Chapter 1

Introduction

There are many appealing features to building with rammed earth. Aesthetically, rammed earth is very pleasing — from the sedimentary layer effect of the lift lines to the surface textures on a wall. Site materials can be used to create major structural and building envelope elements, which means low embodied energy and a small carbon footprint for those components. Rammed earth is inherently massive, which translates into interior thermal stability, even when there are large temperature swings outdoors (especially within an insulated envelope). The mix design generally includes clay, so it has an open pore structure that, depending on the application of sealers, allows rammed earth to absorb and shed water vapor, which can modulate extremes in indoor humidity. Raw rammed earth construction can be carried out using entirely nontoxic materials, fostering a healthy indoor environment with no added volatiles or toxins in the air. Stabilized rammed earth can act as both an interior and an exterior finished wall surface, even in harsh northern climates. This means minimal long-term maintenance because it eliminates the need for paints and stains — although unstabilized mixes on exterior walls may require periodic application of sealers, a protective plaster coating, or even a rainscreen assembly for extreme conditions.

I am currently a practicing professional engineer. While I first came to construction over 30 years ago, it was as a laborer, then a carpenter, and then an amateur mason. Now I collaborate closely with many experienced builders and aspiring ones (along with owner-builders, who usually fall somewhere between the two), but I do not regularly hold tools in my hands other than a computer mouse, a calculator, and pen and paper. I do continue to build things myself as a hobby and for research purposes, and where possible I do like to get my hands dirty on job sites — but the majority of my time is spent at my desk, not on site. That said, this book is directed primarily to builders.

Many professionals in the rammed earth building community have contributed to this book, allowing me to present readers with the current state of the art.

This book is unique because its approach is from a North American point of view, in particular Canada and the northern US, where the cold climate requires additional insulation to be incorporated into the building envelope. Freeze-thaw cycles require considerably more attention in both materials and detailing. High snow loads are common, and wind and seismic loads are also prevalent. Canada also has relatively conservative, limit-states design codes for structural engineering. This book will review several international codes and discuss the ramifications for builders working in Canada and the US.

I am often reminded of a conversation I had with George Nez, a pioneer of thin-shell roof construction. He had traveled up to southern Ontario from his home in Colorado to help run a workshop on how to build roof elements with various fabrics and acrylic-cement-sand mixes applied in layers on first-order hyperbolic shapes. He had been observing how the builders, students, and designers responded to his techniques for several days. We were together in the shade on a hot day watching students apply a second layer to one of the forms. While everyone involved agreed that this was a novel method, most of us were trying to imagine ways we could make these roofs work with our own building modes. In an almost exasperated voice, he told me that we were all "wall builders." He basically thought we were missing the point. The people in the area in Africa that George had been working in during the 1960s needed *overhead* shelter far more than they needed walls. The principal reason for developing this method had been the need for lightweight, durable roofs that could be either built in place or lifted onto simple pole structures. If walls were desired, with this method, they could be in-filled later. But for many reasons (cold weather and swarming insects being the first that come to mind), builders in my part of the world do, indeed, tend to be wall builders first and roof builders second. So, this book begins by examining where and when rammed earth is appropriate, focusing on walls (Chapter 2).

From there the topic shifts to focus on design considerations and building science. The four control layers — water, air vapor, and thermal — are each discussed in detail (Chapter 3).

Consideration of the materials involved in rammed earth follows, including examination of the properties and role of clay, stabilizers, aggregate, and sealers. Appropriate on- and off-site testing is discussed in detail (Chapter 4).

The structural criteria for raw and stabilized rammed earth buildings are covered in Chapter 5. Some of the topics included are wall height/thickness ratios, loads and stresses, wall length limits, openings and attachment points, and provision for utilities. Section and elevation drawings of several wall systems are presented.

After characterizing the material, a discussion of necessary tools and labor follows, covering both state-of-the-art industrial methods and low-tech, pre-industrial techniques (Chapter 6).

A range of formwork options are presented in Chapter 7, and details regarding insulation, corners, different construction configurations, and workflow are discussed. General tips and techniques and instruction about removing formply are given, and a word about volunteer labor is included.

Chapter 8 gives cost estimates based on a 2015 project using cement-stabilized rammed earth with interior insulation. Ranges of costs for materials, design, equipment, and labor are given.

Finishes, maintenance, and repairs are covered in Chapter 9.

Finally, a survey of existing codes, testing standards and building permit considerations is presented. A sample specification is given, as well as an example of an alternative solutions proposal from a recent Canadian project (Chapter 10).

