CIB TG 16, *Sustainable Construction*, Tampa, Florida, USA, November 6–9, 1994.

ANCIENT SOLUTIONS FOR FUTURE SUSTAINABILITY: BUILDING WITH ADOBE, RAMMED EARTH, AND MUD

Michael Moquin
The Adobe Journal
P.O. Box 7725, Albuquerque, New Mexico, 87194 USA

Introduction

The dominant themes of sustainable construction — efficiency, conservation, the use of natural, non-polluting materials, and passive solar design — are already beginning to supplant pure design aesthetics as the essential elements of an architecture for the future. Earthen construction materials such as adobe (sun dried mud brick), rammed earth, and compressed earth block, are especially well suited for sustainable construction. Not only do they reduce the use of scarce and energy intensive products such as lumber and cement in construction; they also possess optimal thermal storage and transmissive properties that, when coupled with passive solar design, can dramatically reduce fuel consumption and pollution.

Over the centuries, indigenous forms of earthen shelter and materials have developed on every continent. Finely tuned to the culture and climate, the sun, and local resources, these traditional regional adaptations have proven to be both practical and effective. They represent a collective wisdom, a body of evolved construction knowledge. It is currently estimated that 40% to 50% of the world's population lives in earthen dwellings (Dethier, 1983). The rediscovery and legitimization of traditional earthen construction techniques and materials through appropriate building codes, not only in developing countries, but also in the First World, can play an important role in mitigating the destructive impact and high energy use of current building practices, and in finding the necessary solutions to the world's housing shortage.

There are many advantages in building with earth. For example, earthen walls reduce the amount of wood needed for house construction by half, and if the roof is constructed of adobe brick barrel vaults or domes, wood use is further reduced to an absolute minimum. Because suitable earth for building is locally available throughout the world, little or no transportation is required. Since minimal processing of earthen materials is usually all that is necessary, production can be local and decentralized, which also promotes self-help housing. While knowledge of masonry skills may be a prerequisite for the more elaborate forms of earthen construction such as vaults and domes, basic construction skills suffice when a simple earth-walled structure is the goal.

An added benefit of earthen building materials is that they are non-toxic. For those who are allergic to modern processed materials and finishes, the healthy interior environment of an earthen home is a refreshing alternative. Through passive solar heating, options for fresh air exchange can be almost limitless, because the earth walls store and radiate heat to maintain an even interior temperature.

Adobe

The invention of sun dried mud brick for home construction has recurred independently throughout the diverse climates and regions of the Earth in response to the need for a strong, comfortable, easy to build, affordable shelter. Indeed, adobe may be the first human-made building material ever developed. Soil is a very inert, non-toxic, naturally occurring material. Ideal soils for adobe making are somewhat sandy, with clay percentages of 30% or less, to avoid excess cracking.

These soils may contain small gravel and some humus. When wetted with water, they form a solid block after being shaped and dried through the action of sun and air.

The word "adobe" originates from the Egyptian "thobe" meaning [mud] brick. In Arabic this became "at-tob," which in Spanish became "adobe," while in French it became "toub" (Mud Village Society, 1991). The earliest permanent dwellings yet discovered are in the Middle East, China, and the Indus Valley. Of these, the oldest excavated site is at Jericho, which dates from 8300 B.C., making it the earliest city in the world. The earthen houses there were round or oval, averaging 16 feet in diameter, with walls made of loaf-shaped sun dried mud bricks (adobe), diagonally grooved on the upper surface to create a better bond for the mud mortar used between courses (Fletcher, 1987). Similar grooves are still used today by Egyptian masons to facilitate bonding of the leaning arched courses of adobes used in barrel vaulted roofs.

Another early settled agricultural village is Ali Kosh, dating from 8000 B.C. and located in what is now southern Iraq. Here, the first homes were small rectangular houses made with hand formed adobes 10"x6"x4" (Fletcher, 1987). In time, the houses became larger, with multiple rooms. The dimensions of the later adobes were 16"x10"x4," almost identical in size to adobes currently being mass produced in New Mexico and Arizona. These modern adobes are 14"x10"x4" and weigh 35 pounds. As at Jericho, the mud bricks from Ali Kosh were tempered with straw from nearby grain fields. Straw accelerates drying, hinders cracking, and moderately increases the tensile strength of the adobe. This early use of straw, together with the evidence of bonding grooves, hints at a state of evolution in the craft of adobe with even earlier origins than Jericho.

