisture content of the rammed earth or infrared heat gains and losses. Similar to most heat loss analysis, it only considers the heat loss that travels horizontally, where in fact, heat also leaves walls at their top and bottom.

Four points to consider when reviewing the above data:

- 1 Notice that in wall assemblies ‘K’ and ‘L’ (the best cases presented), there are ‘shutters’. In this example we use R-20 window covering (e.g. Kalwall) at night and assume that it’s in place for 12 h/day. That provides R-8 for half the day and R-28 for the other half for an average of R-18, which is the number used for this heat loss calculation. This is the kind of technology that needs to be considered to achieve net zero



21.11 Relative impacts of wall and window choices.

- 1 (overall energy consumption does not exceed energy production on an
2 annual basis)
- 3 2 There will be upgrades to windows in the future and they are fairly easily
4 replaced whereas walls are not. If we apply seventh generation thinking
5 then it is important to excel in those parts of the exterior envelope that
6 cannot adjust easily over time, e.g. the wall structure
- 7 3 While energy costs in North America are typically 5 to 25 cents per
8 kWh at present, rates will most probably rise significantly over the next
9 generation or seven
- 10 4. Consider internally generated heat. A person sitting down generates 60
11 W or, including all other higher energy activities, around 2400 W or 876
12 kWh/year. Two people and a dog might generate 2000 kWh/year. Add
13 in the heat from pilot lights, electrical lights, hot water tank heat loss
14 and phantom loads (standby power consumption) and option L above
15 may have the heat loss through the walls fully offset by internal heat
16 gain.

17 18 *Convective Heat Loss* 19

20 Little discussion remains as to whether or not houses should be built with
21 an airtight envelope. There are differences of opinions as to how much
22 makeup air is required and how to provide it, but there is broad agreement
23 that houses ought to be airtight. This correlates with the idea that buildings
24 are intended to create a different temperature, humidity and/or air pressure
25 regimen than exists outdoor at a given moment. The ability to control the
26 indoor environment largely depends on a building's airtightness.

27 The typical percentage of convective heat loss is 25–40% of the total
28 heat loss in a house/building (Natural Resources Canada). The pull across
29 the envelope will vary at different elevations inside the building due to the
30 stack effect. SIREWALL detailing around doors and windows significantly
31 reduces convective heat loss (see Fig. 21.10). The window flange is caulked
32 to recycled composite boards that were previously rammed into place. Our
33 blower door tests show that there is no measurable infiltration/exfiltration
34 of air around the windows or doors with this detail. Once again attention to
35 detail makes all the difference.

36 It is indeed easier to make an earth building tight composed to a building
37 envelope comprised of many different materials (e.g. wood frame construction),
38 but the areas of concern remain the same. Plumbing and electrical runs,
39 electrical plugs switches and lights, window and door detailing and sill
40 plates are the primary culprits for loss of airtightness. In an *insulated*
41 rammed earth house the plumbing runs are usually done in interior wood
42 frame walls, but there is inevitably some plumbing requiring installation in
43 the exterior walls. In these instances, piping can be placed in the interior

wythe to maintain freeze protection. Whenever possible, the water lines are kept inside the plane of the foam (which is obviously not possible with hose bibs) and are run inside conduits. In other words, the conduit is located inside the thermal envelope (embedded rigid insulation) and then after the rammed earth walls are built, the cross-linked polyethylene (PEX) flexible water tubing is fed through that conduit to the interior surfaces where it is desired. This technique keeps water lines inside the thermal envelope and offers seventh generation flexibility in terms of water line replacements. The same is done for hose bibs and other penetrations that can weaken the thermal envelope, but in these cases the conduit will necessarily cross the thermal envelope and the conduit is spray foamed after the PEX is installed (this detail is not for extremely cold climates). The routing of the plumbing and electrical conduits needs to be planned carefully prior to construction of the rammed earth walls and clearly shown on drawings.

As the building becomes tighter the usefulness of an HRV becomes greater. Presently, there is a strong lobby in Canada to modify the Building Code such that all new houses have an (HRV) to ensure indoor air quality.

Radiant heat loss

Warm surfaces radiate heat to colder surfaces, mostly independent of the air through which the radiant infrared heat travels (for short distances). A good example of this is standing by a bonfire on a cold night. The side of one's body that is facing the fire experiences a net gain of infrared energy as the fire radiates far more heat to the cooler surface – your body – than vice versa. On the other side of your body, you are radiating your warm body's heat to cooler surfaces – land, trees and deep space – which in turn radiate less heat back to you. You experience the temperature as being dramatically different from one side of your body to the other, but the air temperature on both sides of your body is about the same. This shows the ability of infrared radiation to transport significant amounts of energy. Radiative energy from the sun travels in the same manner, but at shorter wavelengths.

Roughly one quarter of a building's heat loss has traditionally been attributed to warm interior surfaces radiating to cooler exterior surfaces through windows. The use of drapes and low emissivity (low 'e') coatings on window glazing can minimize these losses.

The ability to emit and absorb radiant energy tends to be correlated with the color of the material. Flat black is typically the best at both emitting and absorbing radiant energy and bright white has the opposite characteristics.

The Trombe wall, popular many decades ago, was a 12 in. thick panel of concrete the same size as the south-facing window it was placed directly inside of. It made use of differing absorption and emission coefficients combined with the heat storage capacity in the Trombe wall material. The black face

1 of the Trombe wall that faced the sun absorbed the day's heat and at day's
 2 end a white-painted surface, shutter or drape minimized re-radiation back
 3 out through the glazing. The captured day's heat slowly moved to the inside
 4 surface of the Trombe wall where it radiated to the cooler surfaces in the
 5 room. In a nutshell, the Trombe wall captured infrared energy, contained
 6 it and then re-radiated it to the living space at a time more useful to the
 7 occupant.

8 There were three main drawbacks to the system.

- 9 1 An interior concrete wall was placed in the living room, entirely blocking
 10 the view and natural lighting from the window
- 11 2 The mechanisms used to contain the heat (drapes, shutters) were difficult
 12 to access and maintain
- 13 3 The barriers to heat loss were minimal – typically R-2 glazing and
 14 drapes. The warmest surface in the system was exposed to the poorest
 15 insulating area of the building envelope

17 While Trombe walls are rare these days, the principle of taking the day's
 18 heat and storing it in a thermal flywheel (significant mass) is effective and
 19 continues in different forms. Dark surfaces can be used to absorb the sun's
 20 energy. Large water containers in the living space can store solar energy.
 21 Concrete slabs can be thickened and darkened. But with *insulated* rammed
 22 earth and low 'e' coatings on the glazing, a new interior environment has
 23 become possible that has all the advantages of the Trombe wall and none of
 24 the disadvantages. We discovered this quite by chance. In a newly completed
 25 SIREWALL project we were exploring the thermal performance in the largest
 26 room which had a 22 ft tall vaulted ceiling and rammed earth on all walls.
 27 We were using a remote thermometer to measure the temperature of the
 28 wall surfaces at different elevations. We expected significant temperature
 29 stratification as is normal in any lightweight structure, but instead we found
 30 that the surface temperatures of all of the walls, ceilings and concrete floors
 31 were within 1°C! This is characteristic of our buildings. The only exception
 32 is when the floor radiant heat is on, in which case the floor is the warmest
 33 surface.

