Introduction

At the beginning of the 20th century, settlers in the timber-poor upper Great Plains of the United States and Canada demonstrated that necessity is the mother of invention; applying the recently invented baling machine to abundant grasslands, they produced bales, and then bale structures. Many bale houses, churches, and even a courthouse were built at this time. However, this unique building approach was bypassed and forgotten with the onset of rapid industrialization, the nationwide homogenization of building techniques, and a newly developed ease in transportation of building materials.

As the 20th century drew to a close, increasing awareness of industrialization's true costs drove emerging concerns for sustainable living. During this time of reevaluation, straw bale construction enjoyed a revival thanks to the pioneering efforts of David Bainbridge, David Eisenberg, Pliny Fisk, Judy Knox, Matts Myhrman, Bill and Athena Steen, and many others. Within the last two decades, the resurgence and evolution of straw bale building has exceeded our expectations.

The California Straw Building Association (CASBA) was formed 20 years ago on the Carrizo Plain of South Central California by a small group of dedicated and inspired building professionals. Since then, it has grown in size and influence. CASBA is devoted to furthering the practice of straw building by facilitating the exchange of current information and practical experience, promoting and conducting research and testing, and making that body of knowledge available to working professionals and the public at large.

We recognize that interest in straw building will continue to flower and hope this detail book nurtures and enables that growth. It gathers, explains, and illustrates current practices in straw bale construction. As most of California lies in moderately high seismic zones, many details in this book are especially appropriate for similar areas. However, most details will also be useful to other parts of North America—and anywhere grain crops are grown that could provide straw building materials.

Whatever the reasons for building with straw, this book will help guide decisions about both architectural and structural design, and offer proven details, methods, and insights into building with bales.

This book is not a step-by-step guide to building a straw bale structure—although it offers plenty of guidance for designing, engineering, and building one. Instead, we crafted this book to inform designers and builders about the many choices they have on the journey to creating a beautiful, healthy, energy-efficient, long-lasting structure.

The first chapter explains why people are drawn to this building system and explains the building science behind it. The second chapter covers design considerations for building with bales. Chapter 3 discusses structural issues unique to straw bale structures. The next few chapters offer practical guidance on installing utilities, stacking the straw bale walls, and finally, applying protective coats of plaster. Conveniently, the final chapter includes the often-referenced straw bale building code.

If you are already familiar with straw bale characteristics, the building design process, and plastering, or if you plan to leave the structural engineering entirely in other hands, feel free to skip directly to the sections that most interest you. Cross-references throughout the book demonstrate the interconnectedness of design and the building process.

1

Why Build with Straw Bales?

Straw bale buildings have been around since the late 1980s, and for 100 years before that, counting the original structures in Nebraska where straw bale building was born. There are now straw bale buildings in every US state—hundreds or thousands in some—and in over 50 countries worldwide. Yet despite this proliferation (along with some excellent coverage in magazines and newspapers and the outreach efforts of regional natural building groups), few people are aware that straw bales can be used to construct buildings. While working on straw bale buildings, conducting building tours, or staffing a green building show, we're often approached by curious people who say "They make buildings out of straw bales?" Yes! And each passing year sees the construction of more straw bale homes and commercial or institutional buildings. When there are so many choices for how to build, it's reasonable to wonder why people choose straw bales. The explanation includes the entire range of why people do anything, from highly emotional to completely rational.

Reasons for Building with Straw Bales

Some might check everything on this list; others just a few.

Aesthetics: Straw bale buildings are beautiful! Plastered straw bale walls offer excellent textures and a palette for natural plasters quite unlike conventional modern finishes. Light and shadow playing across a hand-plastered surface is more alive than light on the flat surfaces found in most buildings today. The deep window and door reveals that are a result of building with bales offer many advantages. They give weight and solidity to the building, while also creating opportunities for rounded corners and soft edges, greater control of how natural light enters a space, and generous window seats. Like thick adobe or stone walls, straw bale walls offer a lasting sensory impression.

Security: Many people feel more secure in a thick-walled building. Thick walls create the opportunity for prospect and refuge—you can see out while feeling secure within. Nowhere is this more evident than when sitting in a window seat nestled in a straw bale wall, where you can be on the edge between inside and out.

Design Flexibility: Straw bales can be used to create straight or curved walls, can be formed and shaped, and allow for a great variety of architectural creativity. Straw bale walls can support roof and floor loads and may also be part of a shear wall system to resist wind and earthquakes. Even when a building has a simple rectangular footprint, the walls can be sculpted with niches and rounded window and door openings that lend dynamic character to an otherwise routine shape.

Insulation: Straw bales in a wall assembly provide excellent thermal insulation; plaster covers the dense straw bale core inside and out and creates a highly effective air barrier. Depending on bale density and orientation, a well-stacked straw bale wall offers insulation values ranging from the mid R-20s to the mid R-30s—which exceeds that of most framed wall systems using conventional insulation.

Thermal Mass: An energy-efficient building also has adequate thermal mass to capture and store solar radiation or heat from another source. The thick plaster on interior straw bale walls provides excellent distributed thermal mass. The complete straw bale wall assembly buffers diurnal temperature changes and keeps a straw bale structure's internal temperature remarkably stable. Thermal mass, combined with good insulation, dramatically lowers heating and cooling costs.

Sound Privacy: Straw bale structures are particularly quiet inside. The walls effectively mute traffic, industrial, agricultural, and other nuisance noise.