The earliest known examples of form-molded adobe brick, dating from 5600 B.C., occurred in present day Iraq at Tell Es Sawwan, a Samarran farming settlement on the east bank of the Tigris River. Foundations of stone gave better protection from moisture for the adobe walls, and external wall buttresses strengthened the walls to carry a flat earthen roof over sticks and reeds (Fletcher, 1987). Form-molding produces a standard sized mud brick, facilitating efficient wall construction and easing the planning and design processes.

By the 7th century B.C. the Tower of Babel had been built of adobe, faced with fired brick and tar mortar. Ninety meters high, it has been called "mankind's first skyscraper" (Dethier, 1983). The making of sun dried mud bricks in Babylon became so important and widespread that the first month of summer (*Sivan*) was known as "the month of the brick" (Mud Village Society, 1991).

Through the writings of the Roman engineer Vitruvius (ca. 30 B.C.), we know that the ancient Greeks had a refined system of adobe brick manufacture and construction. There was the rectangular *Lydian* adobe brick, which averaged 45 cm x 26 cm x 10 cm (18" x 10" x 4"). This size was also used by the Romans. The *pentadoron* adobe (five hand palms square) used for public buildings was 45 cm x 45 cm x 8 cm (18" x 18" x 3"). For private buildings, the *tetradoron* adobe (four palms square) measured 30 cm x 30 cm x 10 cm (12" x 12" x 4"). This system of adobe brick sizes also provided for molds to make half-bricks (Mud Village Society, 1991).

The earliest development of adobe most often occurred where trees were a limited building resource. The human ingenuity expressed in coping with a lack of wood by using the most abundant local material – earth – has continued through time, right up to the present. In Europe until 1800, wood provided the chief fuel for household heating and cooking, as well as the needs of housing, industry and shipbuilding. This almost exclusive dependence on wood resulted in widespread deforestation. As early as the late 16th century, governmental authorities in Germany were insisting that new buildings be made of earth in order to conserve the remaining trees (Guntzel, 1990).

Researcher Jochen Güntzel reports that in Germany during the 18th and 19th centuries, tens of thousands of adobe homes were built. After the First World War, thousands of earth-walled buildings were constructed in response to a lack of available (transported) or processed building material. Locally available earthen materials that did not have to be fired with scarce fuel proved very efficient. After World War II, another 40,000 German homes were built of earth. Regrettably, in spite of this venerable history, the German government in 1970 prohibited any further construction of buildings with structural earthen walls.

Although the use of sun dried mud brick is often perceived to occur primarily in regions of low rainfall such as the American Southwest, this is not necessarily the case. Costa Rica has an old tradition of building with adobe, yet it receives 80 inches of rain a year. Roofs with a wide overhang and foundations of raised stone make the difference. The area of the former Yugoslav republic receives a minimum of 40 inches of rain a year, yet the tradition of building 2- and 3-story adobe homes is centuries old there. Highly effective building techniques have been learned over the generations to make these tall adobe homes resistant to earthquakes, even though they are located within a seismically active region. Stone foundations with mud mortar are built 3 feet above ground level to prevent moisture damage. Very importantly, for every meter of adobe wall height, a horizontal wooden belt (bond beam) made of two parallel boards, is placed within the wall, providing strength and stability. Large houses in this region are often plastered with lime and sand, and regular maintenance with lime wash in the spring has kept them in good shape for hundreds of years (Sumanov, 1991).

Richard Pieper has documented the use of adobe in New York state from the 1830s to the 1880s. Fifteen large adobe homes were built in Geneva, New York, and at least 35 others are scattered throughout the state. The dimensions of the typical adobe (15"x12"x6") point to a connection with an earlier English adobe tradition brought into the area of Toronto, Canada. The Geneva houses were well built two-story homes that reflected a variety of styles. The largest of all the adobe houses in New York state is in Oswego. Built in 1851, this 2-1/2 story adobe home occupies almost 6,000 square feet of floor space and is now part of a Roman Catholic school (Pieper, 1990). The longevity and scale of these New York houses further demonstrates that sun dried mud brick can be practical and durable, even for areas of high rainfall.

