Chapter

13

Earth

Long before the age of manufactured insulation materials, human beings learned to survive against a climate's thermal discomforts by using the most plentiful of all materials at their disposal: earth. Now, at the dawn of the twenty-first century, this same material is experiencing a renaissance in residential construction. Natural building systems such as adobe, cast earth, cob, wattle and daub, earth shelters, PISÉ, Earthships, and rammed earth are a few of the earth-based construction systems receiving attention. (Straw bale construction is discussed in Chap. 15.)

It may not seem within the scope of this book to review materials that at a first glance are not conventional insulation products. On closer inspection, however, earth shelters, rammed earth, and other natural building systems are significant and viable alternatives because of the intrinsic thermal mass possible when implemented in appropriate designs and climates.

Earth architecture may be the oldest form of construction in human history. Various forms of indigenous earthen structures and materials have been developed throughout the world. Today it is estimated that 40 to 50 percent of the world's population still live in earthen dwellings.[1]

Cob is an old technique that offers the potential to create very sculptural wall shapes. Straw is mixed with small gravel into a sandy soil. The mixture is formed into cobs (lumps), which are thrown onto the wall and worked into the previous applied layer. The rough surface is later trimmed and made smooth. The result is often a softly undulating surface that is commonly tapered inward toward the top. Cob has been used mostly in experimental buildings in the United States, while code testing procedures are still being investigated.

Wattle and daub starts with a latticework of light branches or timber. An earth-plaster mix is forced ("daubed") into the gaps in the latticework and finished to give a serviceable surface.

Adobe, or mud brick, is an ancient building technique dating back at least to the days of Jericho (now Israel) in 8300 B.C. Adobe structures built some 900 years ago in the United States are still in use today. The system of fabrication remains virtually unchanged. First, mud bricks are cast in open molds on the ground using a blend of earth and water with the consistency of cake mix. The molds are then removed immediately or allowed to remain until the next day. The bricks are eventually lifted onto their sides, trimmed, and stacked to air dry and cure.[1]

Rammed earth, also called *stabilized rammed earth,* is a process by which walls are formed in place by pounding damp soil into movable, reusable frames. Rammed-earth tire construction, also referred to as *Earthships,* use discarded automobile tires, recycled aluminum cans, and cardboard that are laid flat and rammed with soil.

Passive solar principles are essential to the effectiveness of earth design. Historians are quick to note that these strategies were hardly a result of the 1970s energy crisis. The Anasazi cliff dwellings, for instance, were built into south-facing cliff walls that received the sun's rays during winter months and were shaded from the sun in the summertime. The Anasazi understood that in winter the sun travels low across the southern sky, and in summer it crosses high overhead. As with their cliff dwellings, passive solar homes with south-facing windows welcome the winter sun and are protected from the summer sun. (Fig. 13.1). Once the winter sun's rays are in a home, the next requirement for passive solar heating is a place to store those rays. This is intrinsic to the success of the earth shelter, which uses its thermal mass to temporarily store and release heat.[2]

The ability of solid earth to function as a thermal mass results in interior temperatures that change very little from day to night. Mass walls absorb solar energy during winter days and then reradiate that energy to offset nighttime heat losses within the building. In the summer months, the mass of the walls absorbs excess heat generated during the day, keeping the interior spaces cool. In a properly designed and oriented house, this typically means savings in heating and cooling bills as well as a more comfortable and even

