Introduction: Thinking about sustainable building

There is a remarkable paradox when it comes to introducing new technologies, in construction or any other field. We expect new ideas or technologies to live up to unrealistically high standards, while at the same time we accept as normal many existing ideas or technologies that are inherently deeply flawed.

It is a commendable tendency to try to be "objective" about new ideas and weigh as much evidence as we have at hand in deciding whether or not we think they are worthy. But we tend to be much less than objective about the ideas and technologies we use on a daily basis. Because they are normal to us, we rarely examine them in any meaningful way. A certain degree of inevitability is attributed to the ideas we've normalized; we don't see them as choices in the same way we see new ideas as choices.

There are countless examples of this paradox in everything we do. In the building world, we find a great example in the use of milled lumber as our prime residential building material. Wood has every flaw imaginable for a building material. It burns; it rots; it's insect food; it warps, twists and cracks; it's a great medium for growing mold; its structural properties vary greatly by species, milling, drying and storing practices; it's often grown far from where it's needed; it's heavy; it's dimensionally unstable as climatic conditions change....

And yet it has come to serve us very well as a building material. We used a natural material that was available to us and figured out how to deal with all its "micro-flaws." In the end, we've normalized it and built an entire successful industry around an entirely flawed material! But if we introduce a new material that has even a small number of the flaws inherent in wood, we find ourselves up against naysayers who can only see the flaws and not the possibilities for being able to work with them.

There is no such thing as an idea or technology with no flaws. Recognizing this simple point is key to being able to consider new ideas fairly. There is an experiment I perform at public talks: I ask the audience how many of them have had to deal with a toilet backup at some point in their lives. The show of hands is almost guaranteed to be unanimous. Then I ask that same audience if they think the flush toilet is a bad, flawed idea that "doesn't work"; very few say Yes. And this despite having to regularly deal with some very unpleasant consequences due to an inherent flaw in the technology. We accept the micro-flaw of an occasional toilet backup as a reasonable trade-off for the convenience of using a flush toilet. However, I hear frequently that composting toilets "don't work" based on second-hand reports of a single incidence of the composter smelling or not composting properly. There's the paradox: the "normal" technology fails disgustingly at a rate of 100 percent, and yet the "alternative" is the one that gets branded as something that "doesn't work." In truth, both systems have some inherent flaws, and both will fail on occasion.

We've just learned to accept the micro-flaws of one and reject the micro-flaws of the other.

Every technology that we examine in this book has a number of micro-flaws, as do those conventional technologies they might replace. This book does not attempt to gloss over any micro-flaws. But the comparisons between sustainable technologies and their conventional counterparts do not and cannot stop at the level of micro-flaws. Sustainable building strives to address the larger and much more important macro-flaws in our approach to building.

It is at the macro level that all of the materials in this book have their advantages over conventional practices. To continue the comparison between flush toilets and composting toilets, we can see that both can be practically functional but also have some micro-flaws. On the macro level, however, the flush toilet is part of a system that sees billions of gallons of untreated or partially treated sewage enter our streams, rivers, lakes and oceans, while using vast amounts of clean potable water and a very expensive public infrastructure. Meanwhile, composting toilets can turn human "waste" into a valuable fertilizer with minimal infrastructure and little to no fresh water usage. It is at this macro level that we should be assessing our building technologies. In this case, the advantages of the composting toilet should be very clear.

If we can start making wise choices at the macro level, we can trust ourselves to figure out how to minimize the micro-flaws of any technology. We humans are incredibly good at refining ideas and techniques. Through repetition, we gain insights that allow us to make the process better and better each time we use it. We're good at doing things better, but we're not very good at doing better things. Doing better things means looking beyond the micro-flaws and basing our choices on minimizing impacts at the macro level.

One of the challenges in adopting any new technology is figuring out where we are on the learning curve, and at what point on that curve we feel comfortable jumping on board. Some of the systems presented here are quite well developed, with installation and maintenance instructions that are very complete and manufacturer and installer warranties that back them up. Others are relative newcomers (at least in the modern context) and the instruction manuals are literally being written and refined right now. We may not know the very best way to use some of these systems until a lot more early adopters have trial-and-errored their way to some kind of standardized practice.

This book is about making better buildings. Better buildings don't wreck the planet. Better buildings do not waste resources. Better buildings are healthy places for their occupants. Better buildings are better at the macro level. The micro stuff we will figure out, as we always have done.

How this book works

The past decade has seen an incredible shift in awareness about the environmental impacts of our built environment. The notion of building sustainably has moved from the rumblings and experimentation of a few fringe activists to a pervasive notion that has an entire industry questioning its priorities and methodologies.