Agricultural By-product: Straw bale buildings use the residue from annually harvested food crops—rice, wheat, barley, oats, rye—while usually requiring less dimensional lumber and plywood than conventional structures. Straw is the woody stems left after seed heads (the grain) are removed. Straw has other uses like mulch, animal bedding, erosion control, and additives for livestock feed, but most grain-producing regions have an abundance of straw that can be used as a building material. Every region has a common type of straw and bale size, depending on which grains are farmed locally and the baling machines used for harvesting.

Embodied Energy: Building a structure of any size, for any number of people, is an environmentally costly undertaking—among the most costly things we do during our lives. Almost half of all energy consumed in North America each year goes to constructing and operating buildings. How might we improve the world if we could reduce that amount? Think of energy the way you might think about a building budget. It requires energy to build a structure, and the building needs operating energy over its lifetime. This is a building's energy budget. Could we reduce that budget by using fewer energy-intensive materials to build with? The energy used to create, transport, and assemble the building materials—the embodied energy—will be costly if the materials are highly processed or transported from long distances, and using those materials will add to the energy budget. Even when the finished building is "net zero" (creating as much energy as it consumes) or requires little energy to heat, cool, light, and operate, a high embodied energy building's initial steps backward into energy debt delay the point at which the building becomes a net energy benefit. Locally sourced straw has one of the lowest embodied energy values of any building material. Grain crops, and thus straw bales, require minimal carbon expenditure (in the form of petroleum products like fertilizer and fuel) to plant, fertilize, and harvest. Thoughtful design and material selection can minimize embodied energy in a building and shorten the time for a net-zero structure to overcome its embodied energy and make an energy contribution.

Carbon Sequestration: Unique among building materials, straw stores 60 times more carbon than is used to grow, bale, and transport it to building sites in the same region. The carbon inputs from petroleum-based fuel and fertilizer amount to a tiny fraction of the amount of carbon stored in straw through photosynthesis. If it doesn't burn or decompose, the sequestered carbon in plant-based building materials like wood and straw prevents the formation of CO_2, the potent greenhouse gas. Sequestering straw decreases methane emissions, too, which are more damaging than CO_2 because each methane molecule has 20–25 times the short-term heat-capturing potential of a single CO_2 molecule.

What are the potential benefits? Every pound of carbon stored in growing plants prevents the formation of 3.67 pounds of CO_2. As with most woody plant materials, each straw bale is approximately 40% carbon by weight. If a two-string straw bale weighs about 65 pounds, it sequesters approximately 26 pounds of carbon, preventing the formation of 95 pounds of CO_2. The bales in a 2,000-square-foot straw bale home (approximately 220 two-string bales) sequester 5,720 pounds of carbon, preventing the formation of nearly 21,000 pounds of CO_2. Such a home sequesters almost three tons of carbon and keeps over ten tons of CO_2 from forming.

North America grows a lot of grain. If only one-tenth of the residual straw were used for building, over two million 2,000-square-foot homes could be built each year. For some perspective, there were fewer than one million new home starts in North America in 2016. If that many homes were thoughtfully built with straw each year, they would annually lock up nearly three million tons of carbon and keep 10.5 million tons of CO_2 out of the atmosphere.

Fire Resistance: Straw bale structures have survived wildfires that burned nearby conventional structures to the ground. Why? Dense straw bales covered with thick plasters resist both ignition and heat transference. A straw bale wall with one inch of exterior cement-lime plaster has earned a two-hour fire rating, and with earthen plasters, a one-hour fire rating. This equals or exceeds many conventional wood-frame walls that offer a one-hour or 20-minute fire rating. Other fire-resistant building features like Class A roofing assemblies and safe wildland fire prevention practices like clean gutters and reduced fuels around the building sites improve the odds.

Natural Non-Toxic Materials: Many modern building materials contribute to poor indoor air quality by off-gassing by-products like sulfur dioxide, ozone, acetic acid, chlorides, and formaldehyde; new chemicals are introduced each year that haven't been tested for long-term impacts. Humans have lived with natural building materials like straw, clay, and lime for millennia. These materials promote healthy indoor air quality because they don't off-gas noxious chemicals as they cure or age. When the building reaches the end of its (hopefully) long functional life, its materials can return to the Earth with no ill effect.

Community: Friends, neighbors, and family can assist with many straw bale building projects, much like the barn raisings of an era gone by. Enlisting others to help with bale wall stacking and plastering can be fun, educational, and rewarding. It may also lower building costs.

The Building Science of a Straw Bale Wall Assembly

After expressing surprise that buildings can be made with straw, people often ask "How, exactly, does that work?" They might be thinking about the childhood fable involving a wolf and three little pigs. Or they might be trying to figure out how straw fits into the modern building material framework they're familiar with. Today's building industry uses a wide variety of building methods—stud frame, insulated concrete forms, structural insulated panels, to name a few. Industry has also created a wide variety of insulation and sheathing materials that are combined in different wall systems so the buildings perform as designed. Many of these building materials are airtight and waterproof; when carefully assembled in a high-performance "green" building and combined with an onsite power source like solar panels, they often result in "net-zero" building performance.

Where do plastered straw bale walls fit into this picture? They can achieve the same "net-zero" performance, but they accomplish it differently.