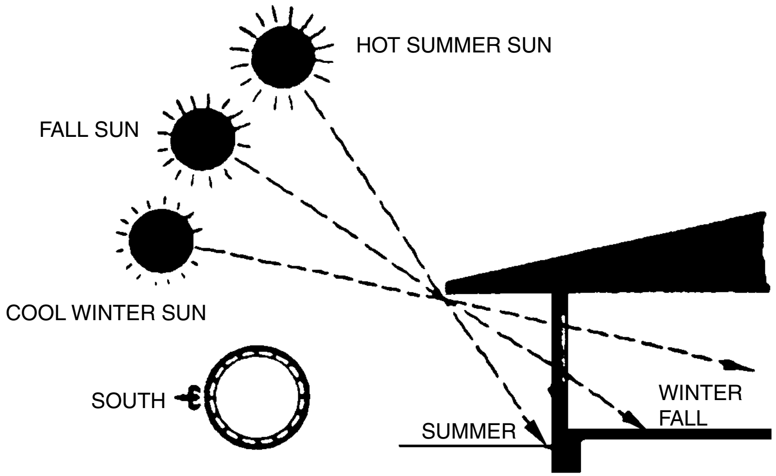

Figure 13.1 Seasonal sun angles. (*McGraw-Hill, Inc.*)

temperature throughout the home. The energy that determines the temperature inside the house radiates directly from the mass of the walls as opposed to a space regulated through mechanically altered air. Each of the systems discussed herein can be constructed with or without additional insulation. Climate, user preferences, and design standards determine the actual assembly configuration.

Ventilation requirements are of prime concern in an earth-integrated home because of the reduced amount of air infiltration. Approximately two air changes per day typically are desirable. Ventilation can be achieved by either a forced-air system or an operable window system with good cross-ventilation that takes advantage of natural air flows. Natural ventilation also can be maximized with a custom ventilation system designed for the particular floor plan, geographic area, and climate. Additional ventilation is also necessary if open-flame or gas appliances are used in the home.

The inclusion of these systems is intended to inform the reader of alternative construction assemblies that may or may not "be for everyone." The very fact that many of these systems have been used for hundreds of years indicates that they are a viable alternative to conventional home construction methods.

Earth Homes

For contemporary residential applications, earthen dwellings are commonly referred to as *earth-sheltered housing*. There are two types of earth home designs. Earth-sheltered housing, or underground housing, is typified by a structure with two or, in most cases, three sides and the roof covered with earth. There are even successful designs that place the entire structure below grade or completely underground (Fig. 13.2). An earth-bermed house uses a conventional roof, with only the sides of the home partially protected with earth (Fig. 13.3). Each type takes advantage of the natural temperature of the earth. At 5 to 7 ft below grade, most climates will only reduce the earth's temperature to around 53°F. This natural temperature regulator means the actual "work" of the mechanical thermal control systems to raise or lower temperatures to the desired human comfort level is greatly reduced.

There are a variety of reasons that homeowners provide when explaining their attraction to living in a home that uses soil as the primary building material. These include

1. Energy efficiency
2. Ecologically sound
3. Unique
4. Low life-cycle cost
5. Reduced maintenance
6. Solar heating
7. Water lines never freeze

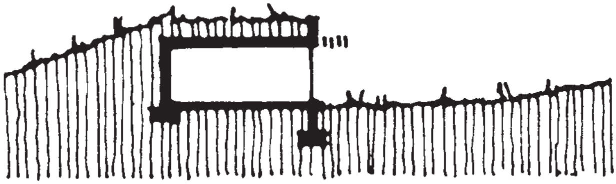

Figure 13.2 Underground earth shelter. (*McGraw-Hill, Inc.*)

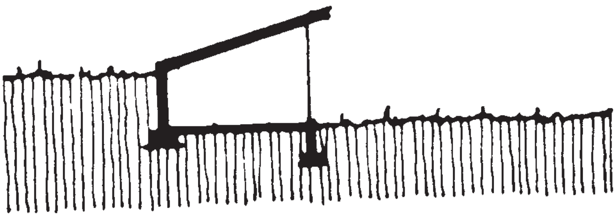

Figure 13.3 Bermed earth shelter. (*McGraw-Hill, Inc.*)

8. Storm resistant
9. Termite resistant
10. Rodent resistant
11. Earthquake resistant
12. Decay resistant
13. Fire resistant
14. Limited visual impact
15. Efficient land use
16. Wood conservation
17. Environmental benefits

The improvement in earth design systems over the past 20 years appears to have corrected many of the mistakes that plagued earth homes in the 1970s. There are a number of variations on a theme when it comes to specifying or constructing this building type. Proper research, inspection of existing structures, and sound construction practice by qualified contractors will provide a comfortable, thermally efficient earth-sheltered home that will last many years.

