MATERIALS

chapter **3**

adobe, rammed earth and straw bale wall systems foundation and roof options

The focus of Chapter 3 is on the material characteristics of traditional and alternative wall systems. Methods of constructing walls of adobe, rammed earth and straw bale are presented and illustrated in depth.

This chapter also reviews options for foundation and roof systems, which are essential considerations in the design of wall systems. Foundation systems considered include traditional stone foundations and contemporary concrete foundations, as they apply to the design and construction of walls of alternative materials. Roof systems discussed include structural framing options, as well as choices for roof coverings.

The review of foundation and roof systems is necessarily limited in scope, as the emphasis of this special study is on alternative and vernacular materials. Conventional foundation and roof systems are widely employed in contemporary construction and are widely known and understood. Hence, less detail is given here on such topics as concrete foundations and metal or asphalt roofing. Such commonly-used materials are the topic of numerous publications and are widely accepted by building code officials throughout the Southwest.

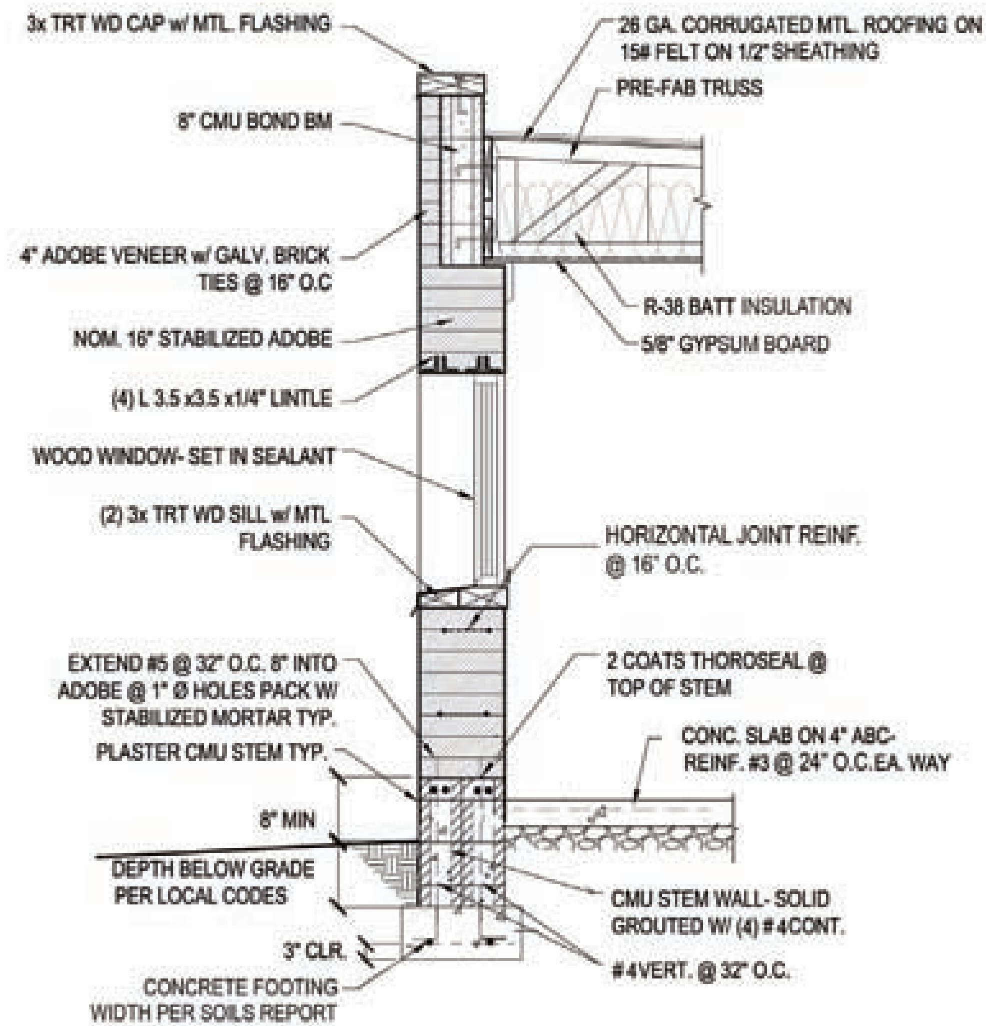
Diagrammatic wall sections are included to illustrate the assembly of adobe, rammed earth and straw bale wall systems. These sections are for general reference only, and should not be applied to specific projects without review by design and building professionals in the locale of the contemplated project. Site analysis is an integral part of the design process, and adaptations may be necessary to address soil conditions and wind or snow loads pertaining to the project location.

Adobe is sun-dried earthen brick, and one of the earliest building materials. There are adobe ruins in Iraq dating back 6000 years B.C. The Maya of Mexico and Central America developed adobe brick prior to the arrival of the Spanish in the early 16th century, although the indigenous of what is now the American Southwest did not use adobe until the Spanish introduced the material in the 1600s.

Adobe was brought to Spain by the Arabs during their 800 year occupation of the Iberian peninsula. The word "adobe" comes from the Arabic "al-tob." From Arabia adobe construction traveled to Egypt, across North Africa to Morocco, and then to Spain. In Morocco the pronunciation of the Arabic word "tob" became "thobe-e," and finally in Spain it became "adobe."

Adobe has been used in the American Southwest since the early 17th century, when the Spanish first built settlements in northern New Mexico. Many of the Pueblo tribes adopted the material for their own use, as evidenced at Taos. In the same period Jesuit missionaries were building simple hall-style churches in native communities along the Rio Sonora in the northwest Mexican state of Sonora, then the Spanish territory of Nueva Viscaya. In the latter part of the 17th Century, Jesuits built mission churches and supporting buildings from adobe in what is now Tucson, Arizona. In their need for expedient shelter, Spanish settlers constructed with locally available materials, turning to adobe for their houses, animal shelters, and other buildings.

The original architecture of frontier towns, such as San Diego, Yuma, Tucson, La Mesilla and El Paso was built of adobe. To this day in the American Southwest, adobe houses are still built, although due to the high labor costs of laying the walls, the cost of building from adobe is higher than that of conventional wood frame or concrete block construction. Ironically, in the U.S., adobe, once the building material of the poor, has become almost exclusively used in custom designed high-cost housing. In Mexico, adobe is still widely used in self help projects.



ADOBE PARAPET WALL SECTION

0 1 2

scale 3/8" =1'-0"

In the making of adobe, earth (composed of sand, silt, and clay) is mixed with enough water to make a stiff mud, which is placed in forms to mold bricks. The bricks, once removed from their molds, are allowed to dry slowly and bake in the sun over several weeks, being turned and stacked to expose the different surfaces to the air and sun for complete drying and curing. Factors such as temperature and humidity affect the requisite drying time. Anyone having spent time in the desert will understand that it really is possible to bake bricks in the sun: the intense sunlight and heat act to harden the mud in a way not possible in cooler, wetter climates. Adobe is truly a material of and for the desert.

A range of sand, clay, and silt is necessary for good adobe soil. Sand grains and silt act as aggregate and filler, while clay is the binder. A wide range in percentages of binder to aggregate can work to produce adequate adobes. There are both scientific and intuitive methods for testing the suitability of soil for adobe, which are well-described in the late P. G. "Buzz" McHenry's book, *Adobe and Rammed Earth Buildings*. Traditional adoberos use field tests (often taste, touch, and smell) and their personal judgment based on experience to tell if the dirt of a given site is suitable, while geotechnical labs measure particle size distribution, consolidation, compressive and tensile strength, and water absorption through testing.

Many types of soil make good adobes. Fine soils with a high silt content make dense blocks, and require relatively less clay binder

Cement stabilized adobe wall under construction. Mud mortar has same percentage of cement content as adobe bricks. Straw is added as a nod to tradition. Note 3/8" diameter steel reinforcing bars placed in mortar joint, where a window sill is to be located and additional tensile strength is desired to prevent cracking. Photo: B. Vint

TABLE 3.1 PARTICLE SIZE CLASSIFICATION

GRAVEL	> 4 mm	> .16 in.
FINE GRAVEL	2 mm - 4 mm	.08 in. - .16 in.
COARSE SAND	500 microns - 2 mm	02 in. - .08 in.
FINE SAND	250 microns - 500 microns	.01 - .02 in.
FINES	< 250 microns	< .01 in.

Courtesy of Pattison-Evanoff Engineering, Tucson, AZ than sandy soils. Sandy or gravelly soils can work as well, if they have an evenly graded distribution of particle size. Around the world are found endless variations of successful adobe soil.

Traditional adobe makers add chopped straw to their mix for several reasons: first, straw adds tensile strength; second, the addition of straw results in a lighter-weight adobe, by increasing the air space in the earth matrix; and third, straw retains moisture to slow drying time for a more uniform curing period, thereby reducing shrinkage cracks as the material dries. This is analogous to adding synthetic fibers to concrete for the same reasons, as is commonly done in contemporary practice.

Adobe blocks range from 3 to 4 inches in thickness, from 8 to 14 inches in width, and from 16 to 18 inches in length. A common nominal adobe size in the United States is 4"H x 12"W x 16"L , nominal meaning that the dimension includes the thickness of mortar joints, which vary from 3/4" to 1' thick. Mortar for laying adobe should be mixed from the same materials used in making the blocks to ensure compatibility in terms of hardness, moisture absorption, thermal movement, etc. Horizontal joint reinforcement of steel wire should be installed at intervals to provide a measure of tensile strength along the wall.

Adobe wall under construction in Tucson, Arizona, illustrating the amount of labor required to raise a wall.
Photo: B. Vint

There are commercial adobe manufacturers across the American southwest in California, Arizona, New Mexico, Texas, as well as throughout Mexico. Unless unstabilized block are requested for historic preservation projects, contemporary manufacturers in the U.S. stabilize their product with Portland cement or asphalt emulsion. Percentages of stabilizer vary with the locale and manufacturer, from five percent to ten percent by volume. Stabilized adobes are resistant to erosion and do not require a protective plaster coating.

Unstabilized adobes are still produced in large quantities in Mexico, but U.S. building codes require that walls made from unstabilized adobe be plastered with cement, which ironically is an incompatible finish for unstabilized adobe, damaging the adobe over the long term: a reminder that building codes are not infallible.

A 20th century innovation in adobe making is the pressed earth block. These can be produced either manually with a brick press, such as the Cinva Ram, or mechanically with a motorized hydraulic brick press. Molding bricks under pressures as high as 30,000 psi results in a denser, more durable adobe weighing 125-135 pcf. Because of their relatively greater density, pressed earth blocks conduct heat somewhat more quickly than traditional adobes.