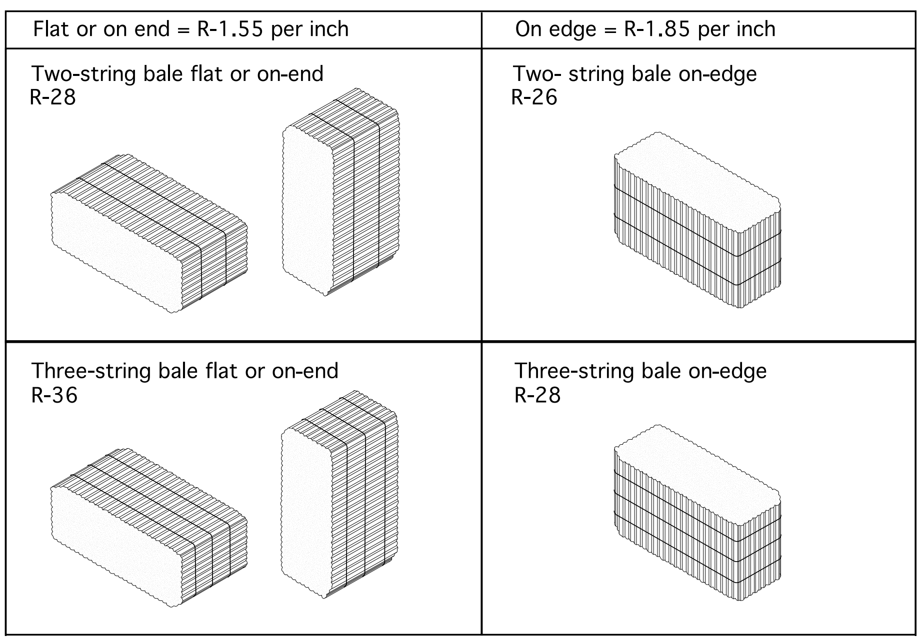
To understand how a straw bale building performs, visualize the straw as tightly bundled hollow cellulose tubes that trap air in and around them, especially when the interior and exterior surfaces of the bales are covered with plaster. This composite wall *assembly* has a number of desirable properties.

Thermal Resistance

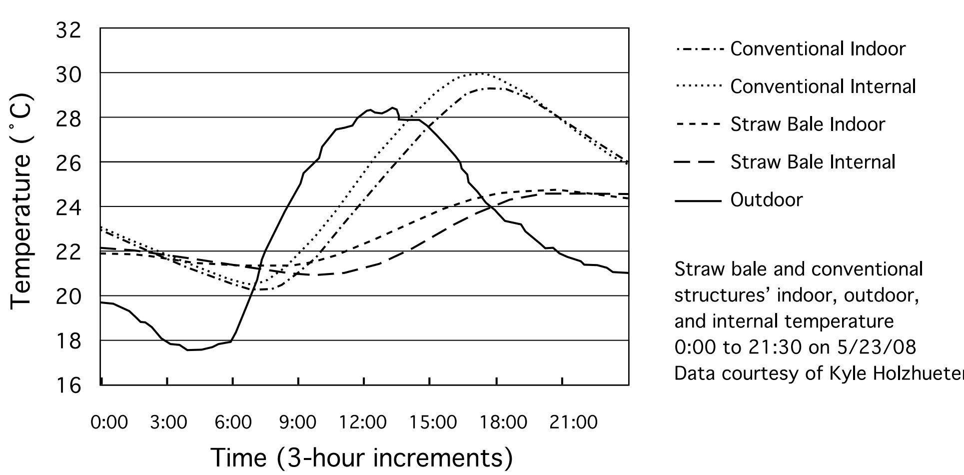
Heat transfer from a warmer entity to a cooler one happens through three mechanisms: conduction, convection, and radiation. All three have a place in understanding the performance of straw bale wall systems. The term *R-value* primarily refers to conductive heat transfer and is widely used to describe the relative performance of various insulation materials. For example, 3½" fiberglass batts are listed at R-13 and R-15. Since they are factory produced, the tested R-values are consistent from one purchase to the next. Straw bales are not produced nearly as consistently, so they generally receive conservative R-values based on test results. Appendix S in the 2018 International Residential Code (IRC) assigns R-1.55 per inch for bales laid flat and R-1.85 per inch for bales stacked on-edge (more on that later). See Figure 1-1. These values are based on the most reliable tests to date, conducted in the UK (2012), Denmark (2004), and at the Oak Ridge National Laboratory in Tennessee (1998).

Given the varied dimensions of the straw bales used in construction and other variables (such as bale density), actual insulation values of anywhere from R-27 and R-34 are possible for a straw bale wall. Visit "Resources" at the California Straw Building Association website, www.strawbuilding.org, for references to more detailed technical discussions.

Keep in mind, though, that tested R-values are barely half the thermal performance story. In stud wall construction, thermal bridges (where the studs connect the interior sheetrock to the exterior siding) can reduce a wall's effective R-value by about a third. Since straw bale wall construction has few thermal bridges, the effective R-value is not reduced. In addition, it takes heat 12 to 15 hours to pass from one side of a wall to the other—the thermal lag time—so straw bale wall assemblies usually perform better than their tested values. In most temperate climates, such as Japan's for example, winter temperatures are higher in the day than at night. This is known as the *diurnal temperature swing*. By the time heat from the interior approaches the wall's exterior, the day is warming up and heat loss is minimized. Conventional stud walls react much more rapidly to changes in temperature. In regions where the temperature drops below freezing and stays there for a week or more, straw bale walls perform more like the tested R-value; but in areas with significant diurnal temperature swings, their effective performance is higher.