Product description

There are three generic design types that are commonly found in earth-sheltered homes. These are referred to in this book as the *atrium* (or *courtyard*) *plan,* the *elevational plan,* and the *penetrational plan*. The atrium design is an underground structure in which an atrium serves as the focus of the house and the entry into the dwelling. Unlike the other two design types, the courtyard design offers an open feeling because it has four walls that give exposure to daylight. The subgrade open area, a central outdoor courtyard, is the entrance into the home and is surrounded by the major living spaces. The windows and glass doors that are on the exposed walls facing the courtyard provide light, solar heat, outside views, and access via a stairway from the ground level. Atrium homes are usually covered with less than 3 ft of earth and provide ample access to natural ventilation, primarily because there is no benefit in energy efficiency from greater depths (Fig. 13.4).

The elevational plan is a bermed and roof-covered structure that typically has a glazed, south-facing entry. The other sides and roof

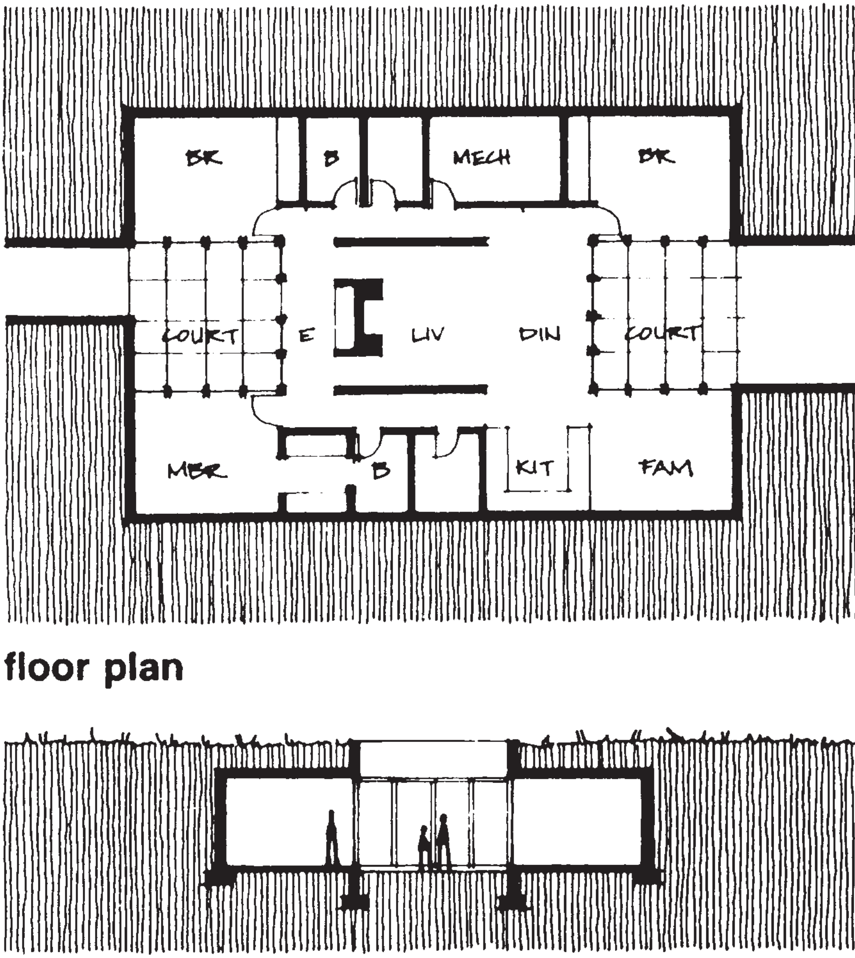

Figure 13.4 Atrium plan and section. (*McGraw-Hill, Inc.*)

are typically covered with earth. The exposed front of the house, usually facing south, allows the sun to light and heat the interior. The floor plan is arranged so that common areas and bedrooms share light and heat from the southern exposure. One drawback is that the northern portions of the house may have reduced daylight and limited internal air circulation unless a custom-designed fresh air ventilation system is installed. Skylights and an open floor plan can help alleviate these problems. Historically, a structure designed in this way has been the most popular and the most economical to build of all earth-sheltered structures. Contemporary