A word about units: I will use both Imperial and SI units in this text, as practicing engineering in Canada brings with it a need to be "bilingual" in terms of measurement. I apologize to anyone for any confusion this may cause, and I trust that we will all check our sums to avoid any errors.

There is a bibliography at the end of the book, but I give notable academic paper references at the end of some of the chapters. This book is not aiming to be a comprehensive survey of the academic literature, but my practice as an engineer is informed by current research whenever possible. The interested reader is encouraged to explore the literature — there is quite a lot of research going on in earthen construction worldwide.

Chapter 2

Rationale and Appropriate Use

I have always been fascinated by the idea of creating a structure entirely out of material found on the site. Rammed earth is not always made up of in-situ material, but it holds that potential. Earth is a material available almost everywhere above sea level, and it is likely that the first permanent buildings were earthen. Pretty much anywhere humans have managed to build maintainable roads, there exist the basic soil elements — gravel, sand, silt, and clay (and water) — necessary to create raw rammed earth. It is because of this availability that earthen construction is among the oldest types on the planet, and it is still common in most of the world. Whether it's adobe, wattle and daub, cob, compressed earth block, or rammed earth — be it raw or stabilized — more than a billion people (as well as other animals, termites and many other insects, and many species of bird) live in earthen structures.

Definitions: Historic and Modern Additives

What is rammed earth? The name tells us both the method and the material. It is a mix of damp soil elements (earth) manually compressed (rammed) to a high density, held together by a combination of some type of binder and the effects of surface tension (what an engineer might call *matric suction*). In the literature on the subject, you will see much discussion about the desirability of *raw* versus *stabilized* rammed earth. Why differentiate between raw rammed earth and stabilized? In simple terms, raw rammed earth is made up of only gravel, sand, silt, clay, air, and water strategically mixed and then rammed into a pre-made formwork.

Stabilized rammed earth adds an additional binder (usually pozzolanic or cementitious) to the clay, which changes the surface tension effects caused by drying. Pozzolanic binders are often referred to as *Roman cement*; the name comes from the volcanic soils found near the town of Pozzuoli in Italy. Modern pozzolans are ground blast-furnace slag, ash from coal-fired power plant operation, and other by-products of high-heat processes such as calcined clay. Cementitious binders are a special set of pozzolans — they are primary products of very high-heat processes. The best-known is Portland cement, but hydrated lime can also fall into this category.

Historically, casein (dairy protein) and tar were the earliest common stabilizers added to soil mixes, along with straw or other fibrous materials to add tensile capacity (although the latter is more common with adobe and cob building). Lime and naturally occurring pozzolans have been added to rammed earth for over a millennia; Portland cement and other artificial pozzolans have been added in more recent centuries.

Raw Earth Versus Stabilized Earth

Some current practitioners, particularly in Europe, promote raw rammed earth over stabilized, citing lower carbon footprint and embodied energy along with total recyclability, among other characteristics. As a builder passionate about sustainable built environments, I agree whole-heartedly. As a professional engineer practicing in Canada, I have a difficult time designing and approving stand-alone raw earth buildings. Both the physical and regulatory climates in North America make it difficult to build code-conforming, durable raw earth structures. Freeze-thaw cycles, a feature of most building sites in Canada and the northern US, make the durability of raw earth walls dubious without the addition of a protective layer on the exterior — either a plaster or some kind of rainscreen assembly. While it is physically possible to use an earthen plaster for this protective layer, and it is theoretically possible to maintain this plaster indefinitely, the code requirements in North America do not provide an easy path to approval for such a design. Further, many clients are principally attracted to rammed earth's aesthetic qualities, and covering it up is counter to that. Additional layers also add cost and complexity to the construction process. That said, there is no practical reason stating that a builder can't construct a raw earth wall and then clad the exterior with a rainscreen to create an assembly that could be defended within the *alternative solutions provisions* of the Canadian building code. I am certain that a similar strategy could be undertaken to meet the requirements of the International Building Code (IBC) in the United States for a raw rammed earth building. In short, in order to have fully exposed rammed earth on both interior and exterior surfaces of a code-conforming structure in North America, stabilization of one sort or another is mandatory. That does not mean raw rammed earth cannot be built in a code-conforming manner, but it will need some kind of external weather protection, and it may be limited to nonseismic areas as a structural element.

In terms of material selection, we will cover both raw and stabilized rammed earth. There is a significant difference in mix design between the two. My experience is primarily with stabilized rammed earth, focusing on pozzolanic binders to increase strength along with silica-based admixtures to reduce permeability in order to promote durability under repeated wet-dry and freeze-thaw load cycles. Detractors may argue that this means we are effectively creating nothing more than damp-pack concrete, and I cannot argue. It is an approach along these lines that has allowed me to obtain a building permit for a rammed earth project in one of Canada's most restrictive jurisdictions — the city of Ottawa.