1-1. R-values of straw bales as determined using the 2018 IRC Appendix S. Note: California's energy code does not reference the IRC. The accepted R-value for straw bale walls in California is R-30.



1-2. Thermal lag time of diurnal temperature swings in conventional and straw bale walls.

Straw bale walls perform similarly to keep out the heat in the summer, but the effect is less pronounced. This is because (1) the temperature differential between indoor and outdoor air is smaller, so wall R-values matter less, and (2) more of the interior heat gains are driven by radiant gains (direct sunlight) through windows and glazed doors than through the walls themselves. Two design features that help minimize summer heat gains are inset windows and wide eaves (or awnings) to shield windows from the direct summer sun.

Convective heat transfer is heat exchange from moving air. When you feel a cold draft from an open or leaky window, that's convection heat transfer. A poorly built straw bale wall has bales that aren't sufficiently dense or has gaps between or around the bales. Small convective loops within areas of loose or poorly compacted straw can significantly degrade a wall's thermal performance. When it comes to windows, keep in mind that air currents constantly wash against the wall's exterior surface. Set-in windows experience somewhat less convective loss than windows mounted flush with the exterior wall plane.

1-3. Emissivity of various materials. Data courtesy of Mikron Instrument Co., Inc.

Surface Material	Emissivity
Aluminum	0.028
Building Bricks	0.450
Cast Iron (smooth plate)	0.800
Copper	0.260
Gypsum	0.930
Human Skin	0.985
Paper	0.940
Plaster	0.910
Plastic	0.950
Soft Wood	0.820
Steel (flat, unpolished)	0.95-0.98
Hardwood (oak)	0.890

Heat transfer through *radiation* is always occurring, everywhere. You are constantly radiating heat to the things around you and the house itself—or they are radiating heat to you. Imagine standing between a wood stove and a single-pane window on a cold night. Since the stove is warmer than you, it gives heat to you, and you are warmer than the window, so you give heat to it. An object's heat content—its temperature—and its emissivity—primarily governs its ability to give off heat. The higher the emissivity, the better the material radiates heat. Most materials found inside the home, with the exception of metals, have similar emissivity. In particular, the plasters on straw bale walls and sheetrock walls have nearly identical emissivities.

Thermal Mass

The straw bale wall's capacity to accept or store heat also affects radiative heat transfer. A simplified way of thinking about this complex subject is contained in the term *thermal mass.*

All else being equal, a home with too little thermal mass will experience much greater temperature fluctuations than one with the appropriate amount of mass. Think of thermal mass as a storage locker for heat that it gains from solar radiation, HVAC operation, appliances, and even the people in a home. To be effective, thermal mass needs to be inside the thermal envelope (insulation), or, in certain cases, part of the thermal envelope. Cooling that mass at night with open windows and skylights allows for a cooler feeling the following day because people are then radiating more heat to the mass than it is giving to them. Mass on the outside of the insulation is of little value in the winter and may actually increase cooling loads in the summer.

For typical stud frame homes, ½" sheetrock is the only significant thermal mass the walls provide. The insulation has effectively zero thermal mass, and the widely spaced studs add only marginal mass. Interior straw bale wall plaster, however, is at least ¾" thick, and its increased thickness and density provide one and a half times as much thermal mass as standard sheetrock. The plaster can be as thick as 2", providing four times the thermal mass of sheetrock. This large surface area of considerable thermal mass allows for a broad heat exchange with interior air, so it moderates interior temperature variations. Thus, it performs like a wall with a much higher R-value (see *Design of Straw Bale Buildings*, Bruce King, Green Building Press, 2006, page 189) and substantially reduces heating or cooling requirements and costs.

Additionally, effective thermal mass in straw bale wall assemblies, just like in log homes, goes deeper than the surface finish. On a pound-for-pound basis, the bales themselves have a heat capacity similar to hardwoods (.48 Btu/lbF) and about double that of concrete or gypsum. However, straw bales weigh much less per volume. They are roughly 1⁄16 the density of concrete. Consequently, they have about ⅛ the thermal mass capacity per inch of thickness. Since straw bale walls are much thicker than stud walls and are uninterrupted instead of spaced, even without plaster, they have 13 times greater heat capacity per lineal foot than a 24" o.c. stud wall with fiberglass insulation.

Realize that walls are only one—and perhaps not the most important—component of an efficient energy design. In a typical house, the major sources of heat loss, from largest to smallest, are fresh air changes, air-leaking windows and doors, poorly insulated ceilings or roofs, then walls, and finally raised or on-grade floors. An energy-efficient design must control air leaks and provide appropriate insulation for the ceiling, floor, and all other spaces or voids. Both the structural and mechanical (HVAC) system designs should be designed to maximize insulation and minimize thermal bridging and gaps. Windows and doors, even those with good U values (U-value is the reciprocal of R-value; it measures the rate of heat transfer) offer very little insulation, and they often have high infiltration.

Moisture Capacity

We know that it is good advice to keep damaging moisture out of walls, but what constitutes "damaging moisture" and how to deal with it is greatly dependent on whether stud walls or straw bale walls are being discussed. Following is a brief overview; for more information, consult the resources listed at www.strawbuilding.org, particularly those by John Straube and Kyle Holzhueter.