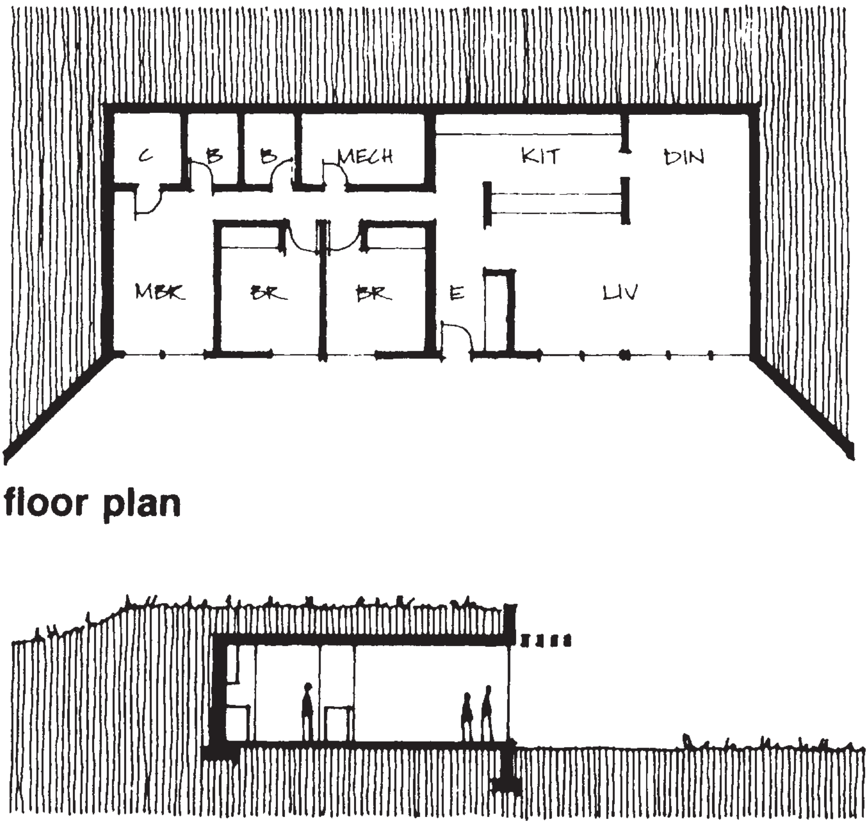

Figure 13.5 Elevational plan and section. (*McGraw-Hill, Inc.*)

designs are now more adventurous; two-story plans, cathedral ceilings, and vaults are slowly becoming the norm (Fig. 13.5).

In the penetrational plan, the house is built at ground level or partially above grade and is bermed to shelter the exterior walls that are not facing south. Earth covers the entire house except around the windows and doors. This design allows cross-ventilation opportunities and access to natural light from more than one side of the house (Fig. 13.6).

The most efficient designs reveal that an airtight wood stove or a small efficient forced-air furnace may be all that is necessary to provide supplemental heat. The only electrical demands come from a small blower that circulates the heat from the wood stove throughout the house. Some homes also have incorporated radiant floor heat, small geoexchange systems, or area heaters in the prime