Adobe has been used for centuries around the world. There are examples of multi-story adobe structures in Yemen and Iran. In the U.S. Southwest most adobe construction has been limited to one and two stories, with the exception of some Native American pueblos. Contemporary building codes make it difficult and expensive to build an adobe dwelling of more than one story in height: therefore this discussion addresses the use of adobe for single-story housing.

Building codes in the states of California, Arizona, New Mexico, and Texas now include adobe as an accepted building material, with restrictions. Codes are prescriptive, specifying a minimum compressive strength of 300 pounds per square inch (psi) and wall height-to-thickness ratios of 10:1. Buildings are limited to one story in height unless designed by a professional structural engineer. Adobe may not be used for foundations or basement walls.

The principal advantages of adobe are:

- *thermal mass*
- *high compressive strength*
- *abundance of its raw material, earth*
- *low embodied energy in production*

The thermal mass of adobe slowly absorbs and releases heat energy. In the arid borderlands, summer days are hot while nights are cool, the dryness of the climate permitting the earth to radiate the day's heat into the dark night sky. The night's coolness is stored in the massive adobe walls and moderates the interior temperatures of the

Effect of cement repairs to adobe: moisture from foundation wicks by capillarity through adobe and is unable to escape through cement stucco. Damp adobe is softened and compresses, pushing stucco off wall; water rises ever higher in wall as further cement repairs are made. The correct finish for unstabilized adobe walls is a "breathing" unamended mud or lime and sand plaster that allows the transpiration of moisture vapor. Photo: B. Vint

Long-term effect of cement on unstabilized adobe: deterioration of wall base due to rising dampness trapped by cement. Walls eroded at the base are prone to collapse, when dampened during the rainy season, for they are weakened exactly where the accumulated weight of the wall above is greatest. Photo: B. Vint

Adobe house under construction Tucson, Arizona. Note mason's corner story pole and electrical wiring being laid in mortar joint so that interior will not have to be furred out. Photo: B. Vint

building during the day, thus keeping the occupants thermally comfortable. Equally useful in the cooler months is the ability of the adobe walls to store heat from the sun during the day and release it to the interior during the night. Thermal mass strategy works only in regions where there is a significant diurnal temperature swing, which means in deserts where humidity is low. The ideal thickness of adobe walls in regard to thermal mass varies as a function of elevation of above sea level, latitude, daily and seasonal temperature patterns, precipitation patterns, etc. In principle, the greater the mass, the greater the stabilizing effect on interior temperatures, as with a cave. As a minimum 16 inches of adobe thickness is recommended, for empirical data shows that heat travels too quickly through anything less than that to be effective. A 3-foot thick wall is ideal, but prohibitively expensive to build. A balance must be struck between cost and benefit.

Adobe is strong in compression, making it adequate to resist gravity loads. At 300 psi minimum strength, a 12 inch square pillar is capable of supporting 43,200 pounds of downward load. However, because adobe has no tensile strength, it cannot resist bending, making it vulnerable to lateral forces (i.e. earthquakes.) Given that earthquake loads are a function of the weight and height of a structure, and adobe is a heavy material (approximately 125 to 140 pounds per cubic foot/pcf), earthquakes are often the controlling factor. Engineers calculate both wind and earthquake loads to determine which is greater, and in the case of adobe garden walls, wind load can control the design.

Contemporary adobe construction utilizes a reinforced concrete or steel bond beam at the top of and around the perimeter of the walls to tie the structure together to resist lateral loads. This requirement favors a simple arrangement of the plan, that is, few corners and ins and outs. It is good practice in adobe construction to have frequent cross-walls, also built of adobe, to act as buttresses. The Pima County, Arizona, Earthen Materials Code requires a cross wall at a maximum spacing of 20 feet.

Earth, the raw material of adobe, has the lowest possible embodied energy content of known building materials, that is, the least energy is required for its production. Adobe is a recyclable material, as it can be dissolved back into the earth. True adobes are dried naturally in the sun, another source of unlimited and free energy. Therefore, the largest cost of adobe manufacturing and construction is human labor.

Research by Professor Gernot Minke of Kassel University has shown that the production of industrially manufactured building materials uses a high amount of energy (refer to Table 3.2). Earthen materials consume only about one percent of the energy required to produce burnt bricks or concrete elements. A further reason to consider earthen construction, beyond its energy efficiency and low life cycle operating costs, is the benefit to the environment of consuming less energy in its production.

In northern Mexico and the southwestern U.S., there is a regionally available material called "burnt adobe", a contradiction in terms, since adobe means unburned brick. In New Mexican Spanish, burnt adobe is known as *adobe quemado*, while in Sonora it is called *tabique* or *ladrillo,* meaning brick.

Burnt adobe is in essence a primitive brick the same size and shape as a mud adobe block. The same mud bricks used unfired as adobes are placed in a kiln and fired, achieving a degree of ceramic vitrification. Because adobe mud is low in clay content, burnt adobe bricks do not achieve the strength of fired clay brick (600 - 900 psi for burnt adobe vs. 6,000 psi for clay brick).

TABLE 3.2 ENERGY EXPENDITURE OF BUILDING MATERIALS

(Kilowatt hours per cubic meter)

MATERIAL	
Steel	54950 kWh/m3
Timber	550 kWh/m3
Concrete	500 kWh/m3
Precast concrete	800 kWh/m3
Perforated brick	600 kWh/m3
Solid brick	1100 kWh/m3
Earth (adobe, rammed earth)	5 -10 kWh/m3

Source: Minke, Gernot "Earth as a Building Material" Out of Earth, First National Conference on Earth Buildings Center for Earthen Architecture, University of Plymouth, UK 1994.

Burnt adobe or *tabique* was popular in Arizona and New Mexico from the 1930s through the 1960s as a locally made, economical alternative to brick, cement block or wood frame construction. It fell from use in the 1970s, as the costs of masonry labor began to escalate, and wood frame and stucco became the least expensive and most widely used method of construction.

Eric Means, mason and general contractor, installs a reinforced concrete block (CMU) bond beam at roof level of adobe wall. Photo: B. Vint

Kilns for burning *tabique* are fired with whatever fuel can be gathered in the small villages where these bricks are made. This has led to the deforestation of mesquite bosques in northern Mexico, and the burning of rare ironwood trees along with mesquite. As brush for fuel grows scarce, some fabricators have turned to burning car and truck tires in their adobe kilns, with environmentally disastrous results. Burnt adobe is not recommended for use in the construction of new dwellings, as sun-baked adobe is environmentally more appropriate.

APPLICATIONS

The greatest limitation to the use of adobe for affordable housing is its relatively high cost in comparison with conventional construction methods. In 2004, the regional cost per square foot (PSF) of wall area was approximately $18.00 for unplastered adobe, compared with $12.00 PSF for an insulated, plastered concrete block wall and $8.00 PSF for a frame/plaster wall. Cost is a significant obstacle to the use of adobe for affordable home building, due to its labor intensive nature.

Another factor in the cost of adobe is that a limited number of masons are experienced with the material. If the labor pool were to grow, competition would reduce costs.

A way to make adobe feasible for affordable housing is to share walls between units, in essence, building a wall once and using it twice. This effectively cuts the cost of the wall in half, making it more competitive with conventional materials. Shared walls have the added advantage of reducing exposure to the elements, reducing both heat loss and gain, resulting in lower air conditioning loads and utility costs. With the higher densities made by the courtyard type house, land use is also more efficient as more houses can fit in the same land area. This reduces the cost per house, as the land cost is distributed over a greater number of houses.

Another approach is to design smaller houses of higher quality in terms of energy performance and durability, considering not only the first cost but the life-cycle cost of operating the house. In this aspect, adobe is superior to conventional methods of construction.

Using stabilized adobe which does not require exterior stucco or interior fur-outs (wood or metal framing added inside masonry walls to create a cavity for insulation and wiring) is also a cost reducer. With exposed stabilized adobe, the mason (1) builds the structure, (2) creates enclosure, and (3) provides a wall finish all in one operation. No framers, drywallers, plasterers, or painters are needed.

All of these factors must be considered in determining the total cost and benefit of adobe construction. Between shared walls, courtyards, lower land costs per dwelling, greater durability, and lower life-cycle costs adobe can be feasible for use in affordable housing. Housing design based on these principles requires special planning and understanding to maintain privacy and quality of life. In *Ch.5* of this report are prototypical designs demonstrating this concept.

Rammed earth is among the oldest building materials and methods. Over 6,000 years ago in ancient Egypt, rammed earth was used to fill the great pyramids. The Great Wall of China is largely rammed earth, again with a stone veneer facing. In the southwestern deserts, the Hohokam site of Casa Grande in central Arizona has stood for over 650 years as an example of the durability of earthen construction. By mixing dirt with water and compacting it in forms, the earth itself can be molded into enduring, energy-efficient architecture.