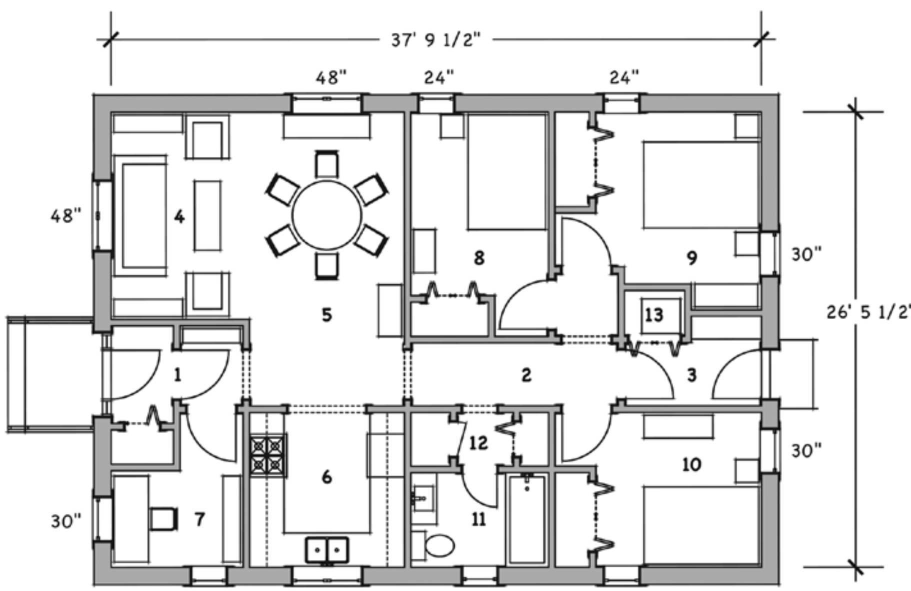
As the building industry reorganizes itself, the first round of changes we are witnessing is the "green building revolution." Green building brings a wide range of improvements to the ways in which we currently make our buildings. It is an important early step in changing a massive, multi-faceted industry, and the inroads made by green building advocates have already brought about remarkable changes in a very short time.

As huge a shift as the green building revolution continues to be, sustainable building activists are attempting to thoroughly reconsider and reinvent how we use materials and energy. The move to more realistically sustainable building will be as remarkable a change as the steel-and-concrete revolution of the early twentieth century.

In the twentieth century, cheap energy dramatically reorganized the building industry. For most of human history, manual labor had been used to convert local raw materials into buildings. The harvesting, processing and crafting of materials into buildings was done regionally, and it was the work of a great number of people in every city, town and village to provide these services. With cheap fossil fuel energy, the economic scale tipped radically in favor of mechanized processes. Materials are now harvested more intensively, transported to centralized factories to be processed, and then transported as building products to distributors, sub-distributors and retailers. Local trades purchase these products and assemble them into buildings using as little manual labor as possible. The occupants of buildings have become far removed from the process of designing and constructing, and therefore know little about what goes into making a building.

Cheap fossil fuel has enabled our society to build more, faster and bigger than anyone could have conceived a century ago. The merits of this growth are endlessly debatable, but we have collectively learned a lot about how to build quickly, efficiently and well. This book is written with the recognition that this era — with all its good and bad points — is coming to an end. The timing and nature of that end are also debatable, but what interests us is, what comes next?

There is no way to predict the direction any major revolution in ideas will take. There are, however, some visible signposts that can be followed in a direction that makes sense from our current vantage point. We aren't forecasting what kinds of new materials might be developed in the future—all of the building materials and systems covered in this book are being used to make buildings right now. Every material and system we examine is currently being



LEGEND

1 - Front Entry	50 SF	6 - Kitchen	81 SF	11- Bathroom	44 SF
2 - Hallways	60 SF	7 - Office/Den	55 SF	12- Linen&Mech	25 SF
3 - Rear Entry	35 SF	8 - Bedroom	104 SF	13- Laundry	10 SF
4 - Living	96 SF	9 - Bedroom	122 SF	**- Walls	55 SF
5 - Dining	153 SF	10- Bedroom	108 SF		

- All Doorways 34" Except: Bathroom 24"; Closets (Varies)

01 / 1000 — 1000 SF Prototype House
Floorplan - 1/8" = 1'-0"

used to make code-approved buildings that can meet modern standards of comfort, climate control and structural stability, yet with substantially lowered environmental impacts.