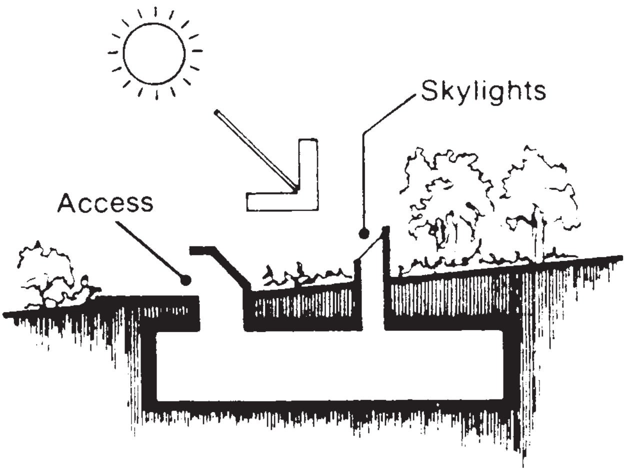

Figure 13.6 Penetrational earth-sheltered home. (*McGraw-Hill, Inc.*)

living areas. Supplemental heat sources also may be preferred in the bathroom areas.

Adequate air exchange must be planned carefully when building an earth-sheltered dwelling. Generally, well-planned natural or mechanical ventilation (by exhaust fans) can dissipate ordinary odors. Any combustion appliances that are installed should be sealed combustion units that have a direct source of outside air for combustion. It is mandatory that the combustion gases are vented directly to the outside. Ventilation and exhaust systems for radon presence also must be addressed in earth-sheltered house design and site selection.

Energy-efficiency claims have far too many variables to rely on one set of statistics in reference to this overview. Typical results based on data gathered for this book show that homeowners may save up to 80 percent in heating and cooling costs as compared with conventional homes, depending on the number, orientation, and treatment of openings. The thermal mass of the earth ensures that the home will never drop to less than +50°F without heat, even in mid-winter.[3]

Additional insulation in an earth-sheltered home will depend on the climate, house design, and construction materials used. For example, cold spots can be eliminated in the structure by specifying 3" of polystyrene insulation placed over the exterior concrete walls prior to backfilling and 6" of insulation over the roof covered by 3 ft of dirt.[3]

Although specifications will be designer-specific, one builder typically constructs homes with a standard 8-ft-high wall of 8"-thick poured-in-place concrete, designed for a minimum of 650 lb/ft^2 lateral load.[4] The standard ceiling is 10 to 12" of concrete designed for a vertical load of 790 lb/ft^2. This system also allows for a minimum of 3 ft of earth cover.[4]

Limitations

Studies show that earth-sheltered houses may be more cost-effective in climates that have significant temperature extremes and low humidity, such as the Rocky Mountains and northern Great Plains. The earth temperatures vary much less than air temperatures in these areas, accentuating the design advantages of the earth berm as a thermal mass, thereby eliminating the need for a more complex heating, ventilation, and air-conditioning (HVAC) system.

Topography plays an important role in site selection. For example, a modest slope requires more excavation than a steep one, whereas a flat site needs the most extensive excavation. Research suggests that the most ideal site is one that has a south-facing slope in a region with moderate to long winters. Construction in other regions or facing in other directions uses skylights and a more complex HVAC system (Figs. 13.7 and 13.8).

Figure 13.7 Earth shelter on a flat site with berm. (*Davis Caves Construction, Inc.*)

Figure 13.8 Earth shelter on a steep slope. (*Davis Caves Construction, Inc.*)

Soil tests must be performed prior to site or design selection because some types of soil are more suitable than others for earth-sheltered construction. For example, the best soils are granular, such as sand and gravel. These soils compact well for bearing the weight of the construction materials and are very permeable, allowing water to drain quickly. The poorest soils are cohesive, like clay, which may expand when wet and has poor permeability. If clay is encountered on site, it is recommended that a porous backfill such as sand or gravel or a drainage mat be used.

Groundwater is also an important factor. Besides building above the water table, choosing a site where the water will naturally drain away from the building is the best way to avoid water pressure against underground walls. Swales and drainage systems must be designed to run water away from the structure to reduce the frequency and length of time the water remains in contact with the building's exterior.