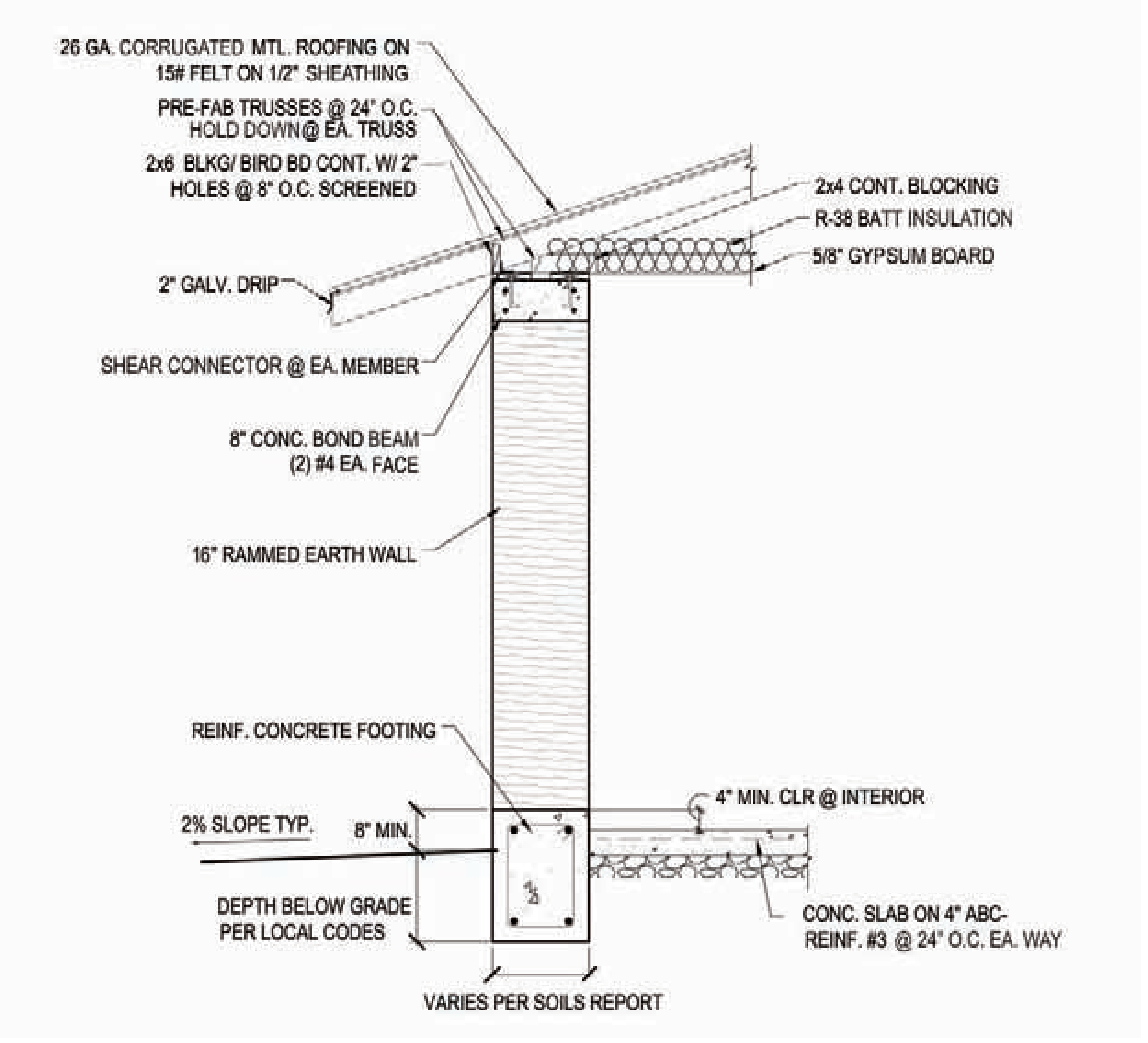
Contemporary rammed earth practice is a mechanized form of achieving an earthen wall. It is in essence industrialized adobe. Earth is dampened to optimum moisture content, which is the point at which no additional water can be added without creating mud. Damp earth is placed inside a braced formwork of wood or steel, and compacted with either hand-tamping rods (also of wood or steel) or pneumatic compressed air tampers.

The earth is rammed into the form until it is fully compacted, at which point it rings in a distinct way discernible to the experienced earth-rammer. Testing of samples taken from the field by a certified testing laboratory is recommended, as described in *Ch. 4*. Because the earth is well compacted and is typically stabilized with a small percentage of Portland cement (3% - 5% by dry volume), it can be left exposed with greater durability than adobe. It reliably attains the minimum compressive strength of 300 pounds per square inch required by building codes. Rammed earth is a superior thermal material when compared to concrete or cement block, and can be a very environmentally responsible option. The amount of energy required to produce a cubic meter of rammed earth is only one percent of that required for the same volume of concrete or brick (*see Table 3.2, p. 87*).

Rammed earth houses in hot-arid regions rely upon the "thermal fly-wheel" principal of using the massive wall to moderate the extreme diurnal temperature swings typical of deserts, as described in the preceding section regarding adobe. To function properly for passive cooling and heating, earth buildings require natural cross ventilation.

Because rammed earth cannot be vertically reinforced with steel reinforcing bars like concrete block, it remains vulnerable to earthquakes. A sound design approach including a maximum wall thickness-to-height ratio of 1:10, adequate cross-walls, and a continuous bond beam is needed to provide adequate resistance to lateral forces.

As with adobe, North American building codes require concrete bond beams for rammed earth walls, although extensive seismic testing in Latin America has shown that wood bond beams are more compatible with earth. The problem is ensuring that the wood is protected from insects, moisture and rot, so that it remains effective. The same is true for bearing lintels in earth walls: current U.S. codes disallow wood lintels in masonry walls of any kind.



RAMMED EARTH WALL SECTION

0 1 2

scale 3/8" =1'-0"

AFFORDABILITY

Although taking advantage of modern mechanized techniques, rammed earth is surprisingly 25 percent more expensive than traditional adobe construction. In 2004, a two-foot thick rammed earth wall constructed by a specialized subcontractor cost from $20 to $24 per square foot of wall surface area, depending upon the height. Walls greater than 12 feet in height cost more than lower walls due to the cost of additional formwork and labor to place the earth.

This means that professionally contracted rammed earth costs two to three times more than conventional wall materials, such as wood frame or concrete block, making it prohibitively expensive. *Only through donated or subsidized labor can this material be considered for widespread use in affordable housing.* An example of this approach is illustrated in the case study which follows this general discussion of the material's properties and limitations.

Another possibility is to use rammed earth in limited ways to make the most of its thermal properties, such as building a single rammed earth wall to act as a thermal mass within a house built largely of other less expensive materials, such as straw bale or wood frame.

Rammed earth may also be used to build benches beneath south-facing windows, to absorb the sun's heat and re-radiate it at night for passive solar heating.

Earth walls can be left exposed, both saving the cost of finish plastering and revealing the aesthetically pleasing pattern of striations of earth as rammed in successive layers.

Ironically, rammed earth has become a material of choice for wealthy people in the building of their "dream homes." Earth, the humble material used to house the world's poor for centuries, has become a luxury in our contemporary society.

The great difference is that the poor who build their own shelters out of earth do so with their own labor. In a cash-based economy, self-sufficiency is exchanged for specialization, and given the relatively high labor costs of an industrialized society, traditional earth construction costs more than building with modern materials.

APPLICATIONS

The ideal wall system for a desert house would have high thermal mass, low thermal conductance, and substantial thickness. Rammed earth fits this description well.

To achieve the thermal benefit of rammed earth the interior surface of the walls should not be furred or insulated, as this would isolate the thermal mass from the living space. Electrical and plumbing lines must be integrated in the earthwork, increasing the cost of these sub-trades.

Ideally the exterior of an earth wall would be insulated and plastered, for this protects the thermal mass from temperature extremes and stabilizes the temperature of the thermal mass. As with adobe, the exterior finish employed with rammed earth must have a "breathing" surface so as not to trap moisture within the wall. If a contemporary foam and synthetic stucco "Exterior Insulation and Finish System" (EIFS) is considered, its permeability and compatibility with an earth substrate must be confirmed. Manufacturer's product data should include test results demonstrating breathability.

Because rammed earth is produced in large, box-like forms, the system favors straight simple walls with few corners. This produces simple rectangular buildings in the tradition of Casa Grande or Sonoran adobe row houses.

Rammed earth is an excellent material due to its durability, high thermal mass, and aesthetic appeal. It is a regionally appropriate, yet costly, material. In order to make use of rammed earth for affordable housing, innovative programs, such as that outlined in the following case study, must be employed.

Striations of rammed earth in approximately 8" lifts.
Photo: C. Neumann

architect/builder

1999 Design/Build Studio University of Arizona College of Architecture and Landscape Architecture in partnership with the Gila River Indian Community (Akimel O'odham)

location

Gila River Indian Community, District 6

clients *Della Hughes Family*

residence area *1120 sf.*

final cost *$51,000 (2001)*

$4 psf rammed earth cost due to use of homemade forms and student labor, $9 psf when student labor paid at minimum wage. Funded by UA/ Community Partnership Grant from the Kellog Foundation

The University of Arizona College of Architecture Design/Build Studio, run by Professor Mary Hardin, has been taking on the challenge of engineering rammed earth construction such that the process becomes more affordable to low/moderate-income families. The high cost of rammed earth results from the overhead expenses of formwork and scaffolding, as well as the greater labor required to place and compact large volumes of earth into the forms. The Studio's interest in experimenting with rammed earth led to a partnership with the Gila Indian River Community, which was facing a housing shortage.

The result of the partnership is the Gila River residence, a rammed earth house designed and built by architecture students at the University of Arizona. In working with Gila River tribal members to train them in rammed

Della Hughes with her family's "sandwich" wall home in background. Photo courtesy of J. Florence

"The family claims that this house has some of the desirable attributes of their traditional architecture, because it maintains a constant interior temperature while using naturally available materials. The community response has been strong and more rammed earth houses are in the planning phase."

Prof. Mary Hardin
"Appropriate Technology: Cycling Between High and Low Tech in the Sonoran Desert"

UA design/build student ramming earth with a pneumatic tamping machine known as a Jumping Jack. Note custom lumber formwork. Photo courtesy of M. Hardin

A tribal member smooths the concrete bond beam where the roof assembly will be connected to the earthen walls. Photo courtesy of M. Hardin

1 *Mixing dry soil and cement.*

2 *Tamping earth within lumber/plywood forms.*

3 *Removal of forms.*

4 *Tamping higher portions of wall.*

5 *Work progressing from building corners.*

6 *Forms built to create voids for windows/doors.*

7 *Concrete pumped into forms for bond beam.*

8 *Sills protected with tile.*

9 *Final earthen house before windows and doors.*

THE BUILDING PROCESS

All photos on this page courtesy of M. Hardin and J. Florence.

earth construction, the students learned of traditional Akimel O'odham building techniques such as the "sandwich house." The sandwich house, with walls composed of mud and straw packed into a frame of heavy vertical posts with light horizontal pieces, has been popular for 80 years, but requires a lot of maintenance.

The native use of compacted earth dates back to the construction of Casa Grande *(see Ch. 2, Design)*. The tribe was interested in continuing their earth building traditions, but with a more permanent product. Densely compacted cement stabilized rammed earth was considered a very viable solution.

After students met with the client family and other tribal members to decide the house configuration and the best way of using the local soils, construction began. The earth wall forming process was streamlined by the investigations of previous UA Design/Build studios. Rammed earth contractors typically form an entire building at once and do the tamping in the shortest possible time to reduce labor costs. In the case of this non-profit partnership where labor was plentiful and cheap, an alternative forming system was pursued in which walls could be formed incrementally by a few people and the forms reused again and again.