In this time of transition it can be difficult to assess new technologies and ideas, and that's where this book's approach attempts to be useful. We recognize that some of the systems examined in this book lend themselves very well to existing approaches to building and are only ever so slightly outside the mainstream. Others are much further from conventional approaches. We are not setting materials or systems against each other in a competitive manner; instead, we're attempting to objectively apply a well-rounded set of criteria to each one. Our criteria are:

Environmental impacts — What effects do the harvesting, manufacturing, transportation and use of this material have on our ecosystem?
Embodied energy — How much energy is required to harvest, process, transport and install this material?
Waste — What happens to the leftover material at the end of a project?
Energy efficiency — What impacts will the use of this material have on the energy efficiency of the finished building?
Material costs — What are the costs of acquiring and installing this material, based on current quotes for a sample home?
Labor input — How much labor is required to acquire and install this material based on current quotes for a sample home?
Ease of construction for homeowners — What level of skill is required for a homeowner to successfully install this material?
Sourcing/Availability — How widely available is this material, and where can it be obtained?
Durability — How long will this material last given appropriate conditions?
Code compliance — Is this material currently compliant with building code prescriptions and, if not, how is it treated/accepted as an alternative method?
Indoor air quality — What impact does the use of this material have on the indoor air quality in the finished building?
Future development — Does this material lend itself to significant improvements and therefore more widespread use in the near future?

All of these criteria are very important to a sustainable way of building, but not every one will have the same degree of importance for you as a designer, builder or homeowner.

There are no prescriptions, no "winners" in this book. In the end it will be up to you to weigh the information presented and make decisions according to your own needs. A builder looking for the lowest-cost options will find different answers than somebody looking for the highest indoor air quality or best energy efficiency.

Every building system summarized here is worthy of a book, and we point to those resources at the end of each section. There is no way to fully explain the intricacies and nuances of every system, and in attempting to summarize them we will certainly offend those who have devoted entire careers to a building method we explain and rate in just a few pages. Our intent is not to provide a "how-to" guide for any of these materials or systems, or a scientifically definitive rating. Instead we provide an attempt at an even-handed, objective comparison of the relative merits of systems that are all good choices. If there was a bad option, it wasn't included. If there were just one choice that trumped all others, we'd all be building that way. There isn't, and we don't. In the comparison charts, a low score is not a bad thing; it just places that material/technology on a spectrum compared to other viable options. Compared to many conventional building options, these choices are all at the same positive end of the spectrum.

Where we use hard figures to quantify certain criteria, we are doing so based on a theoretical building, so that we are comparing identical scenarios across the board. Our theoretical building is a 1,000-square-foot (93-m3) bungalow with a simple hip roof, and the floor plans and elevation are presented. Obviously, your building project is unlikely to match this exact description, but the figures may be extrapolated and used as reasonable guidelines for your project.

This book can provide options, but it is up to each designer/builder to fully understand their own project goals. While this may seem obvious, it is surprising how often a building project moves forward without a comprehensive set of goals. Without well-defined and clearly stated goals it can be difficult to make the choices that face every builder. Why pick one design, material or system over another? Especially when sustainability is a priority, it is important to be clear about goals.

The list of criteria used to rate materials in this book represents a set of goals, and each builder must decide which of these ranks highest for a particular project. It's not enough to simply want "the best building possible." What will make it the best building for you? Designing a building means making compromises between competing factors. You are unlikely to create the most energy-efficient, least environmentally impactful, cheapest, easiest, fastest, most durable, most code-compliant, most recyclable building with the highest possible indoor air quality. You will be able to do reasonably well in some of these aspects, and very well in others. It's best to know in advance which ones you prioritize, and why. Making a building is a time-, resource- and finance-intensive endeavor; you'll want to complete it with the fewest regrets and mistakes possible, and the only way to do that is to start with clear goals.

This book recognizes the extraordinary number of decisions that must be made when planning to build sustainably, and aims to help you with those choices. There is no one way to build sustainably, and it's our hope that the information presented here allows you to bring your needs, climatic conditions, skills and environmental commitment together to make a better building.

Resources for alternative and natural building

Racusin, Jacob Deva, and Ace McArleton. *The Natural Building Companion: A Comprehensive Guide to Integrative Design and Construction.* White River Junction, VT: Chelsea Green, 2012. Print.

Nunan, Jon. *The Complete Guide to Alternative Home Building Materials & Methods: Including Sod, Compressed Earth, Plaster, Straw, Beer Cans, Bottles, Cordwood, and Many Other Low-Cost Materials.* Ocala, FL: Atlantic, 2010. Print.

Kennedy, Joseph F. *The Art of Natural Building: Design, Construction, Resources.* Gabriola Island, BC: New Society, 2002. Print.