Nowadays in the United States, most earth-walled homes are being built in New Mexico and Arizona, where ancient Pueblo Indian and Hispanic adobe traditions are still alive. Professional builders are continuing to build with adobe, especially in the Albuquerque, Santa Fe, and Tucson areas. There are approximately 200,000 homes built of adobe or rammed earth in the U.S., with 97% of these located in the Southwest (Smith and Austin, 1989). Adobe brick is now mass produced with the aid of machinery, with the mud stabilized against moisture damage with the addition of emulsified asphalt (3 to 5% by weight) in New Mexico, Arizona, and California, or occasionally cement (5 to 10% by weight), as in west Texas.

Critics of adobe homes, especially Third World architects trained in the United States, sometimes tend to view them as hovels fit only for the destitute. However, most of the adobe homes now being built in the United States are custom homes that average 2,500 to 4,500 square feet. This fact should alert such cynics to the idea that adobe homes are highly desirable, and not just for the poor. Hopefully, adobe homes and communities can be planned and built for the world's millions needing shelter, but without the unnecessary stigma of poverty or impermanence.

Rammed Earth

The history of rammed earth is not as well known as that of adobe. However, archaeological work shows early evidence of rammed earth dating to 7,000 B.C. in China (Chayet, 1990). By 4000 B.C. in China, rammed earth often appeared as elevated platforms for large meeting houses (Fletcher, 1987). This technique evolved so that by 200 B.C., the Great Wall of China, comprising the largest and longest defensive walls ever constructed, was made of rammed earth. This giant earthwork is the only evidence of human building activity that is visible from outer space. In Tibet, very large rammed earth buildings, four to seven stories high, have been built as Buddhist monasteries over the last 500 years. The thick walls of rammed earth perform particularly well in this region of extreme cold and earthquakes, where wood is a scarce building material. This method of building earthen homes is still practiced throughout Tibet and China.

Carthage, near present day Tunis on the north coast of Africa, contains the remains of rammed earth walls built in 700 B.C. By 200 B.C., the Phoenicians had so refined their building skills that some of their rammed earth buildings attained a height of six stories (Fletcher, 1987). Eventually, the Romans learned rammed earth techniques and diffused them throughout Europe, especially into France, where rammed earth is known as *pisé de terre*. In the vicinity of Lyons, preserved *pisé* buildings date from the 1500s. By the 1800s, some *pisé* structures here reached as high as five stories. Currently, 15% of France's population lives in homes of *pisé* or adobe (Guntzel, 1990). Unfortunately, since World War II, the craft of building in *pisé* has been virtually lost, although the International Centre for Earth Construction (CRATerre), based in Grenoble, is trying to bring about a revival.

According to researcher Jochen Güntzel, the year 1837 witnessed the construction of the tallest earthen building in Germany, a 5 story apartment house built of rammed earth in Weilburg. Its visionary owner also had all his factory buildings built of rammed earth instead of stone because he appreciated the superior thermal properties and comfort of the earthen walls. One of the earliest printed works on earthen construction dates from 1736. Güntzel has attributed it to the Saxon architect Richter, who advocated adobe and rammed earth homes as the ultimate fire resistant structure. Richter proposed using arched vaults to form the roof over the earthen walls onto which a three foot layer of soil would be placed and planted as a garden. Now, that's sustainable architecture!

Rammed earth has the advantage of forming massive walls with much less handling than adobe brick, because the forming and curing (drying) take place on the wall itself. The walls (usually 18" to 36" thick) are formed by pounding 6 to 8 inch layers of soil (clay, sand, and small gravel) within a movable bottomless frame (slip-form or shutter) whose sides are held parallel by external bracing. After compaction is finished within the frames, the form is repositioned for continued ramming. This procedure is repeated until the desired wall height is reached. Small, simply designed, wooden formwork can be very effective, but professional builders often use metal concrete forms or forms of their own design. Each "lift" of soil is completely compacted with upright handled tampers, resulting in a 50% reduction in thickness of each layer of loose fill. The sophistication of the tamping equipment ranges from wooden manual types to the machine powered pneumatic ones used by professional builders. Suitable soil for ramming has a clay content of about 10 to 20%, with a soil moisture content of about 10%. Sand and small gravel make up the remaining 80% of material.