34 When people are heated by thermal radiation from the building interior
 35 surfaces instead of by convection (air temperature), less energy is required
 36 to create comfort. Not only is there minimal air temperature stratification and
 37 resultant heat loss exacerbation, but comfort is achieved at a lower ambient
 38 air temperature. In effect we have recreated the Trombe wall, by capturing
 39 infrared energy, containing it and then re-radiating it to the living space at
 40 a time more useful to the occupant. The dynamic is less concentrated as
 41 heat storage has greater surface area and occurs inside the thermal envelope
 42 around the whole exterior of the building. The three Trombe wall problems
 43 are solved. The window now allows light and view, there are no drapes or

shutters to control manually and the mass is placed directly beside the best-*insulated* parts of the thermal envelope. There are two additional benefits. Unlike the non-structural Trombe wall this new thermal mass is load-bearing and suitable to support the roof. There is no added mass that does nothing but store heat and take space. Due to much larger mass than the Trombe wall, the *insulated* rammed earth walls needn't be black or any color in particular. They collaborate very nicely with the radiant heat in the slab and the low 'e' coating on the windows. As a result most of the infrared energy continues to be exchanged between inside surfaces, rather than exiting through the windows more rapidly as with traditional construction.

21.3.4 Holistic heat loss prevention

The three means of heat loss are interrelated. If the radiant heat is escaping through the windows then the room cools unevenly, drafts occur and there is a call for heat. The forced air furnace or baseboard heaters jump into action and heat the air, which rises creating stratification. **The ΔT at the ceiling might be twice that at the floor and the rate of conductive heat loss therefore doubles at the ceiling.** The stack effect exhausts the hottest air at the high elevations while taking in cooler air at lower elevations causing the occupants discomfort. There is another call for heat.

Thermal stability is best achieved through the flywheel effect of abundant *insulated* mass with substantial heat storage capacity. However, if that mass is radiating its heat to the outdoors through windows that are not low 'e', or if there is a constant bleed of heat on the airstream to the outdoors due to poor airtight envelope detailing, or if the construction detailing around windows and doors creates large thermal bridges, then the benefits of the *insulated* rammed earth are lost or greatly diminished. Heat retention in a building is only as strong as the weakest link(s).

21.4 Applications of earth construction in hot climates

Most of this chapter has been concerned with heat loss and an understanding of how heat moves, such that we can control or interrupt that movement. This understanding has its roots in colder climates. It is ironic then that the largest global opportunity to reduce energy consumption in buildings lies in the hot climates. If we liken the buildings in hot climates to refrigerators, then typically the refrigerator door is left ajar, it is poorly *insulated* (if at all) and the compressor (in the air conditioning) is working overtime to combat these structural shortcomings. There is commonly a generous selection of weakest links causing poor thermal performance. The technique currently being used to create human comfort is air conditioning. The cost of running

1 the air conditioning accrues for the life of the building and air conditioning
2 requires maintenance and replacement. And yet, poor building design is the
3 root cause of the need for air conditioning in the first place. As peak oil and
4 climate warming require large reductions in fossil fuel use, it is imperative
5 that we shift from the first cost, disposable paradigm to long-term sustainable
6 building. The walls of most buildings, when implemented using a holistic
7 thermal approach, can partially or sometimes fully replace the need for air
8 conditioning.

10 21.4.1 Conductive heat gain

11
12 In most circumstances the same principles used to minimize heat loss apply
13 in reverse to hot climates where the concern is heat gain. Minor adjustments
14 might be to lighten the color of the exterior wall surfaces and provide biological
15 or other external shading devices particularly on the western orientation.
16 There may be an opportunity to enhance the conductive connection to the
17 ground and lose heat that way. Contained geothermal coupling could make
18 use of the frost protected shallow foundation (FPSF) system used in cold
19 climates. This technology isolates the ground under and around the building
20 from the outside cold or heat. Once this is done, then the thermal stability
21 or flywheel effect of the temperature of the earth under the building can be
22 tapped. What's important with this system is the thermal continuity either
23 of the slabs to the ground or the inner wythe of the rammed earth walls to
24 the ground.

26 21.4.2 Convective heat gain

27
28 Control the indoor environment by making a rigorous distinction between
29 indoor air and outdoor air via airtight detailing. Bring the HRV supply air
30 into the building after pre-cooling it by running it under the ground for some
31 distance. Carefully consider the locations of the supply and exhaust HRV
32 vents to optimize efficiency and health without disturbing human comfort.

34 21.4.3 Radiant heat gain

35
36 The solar orientation of the glazing is an obvious method to control radiant
37 heat gain. Also well known are the external shading devices such as trellises,
38 pergolas, extended roof overhangs, deciduous trees, etc. Internally, abundant
39 mass, taller ceilings, the reduction of inefficient lighting fixtures and the
40 reduction of phantom loads (the electric power consumed by electronic
41 appliances while they are switched off or in a standby mode) will reduce
42 the cooling requirements. Collecting and venting the heat generated by heat-
43 producing devices such as control motors, pumps and audio/visual components

will reduce the cooling load. Deep space radiators are a promising technology at the cutting edge of passive radiant heat loss. With this system (and there are a number of variations), flat black surfaces emit the heat of the building to deep space. Water cooled in this way at night can be circulated in the day either in the inner wythe of *insulated* walls or in ceilings.

21.5 Applications of earth construction wet and cold climates

The vast majority of traditional earth building has been done in warm, dry climates. The few exceptions to this principle demonstrate that it takes special care and repeated, ongoing maintenance for the rammed earth to endure. For example, the Shanty Bay church in Ontario (built 1842) has its rammed earth covered with plaster or siding to resist the forces of a very cold environment.

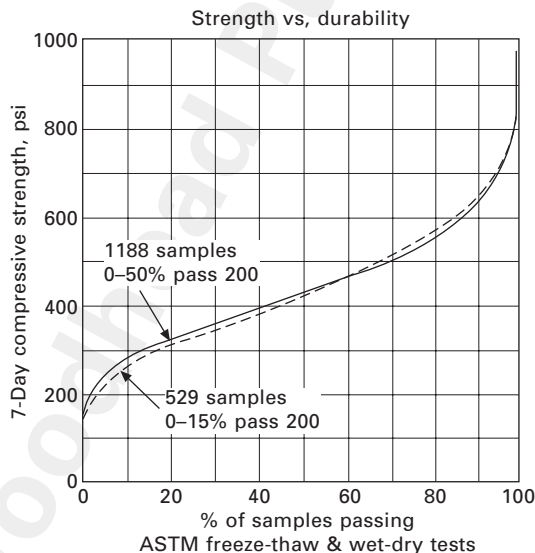
In order to be able to construct modern rammed earth in wet and cold climates within the constraints of Building Codes of Canada or the United States, there are specific details that are typically scrutinized by the approving authorities. First, is the insulating requirement, which is strictly based on conductive heat loss and has no allowances for convective heat loss, radiant heat loss, or the benefits of thermal mass. That objection is easily surpassed. The perm rating issue is also easily resolved with the appropriate rigid insulation product selection.

The issue of water and rammed earth continues to come up despite David Suzuki pressure-washing a 10-year-old SIREWALL with a 2750 psi (19 MPa) pressure washer on film (CBC's 'Nature of Things'). It is true that not all rammed earth can withstand that extreme level of testing. Water can come into rammed earth horizontally via rain (or sprinklers) or vertically via rising damp. Tongue and groove detailing of wall panels such that there is no uninterrupted path of rammed earth from the outside to the inside has never failed to prevent passage of water. Insurance to prevent water coming through the rammed earth is to have a hydrophobic admixture mixed in just prior to ramming such that the rammed earth is hydrophobic throughout. A surface coating is used by some. The rising damp is prevented by the hydrophobic admixture. A belt and suspenders approach is to prevent rising damp by applying a crystalline slurry to the top of the footing prior to ramming the first lift. With regards to concerns about water entry through vertical seams between panels, the SIREWALL system has the panels tongue and grooved such that any water that tries to squeeze into the vertical seam (which has been rammed together) comes up against a recycled plastic lumber face (which has complete water repellence) that has also been rammed into place. Horizontal driving rain in the West Coast of Canada has not found its way past this configuration.