There are a number of waterproofing systems in use today. Although many systems are effective, the best option will possess the following characteristics:

1. Long life-expectancy underground
2. Resealing capacity at underground temperatures

3. Good crack-bridging capability
4. Durability or protection during backfilling

Such systems include but are not limited to

1. Rubberized asphalt (Bituthene)
2. Plastic sheets such as high-density polyethylene and high-density polyethylene
3. Liquid polyurethanes
4. EPDM membranes
5. Bentonite

Installation standards and practices

The characteristics of the site, climate, soils, design, and budget will aid in determining the construction materials to be used. Earth-sheltered houses will require stronger, more durable construction materials than above-grade conventional homes because they must be able to withstand the stress imposed by the surrounding earth. When soil is wet or frozen, it exerts greater pressure on the walls, ceiling, and floors of such a building than the pressure that already exists. Pressure also increases with depth, so a material such as concrete may be the best choice, although reinforced masonry, wood, and steel are also suitable if properly engineered.

Cast-in-place concrete has the most advantages as a construction material. Minimal joints, durability, fire resistance, material strength, and thermal mass qualities are ideal for earth-sheltered design. It also provides a good surface for applying waterproofing. If additional insulation is used, it must be protected to withstand the pressure and moisture of the surrounding ground. Masonry products such as brick or concrete masonry units are also used, but the necessary sealing of mortar joints can be problematic. Although wood can cost less than other materials, it does not offer the strength that a material such as steel does, so it may not be the best choice for structural material in some houses. Steel can be used for beams, bar joists, columns, and concrete reinforcement. Protection against corrosion is required if it is exposed to the elements or to groundwater.

Fire resistance

Depending on the material selection, earth-sheltered houses can be made virtually fire-resistant. Concrete or masonry shells, concrete slab floors, and steel-framed interior walls sheathed with type X or fiber-reinforced gypsum board will eliminate most ignition sources. Special selection of furnishings is necessary to guarantee a comprehensive fire-resistance design.

Rammed Earth

Rammed earth is a building technique that dates back to at least 7000 B.C. in Pakistan. Portions of the Great Wall of China, as well as a five-story hotel built in Germany in 1837, also were constructed of rammed earth. Even in the United States, thousands of rammed-earth houses were built during the Great Depression.[1]

It is important to explain that a rammed-earth wall assembly is not an insulator in the true sense of the definition. The actual insulating value (the resistance to the transmission of heat applied to one side of the wall to the other side) is poor. As mentioned earlier, earth walls are actually good capacitors, serving as good, but temporary, heat-storage masses. Commonly referred to as the *flywheel effect* (the ability to absorb energy and reradiate it over time), the earth can store the energy for constant slow reradiation, resulting in a very smooth temperature swing curve for the building. This principle also applies to the proper placement of thermal mass elements such as floors and interior walls that even out temperature variations in a building due to the temperature storage capabilities of the building's mass.

In a real building application, the interior temperature will be an average of the high and low temperatures outside from several days earlier. This is called the *thermal-lag effect.* While the outdoor temperature may vary 30 to 40°F in a 24-hour period, the inside changes will vary only a few degrees. Thus, when the temperature is 90°F in the day and 60°F at night for several days, the inside of the building will approximate 75°F. The thermal lag is proportional to the wall thickness but influenced by the solar gain. In Arizona, for example, the thermal lag on a 24"-thick rammed-earth wall can be up to 3 days. Designers state that this is most effective when the extreme temperature swings between day and night are over 40°F.[3] Additional insulation also may be necessary, depending on the extent the passive solar principles are applied to the overall design of the home.

Rammed-earth walls are formed in place by pounding damp soil into movable, reusable frames (formwork) with manual or machine-powered pneumatic tampers. The earth material is typically mixed with about 8 percent water and 3 percent cement, although this may vary depending on the soil used. The earth is compacted (tamped) in 4- to 6-in lifts in enclosed formwork similar to that of cast-in-place concrete. Also referred to as *stabilized earth,* these walls achieve compressive strengths estimated to be about half that of concrete. The walls act as a thermal mass, usually requiring no additional insulation. Rammed-earth walls can be 12 to 36" thick but are typically 18 or 24" thick. The final density is usually around 125 lb/ft^3, giving the wall excellent thermal properties. The virtually maintenance-free walls do not require additional finishes unless aesthetically desired. They are also fire-resistant and extremely durable.[1]

One difficulty with the rammed-earth method is that strict limits have to be placed on shrinkage to eliminate cracking. Often cement or hydrated lime is added to improve durability, but successful structures are built using suitable soils without such additives. A sandy, crumbly soil (with a clay content around 15 to 30 percent) may be the best choice because of its good workability and minimal shrinkage.