Rammed earth has many qualities that are well adapted to sustainable construction. Earthen walls built 2 to 3 feet thick possess good thermal qualities, moderating the interior living space temperature against winter cold and summer heat, and requiring only small amounts of supplemental energy (if any) for rooms not passively heated by the sun. Massive rammed earth walls often require no exterior insulation to bolster thermal performance, in contrast to wood frame construction, or to the thinner adobe walls being built today (which average 1 foot thick). Modern insulation materials are often polluting in their manufacture and sometimes adversely affect the interior environment of the home. Rammed earth walls can be virtually maintenance free, and they do not require energy-intensive or polluting finishes like cement plasters, paints, sheet rock, or fired brick veneer to make them more attractive. And of course, by using locally available soils, rammed earth construction consumes far less wood than conventional frame house construction, which is usually transported from hundreds of miles away.

Unfortunately, many building codes across the U.S. have begun to require unnecessary high-tech "improvements" to rammed earth walls. In California, concrete posts and beams are required, with rammed earth used only as infill. These codes also require the addition of 10% cement by volume to "stabilize" the earth walls, even though modern foundations are used, and the walls are covered with cement stucco. Many view these requirements as having intruded upon a centuries-old, proven construction method. Indeed, these additional requirements have increased the costs of labor and material to such impractical levels that rammed earth construction has practically ceased in California. Clearly, a program of collaborative research involving engineers and rammed earth practitioners could result in more intelligent and appropriate building codes.

Coursed Adobe • Cob • Mud Walls

One of the simplest and most direct ways of building an earthen wall is by piling stiff mud up in layers without the use of forms. Known in the American Southwest as *coursed adobe* (sometimes incorrectly called "puddled adobe," which implies formwork), this mud walling technique is called *cob* in England, *bourrine* in Brittany, *chineh* in Iran, and *tauf* in Arabic lands (Moquin, 1992). Coursed adobe also occurs in Yemen, Afghanistan, equatorial Africa, and the Sahel. Common to coursed adobe technologies around the world is a soil moisture content of 15 to 20%.

There are Pueblo pit houses six to ten feet deep in the Taos, New Mexico area that date from 1200 A.D. The walls were made with layers of adobe mud about 6 inches wide and 18 inches high. This "coursed adobe" method involved piling handfuls of mud from a nearby pit onto the wall being built. As each course started to dry, successive layers of mud would be placed on top, eventually reaching to the roof level. By the 1300s, the mud walled method was sufficiently perfected to permit the widespread construction of pueblos with walls one foot thick, up to five stories high. The earliest parts of Taos Pueblo (900 years old) were constructed in this way, making this village, along with Ácoma and Hopi, the oldest continuously inhabited sites in North America. The yearly ritual of mud plastering the exterior adobe walls continues to be a strong tradition at Taos Pueblo, which was designated a World Heritage Site in 1989.

In England, monolithic structural mud walls are commonly known as "cob," a mud and straw mixture that is sometimes very gravelly. Usually 2 to 3 feet thick, some cob walls are as tall as 30 feet. The mud straw mixture was thoroughly trodden by oxen or humans in shallow pits close to the wall being built. Once prepared, the stiff mud mixture was picked up by hand or by fork, placed on the wall and shaped into place with the fork or trodden down underfoot. In a typical English cob mixture, the straw fibers are kept fairly long to aid in binding and drying. Soil clay percentages typically range from 10 to 30%, with an average of 20% working well. Clay percentages over 30% produce shrinkage cracks large enough to weaken wall structure.

During late spring and summer cob construction, each 18 inch high mud course was allowed to dry for 2 weeks before the next course above it was begun. After building the house, a year was needed for the cob walls to dry completely before finish plastering. Cob walls are built upon a foundation of stone rising 18 to 36 inches above ground level to prevent water damage from capillary action ("rising damp") and the impact of direct rainfall. A good foundation and waterproof thatched roof allowed a cob house to last hundreds of years. The old English saying is applicable to earthen buildings everywhere: "Give a cob house a good hat (roof) and a pair of boots (a good foundation) and it will last forever!"