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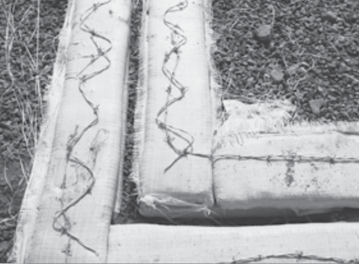


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Foundations

A building's foundation is extremely important to its longevity and performance. As such, it is often the one element where homeowners and builders will tend to choose the "tried and true" techniques and avoid "experimentation."

This is unfortunate, because the "tried and true" methods and materials typically involve the highest environmental impacts and often the lowest energy efficiency. Most North American homes use vast amounts of concrete in their foundations, and concrete is a perfect example of the kind of energy-intensive building material that has led us to our current environmental state. The production of the portland cement that is the "glue" in concrete requires using large quantities of fuel to heat limestone to very high temperatures to change its chemical composition. In the process the carbon dioxide trapped in the stone is released into the atmosphere (along with additional CO_2 released by the fuel used to heat the rock). Cement manufacture is one of the world's leading sources of greenhouse gas emissions.

Widespread and prodigious use of concrete is only possible when vast amounts of cheap energy can be used to quarry, heat, process and transport the material. Every rise in energy costs will be reflected in a rise in concrete costs. Where once this material was the cheap, obvious answer when building foundations, it is becoming less so all the time.

In the attempt to make concrete foundations more energy efficient, concrete is often combined with foam insulations. These insulations also have dramatic environmental impacts. If we can eliminate concrete use in foundations, we also tend to eliminate foams (though not always). In the following discussions about more sustainable foundation materials, careful thought must also be applied to the insulating of these foundations, and insulation options will be addressed for each system examined.

In considering more sustainable foundation systems, a builder is forced to consider a number of challenges to typical expectations. In much of North America, foundations have been twinned with conditioned, subgrade living space: the basement. In many markets, having a basement is so normal that it can be hard to convince a homeowner to imagine a house without one. It is difficult to create a sustainable basement and — unless the home is in the driest, best draining of soils — impossible to create a basement that doesn't rely on several layers of petrochemical products to stay dry.

As you will see in this section, there are many ways to create stable, long-lasting foundations that have reasonable environmental impacts. Most of them, however, do not make basement foundations and those that do come with significant labor requirements. The fact of the matter is that building large, conditioned basements has been a privilege of having cheap energy at our disposal. We are nearing the end of commanding that privilege.

There is one great benefit to moving away from conditioned basement foundations: cost. The cost savings that can be realized by using a sustainable, grade-based foundation are substantial, and can be used to lower the price of the entire project or traded off against sustainable materials or systems that would otherwise drive up the overall cost. It is possible to build with higher-cost renewable energy systems at a competitive cost due to savings on the foundation.

There is no doubt that the most skepticism and wariness about sustainable technologies will happen here, at the foundation. As with any change, the underlying assumption — the "foundation" — is the hardest to change. Yet this is the place that most needs changing.

Building science basics for foundations

A foundation transfers loads from the building to the ground and anchors the building to the ground. To adequately perform this role, a foundation must have enough compressive and shear strength to handle all gravity loads (the weight of roof, walls, floors) and imposed loads (occupants, furniture, snow, rain, wind, earthquakes) placed on the building and prevent the building from moving on the ground.

In areas with cold climates, the foundation must provide stability even when frost has penetrated the soil surrounding the building. When soils containing water freeze, they can expand up to 10 percent in volume and exert pressures upward of 100,000 pounds per square inch, enough to lift or shift a building. When frozen soils thaw, they can become supersaturated with water, resulting in dramatically reduced bearing capacity, enough to cause a building to sink. There are two basic strategies for achieving frost protection for a foundation:

Footings below frost depth. This strategy involves digging into undisturbed soil to a depth lower than the expected frost depth. Building codes will prescribe frost depths regionally. The foundation then becomes a wall that rests on this sub-frost footing and extends to a suitable height above grade to start the floor/walls of the building. *Frost walls, basements* and *piers* fall into this category.

Shallow, frost-protected foundations. This strategy involves installing an insulation blanket horizontally around the perimeter of the building to prevent frost from entering the soil beneath the footings. The footing can be at grade or just below grade, minimizing the amount of excavation and material required to build the foundation. *Grade beams* and *slabs* fall into this category.

Many of the materials examined in this chapter can be used for either kind of foundation, but some can only be used for one or the other.

The foundation also separates the building from the ground, and this separation must include keeping ground moisture from rising into the building and surface moisture from getting into or under the building.

The foundation must also keep out insects, rodents and other unwanted guests trying to enter the walls or the living space. These pests will vary by region, as will the strategies for keeping them out.