Previous testing ruled out the use of forms similar to those used for contemporary concrete work (plywood sheets reinforced with steel members), since they were not easily used on a small scale. The weight of the forms and difficulty connecting courses led the design team to try other options. Another attempt using plywood reinforced by aluminum members was not successful, since the forms moved under the force of pneumatic tampers and caused the walls to "creep" horizontally or "crawl" vertically off the foundation. Finally, the Studio reverted to an established forming system involving planks reinforced by poles and ropes. Quick and easy assembly was the benefit of a system in which milled lumber stiffeners (2x10 walers) were held against plywood forms by pipe clamps to retain the tamped earth. In a previous UA Design/Build project (a 1000 sf rammed earth classroom built in 1998), this two-person incremental forming system cost just $300 for plywood, boards, and pipe clamps.

With the Della Hughes house the forming system was further improved for a small labor force. Breakdown and set-up periods were reduced by using 4' x 10' sheets of plywood with no alterations, except for the holes drilled for pipe clamps. Previously, forms were raised in 2 ft increments: fewer clamps were needed in this case since the seam between forms was eliminated by the use of a higher form. In addition, PVC tubes were used as sleeves for the pipe clamps and wedges/shims were developed to resist the increasing pressure between forms and clamps as the earth was tamped. The PVC sleeves were left in place as conduits for snap ties which held together the plywood forms for the concrete bond beam at the top the walls.

This family has been satisfied with their rammed earth house, made possible by the work and dedication of the University of Arizona Design/Build team and the Gila River tribe. Rammed earth is feasible for affordable housing through donated labor or sweat equity on the part of the owners.

The Della Hughes Family House after rough work (walls and roofing) has been completed. The wide porch which shades the south and west side of the residence aids in passive cooling and provides the family with outdoor living space. Photo courtesy of M. Hardin

Saguaro ribs integrated into the rammed earth during tamping and anchored by 3" drywall screws and inset on the sides by 12". The addition of the ribs was debated between students and tribe members since its function is purely ornamental but tribe members deeply wanted to maintain ties to traditional sandwich wall construction. Photo courtesy of M. Hardin

Straw is the stem material left as a by-product of modern grain harvesting. A common misconception is that straw and hay are the same but they should not be confused. Hay is grown for livestock feed and harvested green, while straw has no nutritional value and is therefore not as susceptible to rot or insects. When properly designed and constructed, straw bale is a viable and sustainable building system.

When harvested, straw is compacted into modular forms and bound with baling wire, sisal or propylene twine to form bales, allowing it to be removed from the fields and stored. There is an abundance of straw across the United States: it is estimated that 140 million tons of loose straw are created in the US every year (Myhrman and Knox, 8).

A relatively short time elapsed between the invention of the mechanized baling and the use of straw bales to build shelters. Midwestern homesteading drove the great agrarian boom of the late 1800s, bringing with it western migration and the invention of machinery to serve the new agricultural society. By 1872, the stationary horse-powered baler was used to produce straw bales. A steam-powered baler was available by 1884. Straw was initially baled as a means of managing it and moving it with machinery, rather than with manual labor (pitch forks and wagons). Straw had to be removed from fields after the harvest, and was useful as animal bedding and floor covering in stables.

For early settlers in the harsh climate of the Nebraskan plains, baled straw was a natural choice as a readily available, economical and highly insulating building block. Settlers recognized the ability of straw bales to retain warmth and provide protection from the elements. Straw bales were stacked with staggered joints like brick construction. The roof was set directly atop the bales. This method of construction is called the “Nebraska style” after its place of origin. Nebraska style is simpler than the “Post and Beam” system, in which bales are fitted into a wood or steel framework.

In addition to housing, straw bale construction was used for farm buildings, churches, schools, and stores. Shelter options for early Great Plains settlers were limited. As the plains have no forests, it was difficult to obtain wood for building houses before rail lines were built to import materials. Sod houses made from layers of cut turf were built, but this method required more labor than building with bales, and stripped productive land of its top soil. Although early straw bale houses were likely intended only as interim shelters, their insulating performance in the extreme temperatures of Nebraska’s blizzards proved so effective that many became permanent dwellings.

According to straw bale experts Matts Myhrman and Judy Knox, at least twenty-eight original midwestern straw bale structures dating from the 1890s to 1930s still exist. Many remain in good condition despite receiving little maintenance. The Scott House is an example of the endurance of a properly built Nebraska style straw bale structure. Built in the 1930s of wheat straw baled with a stationary horse-powered baler, this 900sf house is still lived in by the daughter of the original builder. She recalls her mother objecting to the thought of living in a house made of straw, but once construction was complete, she became convinced. She also reports that her utility bills are 40 percent lower than her neighbor’s.

Arthur, Nebraska: The Martin-Monhart house, built 1925. The house has become a family museum and is open to visitors.
Photo courtesy of M. Myhrman and J. Knox

Huntsville, Alabama: The Burritt Museum, built in 1938, is a post & beam style straw bale. The structural system is concrete.
Photo courtesy of M. Myhrman and J. Knox

"Bailing hay on the Empire Ranch, Buffalo County, Nebraska." 1907 Photo: Solomon D. Butcher, US Library of Congress

Over the forty years following the formative period, straw bale construction declined with the advent of other affordable housing choices, including manufactured housing. It was not revived until the early 1970s when it was "re-discovered" by hippies moving back to the land. Straw bale housing was profiled in the alternative housing publication *Shelter,* published in Berkeley in 1973. From that date forward, straw bale has experienced a renaissance in the US Southwest. In 1991, the first legally permitted, insured and bank financed "Post and Beam" straw bale house was completed by owner/contractor Virginia Carabelli in Tesuque, New Mexico.

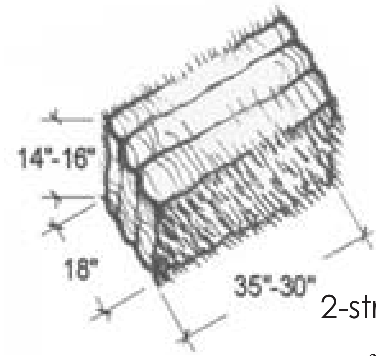
Two years later the first permitted load-bearing Nebraska-style straw bale house was completed in Tucson, Arizona, by Judy Knox and Matts Myhrman. Myhrman and Knox worked closely with David Eisenberg, director of the Development Center for Appropriate Technology (DCAT) of Tucson in developing the Pima County, Arizona, Straw Bale Code. This has become a model code for other southwestern municipalities.

Straw bale residential construction has spread world-wide, from Canada to Austraila and from Mongolia to Mexico. There have been many new developments in the straw bale construction from the mid-1990s onward and interest continues to grow as its affordability, environmental advantages and aesthetic values are recognized.

BALE TYPES AND PROPERTIES

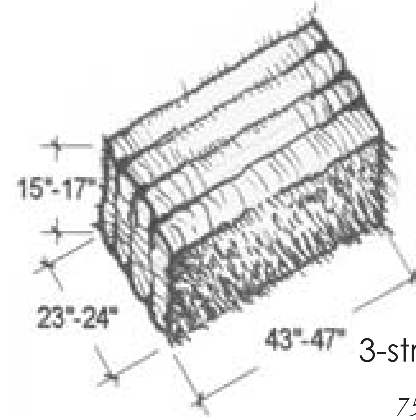
Straw is inherently structural, and maintains its form because of its tubular shape. The material's microscopic waxy coating also makes it slightly water resistant.

A straw bale is a bundle of straw bound with baling wire or polypropylene twine. Sisal has also been used for binding in the past but is not rot resistant. Straw varieties include wheat, rice, barley, hops, and oats. There are two types of bales, 2-string and 3-string. A diagram of each is at right. Bale sizes vary depending on the type of baler used and local practice. Bale weight may also vary, depending on density and moisture content.



2-string bale

35-65 lbs.
on edge: R-29
*laid flat:*R-26



3-string bale

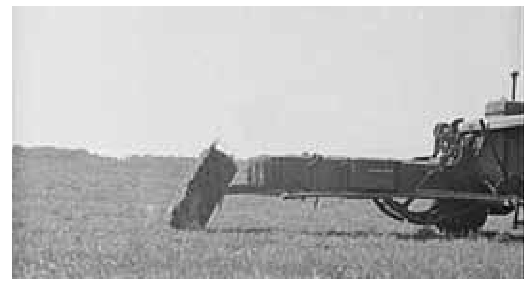
75-100 lbs.
on edge: R-33
laid flat: R-33.5

R-values reflect findings from California Energy Commission testing, 1997.

THE TRADITIONAL BALING MACHINE

Operating a baling machine at the Spring Run Farm. Dresher, Pennsylvania, 1944
Photo: Pauline Ehrlich, US Library of Congress

Baling machine operating at the Spring Run Farm. Dresher , Pennsylvania, 1944
Photo: Pauline Ehrlich, US Library of Congress



A bale being dropped from baling machine. Dresher , Pennsylvania, 1944
Photo: Pauline Ehrlich, US Library of Congress