The ancient country of Yemen has some of the most spectacular mud walled structures in the world, reaching up 6 to 10 stories high. Such outstanding building skills and confidence represent the epitome of an ancient craft tradition distilled through the experience of many generations. Prior to construction, the mud matures in a pit for two days after mixing. Once ready, balls of mud are tossed up to a worker standing on the wall being constructed. Each new course is formed by throwing the mud balls forcefully onto the developing wall. The impacted mud is then beaten and shaped with a wooden mallet to the approximate width of the wall, but slightly narrower than the course below. The corners of these mud walled buildings display a raised "step" in each course that is partly decorative, partly structural. The walls taper slightly inward as they rise, a form of buttressing for greater stability during earthquakes.

Light-Clay *(Leichtlehm)*

One of the last surviving traditions of earthen construction left in Germany is the *light-clay* (*leichtlehm*) technique, in which a clay binder is mixed with large volumes of straw to form wall infill between wooden post and beam framing. The fine clay slurry is prepared within a rectangular trough, into which the straw (15" long) is dipped until it is completely coated. The *light-clay* mixture is then placed onto the wall within a wooden slip form. The mixture is pressed into place by hand, layer upon layer, to build up the height of the wall. The exterior wall thickness is usually about one foot, and interior partition walls are 5" thick, providing good insulation with some thermal mass.

The density of *leichtlehm* varies from 300 kg/m^3 to 1200 kg/m^3, depending upon its use. (By way of contrast, adobe is 2000 kg/m^3.) This material can be used to make floors (requiring densities over 1000 kg/m^3) or ceiling insulation (300 kg/m^3) that is fire and insect resistant due to its the clay coating (Volhard, 1983).

Like most other earthen building materials, light-clay is made from local, inexpensive materials that need little transportation and minimal processing. Only simple, low-tech skills are needed to build with it, and it is non-polluting. Although *leichtlehm* is highly versatile and efficient, little is known of this material and its uses outside of Germany.

Below-Ground Earth Shelters

One of the most ingenious permutations of earthen shelter has been the development of below-ground dwellings, sometimes known as "cave" dwellings. This ancient form of shelter is still used in Tunisia, Libya, and Turkey, but most of all in China. In their pit house form, subterranean dwellings have appeared on most continents from earliest times. In the American Southwest, they were used by the Basketmaker and early Pueblo peoples. Usually 2 to 4 feet deep, they were even deeper in colder regions.

Below-ground dwellings have reached an unparalleled and spectacular development in China, where evidence of their construction predates 2000 B.C. By 100 B.C., "cave" dwellings were already widespread throughout the loess soil region of the Yellow River valley of northern China. Depletion of the forests had reached critical levels by 1400, and there was little option but to seek shelter underground. Today there are 40 million Chinese people living below ground, with 100 million more living in above ground adobe and rammed earth homes (Golany, 1992).

In his most recent book, *Chinese Earth Sheltered Dwellings: Indigenous Lessons for Modern Urban Design*, Gideon Golany reports that there are two basic types of below-ground dwellings in China. The sunken courtyard "pit" dwelling, also known as a "sky-well" or "dugout," has its floor level dug 20 feet deep into the loess soil. Highly stable, earthquake resistant barrel vault shapes are actually hollowed into the soil to within 10 feet of the overlying ground surface. The second type, known as a "cave" dwelling, is tunneled into cliffsides. Yet a third type, the "earth sheltered" home, composed of adobe vaults built above ground and covered with 2 to 3 feet of earth for insulation, is a more recent development.

Each extended family unit averages 8 rooms per underground complex (*Ibid.*). The vaulted rooms are approximately 10 feet high and 10 feet wide. (For structural reasons, the Chinese building tradition discourages the digging of rooms wider than the height of the vault.) Room length is usually 20 feet, with a greater ceiling height at the south facing entrance to allow maximum sunlight penetration. The unexcavated supporting walls between the parallel cave units are 2 to 3 meters thick. As newer units are built underground, the vaulted interiors are often lined with adobe brick or fired brick, particularly in areas of heavy rainfall or earthquake activity.