A foundation can play an important role in the energy efficiency of the building. A properly insulated foundation thermally protects all edges of the building. Where floors and/or walls attach to the foundation, preventing thermal bridging and unwanted air movement is particularly important. Strategies for achieving a well-sealed, well-insulated foundation will change depending on materials used and climatic conditions. Don't fall prey to the common mistake of assuming that "heat rises" and therefore it's not important to insulate around and under foundations. Heated air rises, it's true, but heat energy moves effectively in any direction by radiation and conduction. A warm building in contact with colder soils will continuously transfer heat to the ground, which has an almost infinite capacity to absorb that heat. If you don't want to attempt to heat the entire mass of the Earth's crust, insulate your foundation adequately!

Durability is of exceptional importance when it comes to foundations. All the other components of a building can be repaired, restored or replaced as they age. Foundations can also be fixed, but it's rarely easy and usually expensive to do so. If a foundation has a short life span, the building above it is usually condemned to the same short life span. All of the various building science aspects of the foundation will have an impact on its life span, as will the nature of the materials used.

No foundation can be considered sustainable unless it combines adequate strategies for meeting all of these building science objectives and does so with materials that can last a long time in a demanding environment.

Earthbag (or flexible form rammed earth) foundations

What the cheerleaders say...	*What the detractors say...*
Extremely low environmental impact	Bags won't last
Widely available materials	Too labor intensive
Simple technology, simple tools	Foundation will be leaky
Excellent thermal mass	Low energy performance

Earthbag foundation. (David Elfstrom)

Applications for this foundation system

- Perimeter beams
- Frost walls, including full basement walls
- Piers
- *Can also be used as exterior and interior walls above grade*

Basic materials

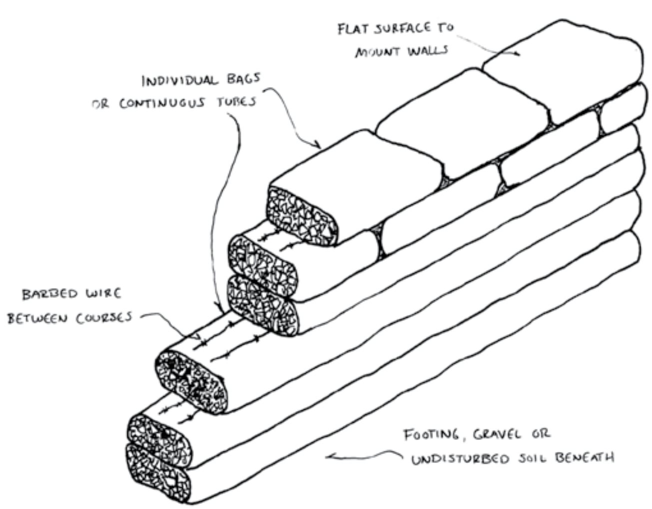
- Woven polypropylene bags (grain or feed bags) or continuous polypropylene tubing
- Soil, typically from site excavation, containing a good mix of gravel, sand, clay and silt
- Amendments for soil mixture, if necessary. Can be graded gravel, sand, road base, portland cement, hydrated or hydraulic lime, blast furnace slag or fly ash

- Barbed wire
- Tampers, manual and/or mechanical
- Many different bag stands or chutes have been custom made to facilitate the bag loading process. None are commercially available, but most can be made quickly and easily with available materials.

How the system works

The more descriptive term for earthbag construction is "flexible form rammed earth," which gives a more accurate impression of how the system works. Woven polypropylene bags or continuous tubes are filled with a gravel-based mixture that will tamp well and solidly. As the mixture in the bag is tamped, it flattens until the bag reaches its maximum stretch, at which point it firmly contains the material and allows for tamping to a high density. The bags or tubes can be laid out in straight lines, using string lines, but can also conform to any building shape.

The fill material that is rammed in the earthbags varies widely by region, builder and code/engineering requirements. A high proportion of aggregate is always used, with the binders ranging from indigenous clay soil to hydraulic agents like hydraulic lime, fly ash, blast furnace slag or portland cement. The compacted mix creates a stable long-lasting mass that does not rely on the bag for containment once it has been compressed and cured or dried to full strength.



Earthbag foundations can be made with fill mixes that rely on the bags for long-term containment of the materials, usually graded gravel or, less frequently, sand. The bags have a long life span when buried, and backfill around them will both protect the bags from degrading in sunlight and provide additional restraint for the materials should the bags fail.