1 The structural integrity of stabilized *insulated* rammed earth may also be
 2 a concern to the building official and the Equivalency Provision of the Code
 3 should be exercised. The Equivalency Provision, which is near the beginning
 4 of most Code books, states that if the proposed material or method meets
 5 or exceeds the requirements in the Code, that material or method shall be
 6 deemed to comply. All *insulated* rammed earth buildings that I know of in
 7 North America have been structurally engineered, and this engineering is
 8 always submitted to the Building Official for approval as per Equivalency.

9 The first place that engineers typically look to, when engineering modern
 10 rammed earth for cold and wet climates, is to determine the unconfined
 11 compressive strength of the rammed earth. In the early 1990s, when we started
 12 out, we did single-storey, thick-wall structures and these worked with 28-day
 13 compressive strengths of 6 MPa or 870 psi. As the engineers continually
 14 wanted more strength, there seemed no way to know how much was too
 15 much or not enough. The Portland Cement Association has done research
 16 (see Fig. 21.12) showing the relationship between strength and durability in
 17 soil cement samples and, as soil cement is a close cousin of modern rammed
 18 earth, the results of that research have become very useful.

19 Note that on the graph, all results are based on 7-day compressive strength.
 20 If the 7-day strength is 600 psi (41 MPa), then 87% of samples passed the
 21 ASTM freeze/thaw and wet/dry tests. If the 7-day strength is 750 psi (5.2
 22 MPa), then 97% of samples passed, and at 850 psi (6 MPa), 100% of the
 23 samples passed. Now, as the result of much R&D involving diamond-drilled
 24 cores and thousands of crush tests, the average compressive strength of
 25



21.12 Strength vs. durability from Portland Cement Association.

SIREWALL is at least double that (at 28 days). On a couple of occasions we've had results over 40 MPa (over 6000 psi) with 10% cement. More typically our crush results come back between 10 MPa and 20 MPa. How is that achieved?

21.6 Optimizing rammed earth compressive strength

Optimizing compressive strength (see Fig. 21.13) in modern stabilized rammed earth is a function of optimizing the soil blending, selecting admixtures and



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Salt Spring Island, British Columbia
V8K 2B9

File No.: 09-166-54

Attention: Jerry Fitzpatrick

Project: GRAND BEACH WASHROOM BUILDING

Reference Number	Field or Sample Number	Date Received	Date Tested	Age at Test (Days)	Compressive Strength (MPa)	Type of Fracture
166-54-1A		July 29/09	July 31/09	10	19.8	
166-54-1B		July 29/09	July 31/09	10	21.7	
166-54-1C		July 29/09	July 31/09	10	18.4	
166-54-1D		July 29/09	Aug 18/09	28	24.6	
166-54-1E		July 29/09	Aug 18/09	28	26.8	
166-54-1F		July 29/09	Aug 18/09	28	22.0	
166-54-1G		July 29/09	Oct 29/09	100	23.7	
166-54-1H		July 29/09	Oct 29/09	100	24.0	
166-54-1I		July 29/09	Oct 29/09	100	26.5	

Specification		Plastic Test Results	
Strength:	- MPa	Mold Type:	Plastic 150mm x 300mm
Slump:	- mm	Slump:	- mm
Air:	- %	Air:	- %
Cement Type:	-	Plastic Density:	- kg/m ³
Aggregate Size:	- mm	Hardened Density:	- kg/m ³
Admixture:	-	Cast By:	Client
Supplier:	-	Cast Time:	-
Ticket Number:	-	Temperature:	-
Mix Number:	-	Concrete:	- °C
Truck Number:	-	Air:	- °C
Batch Time:	-	Initial Curing, Maximum:	- °C
Load Volume:	- m ³	Initial Curing, Minimum:	- °C
Cumulative Volume:	- m ³		

- A
- B
- C
- D
- E
- F

TYPE OF FRACTURE
REQUIRED WHEN
CYLINDER FALLS TO
MEET SPECIFIED 28
DAY STRENGTH

Location:

Cc: Email - jerry@sirewall.com

Comments:

Rammed earth; consisting of a blend of 10% cement and soil compacted with a pneumatic tamper.

ENG-TECH Consulting Limited

[Signature]

Danny Hoffeld, Principal
Ph: (204) 233-1694 Fx: (204) 235-1579

Cylinder initial cured on site.

21.13 Unconfined compressive test results.

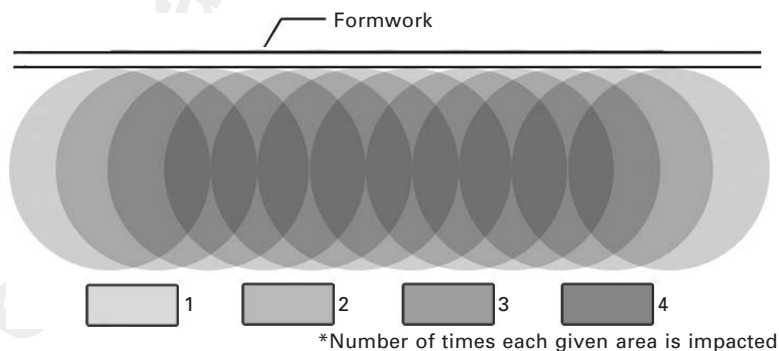
1 pozzolans that augment each other and selecting the best tamper for each
 2 specific project. Also vital is the moisture content, the soil delivery method,
 3 control of lift heights and how the tamping is done.

5 21.6.1 Tampers and tamping 6

7 The type of tampers and approach to tamping have a notable effect on the
 8 visual sedimentary presentation. Depending on how the tamping force is
 9 applied to the earth inside the formwork, the consolidation becomes less as
 10 the distance from the tamper butt increases. The visual face at the top of the
 11 lift displays a very dense matrix with a fine texture and is therefore usually
 12 lighter in color, whereas the bottom of the lift is somewhat less dense, more
 13 textured and therefore slightly darker in color.

14 Is this a problem? Is there any worry about the strength of the rammed
 15 earth at the bottom of the lifts due to less compaction and slightly lower
 16 density? The short answer is no. Part of the answer lies in the selection of
 17 tampers and the lift height. The other part of the answer lies in the fact that
 18 almost all tamper butts are round in shape. Imagine a process of tamping
 19 the visual face of a wall and running the round butt along the forms (Fig.
 20 21.14). Assuming that the 6 in. tamper impacts the earth every 2 in. over
 21 a 6 in. distance, then at the top of the visual face there will be some soil
 22 that has not been impacted. However, 3 in. back from the surface, directly
 23 under the shaft of the tamper, the earth has been impacted four times. That
 24 is a significant difference. Figure 21.14 shows the number of impacts (up
 25 to four) on the surface of the soil being rammed. The figure is intended to
 26 illustrate the principle, not define how frequent the tamping should be.

27 The least compacted earth is on the visual face! This is counterintuitive. If
 28 we imagine being out in nature and taking two slices through a sedimentary
 29 deposit 3 in. apart, we would expect the characteristics to be near identical on
 30 each slice. That's because there are no edges to the layout. We would expect
 31



21.14 The impact of round tamper butts.

the same to be true with rammed earth (that it is consistent throughout), but our test core drilling has revealed the result of ramming against an edge. If there is rilling and a bony appearance at the bottom of a lift, we know that it is a surface condition. We know that to see a slightly coarser texture at the bottom of a lift is a sign of strength, that the moisture content has been well controlled and the ramming well done. We know that an overly wet mix will not show texture, even at the bottom of a lift and that the strength of the material has been compromised by a poor water:cement ratio. Determining the degree of compromise takes an experienced eye and some non-textured rammed earth is very strong.

Most large countries around the world have at least one pneumatic tamper made for the forging or backfilling industries. Some manufacturers offer many models. The size and weight of those tampers varies considerably as do the size and shapes of the butts as can be seen in Fig. 21.15.