As demonstrated by the Chinese example, vernacular practices of building and living underground embody many of the most promising aspects of sustainable construction. One of the most outstanding advantages of subterranean dwellings is their thermal performance. Due to the naturally even temperature of the soil and its thermal properties, the daily interior temperature remains relatively stable throughout all four seasons, with no cooling required in the summer and minimal heating in the winter. This passive heating and cooling leads to minimized energy consumption and pollution, greatly reducing the need to cut trees or burn coal as heating fuel. These "cave" dwellings are durable, lasting for centuries — 1300 years, in one documented case (Golany, 1992). Low maintenance, low cost (often 50% less than above ground construction), and simplicity of construction (at least within the loess soils), have made cave dwelling practical and efficient for millions of Chinese. Another important benefit is that by building into the cliffsides above the valley floor, or belowground within valleys, valuable agricultural land is conserved.

Arches, Barrel Vaults, and Domes

The invention of masonry arches, vaults, and domes is one of the most amazing architectural feats of early civilizations. These curved roof-spanning structures are kept strong by the pull of gravity. Working by means of compression and uniformly distributed loads, these roofing systems can be built with sun dried mud brick (adobe) or compressed earth block (which is usually stabilized with 5 to 10% cement).

Their early development is often attributed to the need to roof over walls in desert regions where wood was scarce or non-existent. Using curved shapes such as barrel vaults and domes to roof buildings not only strengthens the structure as compared to a flat roof, but also reduces the cutting of large trees, since wood beams are not needed.

The earliest arch yet discovered appeared in village domestic architecture on the northern plain of Iraq at Umm Dabaghiya (5500 B.C.). The walls of the houses were made of *tauf*, an Arabic term for coursed mud walling, where the mud is mixed with straw to prevent excessive cracking. These well made earthen homes each had a living room, a kitchen, and one or two more rooms. The walls were buttressed internally. Usually, one of the rooms was divided by an arch spanning its width (Fletcher, 1987).

Through time, trial and error, a curved arched roofing system was eventually developed by leaning a series of arches against a thick end-wall. We call this method barrel vault construction. The earliest evidence for such a roofing system has been dated to 3,200 B.C. at Nineveh, also in Iraq. At the Ramesseum granaries in Luxor, Egypt, a long parallel grouping of adobe brick barrel vaults dates from 1400 B.C. The present day Nubian vault design, which is almost identical to the ancient technique, uses small, thin adobe bricks (10" x 6" x 2," weight 8 pounds), with extra straw added for lightness. Parallel diagonal grooves are inscribed on the surfaces for better bonding with the sticky mud mortar. No wood forms or centering devices are needed for this type of construction (Fathy, 1973).

The largest barrel vault ever built is located near Baghdad at Ctesiphon, which dates from the fourth century A.D. The large open-ended banquet hall of this palace is covered with an elliptical vault 120 feet above the ground. The walls are 24 feet thick at the base, with the vault tapering to a slender profile at its greatest height. The vault spans the incredible 83 foot width of this magnificent hall (Fletcher, 1987).

For domes and vaults to be viable outside of desert regions, the mud brick must be protected against increased amounts of rain and snow. Fired clay tiles, cement stuccos, or asphalt stabilized mud plasters are available solutions. In the early 1800s Wilhelm Tappe of Germany, working out of a concern for the housing problems of the poor, proposed earth walled dwellings with a circular floor plan for both aesthetic and economic reasons, built in a beehive dome shape for stability and endurance (Guntzel, 1990). By laying each circular course of mud brick flat, overhanging the course below, a parabolic shaped dome can be created without the need for wooden centering forms. This corbelling technique is the oldest and simplest way of building domes. It is still well suited for the owner builder. As protection against moisture damage, Tappe chose fired tile as an exterior surface rendering for his homes.

In areas where wood or cement is difficult or expensive to obtain for roofing, adobe vaults and domes can be an economical, safe, and practical solution. They are especially promising as a way to reduce the need for large wooden beams, which usually come from old growth forests. Although code officials, schools of architecture, and engineers have been slow to appreciate them, these ways of building offer valuable solutions for sustainable design and construction.