The bags and tubing come in a wide range of widths, from 9–24 inches (230–600 mm), so a foundation can be designed according to the stability and strength requirements of any building. A double wythe system can also be designed, using two rows of narrow bags to create an inner and outer foundation wall for wide wall systems and to allow for internal insulation strategies.

The construction methodology is the same regardless of bag size or fill type. The mix is created, moistened to the correct degree and placed into the bag or tube. When the bag contains the correct amount of mix it is tamped vigorously, manually or mechanically. The tamping process subjects the mix to a force greater than the force that will be placed on the foundation by the building loads.

The foundation wall is built up in a number of courses. The thickness of each course depends on bag size, amount of fill and degree of compaction. Typical earthbag courses range from 4–8 inches (100–200 mm) in thickness.

Between each course of earthbag, a strand or two of barbed wire is typically used to prevent the bags from sliding on top of one another in any direction. Multi-pointed wire (three or preferably four barbs) ensures that every knot is making good contact with both bags. The wire is treated like rebar in concrete, with continuous corners and overlapped joints.

Walls will sometimes be installed directly on the earthbag (with a suitable moisture break), or wooden sill plates or a thin concrete beam can be used.

With practice, an experienced crew can build courses of earthbag quite quickly and with a high degree of level and plumbness and a consistent compaction.

Tips for a successful earthbag foundation

1. Placement of materials to be mixed should facilitate easy delivery to all points of the foundation.
2. Don't lay string lines directly on the foundation lines, as the bags will nudge the string constantly. Instead, lay out lines that are a couple inches wider than the foundation and measure into the bags.
3. A sturdy loading stand will make the job much faster. The resources listed below describe various loading stand options.
4. A practiced team can move quickly and create a very level surface. As you are learning, don't worry about every course being perfectly level. In the end, only the top course matters and you can make corrections on successive courses. A transit or laser level makes the job much more accurate.
5. Fill a sample bag to determine the height of each course to plan the number of courses and quantity of bag material required.
6. Secure the bag material well in advance to ensure supply and sizing.

Pros and cons

Environmental impacts: *Low*

Bags:

Harvesting — ***High.*** Polypropylene (PP) is a resin of the polyolefin family derived from crude oil and natural gas. Impacts include significant habitat destruction and air and water pollution.

Manufacturing — ***Moderate to High.*** Polypropylene is among the least energy-intensive plastics to manufacture, and a growing percentage of PP is derived from recycled sources. Impacts include significant air and water pollution. Weaving PP strands into bags is a moderately intensive mechanical process with no significant impacts.

Transportation — ***Moderate.*** Sample house uses 26.25 kg of bag material:

0.04 MJ per km by 15 ton truck
0.025 MJ per km by 35 ton truck
0.0065 MJ per km by rail
0.0042 MJ per km by ocean freighter

The majority of bag production is in Asia, ensuring that most bags used in North America have relatively high transportation distances. Quantity of material required is low, mitigating impacts.

Installation — ***Negligible.***

Fill:

Harvesting — ***Negligible to High.*** Site soil fill will have negligible impacts.

Aggregate and virgin hydraulic binders (if required) are mechanically extracted from quarries and can have low to high impacts on habitat and ground and surface water contamination and flow.

Manufacturing — ***Negligible to High.*** Site soil fill will have negligible impacts.

Aggregate is mechanically crushed and has moderate impacts for fuel use for machinery and dust dispersion.

Virgin hydraulic binders like lime and portland cement are fired at extremely high temperatures and have high impacts, including fossil fuel use, air and water pollution and greenhouse gas emissions.

Recycled hydraulic binders like fly ash and blast furnace slag are the by-products of industrial processes that have high impacts, but these can be mitigated to some degree by diverting these materials from landfill.

Transportation — ***Negligible to High.*** Sample house uses 15,616 kg of fill material:

23.4 MJ per km by 15 ton truck
14.7 MJ per km by 35 ton truck

Site soil will require no transportatiozn. Locally obtained soils will have negligible to low impacts.

Aggregate is typically sourced nearby the project site, and will have low to moderate impacts depending on distance traveled.

Hydraulic binders are often sourced nearby the project site, but may have to travel long distances.

Installation — ***Negligible.***

Waste: *Negligible to Low*

Biodegradable/Compostable — All natural soil material.

Recyclable — Polypropylene bag material, barbed wire offcuts.

Landfill — Cement and/or lime containers.

Energy efficiency: *Very Low*

A rammed earth foundation has very little thermal resistance. In cold climates, it will need to be properly insulated in order to contribute to an energy-efficient building. Insulation strategies can vary depending on the style of foundation, the climate and the type of insulation used. If the design for the building has accounted for potential heat loss through the earthbag foundation it can easily be part of a well-designed, thermally appropriate structure in a wide range of climates.