The butt at the bottom of the tamper delivers the impact to the earth. Though there are many options to choose from, two fairly common options can be compared to understand the theory behind tamper selection. If a lightweight (15#) tamper with a 3 in. butt is compared to a heavy (45#) tamper with a 6 in. butt, one would at first think that the earth would be better compacted by using the heavy tamper with the 6 in. butt. It is true



*Ingersoll Rand products

21.15 Some tamper butt options.

1 that the 6 in. tamper will cover a lot more ‘ground’ in less time than the
2 smaller tamper, but a close look reveals more insight.

3 The 3 in. butt has an impact surface area of 7 sq in., whereas the 6 in.
4 tamper has an impact area of 28 sq in. That means that, if the blows per minute
5 and the stroke length are the same for both tampers, then the large tamper
6 has 3 \times the force being applied to the earth (force = mass \times acceleration) due
7 to its extra weight, but the smaller tamper applies its load in a (4 \times) more
8 concentrated manner (higher stress (stress = force/area), N/mm² or MPa).

9 Overall, the smaller tamper creates a denser matrix and has deeper
10 penetration into the loose earth that is delivered into the forms. Empirically
11 and from compressive testing of diamond-drilled cores in test walls, we know
12 that the compressive strength created by smaller tampers is significantly
13 higher than large tampers. It is also important to note that hand tampers are
14 not equivalent when compared with pneumatic tools.

15 If the mass of the tampers are equal and the length of the stroke and thrust
16 applied (in other words, the force) is equal, then the only significant variable
17 is the impact surface area. The compressive strength of hand rammed earth,
18 created by using a 20 sq in. impact face, is half the strength of that created
19 using a large 45 lb tamper with a 6 in. butt.

20 Given the many different tampers that we’ve used on many different types
21 of soils, we only have rules of thumb to offer on the most popular tampers.
22 We believe that hand tamping creates half the compressive strength of 6 in.
23 tampers and 3 in. tampers are 20–25% above the 6 in. tamper results. What
24 follows from this is that the depth of lifts for large tampers should be less
25 tall than those of small tampers and less still for hand tamping.

26

27 21.6.2 Formwork

28
29 In the close relationship of tamping and formwork, the large tamper exerts
30 a higher force overall on the soil and on the formwork, whereas the smaller
31 tamper exerts a higher stress on the specific areas of impact and less on
32 the formwork. The formwork strength required to withstand the force of a
33 6 in. tamper is higher than the force required to withstand a 3 in. tamper.
34 It is important to understand that most widely available formwork has been
35 created to withstand the forces exerted by wet concrete. Wet concrete exerts
36 hydrostatic pressure, which is to say that if 10 ft of concrete is poured at once,
37 then the force at the bottom of the forms will be the sum of all the mass of
38 the concrete above. With concrete at 150 lb/cu ft (2403 kg/m³), a 10 ft tall
39 wall of wet concrete will exert 1500 lb (680 kg) of force per square foot on
40 the bottom of the forms. In sharp contrast, when tamping is taking place at
41 a 10 ft height the force at the bottom of the rammed earth wall is zero. In
42 fact, there are rammed earth forming systems where there is no formwork
43 in place below when the tamping has moved up to the top of the wall.

There is a difference between the forces exerted on formwork by small and large tampers, but both are typically an order of magnitude lower than that required for concrete. Every different tamper will exert a different force on the formwork and those forces can be plus or minus 50%, so it is important and useful to synchronize the formwork with the tampers used. To use concrete formwork for rammed earth has the big advantage of availability, but is usually 10–20 % stronger than required (Fig. 21.16) and most of it comes with throughties, making it almost impossible to insert the insulation as the wall is rammed. Throughties also require hole patching, which can be unsightly. Unneeded strength carries unneeded weight (and cost) and thereby more time and work is needed to set up and take down the formwork on site.

We have looked at the dynamic forces on strongback and whaler forming by carefully measuring the deflections in existing rammed earth walls. Every deflection is an expression of the tamper selected for that wall, so deflection data are always correlated with the tamper used. Based on measurements that we have done we believe that the deflection in the plywood gives an indication of the local pressures and is never more than 150 kPa. The deflection in the whalers gives an indication of the global pressures. We believe that small tampers create higher local pressures and large tampers create higher global pressures. The deflection in the strong backs is dynamic in nature.



21.16 Concrete formwork used for curving rammed earth walls.

1 At an elevation of 1 ft, the pressure is, say 100 kPa. When the ramming is
2 being done at an elevation of 5 ft, which might be hours later than the initial
3 first foot of the wall, the pressure is still 100 kPa and the rammed earth at
4 1 ft elevation is already curing and shrinking away from the formwork,
5 therefore, it is applying no pressure to the formwork. We know that if there
6 is a wall that cannot be done in a day and there will be a horizontal cold
7 joint seam as a result; the wall will have shrunk overnight by 1/16 in. to
8 1/8 in. on each side. This makes the following day's work appear to be a
9 very slightly thicker wall above the cold joint. That 'overhang' cold joint
10 can be minimized or exaggerated for visual interest. The relevance of these
11 observations is to understand the dynamic nature of the form 'pressure' as
12 the walls are being rammed. A similar process takes place if one places a
13 plank across a stream and walks across it. With each step the plank bends
14 at the place where the foot is placed and then it bounces back when the
15 next foot is placed. Although the rammed earth formwork operating in the
16 vertical plane is not quite so dynamic or quick in action (the spring back is
17 not as quick), the principle remains. Understanding the close relationship
18 between tampers and formwork appears to offer significant opportunities for
19 optimizing efficiency, ensuring predictable quality and reducing costs.

20 Increasing the form panel module size also offers significant opportunities.
21 Smaller projects with fewer repetitions are built with incremental forms.
22 Larger projects with repetitive design elements allow for the efficiencies of
23 modular form panels (gangforming). We have used handset form panels as
24 small as 30 sq ft and crane-erected form panels over 300 sq ft. Removing
25 a large form panel from a recently finished wall and immediately placing it
26 such that it is ready for the next wall is highly efficient.

27

28 21.6.3 Delivery

29

30 The method of delivery of the earth into the forms will affect the appearance,
31 the strength and the cost. Techniques like loading the forms with earth by
32 dumping it in with a skidsteer, telehandler or conveyor will usually result in
33 a certain amount of rilling and lack of control over surface texture. Rilling
34 is where the larger aggregate will roll down the angle of repose to the visual
35 surface and create a visual effect referred to as 'boney' texture.

36 The rilling only occurs on the surface and is not consistent throughout the
37 wall. Those familiar with the concrete industry would mistakenly assume
38 that the boney appearance runs right through the wall, as it would with
39 honeycombed concrete. Having the surface boney does appeal to some as
40 it creates a natural-looking effect. To avoid rilling, the soil is delivered into
41 the formwork such that if there is rilling, it happens in the middle of the
42 wall, not on a visual surface.

43

21.6.4 Moisture content

The moisture content of the soil has a large impact on the final compressive strength of the wall. We know from the concrete industry that the water/cement ratio has a big influence on the compressive strength. The more water, the less strength there is. Rammed earth usually takes full advantage of this relationship, as it is much dryer than even a zero slump concrete. What about moisture starvation? If the water/cement ratio is below 0.42 (optimum) then you will have unhydrated cement and less strength. This seldom happens. However, it is possible (and too easy) to make the rammed earth mix overwet, using the excess water as a lubricant to ease the ramming process. This technique is often used when people are hand ramming or pneumatically ramming tall lifts. Labor costs are cut at the expense of the strength of the rammed earth wall.