Thermal Mass

Solar heating a dwelling by passive (non-mechanical) means requires two things: south-facing windows to admit the sun's radiation, and interior thermal mass for heat absorption, heat storage, and heat release. Thermal mass materials include high density substances such as adobe, rammed earth, fired brick, or concrete. Excess thermal energy beyond the needs of daytime heating is stored within the mass walls and floor. As the sun sets and the interior temperature begins to change, the stored solar energy is naturally radiated from the mass floors and walls, keeping the interior warm.

Thermal mass is now understood to moderate and stabilize the daily fluctuation of the interior air temperature of a structure by delaying the timing of the maximum and minimum heat flow through the dense mass walls (the "flywheel effect"). This was discovered through comparisons of insulated and uninsulated mass walled buildings by tracking periods of net energy loss and net energy gain through the walls during the daily solar cycle. Folk wisdom around the world has long maintained that adobe and other earth walled homes are warmer in the winter and cooler in the summer than other types. Modern research over the last 20 years has linked this phenomenon to thermal mass and its parameters of high density (adobe = 106 lbs/ft^3), relatively high thermal conductivity (adobe = 0.3 BTU hr/ft^{2}-°F/ft), and specific heat, or ability to store thermal energy (adobe = 0.24 BTU/lb-°F) (Mazria, 1979).

Adobe home construction experience over the last 20 years has shown that insulating the exterior of the walls to R-20, ceilings to R-40, and the outer foundation-stem walls to R-10 greatly enhances thermal efficiency. Thermal mass floors of adobe, brick on sand, stone, or concrete can play a key role in improving a building's thermal performance by increasing the surface area of the available heat absorbent material. Locating thermal mass floor areas near south facing windows to receive direct gain solar radiation is the most effective way to guarantee abundant stored heat.

Insulating the exterior of the mass walled building minimizes the rate of heat loss in winter, resulting in reduced heating costs of at least 70 to 80%, and sometimes 100%. In this system the optimum adobe wall thickness is 8-12 inches, with a 12 inch wall having only a 7 degree daily indoor air temperature fluctuation. For somewhat similar results, a concrete wall should be 19 inches thick, while a fired brick wall should be 16 inches thick to attain the same minimal temperature fluctuation as adobe. (Mazria, 1979). Generally, thick mass walls work better than low mass walls (such as wood frame).

Less sustainable materials (those requiring high amounts of processing energy) such as cement, fired brick, or steel often require greater transportation to construction sites than adobe or rammed earth. Likewise, lumber that is transported long distances, or is gas kiln dried or machine surfaced, also requires large amounts of processing energy.

If one were to construct a solar building that had little thermal mass, such as wood frame, only daytime heating would be available in the winter. In fact, such a low mass house would actually overheat in the daytime, and feel cold at night. With thermal mass, the excess solar heat would be passively stored within the adobe (or other mass material), to be released gradually at nighttime and during periods of daytime cloudiness. It is unfortunate that residential and commercial passive solar heating and cooling is not employed more often.

Conclusion

Sustainable construction and the philosophy of energy efficiency and environmental conservation will pose many challenges for architects, builders, engineers, and code bureaucrats trained during times of cheap energy and abundant building materials. One very obvious solution is to build with earthen construction materials (adobe, rammed earth, compressed earth block, and mud). Due to their inherent qualities of appropriateness, such as universal local availability, minimal processing, minimal transportation costs, simple construction methods and outstanding thermal storage properties, earthen construction materials should certainly play a role in the present and future construction of homes and businesses throughout this country. Unfortunately, earthen construction faces several bureaucratic and political obstacles that prevent its application from being as widespread as it should.

First, the developed world, through its institutional decision makers in government, education, banking, and business, has tended to view earthen construction incorrectly as primitive, unreliable, or inappropriate for certain regions. These misconceptions are further distorted by the cement manufacturing and wood products lobbies and trade associations, whose powerful influence is widely reflected in national building codes that are biased against earthen construction through their over-specification. In contrast, those who are actively engaged in building and designing with earthen materials have not organized into a trade association to finance the research and documentation of earth walled construction systems. This situation has resulted in notable gaps in the Uniform Building Code, such as a complete failure to address fire ratings for earthen walls. Fortunately, in New Mexico and Arizona, state and county building code officials, insurance, and banking institutions have recognized the outstanding permanence and durability of earthen construction, with its long record of success as a building material.