While it is not the purpose of this volume to go into detail regarding engineering design, it bears stating that my current engineering design methodology follows the Canadian Masonry Design Code — CSA S304.1. There are several reasons for working with masonry codes rather than codes that deal with concrete building:

- Clay is a significant portion of the aggregate mix. Soil mixes containing particles smaller than 80 microns are not allowed in code-conforming concrete design. This is true in both the US and Canada.
- In masonry design, there is no prescriptively defined minimum compressive strength. For code-conforming concrete design, there is a minimum 28-day compressive strength required in prescriptive building codes by both American Concrete Institute (ACI) and Canadian Standards Association (CSA) design standards. In order to achieve these strengths a mere four weeks after mixing and placing, relatively high amounts of Portland cement are required, and this increases the carbon footprint and embodied energy of the material to the same levels as conventional ready-mix concrete. Masonry design codes allow for the compressive strength of a wall system to be designed in accordance with the actual load requirements of the intended building and the particular material assembly of masonry units and mortar proposed.

- Within masonry codes, there are lower minimum requirements for amount and spacing of reinforcing steel. For many reasons, the minimum cross-sectional area of reinforcing steel to cross-sectional area of a given masonry wall element is considerably less than the minimum cross-sectional area of reinforcing steel in a comparable concrete wall element.
- There are established existing masonry building codes that work in rammed earth's favor, rather than against it. One of the most complete current national rammed earth building codes, from New Zealand, is based on an engineered masonry design methodology.

Embodied Energy and Carbon

While this book is not aiming to be a comprehensive source of information on the embodied energy and carbon in rammed earth, I will attempt to give the reader tools to help evaluate their design mixes with respect to these important, but not commonly understood characteristics. Like the other volumes in the *Sustainable Building Essentials* series, as well as Chris Magwood's *Making Better Buildings*, I am using the Inventory of Carbon & Energy (ICE) as the source for data on embodied energy and carbon for the materials used in rammed earth construction. The ICE database gives "cradle to gate" data for the manufacture and transport of materials only, and does not account for operational energy or thermal characteristics of the buildings created using them. The ICE was developed by professors Geoff Hammond and Craig Jones from the Sustainable Energy Research Team (SERT) in the Department of Mechanical Engineering at the University of Bath, UK. The version used in this book is V2.0, last updated January 2011. The database is open for use by the public, and the boundary conditions of its definitions and calculations are available for review. The database is hosted at circularecology.com.

The table below is a summary of the embodied energy and carbon for the basic ingredients used in rammed earth mixes, as well as several complete mixes (both raw and stabilized rammed earth) and comparable structural materials, like concrete. I have also included numbers for reinforcing steel and some common insulation materials. The first column to the right of the material's name is the embodied energy in mega-Joules per kilogram, followed by the embodied carbon in kilograms of carbon dioxide per kilogram of material, and finally the embodied carbon in kilograms of carbon dioxide equivalent per kilogram of material. The embodied carbon in kg/CO_2 is a measure of CO_2 emissions generated during the lifespan of the product or material in question. The embodied carbon dioxide equivalent, in kg/CO_2e, is a measure of all the greenhouse gases generated, normalized to CO_2. For instance, if 1 kg of methane (CH_4) is emitted during production of a given material, that portion would be added in as approximately 28 kg/CO_2e.

The data in the table is not likely to be accurately representative of the wide variety of material sources currently available in North America, but it nonetheless represents one of the best-researched collections for building materials, and it is still very useful for meaningful comparisons within its scope. That is to say, while the final number for any given material may not be exactly correct for that material in your particular neighborhood, all of these numbers are based on a consistent methodology and are useful for comparing with each other.

For example, it is interesting to note that the relative increase in embodied *energy,* measured in mega-Joules per kilogram, going from raw rammed earth to stabilized rammed earth with 5% Portland cement (by mass) is 0.68 – 0.45 = 0.23, or just over 50%. At the same time, the relative embodied *carbon* increase, measured in kilograms of carbon equivalent, from the addition of this small amount of stabilizer is 0.061 – 0.024 = 0.037, or more than 160%. This is a useful "apples-to-apples" comparison.

Full life-cycle analysis (LCA) and general accounting of embodied energy and carbon is beyond the scope of this book, but it is a rapidly developing field that promises better-informed design comparisons for all building materials in the near future. Environmental Product Declarations (EPDs) are becoming mandatory for manufacturers to provide in order to meet tender and specification requirements, and this holds promise of greater transparency when sourcing materials. Recent legislation in Washington State and California requires EPDs to facilitate carbon accounting in order to meet climate change commitments.