"For moisture-related problems to occur, at least four conditions must be satisfied:

1. A moisture source must be available,
2. There must be a route or means for this moisture to travel,
3. There must be some driving force to cause moisture movement, and
4. The material and/or assembly must be susceptible to moisture damage."

(From *Design of Straw Bale Buildings*, B. King, et al., 2006.)

Straw bale walls in a well-built home will absorb moisture under certain circumstances, from interior as well as exterior sources. They also have a comparatively huge capacity for storing moisture before damage occurs, especially if moisture can leave through diffusion in sufficient time. In general, straw bale wall construction should prevent moisture intrusion, but not stop moisture movement. Examples of appropriate prevention features include locally appropriate roof overhangs and relatively tall foundation walls to prevent rain and splash from excessively wetting the walls. Allowing moisture movement means avoiding relatively impermeable membranes (e.g., polyethylene, aluminum-faced paper) and finishes (e.g., Portland cement, veneer tile, or stone). More on this, below.

Bale walls can hold moisture either as vapor, water, or ice. Water and ice (after it melts) will almost certainly cause problems unless the water escapes as vapor through the surface finishes. Straw bale walls can have a higher vapor moisture content than most conventional walls in buildings with the same relative humidity before saturation (the point at which the vapor becomes liquid). At 80% relative humidity (RH), straw can have approximately 60% higher moisture content than fiberboard, and 25% more than plywood.

However, liquid water left in place over time will cause mold, mildew, and straw decomposition, just like it does with wood. And, straw will decompose faster than wood due to its lower density and greater surface area. Leaks from plumbing, poorly executed detailing around doors, windows, and other penetrations often cause problems when moisture enters the walls through these poorly detailed openings and edges faster than it can leave.

What Is Vapor Permeability?

"If a material has a perm rating of 1.0, 1 grain of water vapor will pass through 1 square foot of the material, provided the vapor pressure difference between the cold side and the warm side of the material is equal to 1 inch of mercury (1 inch Hg).

"As temperature and relative humidity (RH) go up, vapor pressure gets higher. The greater the vapor pressure differential across or through the material, the greater the tendency for water vapor to migrate from the high pressure side to the low pressure side." (University of Alaska, Cooperative Extension Service, 2017)

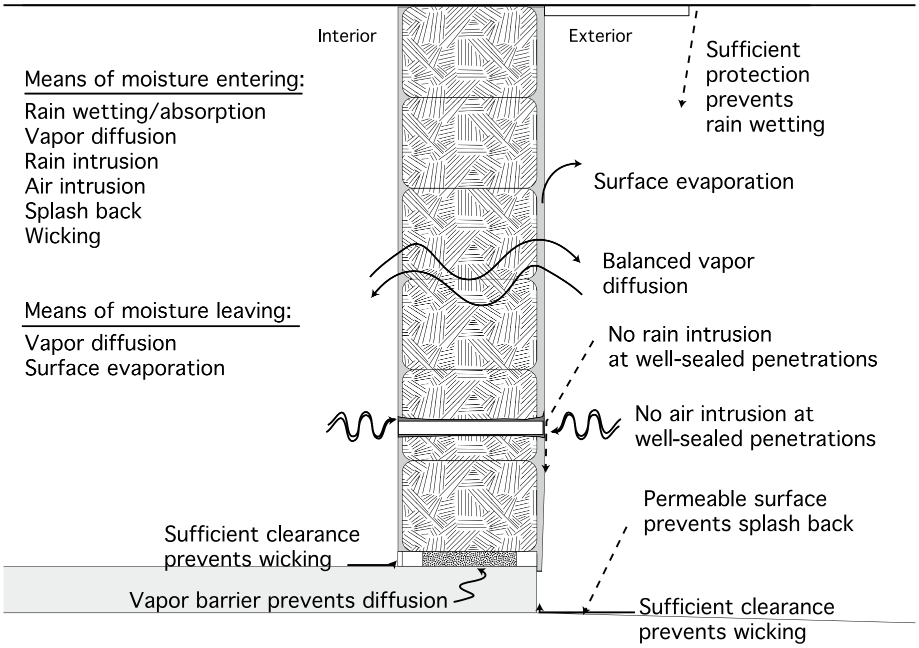
Vapor Permeability

When talking about straw bale wall finishes, builders often use the term *breathability*. They are referring to how well the wall permits water vapor movement. To be considered vapor permeable, all of the wall materials, especially the finishes, must allow for any moisture that enters the wall to escape. When interior temperature and vapor pressure force water vapor in a straw bale wall to move toward the exterior, it needs to escape. If it hits an impermeable surface (e.g., plastic sheeting or certain paints) at or below dew point, it will condense back into water and accumulate, creating conditions for the straw to decompose.

If using paint of any kind on a plastered straw bale wall, make certain that it is highly vapor permeable even after several coats are applied. Paint invites more paint (as new owners decide to change colors), and additional layers of latex paint may make the wall surface increasingly impermeable. Consider clay paint or milk paint for interior surfaces, or mineral paint for either interior or exterior walls.