A second and equally imposing obstacle is that the formal education of architects and structural engineers is grossly deficient in its omission of information concerning the structure and performance of earth walled systems. Incredibly, there is virtually no such academic training available within the United States. Conventional construction as taught in the universities relies on cement, fired brick, steel, and aluminum – all highly processed, costly materials that have to be imported if used in most Third World countries. Sadly, at a time when the pressing need for more sustainable design and construction is upon us, passive solar heating and cooling principles and priorities are nearly ignored.

Another challenging barrier to the acceptance of earthen construction is a pervasive skepticism toward the validity of building alternatives whose sources are outside the boundaries of mainstream, modern, high tech processes. Many of those who build with earth are not architects or engineers. As a result, they are not accorded the respect and credibility their experience and skills deserve. Great progress toward a more environmentally conscious, sustainable construction can be achieved, if those who are actively building with adobe, rammed earth, and compressed earth block are included in the discussion and planning of codes and education. National building code and HUD officials should make the effort to reach out to these practical experts. Given the current situation, there needs to be an openness to new paradigms outside the narrow focus of "architecture by architects."

Traditions of designing and building with earthen materials have a long history of sustainability throughout the world. As world population approaches the earth's carrying capacity, ethical and social responsibility demands that we design and build in harmony with the environment in ways that guarantee sufficient resources for future generations. Earth is ideal as a sustainable construction material. Possibly this conference and others to follow will help bridge the artificial barriers between architects, engineers, and code officials on the one side, and the earthbuilders and environmentalists on the other. Hopefully, this ancient, natural way of building may be more fully employed to provide the construction of safe, efficient, and harmonious shelter for humanity's present and future generations.

References

Chayet, A., Jest, C., Sandy, J., 1990: Earth used for Building in the Himalayas, the Karakoram, and Central Asia, *Proceedings of the 6th International Conference on the Conservation of Earthen Architecture*, 29-34.

Dethier, Jean, 1983: *Down to Earth; Adobe Architecture: An Old Idea, A New Future*, Facts on File, New York, 192 pp.

Fletcher, Banister, 1987: *A History of Architecture*, 19th Edition, Butterworths, London, 1622 pp.

Fathy, Hassan, 1973: *Architecture for the Poor: An Experiment in Rural Egypt*, University of Chicago Press, 255 pp.

Golany, Gideon S., 1992: *Chinese Earth-Sheltered Dwellings: Indigenous Lessons for Modern Urban Design*, University of Hawaii Press, 179 pp.

Guntzel, Jochen G., 1990: On the History of Clay Buildings in Germany, *Proceedings of the 6th International Conference on the Conservation of Earthen Architecture*, 57-65.

Mazria, Edward, 1979: *The Passive Solar Energy Book*, Rodale Press, Emmaus, Pennsylvania, 435 pp.

Moquin, Michael, 1992: From Bis Sá Ani to Picurís: Early Pueblo Technology of New Mexico and the Southwest, *Adobe Journal*, No. 8, 10-27.

Mud Village Society, 1991: *Building with Earth*, New Delhi, India, 284 pp.

Pieper, Richard, 1990: Earthen Architecture of New York State: Adobe Construction in a Non-Arid Climate, *Proceedings of the 6th International Conference of Earthen Architecture*, 117-121.

Smith, Edward W. and George S. Austin, 1989: Adobe, Pressed-Earth, and Rammed-Earth Industries in New Mexico, *New Mexico Bureau of Mines and Mineral Resources*, Bulletin 127, 60 pp.

Sumanov, Lazar, 1990: Traditional Sun-Baked (Adobe) Brick Structures in Macedonia, Yugoslavia, *Proceedings of the 6th International Conference on the Conservation of Earthen Architecture*, 131-136.

Volhard, Franz, 1983: *Leichtlehmbau: alter Baustoff-neue Technik*, C.F. Müller, 160 pp.