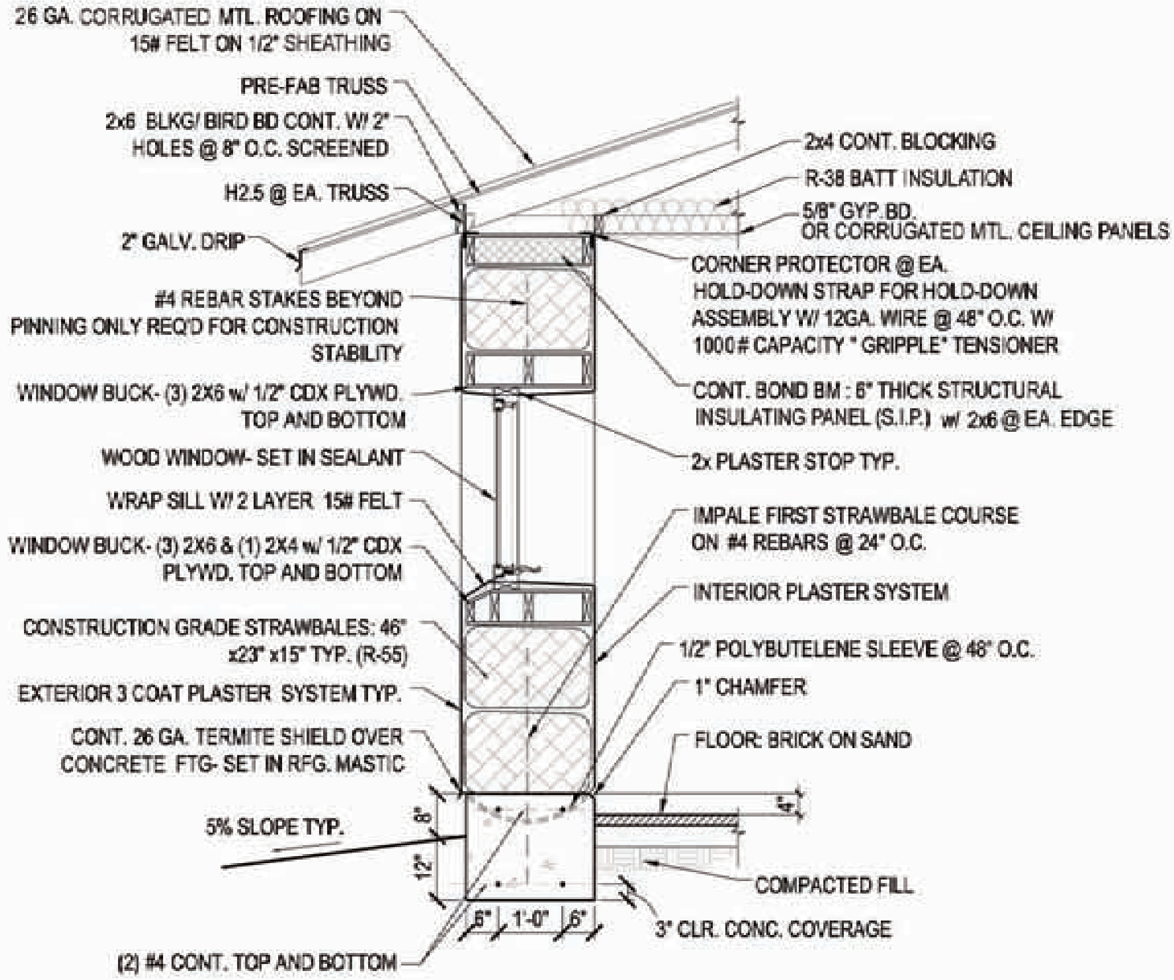
Making adjustments to a baling machine. Dresher, Pennsylvania, 1944
Photo: Pauline Ehrlich, US Library of Congress

Detail of a baler showing rotating knives which cut hay into proper lengths.
Photo: Pauline Ehrlich, US Library of Congress

Detail of bailing machine. The propylene twine which binds the bales is inserted in spools.
Photo: Pauline Ehrlich, US Library of Congress

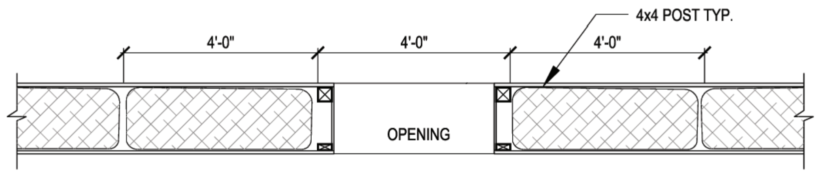
NEBRASKA STYLE

Bales are load-bearing, supporting themselves and the roof load. Wind uplift is resisted by cables or threaded rods that are anchored in the concrete footing. Plaster is a structural component used to stiffen the wall and transfer lateral loads to the foundation. The Pima County Code limits the height-to-thickness ratio to 1:5.6 (equalling a 10'-8" height for a 23" wide wall, the approximate width of a bale laid flat). The length-to-thickness ratio in plan view is limited to 1:13 (25' length for a 23" wide wall). Advantages of this system include the efficiency of combining structure with enclosure and reduction in use of lumber, and the lowest possible construction cost. This system lends itself well to self-help housing. A disadvantage is the dimensional restriction in height and plan configuration, in contrast with the Infill/Post & Beam style illustrated on the facing page.



NEBRASKA STYLE (LOAD BEARING) WALL SECTION

0 1 2
scale 3/8" =1'-0"



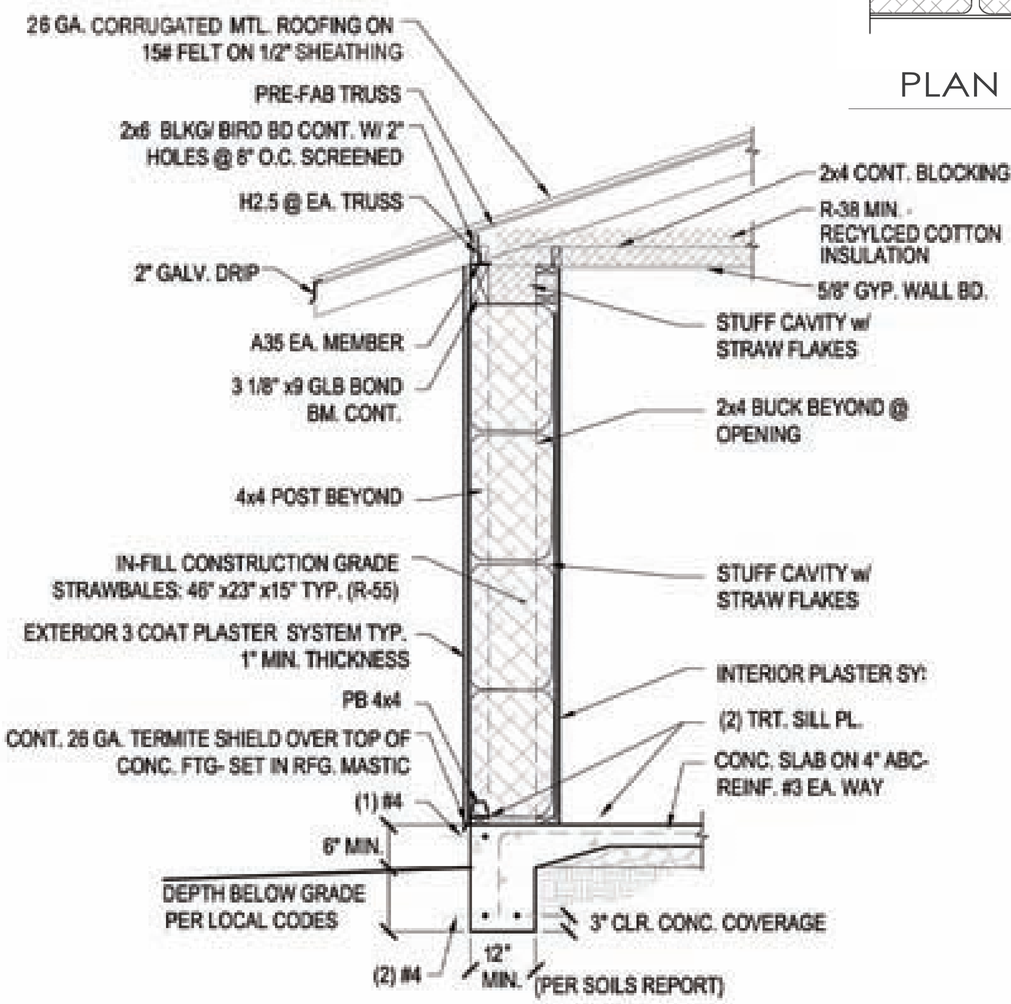
PLAN DETAIL

0 1 2

scale 1/4" =1'-0"

INFILL STYLE

With the infill "Post and Beam" style, an independent structural system carries the loads from roof to foundation, and straw bales are used as infill to create the enclosure. Milled lumber is the most frequent material for supporting elements, although concrete block piers and concrete or steel columns have been used. The advantage of this system is greater design flexibility, including the possibility of designing for more than one story in height. This system has greater long-term stability and can be custom-engineered, in contrast with the prescriptive approach used in the Nebraska style. It is a more sophisticated system requiring skilled labor, and is, therefore, more costly.



INFILL (POST AND BEAM) STRAWBALE WALL SECTION

0 1 2

scale 3/8" =1'-0"

While baled straw is not a traditional building material of the U.S. Southwest, straw bale houses have been proven to adapt well to the desert climate. Many lessons learned from traditional desert housing have been incorporated into straw bale design. The native material palette of earth, sand, lime, and small diameter timber (saguaro ribs, ocotillo stalks and mesquite branches) integrates well with straw bale construction techniques.

The use of straw has precedents in regional building traditions. Straw was commonly mixed with mud for adobe blocks and earth plasters. Loose straw left over from erecting bales can be used in mud plasters and earth floors, lending tensile strength to the earth.

The relative softness and elasticity of earth plaster is more structurally compatible with straw than cement plaster in terms of thermal expansion and contraction. This relationship is important given the great diurnal and seasonal temperature swings of the desert.

Straw bale walls must be protected from moisture, insects and fire, by plastering both the interior and exterior surfaces. The plaster coating is one inch or greater in thickness, varying with the irregular surface of the bales. Stucco netting is often wired to the bales to provide greater adherence and reinforcement to the plaster. As with adobe, the plaster skin of a straw bale wall must "breathe" (i.e. permit the transpiration of water vapor) to prevent the accumulation of moisture within the wall.

Tucson, AZ: Volunteers place straw bales around a window buck. This one-bedroom house has a modest 676 sf net floor area, but has been enjoyed by the owner since 1997. Design: B. Vint, Architect Photo: B. Vint

Tucson, AZ: The finished house has an east-facing porch, a sheltered transition from the interior to the desert environment. Earth plaster stabilized with lime and mesquite porch posts from the site demonstrate the integration of regional materials. Deep overhanging eaves provide shade and protect walls from rainfall. Photo: B. Vint

Plaster finishes also serve to stiffen straw bale walls, and to transfer lateral and gravity loads from the roof diaphragm to the foundation. The interior and exterior layers of plaster, when well-tied through the straw, create a sandwich panel analogous to corrugated cardboard.

While current building codes recognize cement plaster as the most structurally reliable finish for straw bale walls, earth or lime-based plasters are in fact superior for their greater breathability and material compatibility. Standards must be developed, and building codes must be revised to include earth and lime plasters.

Simple traditional building forms which evolved from the masonry tradition of the Southwest can be readily adapted to straw bale construction. Many straw bale houses being built today (especially of the Nebraska style with load-bearing walls) feature simple plans of less than 1,200 net square feet in floor area, with gabled roofs for shedding water quickly .

Attached porches are a traditional design element that provide shaded outdoor space and additional protection for the straw bale walls from both the sun and rain. Porches are inexpensive to build and can augment the compact living area of an affordable house.

A great advantage of straw bale construction is that it is highly insulating. Research by the California Energy Commission in 1998 found that a typical 3-string bale laid flat in a Nebraska style load-bearing wall has a thermal resistance factor or R-value (the measure of a material's ability to prevent heat transfer) of 33.5. The same type of bale laid on edge in a post and beam structure achieves an R-33. The R-value of a 2-string bale laid flat is approximately R-29, while on edge it is R-26. This compares favorably with a conventional 2x6 wood frame wall, which has an insulating factor of R-19.