Vapor Transfer

Straw bale walls plastered with clay, lime, cement-lime, soil-cement, or gypsum plasters remain vapor permeable; water in vapor form can move relatively easily through the wall, passing through the straw and both plaster surfaces. Because of the way water vapor diffuses—driven by differences in vapor pressure and temperature—it may be constantly moving in and out of a wall assembly. Water vapor



1-4. Moisture and straw bale walls.

moves, or diffuses, through vapor-permeable materials from areas of higher vapor pressure to lower, and from warm areas to cold. When the interior of a structure has a higher vapor pressure and temperature than outside, moisture will tend to move from inside to outside. This describes typical winter conditions in temperate climates. In summer, the moisture path may be reversed, depending on outside vapor pressure (humidity) and interior temperature. When the interior of a structure has a lower vapor pressure and temperature than outside, moisture will tend to move from outside to inside.

Different plasters have different permeances. The relatively thin (1"–2") layers of plaster on each side of a straw bale wall must be vapor permeable. Clay plasters are among the most permeable, rated at 11 US perms for a 2" thickness. A lime plaster has 9 US perms for a 2" thickness. Adding cement to the lime at a 1:2 ratio (1 part cement to 2 parts lime) maintains 9 perms at 1.5" thickness, but increasing the amount of cement steadily reduces permeability. A straight cement plaster at 1.5" thickness is rated at 1 perm, so it is prohibited by code on straw bale walls (IRC Appendix S requires a minimum of 3 US perms).

In dry regions and temperate climates, it's common to use a lime exterior plaster for durability and a clay interior plaster for easier application and maintenance—they have similar permeance. In cold climates, it's best for the exterior plaster to be more permeable than the interior plaster because when water vapor driven by moist, warm interior conditions passes through a more permeable interior plaster, it may slow and condense where it meets a cold, less permeable exterior plaster.

Although straw and wood are both cellulose materials, straw is more susceptible to damage from free moisture—moisture not bound in the material—than wood is because the countless straws in the wall have much more surface area than the wood framing. This same feature also allows the straw to absorb more moisture, and, so long as that moisture stays below 20% (the level at which microbes become active and can begin to digest the straw), the walls will do their job.

Exterior plasters protect the straw bale walls from bulk moisture intrusion from wind-driven rain, but only to a point. Lime and lime-cement plasters are porous and can absorb water. How much depends on thickness, aggregate size, and application. Lime plasters can be relied on to protect the underlying straw bales as long as the absorbed moisture can regularly evaporate to the exterior on dry, warm days. Lime plasters subjected to repeated wetting with little opportunity to dry have failed; the plaster becomes saturated, and moisture wicks into the straw bales themselves. A few minutes of wind-driven rain is generally not a problem so long as the walls can dry between storms. Days, or even many hours of heavy wind-driven rain can overwhelm the plaster. If a given location is known to receive wind-driven rain without opportunities for drying, avoid relying on plaster alone to protect the walls. Design the structure with generous roof overhangs, install gutters, wrap the straw bale walls with porches, or consider using a rainscreen—siding over the plastered straw bale wall with an air gap between. See *Straw Bale Rainscreen Detail* in Chapter 2.

Exterior clay plasters behave differently when wetted, but they are also vulnerable to excessive exposure to water. Clay is hydrophilic; it attracts moisture. When wet, it swells, effectively sealing a wall from further penetration. However, it can also become soft, and if clay plaster receives frequent rain, it will eventually erode, exposing the straw bales to the elements. The same design features used to protect lime plasters are effective with clay plasters too: large roof overhangs, porches, and rainscreens.

The vapor transfer topic has been explored both through scientific testing and a lot of hands-on experience. But research continues, and the last word has not been written. Better understanding of how straw bale wall systems manage moisture will result in better buildings.

Keep liquid water out of the walls. Assume water vapor will be driven into the walls, and make sure that nothing stops its diffusion and evaporation from the wall surfaces. Understand the local climate and design for it. Understand internal moisture loads; a family of four will produce about two gallons of moisture per day, but the number can be much higher. According to the Canada Mortgage and Housing Corporation, an average home must manage 400 to 2,000 gallons of water in the air during a typical heating season. Use mechanical methods to remove moisture. Codes often require venting of range hoods, clothes dryers, and bathrooms to the outside.

Types of Straw

Sometimes people wonder if any kind of straw can be used. Five grain crops—wheat, rice, barley, oats, and rye—produce what we know as straw (not to be confused with hay, which should *not* be used for building). Straw bale building codes don't differentiate between straw bales made from different grain crops, so long as the bales meet minimum requirements for density and moisture content. But when builders have choices, they may prefer one over another.

In the United States, rice straw is available mostly in Northern California, the Mississippi River valley, and the Gulf Coast. It contains silica, which makes it more rot resistant when exposed to moisture. This is one reason rice farmers once burned their fields to clear straw after harvest—it can take years to decompose. The high silica content also makes rice straw unpalatable to ants and termites. Because of how rice straw lays on the ground when it is cut, bales tend to be dense and dusty, with intertwined stems. Compared to other types of bales, rice bales hold their shape and compression better when notched, and the bales separate into more distinct flakes when the strings are removed, making resizing and retying easier. Rice stems don't splinter as much as wheat straw, making them less likely to embed tiny fragments in exposed skin. On the downside, silica more quickly dulls cutting tools, and the silica in rice straw dust is irritating to breathe. Anyone cutting bales should wear a dust mask, particularly while working with rice straw. Some people have an allergic reaction to rice straw dust, and it seems to have a cumulative effect. Finally, rice straw bales may be heavier, requiring two people to lift and handle them. A three-string rice straw bale can weigh over 80 pounds, and a two-string bale weighs up to 65 pounds.