Product description

Rammed-earth walls can be constructed in one of three typical systems:

1. Individual panels of earth are enclosed within a framework of cast-in-place concrete.
2. The earth walls are fully reinforced with an integral grid of steel reinforcing rods.
3. A continuous solid-earth wall is topped with a bond beam of reinforced concrete.

The finished solid-mass earthen wall, as it comes out of the form, may be finished with exterior stucco and interior plaster. Newer design trends seem to indicate that the natural finish of the rammed-earth wall is growing in popularity. In climates where rainfall can be extreme, walls should be protected against saturation with roof overhangs and elevated foundations. If waterproofing is omitted, moisture may penetrate all the way to the inside surface of the walls during prolonged wind-driven rainstorms.

Additional costs incurred will vary depending on the site, the height and complexity of the wall system, the available soil, and the seismic safety factors. The cost increase over conventional wood-frame construction will be a minimum of 10 percent.

Limitations

It is important to recognize that rammed-earth construction is a "made by hand" product and will exhibit the inconsistencies that characterize any handmade item. For example, the color and texture of the finished wall will vary. Some areas may be rough or inconsistent in density. Construction tolerances will need to be more forgiving than those used in typical construction practice. Shrinkage cracks, honeycombing, and voids are also likely to occur.

PISÉ (Pneumatically Impacted Stabilized Earth)

Another form of monolithic earth wall construction is PISÉ (Pneumatically Impacted Stabilized Earth). A single form is constructed to shape the interior wall surface. Wire reinforcement is then attached, and a mix of earth and cement is sprayed onto the outside. A patented process developed by David Easton, PISÉ uses a gunite hose (similar to the hose used to spray concrete to wall forms or pools) to directly apply rammed earth into the frames. Using one-sided formwork and high-pressure air delivery, trained crews can complete up to 1200 ft^2 of 18"-thick wall per day. A training program is required before a subcontractor is qualified to shoot PISÉ walls.

Earthships

Earthships is the popular term for what are actually rammed-earth tire homes. This construction system, using passive solar design and recycled materials, was developed by Michael Reynolds of Solar Survival Architecture. The environmentally conscious system uses recycled automobile tires filled with compacted earth for thermal mass and structure. The homes can be dug into south-facing hillsides or located on flat sites and bermed to obtain additional thermal mass.

The construction system is actually very simple. The first course of tires of any tire wall must be leveled and dug into undisturbed soil. Tires are laid flat and rammed full of approximately three wheelbarrow-loads of soil. Each tire weighs about 350 lb, and the tires are set in a running-bond fashion. All tire walls that are an integral part of the roofed building should have a continuous wood or concrete bond beam serving as a top plate.

Between 500 and 2500 tires are used in a rammed-earth tire home (for homes of 1000 to 4000 ft^2). Earth is bermed against the outsides of the tire walls, while 2 to 4" of plaster or stucco cover the inside of the tire wall. (Foam insulation also can be applied to exposed exterior or interior walls and covered with stucco.) The building is framed in wood on the south side and roofed with metal to collect rainwater. Aluminum or tin cans are also used for filling in concrete walls that are not load-bearing. Other systems include integrated wastewater treatment, photovoltaic electrical systems, solar hot water, and passive solar heating.

Indoor air quality and other potential environmental problems are still being studied. Published research at present seems to suggest that rubber degradation, carbon black vapor, or other chemical off-gassing may not pose a serious health hazard in this type of construction.[5]

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