In construction, gaps between bales must be packed with loose straw (called "flakes" in the bale builder's terminology) before plaster is applied, to prevent air infiltration which would reduce the wall's insulating efficiency.

To maintain a continuous building envelope roofs must also be well-insulated. High insulation conserves energy and reduces utility bills for the home owner. Many types of insulation are available, including fiberglass, recycled cotton fiber batting and cellulose made from recycled newspaper. Straw bales themselves may be used to fill spaces between roof trusses. While a deeper discussion of these materials is outside the scope of this study, a minimum roof insulation of R-38 is recommended.

A highly insulated exterior combined with high thermal mass interior materials (such as earth walls, floors, or benches) creates ideal conditions for a "passive-solar home." South-facing windows with properly sized overhangs allow direct solar energy to enter the house, where the heat is stored in the thermal mass to warm the house overnight. Owners of straw bale homes report interior temperatures in the 70s° F year-round with minimal mechanical heating and cooling.

Since the early 1990s, several non-profit groups including the Proyección Humana de Mexico, the Kutunza Institute, the Canelo Project, and Builders Without Borders, have worked to teach self-help straw bale construction to needy families in the Southwest. Straw bale is an affordable and advantageous alternative to shipping pallets and tar paper used to build houses in the border colonias and on Native American reservations.

Katia LeMone of the Kutunza Institute reports an interesting adaptation of straw bale in Mexico, where straw has been used in place of the usual concrete block infill in concrete post and beam structures which are typical of Mexico. Straw insulation greatly reduces heat loss and gain, keeping the houses much more comfortable for the low-income families who dwell in them.

Guadalupe, AZ: 1,100 sf three bedroom, load bearing straw bale home financed by HUD for a low-income family in 1997. 160 volunteers raised the bale walls and framed and sheathed the roof in a single day. The interior and exterior stucco was done later. This project was a joint effort of HUD, The Development Center for Appropriate Technology (DCAT) and Out-On-Bale (un)Ltd. Photos courtesy of M. Myhrman & J. Knox

AFFORDABILITY
RESOURCE RECYCLING

Of the three alternative materials considered here, straw bale is the least expensive in terms of first cost. The overall construction cost for a straw bale home is comparable to that of a conventional wood framed house. Straw is a plentiful by-product of industrial agriculture, a viable building material that otherwise becomes compost or is burned. Straw bale is an especially economical choice for rural housing, since the raw material is readily at hand and shipping costs are low. Yet savings can be realized in both rural and urban housing. Because the supply is high, bales are inexpensive. It is estimated that the amount of timber in a conventional home may be decreased by 50 percent through the use of straw bale. Reduced use of lumber saves logging and trucking costs, and preserves the nation's forests. A well-built and maintained straw bale house can last for generations, as evidenced by the first generation of straw bale buildings in Nebraska which are now a century old. When a building has lived its useful life and is finally torn down, the wall material can return to the earth as straw is biodegradable.

When straw is in excess some farmers resort to burning it. Increased demand for baled straw will not only reuse the resource but prevent carbon dioxide emissions.
Photo: University of Arkansas Division of Agriculture

EFFICIENCY
SPACE AND ENERGY

The high R-value of straw bales and the use of compact, simple house designs increases the energy efficiency of housing. This translates into significant reductions in utility costs over the life of the dwelling. As analyzed by David A. Bainbridge in the "Life Cycle Cost and Value of Four Homes" in *The Art of Natural Building*, a 100 year life cycle cost for an owner-built passive solar straw bale home is estimated to be 37 percent of the cost of owning, maintaining and operating a conventional house ($347,700 vs. $947,900). Compared with a conventional house, a contractor-built straw bale home is predicted to have a cost savings of 11 percent over the same 100 year period ($843,300 vs. $947,900).

The environmental impact of the energy savings of straw bale construction is dramatic. A passive solar straw bale home is estimated to reduce carbon dioxide emissions by nearly 85 percent in comparison with a conventional wood frame house (CO_2 emissions reduced from 9.3 tons/year to 1.4 tons/year according to the study cited above).

In the Colonia Anapra straw bale house, bales are used as roof insulation between palette trusses.
Photo: C. Wanek

SELF - HELP
CONSTRUCTION

Straw bale construction can be done using unskilled labor in several phases. Pouring concrete footings, placing bales to raise the walls, applying interior and exterior plaster and installing earth floors are examples of tasks that can readily be done by volunteers or owner/builders. Framing roofs and installing jambs (or "bucks") around windows and doors requires greater skill, and is often done by professional carpenters working in conjunction with a crew of volunteers. Licensed electricians, plumbers, and heating, ventilating and air conditioning technicians are brought in to perform their trades. In particularly with the Nebraska style of load-bearing straw bale construction, family members including children are able to participate in the construction of their own home. In owner-built or sweat equity housing, opportunities for personal and family expression can be found. The use of clay paints, sculpted plaster and carved niches are part of the folk-art tradition of the border region. Following are two case studies of successful affordable straw bale houses built with direct owner participation.

Volunteers from the earthen plastering work day leave an impression at the entrance of Carolyn Robert's home.
Photo: C. Robert

COLONIA ANAPRA STRAW BALE HOUSING

designer/builder

Builders Without Borders (www.builderswithoutborders.org)
World Hands Project (www.worldhandsproject.org)
Casa de la Cruz in conjunction with local labor trainees

location

Colonia Anapra (pop. ca. 20,000 in 2001)
Ciudad Juarez, Chihuahua, Mexico

clients *families of Anapra Colonia*

Since the mid 1960s, US/Mexico border cities have experienced rapid population growth, far outstripping the housing supply. Many families live in poverty without proper shelter or sanitation. There are over 200 *colonias* (informal settlements) in and around Ciudad Juarez, the Mexican city of 3,000,000 inhabitants just across the international border from El Paso, Texas. Discarded shipping pallets and tar paper are the common building materials for *jacales* (huts) inadequate to shelter their inhabitants from climatic extremes.

Among the private non-profits working to improve health and living conditions in Ciudad Juarez is Builders Without Borders. This humanitarian group has organized direct assistance for families of the Colonia Anapra in Juarez. In cooperation with The World Hands Project and Casa de la Cruz, BWB has organized affordable housing projects that are "culturally appropriate, economically profitable, and environmentally sound" (*builderswithoutborders.org*). These groups demonstrate that straw bale housing is a viable answer to the housing needs of Colonia Anapra and beyond.

View of Colonia Anapra, Ciudad Juarez, Chihuahua. Photo courtesy of The World Hands Project

Volunteers carry pallet trusses to be set atop the completed bale walls. The trusses rest on a continuous wood bond beam which ties all the walls together. Photo: C. Wanek

The straw bale house of José Luis before exterior plastering. Photo: C. Wanek

"BWB has assisted in the building of four homes for local families. The houses are intended to demonstrate to the residents how to build comfortable, well-insulated, low-cost homes out of natural and recycled materials. They are designed to make use of passive solar heating and utilize shipping pallets to fabricate roof trusses. The straw bale walls rise from simple foundations, the walls are finished with earthen plasters."

Builders Without Borders
February 2004 Newsletter

Applying earth plaster to the interior of a straw bale house in Colonia Anapra. Photo: C. Wanek

"Adriana and her children in front of their old house." March 2002, Colonia Anapra
Photo courtesy of The World Hands Project/BWB

"The group (family and volunteers) in front of Adriana's finished house." March 2002, Colonia Anapra
Photo courtesy of The World Hands Project/BWB

Volunteers build pallet trusses. Wooden pallets are plentiful in Mexican border towns as a result of the maquiladora factories. Re-using pallets not only saves the homeowner material costs, but is environmentally advantageous both for forest preservation and a reduction of carbon dioxide emissions due to reduced trucking of materials. Photo: C. Wanek

By organizing straw bale housing workshops in Colonia Anapra, BWB trains home-owners and local workers in building with straw, earth, and available natural resources. The workshops include all stages of straw bale construction beginning with site preparation, bale raising, window/door buck framing, bond beam and pallet truss installation, wall pinning and strapping, straw ceiling insulation, roof assembly, electrical wiring and earthen plastering.

Stages of a complete project are outlined here:

1. *Develop home designs and gather owner input and feedback.*

2. *Require direct participation of owners who will have a specified number of hours on construction required through a family and friend network.*

3. *All homes will feature thermally efficient envelopes, passive solar design using natural building materials and methods.*

4. *Simple electrical and plumbing systems, including a biological waste system utilizing waste water for landscaping and food production, if applicable.*

5. *The option for owners to finance amenities such as solar hot water heaters, solar stills, solar ovens and cisterns.*

6. *Insulated metal roofs assuring longevity of the building and a thermal break from the extreme heat and cold.*

7. *Simple rainwater catchment systems*

Funding for the housing is organized so that repayment of "micro-loans" is re-invested in the local community. The houses take a month to complete at an average cost of $6,500 for materials and labor, due to the donation of labor and the resourcefulness of participants.

CAROLYN ROBERTS STRAW BALE HOUSE

owner/builder

Carolyn Roberts
Jon Ruez, Straw Building Consultant

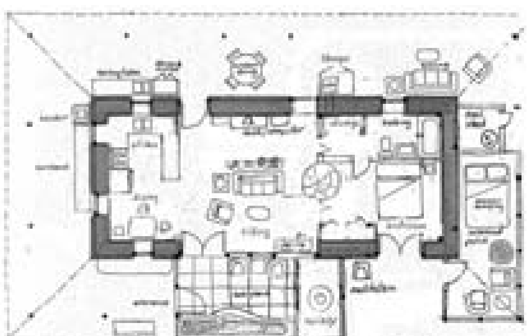
location

Avra Valley west of Tucson, Arizona

residence area *1,200 sf (gross)*
995 sf (net)

final cost *$51,450. (2002)*

This straw bale house was designed and built using the owner/builder method. Because she was involved in the process from beginning to end, the owner saved a considerable amount of money. Her personal documentary of the process of building her straw bale house, entitled *A House of Straw: A Natural Building Odyssey,* was published in 2002. The next few pages show the progression of her Nebraska style straw bale project, from laying out the foundation to earth plastering the interior and exterior walls.



Plan of the Roberts house, planned for maximum use of limited space. The southern "Sun Room" acts as a passive solar collector. Illustration: Wayne Bingham

final cost per square foot (2002)

"Without the porch expenses, using exterior dimensions for 1200 sq ft, cost was $37.00/sq ft."