21.6.5 Earth blending

Insulated rammed earth requires higher strengths than its *uninsulated* cousin. As a result, *insulated* rammed earth builders largely ignore the color of the soils being considered and instead focus almost entirely on the soil's strength potential. Distinct from concrete (manufactured aggregate), earth blending uses full spectrum particle sizes sourced (when possible) either directly from nature or industrial waste, e.g. pit run, limestone tailings, recycled concrete. This allows for more strength with less cement and has a much smaller environmental footprint. Using the best of what's available requires soils analysis for every new location. Only once in 20 years have we been able to use the earth as it is available without blending. Compaction factors can vary from 0.54 to 0.97, and heavy concentrations in a specific particle size are normal. Organic materials in the soil have a deleterious effect on the strength of the wall (organic materials blow walls apart in slow motion), so they are rigorously avoided. In the early days the Fineness Modulus (FM) was the favored tool for quick evaluation of soils and soil blends. The FM is a number used to describe the mean particle size of a soil sample, e.g. an FM of 2 describes a sandy soil and an FM of 7 is a blend too coarse for rammed earth. It was developed by the US Army Corps of Engineers. As time went by we became aware of how significant it was that the silt and clay content was not factored into the FM calculation and that two soils with the same FM but different clay and silt contents can and do behave quite differently. As a result we created a rammed earth FM and a number of other metrics to quantify all the variables in earth blending, using a computer program. Now we no longer physically test different blends looking for the right soil combination with the best proportions to optimize strength. Data from all the candidate soils are sent to the SIREWALL head office and the best

1 blend determined theoretically. Only that blend is rammed into cylinders
 2 and sent to the lab for testing. The goal with our earth blending technology
 3 is to move beyond determining the best blend, to being predictive. We see
 4 a time, when we have gathered enough data, that we receive data on all
 5 the candidate soils from anywhere in the world and are not only able to
 6 determine the optimal blend (we already do that), but also able to provide
 7 what strength one might expect to obtain from that optimal blend. To this
 8 point our success has been beyond our expectations. Only 5 years ago we
 9 were pleased with compressive strength results over 6 MPa. We now expect
 10 10 MPa and are not surprised to see results of 20–30 MPa. Our record with
 11 10% cement is an average of 46.0 MPa (see Fig. 21.17).

12 The best blend is typically weighted mostly toward optimal strength, but
 13 more and more now we are also blending for a desired finish texture, e.g.
 14 a 600 mm finish. Color is seldom a blending consideration as almost any
 15 desired color can be created by varying the iron oxides, the cement color
 16 and the pozzolans.

18 21.7 North American style rammed earth

19
 20 There is no one distinctive style of rammed earth in North America, as there
 21 is in Australia. Australian rammed earth is immediately recognizable due
 22 to the 2 ft ¥ 8 ft form panels and the riveted appearance. Rammed earth
 23 builders in North America respond to a wide variety of local conditions
 24 and local economies. When there is a structural or durability requirement
 25 then stabilization is used. Insulation is used for both hot and cold climates.
 26 Unstabilized rammed earth is still prevalent in the southern USA or where
 27 walls are used as infill or for landscaping. North American rammed earth
 28 builders are rugged individualists who like to innovate, ensuring that the
 29 definition of a continental style is hard to determine.

30 The climates, in terms of geographical area in North America, for which
 31 stabilized *insulated* rammed earth is suitable, are many times greater than
 32 the areas of those climates for which *uninsulated* rammed earth is suitable.
 33 All of Canada and the northern half of the USA are areas where insulation
 34 in rammed earth is essential. In the southern half of the USA, there are as
 35 well, climates that are too cold, too hot or too damp for *uninsulated* stabilized
 36 rammed earth.

37 Where insulation in rammed earth is necessary and where it's not have
 38 yet to be determined and that's likely to alter with climate change.

39 With cold-climate *insulated* rammed earth building, the necessary emphasis
 40 on strength for durability ensures a strong sedimentary appearance and
 41 controlled lift heights. In climates where insulation is not necessary in the
 42 rammed earth and where there is little seismicity, high strength is not as
 43 important as there is no freeze/thaw concern. In that situation it is possible



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CONCRETE TEST REPORT

PROJECT NO. 14143
 CLIENT TERRA FIRMA BUILDERS
 C.C. LEDCOR CONSTRUCTION LIMITED

TO Site TERRA FIRMA BUILDERS
 212 CUSHEON LAKE RD
 SALT SPRING ISLAND, BC
 V8K 2B9

ATTN: MEROR KRAYENHOFF

PROJECT VANDUSEN BOTANICAL GARDEN OAK ST, 5251
 CST BURNABY

SET NO. 1 NO. OF SPECIMENS 9 DATE RECEIVED 2010.Aug.16 DATE CAST 2010.Aug.09

SPCM NO.	SPECIMEN TYPE	CURE COND	DATE TESTED	AGE AT TEST (DAYS)	AVERAGE DIAMETER (mm) OR SIDE (mm x mm)	AVERAGE LENGTH OR SPAN (mm)	MAXIMUM LOAD (kN)	COMPRESSIVE OR FLEXURAL STRENGTH (MPa) Average	FAILURE TYPE
A	Core	Lab	Aug.19	10	150.0	285.0	632.0	35.5	[Failure Type Diagram]
B	Core	Lab	Aug.19	10	150.0	270.0	628.0	35.0	
C	Core	Lab	Aug.19	10	150.0	290.0	756.0	42.6 37.7	
D	Core	Lab	Sep.06	28	150.0	280.0	871.0	48.8	
E	Core	Lab	Sep.06	28	150.0	300.0	852.0	48.2	
F	Core	Lab	Sep.06	28	150.0	262.0	698.0	38.7 45.2	
G	Core	Lab	Nov.17	100	150.0	283.0	649.0	36.4	
H	Core	Lab	Nov.17	100	150.0	288.0	859.0	48.3	
I	Core	Lab	Nov.17	100	150.0	262.0	963.0	53.4 46.0	

SPECIFIED STRENGTH	MPa @	DAYS	CONCRETE TEMPERATURE	°C	TREND GRAPH
CEMENT CONTENT	kg/m ³		AIR TEMPERATURE	°C	
CEMENT TYPE			SLUMP	mm SPEC. ±	
POZZOLAN CONTENT	kg/m ³		SLUMP FLOW	mm SPEC. ±	
POZZOLAN TYPE			FLOW TIME	sec SPEC. ±	
MAXIMUM SIZE AGGREGATE	mm		AIR	% SPEC. ±	
BATCH TIME			PLASTIC DENSITY	kg/m	
ADMIXTURES			HARDENED DENSITY	kg/m ³	
			CAST TIME		
			CAST BY	CLI	
			CURING CONDITIONS		
			INITIAL CURING TEMP-MAXIMUM	°C MINIMUM °C	
SUPPLIER			LOCATION		
MIX NO.			COMMENTS		
TRUCK NO.	TICKET NO.		6 (6X12) CORES DELIVERED BY CLIENT.		
LOAD VOL.	m ³ CUM. VOL.	m ³			
WATER ADDED	I AUTH. BY				
Page 1 of 1	2010.Nov.19		METRO TESTING LABORATORIES LTD. PER. <i>Joy You</i>		

Reporting of these test results constitutes a testing service only. Engineering interpretation or evaluation of test results is provided only on written request.

21.17 Record strength with 10% cement.

to be not so rigorous on soil selection, tamper selection and lift heights. The polar opposite of cold-climate rammed earth is where lift height is measured by dumping earth into forms with a skidsteer and ramming with large tampers to create thick walls that have no rebar and no foam. This approach boosts production (and economy) significantly. If the appearance of the walls is unsatisfactory, then they are plastered for a desired finish or color. It's all about getting as much earth mass rammed as quickly as possible. Another

1 polar opposite of cold-climate rammed earth is the unstabilized or barely
 2 stabilized rammed earth that is still being built (often without permit). These
 3 projects have a very small carbon footprint but are vulnerable to erosion.