In some areas, insulative aggregate may be available in the form of pumice, volcanic rock or other "expanded" minerals. Depending on the type of aggregate and the loads imposed on the foundation, high percentages of these aggregates can result in a foundation with reasonable strength and thermal characteristics.

Earthbag Foundation Embodied Energy

Wall type: 1220x200mm (4ft x 8in) wall, 10 courses of earthbag	Material embodied energy from I.C.E. in MJ/kg	Weight to volume ratio of material*	Volume of material in sample 1000sf/92.9m^2 building	Sample building embodied energy	Material embodied carbon from I.C.E. in kgCO_2e/kg	Sample building embodied carbon	Notes
Lowest Impact							
Recycled bags	0	6.56kg/100m @ 0.3m bag width	400m 26.24 kg	0 MJ	0	0kg	No embodied energy for repurposed materials.
Rammed earth soil fill from site	0.45	1600kg/m^3	9.76m^3 15,616 kg	0 MJ	0.024	0kg	No embodied energy for site materials.
Recycled barbed wire	36	0.085kg/m	360m 30.6 kg	0 MJ	3.02	0kg	No embodied energy for repurposed materials.
Totals				**0 MJ**		**0kg**	
Highest Impact							
Virgin bag or tube	99.2 (polypropylene film)	6.56 kg/100m @ 0.3m bag width	400m 26.24 kg	2603 MJ	3.43	90kg	
8% cement stabilized soil	0.83	1600 kg/m^3	9.76 m^3 15,616kg	12,961 MJ	0.084	1311 kg	
Barbed wire	36 (wire – virgin)	0.085 kg/m	360m 30.6 kg	1,101 MJ	3.02	92 kg	
Totals				**16,665 MJ**		**1,493 kg**	Figures do not include parging, waterproofing or insulating of foundation.

Transportation: Soil transportation by 35 ton truck would equate to 14.7 MJ per kilometer of travel to the building site *Typically from engineeringtoolbox.com

Material costs: *Low*

Soil, aggregate, bags and barbed wire are all relatively inexpensive. Site preparation costs are similar to other comparable foundations.

Labor input: *High to Very High*

Those used to the mechanical mixing and placement of concrete into formwork may find the amount of physical effort involved with earthbag daunting. However, a large part of the labor required to build concrete foundations is in the construction and removal of the formwork that holds the liquid concrete. Because the bags are the formwork for earthbag, this labor-intensive step is eliminated. Once lines are laid for the foundation, earthbag construction begins immediately. When compared this way, the labor balance becomes much more favorable. As there are currently no mechanical means for filling bags or tubes with mix, all work is manual.

Skill level required for homeowners: *Negligible to Low*

Earthbag building is very simple in practice, and the skills required can be picked up relatively quickly. The process is quite forgiving, as it's possible to correct for errors on a subsequent course. Only the final course needs to be completely level, and most crews will have the methodology developed by then.

It definitely helps to have at least one experienced earthbagger on a crew to get started. One person can usually direct an entire crew until everybody understands the process. If nobody has previous experience, it's worth looking into workshops or other training opportunities before commencing with a foundation.

Health Warnings — Powdered binders are high in silica content, and are dangerous to breathe. Wear proper breathing protection.

Sourcing/availability: *Easy to Difficult*

Obtaining large quantities of bags/tubes can be difficult. Farm co-ops or grain and feed stores will have new bags, and their customers will have used bags. Bag printers will sometimes have misprinted bags that are given away or sold below cost. Bag manufacturers and printers will have rolls of tube, and may be willing to sell full rolls. Otherwise, rolls of tube will have to come direct from the manufacturer in Asia, or their North American distributor.

Fill materials are typically easy to source. Grades of aggregate will vary by region, but easily tamped mixtures are required for many purposes and are available everywhere. The road-building industry relies heavily on compacted aggregates for road base, and finding out what is being used locally for this purpose can help determine what you should be using in your earthbag mix.

Virgin binders are available from masonry supply stores and well-stocked building supply yards. Recycled binders like slag or fly ash may be easily available, or may require extra effort to obtain. If a local concrete batching plant is adding recycled binders to their mixes, they should be willing to sell the binder in bulk.

Barbed wire is easy to obtain from farm, fencing or hardware stores. The barbs should be at least three- and preferably four-point, but never two-point.

Durability: *High to Very High*

The durability of earthbag foundations has not been proven by the test of time. As a relatively recent form of construction, there aren't any historical examples upon which to base durability parameters.

However, rammed earth construction without the poly bags as formwork has a long history of durability. In climates where rammed earth has proven to be viable, earthbag using a soil mixture can be expected to have a similar or longer life span.