"Without the porch expenses, using interior living space of 995 sq ft., cost was $45.00/ sq ft."

"Porch costs were $7,000.00 for 925 sq ft of covered porch, or $7.50/sq ft. "

Expense information from *www.houseofstraw.com*

BREAKDOWN OF COSTS
CAROLYN ROBERTS STRAW BALE HOUSE

ITEM	ACTUAL COST	HRS. OF LABOR	% HIRED LABOR
PLANS	$1,050	MANY	100
TOOLS	$1,900	--	--
CONSULT.	$5,000	--	--
PERMIT	$3,500	--	--
SEPTIC	$1,500	NONE	100
FOUND.+ STEM	$5,500	235	25
FLOORS	$ 600	131	0
BALES+ WALLS+ PLASTER	$4,800	970	110
TRUSSES+ ROOF	$5,200	188	25
PLUMB.+ FIXTURES	$3,000	107	0
ELECTRIC+ APPLI.	$4,500	133	20
MISC.	$2,000	--	--
WINDOW+ DOOR	$3,000	97	25
LOFT+ STAIRWAY	$3,000	110	50
PORCH	$7,000	155	85
CABINET	$ 300	15	0
TOTAL	$51,450	2,041	--

"My greatest savings would come from doing the majority of the labor myself, so I kept it simple. In the passive solar design, I considered my desert environment and the angles of the sun to keep the house cool. In the construction, I used nature's gifts of straw, sand and clay wherever possible, because they are beautiful, inexpensive and harvested with minimal damage to the earth."
Carolyn Roberts

The owner atop prefabricated 2x4 wood trusses which form the gable roof structure. Photo: A. Proczka

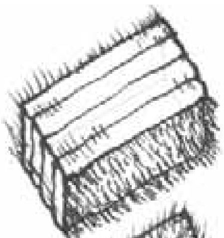
APPLICATIONS

"The truck is called a 'bale squeeze.' It has a big gripper on the back that tips up like a dump truck and stands the entire truckload of bales in a big stack. Then we slid them down some plywood planks to reach the ground. They were able to stay intact and undamaged this way."

Quote & photo: C. Roberts

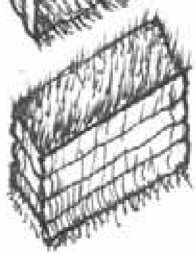
laid flat

for use with
Nebraska style
load-bearing walls.



on edge

for use with
post & beam
infill construction.



All dimensions of a straw bale house depend on the length, width, and height of the bales to be used. Straw bale houses must be designed using the module of the bales as a planning unit, with allowances for window and door bucks and/or support posts (if the post and beam system is used). Designers should verify locally available sizes, as there are variations resulting from the baler used in harvesting. A common nominal size is 48" in length, 24" in width and 16" in height.

WALL SYSTEMS

The wall sections at the beginning of this chapter illustrate the two basic straw bale wall types: 1. Nebraska style (load bearing wall) and 2. Post & Beam style (infill wall). These two methods of employing straw bales in construction are described in the Pima County (Arizona) Straw Bale Building Code, Section 7203:

1. Laid Flat refers to stacking bales so that the sides with the largest cross sectional area are vertical, and the longest dimension is parallel with the wall plane.

2. Laid On-Edge refers to stacking bales so that the sides with the largest cross-sectional area are vertical, and the longest dimension is parallel with the wall plane.

Bales laid flat rest on their largest surface and can accept more load than bales laid on-edge. When bales are laid flat the straw fibers are oriented horizontally, and the ties are subjected to less tension than the ties of bales placed vertically. The "Bou-Ali tests" (from a Master's thesis at the University of Arizona College of Architecture) found the compressive strength of 3-string bales laid flat to be three times greater than that of bales laid on-edge. This study also found that plaster bonds better to bales laid flat, since the rough edges provide a good "key" for plaster to interlock with.

"Construction grade" bales should have a moisture content less than 20 percent by weight at time of installation, and should be allowed to dry further before plastering. The minimum dry density should be equal to or greater than 7.0 lbs. per cubic foot per Pima County Code.

FOUNDATIONS

Conventional foundation systems are suitable to support straw bale walls. Concrete grade beams or slabs-on-grade with a continuous slab-edge toe-down are the most economical choices for dry climates and where no basement is desired. A steel-reinforced spread footing with a concrete or cement block stem wall may be used to support a wood floor system. The bales must be elevated a minimum of 8" above exterior finish grade and no less than 1 1/2" above the interior floor level with a pressure treated plate. Damp-proofing of the top of the foundation and a sheet metal termite shield will also help prevent water from wicking into the straw bale walls. A final structural requirement is that both interior and exterior plaster layers should bear on the foundation to transfer lateral forces into the foundation.

ROOFS

Preventing moisture penetration is the most important factor in a straw bale building. Corrugated pre-finished metal panels are the most reliable roofing material. Gabled or hipped roof forms, with a 4:12 or greater pitch to quickly shed water, are preferred. In dry climates, shed roofs should have a slope of no less than 2:12. Local codes should be consulted to confirm minimum slopes. Roof overhangs are recommended to be at least two to three feet beyond the face of the wall. Proper flashing of roof/wall intersections is imperative. Deep porches keep rain away from exterior walls. Roofs should be insulated to R-38, consistent with the R-value of the bale walls..

1 *Foundation staked and layed out w/ spraypaint.*

2 *Concrete footing poured and block stem wall built.*

3 *Window and door bucks built and set in place.*

4 *Volunteers erect bale walls on workday.*

5 *Bond beam evenly puts 4 bale walls in compression*

6 *Roof trusses mounted to bond beam*

7 *metal roofing added and porches framed*

8 *electrical conduit integrated with bales*

9 *clay slip pressure applied before earth plastering*

THE BUILDING PROCESS

All photos on this page courtesy of C. Roberts.

View of completed home from west. Photo: C. Roberts

View of completed home from south showing sun space at entry with aviary. Photo: C. Roberts

Interior view showing living area and loft. Photo: R. Peterson

View from west. Photo: J. Ruez

stone and concrete **FOUNDATION SYSTEMS**

Traditional houses built in the U.S. Southwest during the 19th and early 20th centuries, prior to the common use of concrete, typically had foundations built of stone, if they had foundations at all, which some did not. The use of stone for foundations dates back 300 years to the early mission churches of northern Mexico that were built of adobe on dry stacked (mortarless) stone foundations. The mission church of San Xavier near Tucson (ca. 1783) has a volcanic stone foundation laid in lime mortar supporting its massive walls of fired brick. Stone is much harder than brick, and in human terms is impervious to water. It is, therefore, a logical choice as a foundation material, to bear the weight of the structure above, transfer it into the ground, and resist the weathering that takes place where buildings meet the earth.

structure and covering **ROOF SYSTEMS**

The roof system of an adobe, rammed earth or straw bale house is of equal importance to the foundation in maintaining structural integrity and protecting the walls from moisture. Traditional materials must be kept dry, or failure of the wall system results. Furthermore the roof diaphragm serves to brace the walls against lateral forces resulting from wind or earthquakes.

STONE FOUNDATIONS

Dressed stone foundation at La Casa Cordova Tucson, AZ. Height of stone above grade protects adobe from splashing of rainwater and isolates wall from rising foundation moisture. Photo: B. Vint

Vernacular builders used whatever materials were available, and naturally employed local stone for foundations. Limestone, granite, and volcanic basalt are found along the U.S./Mexico border. Igneous and metamorphic stones, being extremely hard, were used as they were found, as rubble or fieldstone. Relatively softer limestone was typically dressed or squared into building blocks.

Foundations were laid in trenches excavated to a level of hard bearing soil, varying in practice from 12 inches to 36 inches in depth. Prior to the widespread availability of Portland cement in the early 20th century, stone was set in locally produced lime and sand mortar. Rubble stone is irregular in shape and size, hence mortar joints are wide, with smaller stones used to chink spaces between larger ones. Dressed stone is cut to regular sizes and requires thin mortar joints.

Volcanic basalt used for site retaining wall and foundation early 20th C. bungalow, West University, Tucson AZ Photo: B. Vint

Elder's Center, San Xavier District. Foundation and walls built of volcanic stone. Gibbs & Vint, Architects Photo: B. Vint

Stone foundations are a traditional vernacular response to building in pre-industrial times. However they cannot easily be reinforced with steel to resist bending caused by differential settlement, and they are labor intensive and, therefore, costly in today's marketplace. For both structural and practical reasons, reinforced concrete and concrete block have replaced the traditional stone foundation.

Among Southwestern vernacular dwellings, stone foundations were often left exposed for protection against water or for aesthetic reasons. The rich texture and color of stone add visual interest to a simple facade. In bungalows, stone was often exposed along the base of the structure for a rustic appearance in keeping with the romantic quality of the style.

The conditions under which stone foundations are feasible today are (1) a ready supply of stone is available on site, and (2) local masons are willing to donate or discount their labor in the installation. Such a process was followed for the Elder's Center of the Tohono O'odham Nation, in which the entire building was constructed of volcanic stone from a nearby sacred mountain. This is a unique project, and not readily reproducible.

CONCRETE FOUNDATIONS

Concrete foundations are suitable for any of the three wall systems addressed in this study. Because adobe and rammed earth are both heavy and brittle materials, the slightest settlement of the foundation causes cracking. Earthen walls require a well-designed footing specifically engineered for site soil conditions and actual live and dead loads. A geotechnical investigation of the building site is recommended to determine the allowable soil bearing pressure, and to check for the presence of collapsible soils or expansive clays that may require additional site work, such as over-excavation, re-compaction, and/or greater footing width, depth or reinforcement.

There are several types of foundations used for residential construction, with advantages and disadvantages for varying materials and site conditions. For adobe walls, a concrete foundation system consists of a footing to distribute the wall load evenly into the earth, and a stem wall to bring the bearing level of the wall above grade. Steel reinforcing bars are placed in both footings and stem walls to provide tensile strength such that the foundation can span over areas of settlement, or should the soil become saturated.

In all cases, the builder must provide a minimum six inch separation between the adjacent finished grade and the earthen or straw bale wall to be supported, to protect the wall base from moisture.