4 North Americans have played extensively with the visual presentation of
 5 rammed earth. The most common variables are the shape and color of the
 6 rammed earth, while less frequent are the forays into creative mix design,
 7 thin colored feature lines, creative volume displacement boxes (including
 8 fiber optics for example), carving of the formwork before ramming, carving
 9 of the rammed earth just after it's rammed, sanding the rammed earth,
 10 sandblasting, pressure washing, embeds, inserts, fabric forming, patchwork
 11 forming and enhanced overhangs. Forming techniques vary depending on
 12 whether insulation is necessary.

13 The stabilized *uninsulated* rammed earth builders typically use concrete
 14 formwork with through-wall tensile connectors or the California system
 15 using pipe clamps, which was popularized by David Easton, whereas the
 16 stabilized *insulated* rammed earth builders use a fully external formwork
 17 system that has no through-wall connectors as in Fig. 21.18.

18 Although there are many possible ways to form *insulated* rammed earth,
 19 all the stabilized *insulated* rammed earth builders in North America use the
 20 SIREWALL System or a derivative thereof. There are many ways to build
 21 fully external formworks and that topic is a book in itself. If you get a group
 22 of *insulated* rammed earth builders together, you will find many strongly held
 23 opinions about such things as strongback and waler formwork, torsion box



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43 21.18 Common SIREWALL forming system.

formwork, gang forming, canyon forming, form shoes, strongback options, modular options vs. full length and the plethora of materials to form with such as steel, aluminum, stainless, high density polyethylene, high density overlay, medium density overlay and fabrics or membranes.

Through-wall connectors make it extremely difficult to place rigid insulation in the center of the wall as the wall is being erected unless the formwork is being placed in very small modules, e.g. 24 in. tall. SIREWALL has developed the ability to avoid this issue all together by devising a formwork that is fully external, with no horizontal tensile through ties. A side benefit of no through-wall connectors is the elimination of unsightly patching.

Engineering stabilized *uninsulated* rammed earth buildings typically rely on a wall-width concrete bond beam at the top of the rammed earth wall. Bond beams are terrible thermal leaks and should never be used in stabilized *insulated* rammed earth. Engineers of *insulated* rammed earth have broadly adopted the vertical cantilever for one- and two-storey walls. With this system, each individual wall is vertically cantilevered off the footing to address overturning moments. The fact that the individual walls are usually connected in the finished building is an uncalculated bonus/safety margin. This system gives the designer a lot of freedom.

For both *insulated* and *uninsulated* rammed earth, the use of wood or concrete floor and ceiling diaphragms can make the next storey of rammed earth very stable. The diaphragm configuration should be considered in an integrated design phase. A common passive solar design element in North America is to incorporate a large, uninterrupted glass expanse on the south side of the building. While that may be good for passive solar, it often creates a 'soft' wall that has little lateral or shear strength. A surprise solution to this problem, which avoids the use of expensive engineering techniques (such as steel moment frames) is the unique ability of rammed earth to extend as a buttress beyond the roofline, fully exposed to the elements. This capacity to have the rammed earth walls connected to and part of the structure, but not necessarily under the roof, creates a whole new level of design freedom along with the ability to integrate the structure into the landscape (Figure 21.19).

For green builders in North America, using either *insulated* or *uninsulated* rammed earth is an ideal way to meet the certification requirements for LEED, Living Building Challenge (LBC) and Cradle to Cradle (C2C) building perspectives. Similarly, net zero buildings, off grid buildings and Passive House designs are very compatible with rammed earth construction.

21.7.1 Insulated rammed earth business models

Most of the building of *insulated* rammed earth walls in North America takes place in the warm 7 months of the year (except in the Pacific northwest).



21.19 Rammed Earth buttress/ retaining wall.

Building under a heated tent (heating and hoarding) in cold weather adds significant expense (when done on a one-off basis). It's a short building season for those locations that have sub-zero temperatures for 5 months per year and ironically it's those locations that stand to benefit the most from the excellent thermal performance of *insulated* rammed earth. To meet the demand in the short seasonal time frame that's available it is necessary to encourage investment in such things as custom volumetric mixers, custom conveyors, custom hoppers and custom formwork, all in the interest of getting as much done as possible in the short building season that's available. Only in the Pacific northwest is it possible to build year-round. It is therefore no surprise that the majority of *insulated* rammed earth builders are located there and that the scale of investment in equipment there is less imperative.

With a few exceptions, the demand for *insulated* rammed earth is very spread out geographically. Moving from one site to the next can and has crossed 4.5 time zones. Travel and accommodation costs can be a significant cost element for an entire crew. Transporting forms and equipment over such long distances has been problematic. The most common solution is to build *insulated* rammed earth forms on the patent pending SIREWALL System (with or without permission) using locally available wooden materials. Rather than transport an entire crew, highly trained foremen use local unskilled labor to get the job done. Only SIREWALL provides the training for these roving foremen and that training is updated every month.

Seasonal work and much travel are typical of an emerging industry. In the not-too-distant future there will be enough demand to have many centers so that there's not so much travel. The ways of dealing with seasonality will become similar to the rest of the construction industry.

These two factors currently challenge the economic viability of running an *insulated* rammed earth business. Two business responses have evolved. First is the approach of having another primary business that is viable year-round and only taking on the rammed earth work when it is local. This is the part-time approach that is favored by many. Second is the approach of training highly skilled foremen to build using local labor. This full-time approach needs sufficient winter work in the Pacific northwest or in very hot climates (like India, Mexico, Sri Lanka, Portugal, Ghana, Australia, southern USA, etc). The challenge is to have enough trained people on the team when there is a feast and to keep them when there is a famine.

21.7.2 Costs

People understand that it costs lots of money to drive a car off the lot and that depreciation cost is immediate and ongoing. Depreciation in housing is rarely understood. For example, a house that lasts 50 years and costs \$500,000 will depreciate \$10,000 per year on average. The bulk of the depreciation takes place in the first 20 years and after that the repair costs begin to kick in. Most North Americans confuse land price with the cost of the house and it is common to hear ‘My house has more than doubled in the last 20 years!’ This is far from the truth. The value of the house has probably dropped by more than 50% while the value of the land may have tripled. The impact of this misunderstanding is detrimental in the housing market especially for homes that are designed to be sustainable. Because of this misunderstanding and despite the punitive depreciation, North Americans still base most of their decisions on first cost and appearance.

An *insulated* rammed earth building with rigorous attention to thermal envelope detailing can be net zero or have low heating/cooling bills. If not net zero the heating plant or air conditioning unit will be much smaller, hence less initial cost and less cost to run. Maintenance and repair costs of rammed earth walls (inside and out) are near zero for a very long time. Although difficult to quantify on a cost basis, there are health benefits to living inside non-toxic walls.

Payback periods depend on what is factored in (e.g. health, maintenance), the climate and the rigor of the thermal envelope. At today’s energy costs, a payback of at least 10 years is probable, but would need to be calculated for each specific circumstance. North Americans select rammed earth or *insulated* rammed earth to hedge against future energy costs, for thermal and humidity comfort, for health, for low maintenance and to walk the environmental talk.