Where soil mixtures are not deemed durable enough, the addition of binders creates a concrete-like material inside the bags and this can be expected to share high durability expectations with other concrete materials.

In an area where rammed earth has little history, and even where the materials in the bag lack sufficient binder or are soil-based, an earthbag foundation can be expected to be quite durable as long as the bag material is protected from UV radiation. Polypropylene has shown itself to be very persistent when buried and the bags should maintain their integrity for a long time, continuing to contain the fill for decades or even centuries.

Code compliance: *Not an accepted solution in any codes*

Alternative compliance applications will need to be based on accurate load calculations and engineering principles, along with the small amount of study data that currently exists. Soils engineering principles and data are highly applicable and can provide the basis for justification. A mixture that is adequately tamped and has a good degree of internal cohesion can be shown to be feasible in most conditions. It is highly advisable to discuss the earthbag option with code officials and find out whether or not they are willing to consider it, and under what conditions, *before* proceeding with plans to use an earthbag foundation.

It may seem obvious, but it can be worth pointing out to code officials that all buildings with concrete foundations sit on a bed of tamped gravel beneath the footings, so codes already accept the use of restrained, tamped fill for structural purposes.

Indoor air quality

Earthbag foundations will have no direct impact on indoor air quality. A well-built foundation can help

Earthbag Foundation Ratings

	Best 1 2 3 4 5 6 7 8 9 10 Worst	Notes
Environmental Impacts	1–3	All materials can be from site and recycled. Bag material high impact, but used in low quantities. Addition of insulation will raise impacts.
Embodied Energy	1–5	Use of cement-stabilized earth will raise EE dramatically. Addition of insulation will raise EE.
Waste Generated	1–2	
Energy Efficiency	9–10	System requires addition of insulation to provide energy efficiency.
Material Costs	1–2	Addition of insulation will raise costs.
Labor Inputs	7–10	
Skill Level Required by Homeowner	1–4	
Sourcing and Availability	4–10	Bag/tube material requires direct sourcing from manufacturer.
Durability and Longevity	1–4	Untested, but rammed earth mixes have historical durability precedent.
Building Code Compliance	6–10	Structural engineering and/or alternative compliance required.
Indoor Air Quality	1–3	Foundation will not typically affect IAQ, but if used as a wall system, impacts are low.

keep the floors and walls of the building dry and prevent other IAQ issues.

Future development

Simplicity, low cost and effectiveness make earthbags attractive. Earthbag foundations are relative newcomers to construction, though their use in civil engineering projects and flood control provides some performance basis. There is a lot of room for the development of earthbag foundations into a more refined, more widely accepted system.

New research is ongoing into the strengths of different mixes, which should help with code compliance issues. As the system becomes more widely used, new tools and techniques are sure to be developed that will streamline the process. Mixing and pouring concrete foundations used to involve large amounts of labor input that have, over time, been replaced with mechanical devices. The same could easily happen to earthbag foundations, making them even more attractive than they already are.

Resources for further research

Geiger, Owen. "Earthbag Building: Earthbag Building Guide." *Earthbag Building: Earthbag Building Guide.* N.p., n.d. Web. 13 Apr. 2013.

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Khalili, Nader, and Iliona Outram. *Emergency Sandbag Shelter and Eco-village: Manual—How to Build Your Own with Superadobe/Earthbag.* Hesperia, CA: Cal-Earth, 2008. Print.

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Dry stone and mortared stone foundations

What the cheerleaders say...	*What the detractors say...*
Historically proven durability	Too labor intensive
Extremely low environmental impact	Foundation will be leaky
Widely available materials	Poor energy performance
Simple technology, simple tools	Expensive to import stone
Excellent thermal mass	
Aesthetically pleasing	

Applications for this foundation system

- Perimeter beams
- Frost walls, including full basement walls
- Piers

Basic materials

- Stone. Can be available fieldstone, cut stone or rubble. Dry stone walls are best built with stone that has a flat profile.
- Mortar. Can be typical masonry cement or traditional lime mortars.

How the system works

Mortared stone foundations. Stone is gathered to the building site and laid up by choosing stones of appropriate sizes to form courses and staggered joints between courses. Mortar is placed between courses and between the ends of each stone, so that each adjacent face of stone in the wall is embedded in mortar. A mortar cap typically provides a flat, level surface for the sill plates/walls.

Mortared stone foundations can be used for perimeter beam, frost wall and basement style foundations, as well as piers. In basement scenarios, proper drainage and moisture protection must be used as water can penetrate mortar joints and pass into the building.