Wheat straw bales are more widely available throughout continental North America. They are less dusty, although wearing a dust mask is still prudent, especially when cutting bales. Wheat straw bales don't dull tools as fast, and they tend to be lighter, but they may still require two people to lift and place safely. Wheat straw will deteriorate more quickly if it comes in prolonged contact with moisture. As with any straw bale, it is imperative to keep them dry! Wheat bales have sharper edges because the straw tends to lay front-to-back instead of tangled like rice straw, so it can more easily scratch bare skin. Wear long sleeves when handling wheat bales.

Barley, oat, and rye straw are less widely available, but they are often used in straw bale structures. Their qualities are similar to wheat straw, and as long as the bales are

Organic Bales or Conventionally Grown Bales?

Finding organic straw bales can be a challenge for those who want a completely natural, chemical-free house. Organic farmers usually till straw back into the soil to recycle nutrients, control weeds, and lessen the need for other soil amendments. Still, conventionally grown rice, wheat, barley, and other grains and their straw are relatively free of pesticides. For example, rice farmers use commercial nitrogen fertilizers, usually in the form of hydrous ammonia applied to the soil prior to planting. When soil samples indicate deficiencies, farmers apply certain soil amendments prior to planting. They use various weed-control herbicides, usually within the first 30 days of the rice plant's growth. At this time, a rice plant is less than a foot tall, and by full maturity, this part of the plant makes up a small portion of the total mass because the plant develops new tillers until it reaches the seed-production stage. Rice reaches maturity in 135 to 165 days, so these herbicides, applied in very small quantities (usually a few ounces up to a pound of active ingredient per acre), have long been dissipated and broken down to very low levels. The pictures you see of crop dusters trailing a fog from a spray boom are actually the aforementioned amount of herbicide diluted in 10 to 15 gallons of water, applied per acre. Pesticides are seldom used on rice crops, and if used, they are applied very early in the plant's growth. Fungicide might be the only chemical applied, if conditions warrant, at mid-growth. The same holds true for wheat production, which usually requires even less herbicide application. In recent years, however, the striped rust fungus has forced many farmers to double the amount of fungicides, applied right up to wheat's mid-maturity stage.

sufficiently dense and dry, they are entirely suited to straw bale construction. For a more detailed discussion about sourcing, ordering, handling, shaping, and cutting bales, see Chapter 5, Stacking Straw Bale Walls.

Historical Note

After the practice of burning rice straw was banned to improve air quality, California rice farmers began flooding fields to hasten the decomposition process, worrying fisherman who thought too much water might be directed away from fisheries. In 1993, the fishermen teamed with the newly formed California Rice Commission to initiate the first state code guidelines for straw bale construction, which were adopted in 1996.

Bale Size

North American farmers gather the vast majority of straw in big bales because in that form they are more economical to produce, handle, and ship. These bales are usually 3'×4'×8', or less commonly 4'×4'×8', and they weigh from 1,000 to 1,500 pounds. Their large size generally makes them unsuitable for straw bale construction.

The bales used in straw bale structures are tied with polypropylene twine to make two-string and three-string bales. Though baling equipment can vary, and the bale dimensions are not precise, three-string bales tend to be about 15"×23"×46", and two-string bales tend to be about 14"×18"×36". The length dimension varies the most. Some farmers bale their own straw; others hire contract baling operators who also bale hay from alfalfa and other forage crops. Shifting crop and land values can impact the amount of grain grown in any particular area; as land values rise or more profitable crops displace less profitable ones, straw availability can fluctuate.

Straw Harvest, Baling, and Availability

Most small bales made from wheat straw are suitable for straw bale construction because they are dry and dense. Wheat, barley, oats, and rye are harvested in summer from completely mature crops, so the straw baled from these fields tends to be very dry. In fact, in extremely dry-summer regions in the West, many farmers bale the wheat straw in the morning or evening when dew increases the moisture content enough to make the straw stems more pliable and able to resist shattering as they are baled. Wheat straw typically comes from stripper-harvested wheat fields baled from the swathed rows after the stripper header harvests the grain and leaves the seedless plants standing. Because the harvest occurs during the summer building season, wheat straw bales are readily available directly from the field. Established markets maintain a high demand for clean wheat straw—it doesn't sit around long after harvest.

Rice plants grow in standing water. Rice is harvested from a plant that is mature, though still green. Weather plays a major role in producing rice straw bales for building purposes. The harvest takes place in the fall after the water has been drained and the fields are allowed to dry for three or four weeks. The ground is still damp just below the surface; the fall days are shorter, and morning and evening dew is heavier. This shortens the available time window when rice straw can be baled because conditions must be as dry as possible. The harvested straw must lay in the sun for at least four days for plant stems to lose their green moisture. After the initial dry-down period, the straw is raked into windrows to be baled. Before baling, windrowed straw is tested with a moisture meter to determine that it's dry enough to bale—it must be at 10% before baling commences.

The longer-stemmed straw preferred by straw bale builders requires the longest drying period. Flail-chopped straw or straw partially shredded by rotary combine-harvesters dries faster because moisture exits the stem via a shorter path. This straw is most often used for erosion control, and more recently, in fiberboard products. Builders prefer longer-stemmed rice straw bales made by older-style cylinder and straw-walker combine-harvesters because they damage straw residue the least—but these have become increasingly scarce. Although rice crops are grown in Gulf states like Mississippi, Arkansas, and Texas, higher humidity makes baling dry straw even more challenging.