At this point in time, properly constructed rammed earth is not for the do-it-yourselfers and is not inexpensive on a first-cost basis (it’s a terrific bargain in life-cycle analysis). The range of cost is affected by architectural

1 complexity, whether the design is sympathetic to the formwork and ramming
 2 process, material selection (e.g. white cement, multi-colors, monochromatic),
 3 weather (ramming in monsoon, high heat, freezing and hoarding (building
 4 inside a tent)) and difficulty of site (little room, steep site). Other variables
 5 include location of the project, volume of work, experience of the crew,
 6 source of the material, etc. Most *insulated* rammed earth is 24 in. thick and
 7 occasionally as thin as 18 in.. Most *uninsulated* rammed earth is 12 in. to
 8 24 in. thick. Most, if not all, rammed earth built to Code in North America
 9 requires some steel rebar reinforcing. At present (2011), most *insulated*
 10 rammed earth costs start at \$90/sq ft and *uninsulated* begins at \$60/sq ft.
 11 Costs are widely variable as per the quality of the work and complexity of
 12 the design. Walls that are over 10 ft tall have a premium of typically 50%
 13 applied due to the necessity of fall restraint, Worker Safety Board Compliance
 14 and the 10 ft delivery height limitation of most skidsteers (assuming that
 15 is the delivery method). Mobilization costs can be significant for smaller
 16 projects and large project volumes should reduce costs.

17 Commercial projects carry a premium.
 18

19 **21.8 Case studies of North American earth** 20 **construction**

21 21.8.1 Case study 1: commercial stabilized insulated 22 rammed earth (SIREWALL) in a cold climate 23 24

25 Librarian, Daphne Platte, and architect, John Carney, spearheaded the first
 26 use of *insulated* rammed earth in Wyoming. Pinedale sits at an elevation of
 27 over 7000 ft near the Continental Divide. The weather is cold and windy
 28 in the winter with lows of -30°F (-34°C) (record low -49°F (-45°C)). The
 29 construction was done in the winter inside a heated plastic tent (known as
 30 heating and hoarding). With only three summer months that have never
 31 seen sub-zero temperatures, the time available for building was to be short.
 32 The danger of a power failure (there was one) and the constant high winds,
 33 made the thermal and structural integrity of the tent a focus of concern.
 34 Also, working inside the tent with the exhaust from the skidsteer and the
 35 generator was at times difficult. On the other hand working in T-shirts when
 36 it was -20°F outside was a pleasant respite.

37 There were three rammed earth areas to this building: the large auditorium,
 38 the entry foyer and kitchen and the long hallway. The new construction
 39 was an addition to an older log library and is quite separate in floor plan.
 40 The stabilized *insulated* rammed earth walls are 16 ft tall in the auditorium
 41 and 11 ft tall elsewhere. They are 24 in. thick overall and have 4 in. of
 42 polyisocyanurate foam embedded in the middle. The coloration is a specific
 43 iron oxide and the proportions were slightly varied (for visual interest) as



21.20 Sublette County Public Library in Pinedale, Wyoming – AIA winner of Distinguished Building Award of Citation.

the wall was rammed. The texture of the walls is very effective at creating a good sound quality in the spaces and the building is very quiet (in downtown Pinedale) due to the acoustical attenuation of the thick, *insulated* walls. The earth was a crushed glacial till combined with a coarse angular granitic sand. The average compressive strength of the blend of these two materials combined with 10% Portland cement was 4205 psi (29 MPa) with some results exceeding 6000 psi (41 MPa).

21.8.2 Case study 2: commercial stabilized uninsulated rammed earth in a cold climate

The wall is 15 ft tall by 100 ft long and is straight with a curve towards the end. It sits on a concrete upstand stem wall. The climate is harsher than Wyoming with a range between -57°C and 42°C . The material for the walls came from a limestone quarry and was predominantly a waste product. The compressive strength at 28 days (with only 10% cement) was 24.5 MPa (3550 psi). We used a hydrophobic admixture and a crystalline admixture. There is zero erosion after two winters.

Although we applied an anti-graffiti coating, the SIREWALLs have never been ‘tagged’, despite the adjacent block walls being tagged repeatedly. We conclude that taggers don’t think it’s cool to mark rammed earth.

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21.21 Grand Beach Public Washrooms north of Winnipeg, Manitoba.



21.22 Nk'Mip Desert Cultural Center, Osoyoos, BC – World Architecture Festival Winner, Governor General's Award.

21.8.3 Case study 3: commercial stabilized insulated rammed earth in a desert climate

This award-winning project is located in Canada's only desert, with temperatures that vary between -30°C and 40°C . The main wall measures

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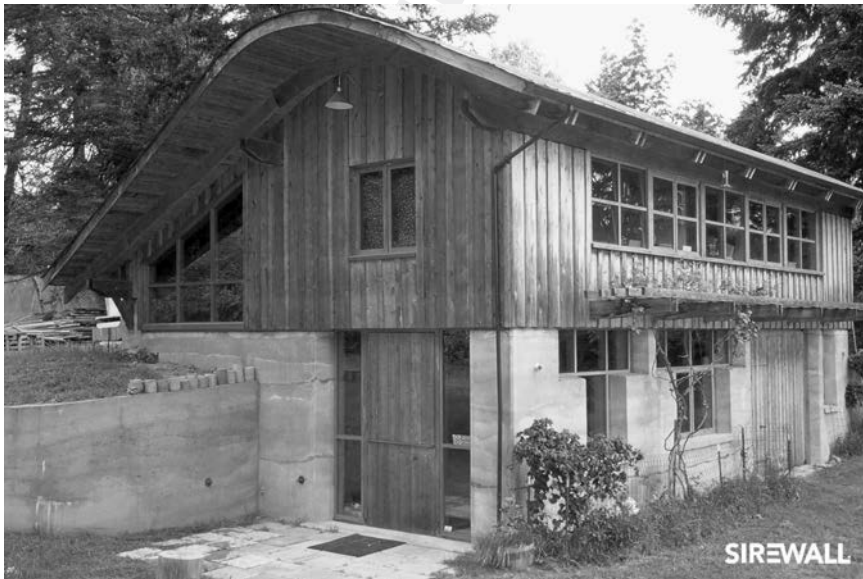
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200 ft ¥ 20 ft tall and is composed of 30 different lifts. Each lift color was specified by the architect after reviewing 40 test color samples. The intention of the building blending into its surroundings was very successfully met. The most challenging technical aspect of this project was the 100 tons of hanging rammed earth over the horizontal slot window.

There was a surprising lack of non-structural cracking in these walls despite the paucity of control joints specified by the architect.

21.8.4 Case study 4: residential stabilized insulated rammed earth in a wet climate

This 2000 sq ft building constructed in 1994, has passive solar exposure to the south and is backfilled to 12 ft on the north side. Extending out the west side of the building is a buttress wall that has a cistern behind it. The buttress wall is fully exposed to the elements and shows no sign of deterioration. The acoustical attenuation is very important as the sounds from the inside shouldn't disturb neighbors, and conversely any outside sounds need to be absent when recording is underway. This is one of very few projects where soils were not blended to come up with the wall mix. This was because the local pit, at the time (lasted only a few years), had a very good particle size distribution in its glacial till, therefore soil blending wasn't necessary.



21.23 Music studio in residential neighborhood on Saltspring Island, BC.

21.9 Design elegance of modern earth buildings

Design usually considers such things as proportion, rhythm, inferred space, texture, color, massing, etc. All these are vital and valid considerations. What's missing are the three seventh generation considerations that ensure sustainability: durability, simplicity and multifunctionality. Durability answers the problems caused by our disposable approach to building and is essential if we want to leave gifts to the seventh generation. As yet few greenbuilding metrics appreciate that durability is core to sustainability.

The pursuit of simplicity, particularly in electrical/mechanical systems, is difficult to realize in isolation from the rest of the building's systems. There are net zero buildings being built, ostensibly as an expression of concern for the environment, that have mechanical rooms full of equipment sufficient for a building many times their size. The thinking is that the route to net zero is more and more photovoltaics, more and more geothermal, all of which address the supply side. Reducing the need for energy doesn't require pumps, fans, compressors, relays, anticipators, valves or all the electrical requirements. Conservation is not particularly sexy, but it has nothing to break down or maintain. If we imagine a SIREWALL in seven generations (nothing has changed) and compare it with an electrical/mechanical room in seven generations, the contrast is stark indeed. Probably nothing of the original electrical/mechanical room is original, even in two generations and if there is something original, one can be sure that parts are unavailable. Every pump, relay, compressor, alternator, electrical panel and control is a strike against sustainability. Simplicity involves using nature's tools, such as gravity, thermosyphons, radiant heat distribution, conduction and convection. Reduction of moving parts and complex manufactured components is the goal.