That said, a building material like rammed earth, which is not a consistently manufactured product, may find itself on the outside looking in if this type of accounting cannot accommodate site-built construction types. There are many natural building practitioners, designers, and academics working on this. I encourage the interested reader to look up the Embodied Carbon Network, which is part of the Carbon Leadership Forum. In particular, review the work of the task force on renewable materials for more current and detailed information.

Relevant Research

Arrigoni, Alessandro Marocco. "How sustainable are natural construction materials? Stabilized rammed earth, hempcrete and other strategies to reduce the life cycle environmental impact of buildings." Doctoral thesis, Politecnico di Milano, 2017.

Arrigoni, Alessandro, et al. "Life cycle analysis of environmental impact vs. durability of stabilized rammed earth." *Construction and Building Materials* 142, 2017, pp. 128–136.

Table 2.1: ICE values for embodied energy and carbon in materials relevant to rammed earth building

Material	Embodied energy in MJ/kg	Embodied carbon dioxide in kgCO_2/kg	Embodied CO_2e (carbon dioxide equivalent) in kgCO_2e/kg	Comments
Rammed earth — site soil	0.45	0.023	0.024	Raw earth — no chemical stabilizer added
Stabilized rammed earth — 5% cement	0.68	0.060	0.061	5% Portland cement added (by mass)
Stabilized rammed earth — 8% cement	0.83	0.082	0.084	8% stabilizer — 6% Portland cement, 2% lime (by mass)
Sand	0.081	0.0048	0.0051	UK data — heavily influenced by fuel/transport costs
Aggregate — general	0.083	0.0048	0.0052	UK data — heavily influenced by fuel/transport costs
Ground limestone	0.62	0.032	—	Not based on a large sample size*
Regular Portland cement	5.50	0.93	0.95	Normal Portland cement — 94% clinker, 5% gypsum, 1% minor additional constituents
Cement with 6%–20% fly ash	5.28 (6%) to 4.51 (20%)	0.88 (6%) to 0.75 (20%)	0.89 (6%) to 0.76 (20%)	Regular Portland cement amended with fly ash from coal-fired electricity generation
Cement with 21%–35% fly ash	4.45 (21%) to 3.68 (35%)	0.74 (21%) to 0.61 (35%)	0.75 (21%) to 0.62 (35%)	Regular Portland cement amended with fly ash from coal-fired electricity generation
Lime	5.30	0.76	0.78	ICE researchers noted that embodied carbon was difficult to measure for lime**
Concrete	0.75	0.100	0.107	25 MPa concrete — common compressive strength threshold for reinforced structural concrete ~12% cement binder by mass
Bitumen	51	0.38 to 0.43	0.43 to 0.55	42 MJ/kg feedstock energy included. CO_2 emissions are difficult to determine, so a range is given
Glass Fiber Reinforced Plastic (GFRP)	100	8.1	—	1998 data from the Steel Construction Institute
Steel rebar	21.60	1.74	1.86	World average recycled content
Cellular glass	27	—	—	No CO_2 data available in the ICE database
Cellulose	0.94 to 3.3	—	—	No CO_2 data available in the ICE database
Cork	4	0.19	—	2003 data from "Ecohouse 2: A Design Guide," Roaf, Fuentes, and Thomas
Mineral wool	16.60	1.20	1.28	2003 data from LCA documents 8, Eco-Informa Press
Rock wool	16.80	1.05	1.12	
Expanded polystyrene	88.60	2.55	3.29	46.2 MJ/kg feedstock energy included
Extruded polystyrene	109.20	3.45	4.39	49.7 MJ/kg feedstock energy included
Polyurethane rigid foam	101.50	3.48	4.26	37.1 MJ/kg feedstock energy included

Source: Inventory of Carbon & Energy (ICE) Version 2.0.

*Crushed limestone is included because it is similar in chemical composition to limestone screenings, which have been used with some success as a part of a stabilizer substitute/reducer for Portland cement. Limestone screenings, a by-product of aggregate extraction and processing in limestone rich quarries is not the same as industrially ground limestone, purposely made into a fine powder, nor does it have the same embodied energy, as the process is less intense. Crushed limestone is commonly used as a base for stabilized rammed earth in western Australia, and may be a good option for places where it is available and the site sub-soils are not suitable for rammed earth.

**There is no clear agreement in the scientific community on how to account for carbonation that occurs during the operating life of a lime-based element like an exterior plaster. The laws of thermodynamics dictate that it cannot be carbon neutral.