The fall rice harvest also comes late in the building season, when winter weather threatens. The major markets for rice straw—erosion and livestock feed and bedding—take delivery before winter is over, so you may need to take delivery directly from the field or arrange for dry winter storage. Since rice straw harvesting varies, work with a supplier who knows the difference between bales used for erosion control and bales used for building.

Environmentally Sustainable Design

Besides using a super-insulating, low-embodied-energy, carbon-sequestering agricultural by-product in the walls, consider other steps to ensure your building consumes less energy and has a smaller carbon footprint.

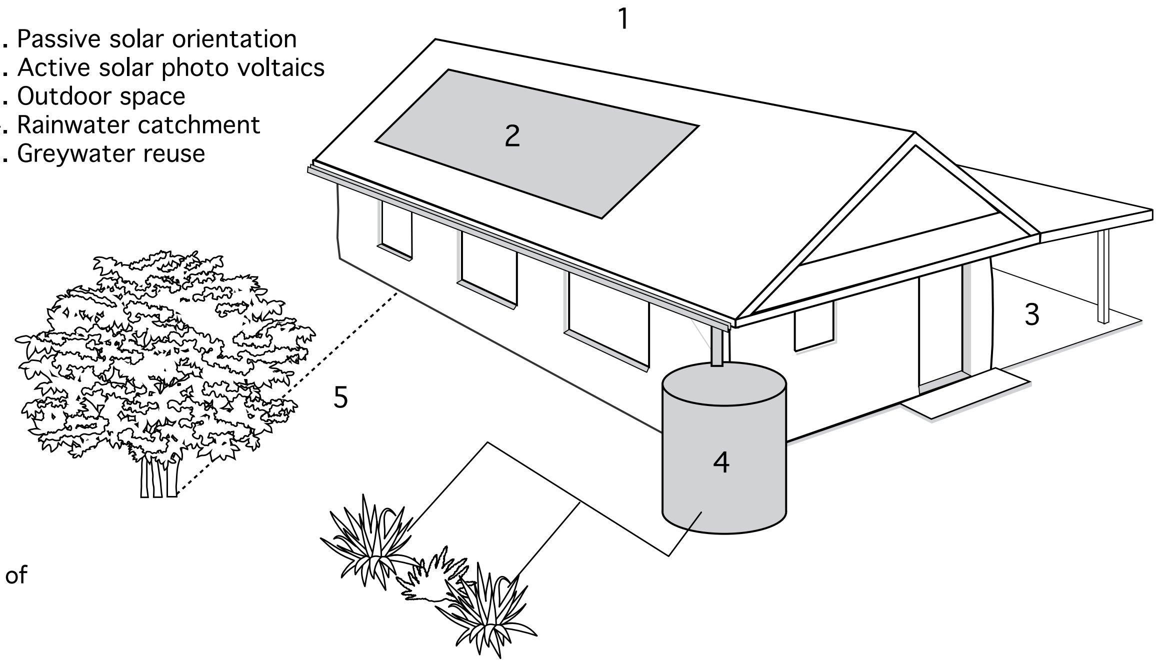
Regions graced with a Mediterranean climate or mild winters make it practical to live in smaller buildings wrapped with porches and patios for outdoor living. Smaller buildings consume fewer building materials, are faster and less expensive to build, and they cost less to heat and cool. If the structure is built in a forested area, consider locally harvested trees for posts, beams, and other dimensional lumber. Also consider using site-excavated or locally available clay-rich soils for plasters. All else being equal, using local materials is less energy and carbon intensive than using materials from far away.

The concrete in a typical foundation is a large percentage of a building's carbon footprint. Look for ways to trim the amount of concrete to what is actually needed, and inquire at the local mixing plant how much of the cement in the mix can be replaced with fly ash, a waste product from coal-burning power plants.

Note that these choices can affect the building schedule, structural system, and building maintenance. For example, high-fly-ash concrete is stronger, but it sets more slowly, and exterior clay plasters may need additional weather protection.

Those drawn to building with straw bales often incorporate other aspects of sustainable design:

- Build in a walkable neighborhood to reduce car use and make aging in place easier.
- Renovate an existing building, rather than building from scratch.
- Design with a potential addition in mind.
- Incorporate passive solar features.
- Install energy-efficient lighting and appliances.
- Use recycled-content ceiling insulation, like treated cellulose or cotton.



1-5. Other aspects of sustainable design.

- Use salvaged materials.
- Use solar electric power and heat pumps.
- Harvest rainwater from the roof for landscape and garden use.
- Plumb for greywater use.

Many of the items in this list can be incorporated into the design, and some can be added later. An environmentally sustainable design will consider these options in the building's short- and long-term environmental cost.

Conclusion

We've covered why people build with straw and touched on the building science of how a straw bale wall assembly insulates, stores heat, and handles moisture. Subsequent chapters explain design and construction as it pertains to building with bales: general design considerations, structural design issues, electrical and plumbing, stacking straw bale walls, and plaster options, including preparation and application. The last chapter contains the International Residential Code's (IRC) Appendix S: Strawbale Construction, along with its informative commentary. Finally, the appendices address fire safety during and after construction, and straw bale work parties.

If you are already familiar with the subject in any of these chapters, feel free to skip directly to the chapter(s) that interests you most. Cross-references throughout the book illustrate the interconnectedness of the building process and demonstrate how design choices can impact the finished structure.