One material or idea serving multiple functions runs against the theme of specialization that is so prevalent today. An exterior wood frame wall requires many trades (framer, electrician, plumber, insulator, drywaller, sider, painter) and the number of materials is several times that. All that complexity can be replaced by one trade using rammed earth, rebar, conduits and insulation.

It is possible for rammed earth or *insulated* rammed earth to provide the following:

- 1 conductive, convective and radiant thermal performance in one material/process
- 2 loadbearing capability
- 3 toxin-free walls for healthy living
- 4 stable thermal and humidity interior profiles through temperature and humidity flywheel effects
- 5 a radiant environment with reduced dust and other airborne undesirables (bacteriophage, viruses, molds, dander, etc.)

- 6 acoustic attenuation from outdoor noises such as airplanes, lawnmowers, barking dogs, traffic, construction noise, etc.
- 7 acoustic dispersion qualities for high-quality interior acoustic environments through careful attention to the mix design
- 8 a strong statement about concern for the environment – expressing leadership
- 9 ongoing energy savings – net zero for heating and cooling
- 10 ongoing energy security – not worrying about where energy costs might go
- 11 durability – reduced maintenance and reduced depreciation
- 12 fire safety – protection from wildfires and in-house fires
- 13 beauty, drama and grace.

All of the above is achieved with *insulated* rammed earth and as one building trade.

Earlier in this chapter was the example of how the single-purpose Trombe wall was upgraded by SIREWALL into a structural element with inherent visual appeal while retaining its usefulness as a thermal flywheel (only better due to much greater heat exchange surface area). By contrast there exist a couple of SIREWALL structures where the client and architect were solely interested in the visual, visceral beauty of the material. Those structures have steel columns embedded within the SIREWALL to carry the roof loads (redundant) and unfortunately few other benefits were realized. If I were to imagine the most elegant use of the material it would be for a concert hall, museum, art gallery or winery. The *insulated* rammed earth walls would be structural, the quick-response heating, ventilation and air conditioning (HVAC) system would be one-quarter of its normal size taking advantage of the humidity and thermal flywheels, the texture of the walls would be selected for optimal acoustical dispersion, the fire-resistant capabilities of rammed earth so important for public assembly would be taken advantage of, the acoustical attenuation would allow the building to be built in almost any acoustical environment (near airports and fire or ambulance stations) and all the other benefits would come along for the ride. Note the possibility of replacing the moving parts and maintenance of HVAC with earth. Now that is design elegance!

Because the benefit most appreciated by clients is the visual appeal, let's unpack that and take a look at some of what's possible:

- 1 metaphorically, the visual intent is to have the wall look as though a laser has sliced twice through a mountain and the resulting slab has been delivered to site
- 2 an alternative visual intent is to have the wall look as though the ground around it has been cut away
- 3 the intent is to have the means of construction visible in the outcome, including tie-holes, seams and any fastenings

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- 1 4 carving of the formwork to allow the rammed earth to sit proud as per
- 2 the carving. Natural carving subjects are fossils and prehistoric plants,
- 3 animals
- 4 5 embedding of geodes, abalone shells, oyster shells, clam shells, etc.
- 5 6 feature lines of contrasting, complementary or shaded coloration
- 6 7 'soft' details like bullnosed wall ends, curved walls, bullnosed buttresses,
- 7 round columns
- 8 8 'crisp' details like hard corners, crisp chamfers of many sizes, 45°
- 9 corners
- 10 9 multi-color sedimentary layers
- 11 10 rhythmic, undulating and 'wavy gravy', non-horizontal lifts.

12 It is important to note that the beauty of rammed earth is, in part, derived
 13 from its inconsistency. It is inconsistent in color and texture and may have
 14 a little efflorescence or hairline cracks. That inconsistency can make it
 15 difficult to determine what is acceptable. The danger is to require uniformity
 16 and thereby compromise the raw, natural beauty. It would be like requiring
 17 raw silk to look like finished silk. The 'flaws' are what make it interesting!
 18 What is really important is that there is no compromise on functionality (e.g.
 19 strength, water-tight integrity, thermal envelope integrity, etc.)

22 21.10 Future trends

23 Whether there is a future for rammed earth in North America is not in question.
 24 The question is when. Rammed earth and particularly *insulated* rammed
 25 earth are waiting for the market to catch up. As time goes by there is more
 26 public awareness as to the importance of durable, healthy, energy-efficient
 27 buildings that don't consume organic building materials. For our species'
 28 survival, we will need to broadly adopt seventh generation thinking and the
 29 C2C approach. As energy costs go up and our organic resources become more
 30 expensive, the first cost viability of all rammed earth will flourish (having a
 31 great life cycle cost seems to have little impact on market acceptance). The
 32 market will expand from the visionary first adopters to the mainstream.

33 The future potential of rammed earth is easily understood if one compares
 34 with a brick wall, where every brick is manufactured offsite, delivered to the
 35 site, delivered to the mason, picked up by hand, buttered, put in place and
 36 tapped to its final position. This process of repeatedly placing tiny modules
 37 (bricks) to create a wall is, surprisingly, economically viable. It would seem
 38 not very difficult to create rammed earth that is quicker to build than a brick
 39 wall. Rammed earth walls can be thought of as much larger modules than
 40 the brick. If rammed earth can be placed a cubic yard at a time inside of
 41 formwork that takes very little time to erect or strip and is rammed as it is
 42 now then the rammed earth labor costs will be a fraction of what they are
 43

now and the material costs not far different. However the product will be far superior, while being financially competitive. Manufacturing large modules on site has the potential to be much more efficient than the brick industry. It will take more research and development to realize that potential.

Further R&D of large rammed earth modules in North America will lead to:

- simpler, quicker forming systems, perhaps with fabric
- simpler, quicker delivery to the forms
- quicker, more reliable and accurate mixing
- offsite manufacturing of large *insulated* rammed earth modules in warehouses in winter to allow rapid erection in the summer (as a means of dealing with seasonality)
- faster and more cost-effective manufacturing processes than the current cottage industry/artisanal approaches
- less cement required but more pozzolans
- a network of architects and engineers who appreciate and implement the benefits and unique considerations for rammed earth fabrication through an integrated design process when possible.
- a network of general contractors who have learned how to work with the rammed earth process
- broad acceptance and Code approval
- established through material testing and international material standards as well as being included in national master specification systems
- recognized as a green building and regenerative building product by the most stringent green building and regenerative rating systems
- greatly expanded North American and global applications, and opportunities for *insulated* and *uninsulated* rammed earth for the full range of building and mixed-use occupancies from assembly occupancies with public and educational facilities, business, institutional and healthcare, commercial and mercantile, residential and housing and factory and high-hazard occupancies.

The future increased viability of modern rammed earth will depend on developing systems and technologies that allow scaling up and vastly increased efficiencies. As with most emerging technologies, it is difficult to afford the R&D to develop the systems and technologies that will allow rammed earth to evolve to its full potential. Until now, it is the passionate builders who, with their personal savings and/or profits, fund the incremental improvements that have made North American rammed earth so much better than it used to be.

1 **21.11 Sources of further information**

2 SIREWALL Introduction to *Insulated* Rammed Earth course
3 SIREWALL website and newsletters
4
5

6 **21.12 Acknowledgments**

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