Cast in place foundation for a straw bale house in Tucson, Arizona. Continuous concrete perimeter ties bale walls together and elevates them above ground level to keep them dry. Vertical rebar dowels are used to pin first course of bales to foundation to prevent them from sliding under lateral loads. Floors will be brick laid over sand. Architect: Bob Vint., Tucson. Photo: B. Vint

Foundation stem wall for an adobe house in Tucson, Arizona. The stem wall is solid grouted CMU with horizontal and vertical reinforcing. It is supported on a reinforced concrete footing approximately 12 inches thick, placed at two feet below grade. The footing and stem wall together constitute the foundation system. Floors are to be colored concrete slabs on grade. Architect: Bob Vint, Tucson. Photo: B. Vint

WATERPROOFING FOUNDATIONS

Unlike other regions of the US, subterranean water is not a common problem in the Southwest. Stemwalls typically do not require damp-proofing. Nonetheless, it is required to waterproof the top of foundations for either straw bale or earthen wall system to prevent moisture from wicking up in the walls following the brief, heavy rainstorms of the desert.

SPREAD FOOTING AND STEM WALL

The most common foundation system for masonry walls (including adobe and rammed earth) is a continuous cast-in-place reinforced concrete spread footing, with a either a concrete or a solid-grouted concrete masonry unit (CMU) stem wall. For rammed earth construction, where masons are not typically on the job site, a concrete stem wall is more common than CMU. This type of foundation is illustrated in the adobe wall section at *p.82* of this study.

CONCRETE GRADE BEAM

If there is adequate soil bearing capacity, the required footing width often matches the wall width for earthen materials (adobe or rammed earth). In this case the stem wall and footing are placed with a single pour, reinforced top and bottom with steel bars. It is termed a grade beam foundation, for it acts as a concrete beam cast in the earth. This system may also be used for straw bale walls, if deemed appropriate. A grade beam type of foundation is illustrated in the rammed earth wall section at *p.90*.

FLOOR SLABS

Concrete slabs-on-grade are typically 4 inches thick. To limit cracking, slabs can be reinforced with welded wire fabric (WWF) or with #3 steel reinforcing bars at 24 inches on center each way. Rebar are placed 1-1/2" inches below the top of the slab. Tooled or saw-cut joints can also be used to control cracking that results from expansion and contraction. This approach plans where the crack will occur, rather than trying to prevent it. Workmen must properly score the joints deep enough to establish a weakened plane in the concrete slab, so that the crack occurs where intended. A cast-in-place concrete slab with integral color powder added the mix creates a durable, economical and aesthetically pleasing floor is.

Concrete colors are mineral based and permanent. The concrete can be sealed and polished, and provides a large thermal mass for use in passive heating and cooling. Exposed concrete floors should have a well-thought out pattern of score joints to control cracking.

SLAB EDGE TOE-DOWN

Wood frame walls in conventional construction are typically supported by a thickened slab-edge footing, or toe-down, which runs around the perimeter of the house. Horizontal rebar are placed longitudinally in the toe-down to provide bending strength. Anchor bolts are spaced as needed to anchor the walls resisting lateral forces (wind or earthquake).

Straw bale is more closely related to wood frame construction than to masonry. A slab edge toe-down foundation may be used to support straw bale walls. The bales are pinned to the slab with rebar extending from the footing. A toe-down footing is illustrated at the straw bale wall section at *p.99*.

POST-TENSIONED SLAB FOUNDATION

Post-tensioned slabs on grade have been increasing in popularity in the Southwest since 1995. They have advantages where soil conditions are poor, and can minimize slab cracking. They are not as prevalent with heavily edge-loaded wall systems, such as adobe or rammed earth, because of potentially increased edge deflections due to the heavy wall loads.

HEAVY TIMBER

Traditional adobe houses were roofed with timber beams hewn from local trees. Along the U.S../Mexico border, this includes mesquite, pine and cottonwood. The size of beams was derived from the nature of available trees. Mesquite is a dense, hard wood, excellent for use as lintels in adobe walls: however, mesquites do not grow more than twenty to thirty feet in height, and their twisted branch structure does not produce long straight timbers for roof framing.

Pine trees are more suitable for use as roof beams, growing straight and tall: yet they grow only in the surrounding mountains, and in the historic period the greater effort required in bringing them to the building site posed a great disincentive to their use. Cottonwood is a faster-growing wood less suited to structural use. Despite its limitations, mesquite was the most frequently used timber in the Arizona/Sonora border region. A typical maximum span is 14 feet, limiting the size of rooms.

Installation of prefab wood trusses in new adobe house. Porch is framed with recycled timbers. Sloped trusses composed of 2x4's are an economical means of creating a pitched roof with attic space. Design: Bob Vint, Architect. Photo: B. Vint

Beams varied in size, from 6 to 8 inches in width and from 10 to 12 inches in depth. The spacing of beams was from 18 to 30 inches on center, made necessary by the weight of the earthen roof carried on cactus rib or cane lathing (*latillas*). The vernacular desert adobe house was a model of organic environmental architecture, built of natural, recyclable materials.

Nonetheless, the roof framing system is not reproducible in contemporary society for several reasons: (1) use of large timbers is prohibitively expensive due to labor, material and transportation costs; (2) heavy timber is environmentally destructive, as old-growth trees have become scarce due to long-term unsustainable logging practices; (3) the use of saguaro cactus ribs for ceilings is impossible, as the large-scale demand for ribs would deplete the desert of saguaros, quite apart from the fact that the saguaro is now a protected plant; and, (4) traditional earthen roofs are excessively heavy, prone to damage in earthquakes, have little insulation value, and leak. Although the traditional method of framing roofs is aesthetically appealing, it is not practical for contemporary affordable housing.

MILLED LUMBER AND PREFABRICATED TRUSSES

An alternative to heavy timber is milled dimension lumber, which supplanted timber in the late 19th century. The ubiquitous two-by-four was used to frame roofs throughout the west from 1880 on. A contemporary adaptation of light two-by framing is the prefabricated wood truss, a method of factory-building longer span elements. This is a relevant method for framing today's affordable housing, as it is among the most economical systems now in use. Its limitations are the vulnerability of wood to fire, moisture and termites.

With the growing public consciousness regarding green building, the Forest Stewardship Council (FSC) has been formed to encourage sustainable timber practices. Developers, architects and builders can now specify FSC Certified lumber, which indicates that sustainable practices are employed in growing harvesting the timber.

Wood is a renewable resource if it is well-managed, even more so if timber for construction is grown on tree farms rather than harvested from our national forests.
In contrast with finite mineral resources, such as iron, coal or oil, which must be mined and refined, wood is organic and naturally regenerates itself. One can always plant a new tree.

ROOF STRUCTURE
LIGHT GAUGE STEEL TRUSSES

Currently, light gauge cold-rolled steel trusses are becoming an alternative to wood trusses in the affordable housing market. They have many advantages in comparison with wood trusses. Steel trusses are more dimensionally stable than wood as they are not prone to pests, rotting, warping or swelling with changes in humidity. In addition, they are noncombustible and, if galvanized, impervious to water. Their cost is variable as the price of steel varies with market conditions.

However, metal trusses and metal roof structural systems have not been as well accepted in conventional practice as metal framing for walls. All connections must be screwed, hence they cannot be easily assembled with nail guns and circular saws. Sheet metal reacts differently than wood when cut, and the sharp edges of metal angles and channels pose an occupational hazard. Nonetheless, this is a valid system to consider, provided there is a local truss plant that fabricates with light gauge steel. Local manufacturers are emerging throughout the U.S. Southwest.

Municipal building safety departments typically require detailed shop drawings and structural calculations sealed by a registered engineer for both steel and wood truss systems. These are generally provided by the truss manufacturer.

Light gauge steel truss framed roof with metal framing at gable end. Affordable row house under construction in Tucson, AZ Architect: Joe Comella, City of Tucson Community Services Department. Photo: B. Vint

Tucson, AZ: Asphalt roll roofing on the hipped roof of a historic building. Roll roofing is the least expensive and least durable roofing option. Photo: B. Vint

ROOF COVERING
ASPHALT AND ELASTOMERIC

Nationally, the most common roof coverings are asphalt based. These are among the least expensive roofing systems when considering initial installation costs.

Asphalt-impregnated felt paper has long been used in waterproofing low-slope roofs, pitched at 2:12 or less. Built-up roof systems comprise three to four layers of roofing felts laid with asphalt emulsion.

For sloped roofs pitched at 3:12 or greater and exposed to view, asphalt roll-roofing with a mineral cap surface was a common material over the first half of the 20th Century. Asphalt-based fiberglass shingles have been widely used on sloped roofs for the past 50 years.

The limitation of asphalt roofing in the Southwest border region is the drying effect of the intense desert sun, which causes the felt layers to crack and separate. In recent years, elastomeric roof coatings have been developed to protect and renew asphalt roofs. It is recommended to re-coat asphalt roofs every two years to extend the expected ten-year life time of the roof.

A disadvantage of asphalt roofing is that when rainwater harvesting is desired, emulsion will find its way into the runoff.

Single-ply membrane and elastomeric roof coverings, either in sheets or fluid-applied, are contemporary systems with higher first-costs, but greater durability relative to asphalt-based systems.

METAL

Corrugated galvanized iron (CGI), has been available for over a century in the U.S. Southwest. Its use became widespread in the late 19th century, in western mining camps and other provisional settings. CGI roofing was used on ranches and in the historic barrios, for then as now it proved to be an economical and effective waterproofing choice.

CGI is available in a range of gauges and configurations. A mid-range specification is 26 gage, 3/4" C-panel, being among the most common. Heavier gauges last longer, but are more expensive. A properly secured CGI roof, with the correct felt or membrane underlayment and sheathing, can last for over 20 years. It is also suitable for the harvesting of rainwater, as the metal surface can be cleaned and does not release petrochemical residue as does asphalt roofing

Corrugated metal roofing is a logical and responsible choice for affordable housing, and its use is an extension of the vernacular tradition.

However, while CGI is relatively inexpensive, effective and durable, it also has three disadvantages: (1) metal is an excellent conductor of heat, hence additional insulation is advisable; (2) factory galvanized metal is reflective and creates glare, hence some treatment to dull the surface or finish it is needed; and, (3) rain falling on a metal roof is noisy.

Another type of metal roofing is known as standing seam. This is fabricated from sheet metal panels in widths from 12 inches to 20 inches, which are joined at the seams and crimped to lock them together. A standing seam roof is typically pre-finished with a factory applied paint and is good for 50 years. This is a more advanced, and more expensive roofing system than CGI. It is generally not considered feasible for affordable housing.

New Mexican ranch house with corrugated galvanized iron roofing. This metal roof is approximately 50 years old, and is still effective. Photo: B. Vint