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Adobe, pressed-earth, and rammed-earth industries in New Mexico

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Preface

Mud is the oldest building material mastered by early man. Since the birth of the great ancient civilizations, people have used mud to construct homes. Today, soil remains the primary building material for over 50% of the world's population. In the United States, one third of the nation's adobe dwellings are in New Mexico.

This study attempts to document the current adobe industry in New Mexico and to update the 1980 investigation, *Adobe bricks in New Mexico* (Smith, 1982a). Since 1980, new findings have emerged concerning the history and characteristics of adobe, the geology and mineralogy of adobe soil, the physical properties of adobe bricks, and the production techniques and market trends of the adobe industry. This report discusses these findings and surveys recent developments in the adobe-brick, pressed-earth-block, and rammed-earth industries.

Current commercial adobe-brick producers, as well as manufacturers of pressed-earth-block machines, producers of pressed-earth blocks, and builders of rammed-earth walls, were included in the present survey. Soil samples were collected from the majority of producers and were analyzed for particle sizes and clay minerals. Some samples of adobe bricks and pressed-earth blocks from selected producers were tested for durability, strength, and moisture content by Dr. Kalman I. Oravecz at the United Nuclear Rock Mechanics Laboratory, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

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Special thanks are given to architects William Lumpkins, P. G. McHenry, Jr., and Dale Zinn, and to Michael Taylor, Museum of New Mexico, for their assistance in reviewing the manuscript.

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Abstract

New Mexico continues to be the largest producer and user of adobe bricks and pressed-earth blocks in the nation. During field investigation and sampling in New Mexico in 1987-88, 33 commercial adobe-brick producers, 28 companies with pressed-earth-block machines, and 2 rammed-earth contractors were located. A significant number and variety of pressed-earth-block machines were in use; the gasoline- and diesel-powered machines were being made by five active New Mexico manufacturers. In 1987, 3,124,000 adobe bricks and 642,000 pressed-earth blocks were produced. A breakdown on the types of adobe bricks produced in 1987 shows that 20 adobe-brick producers made 849,000 traditional (untreated) adobe bricks, which sold for 21 to 40¢ per brick; 2,110,000 semistabilized adobe bricks, which sold for 30 to 35¢ per brick; and 165,000 stabilized adobe bricks, which sold for 59¢ per brick. The 642,000 pressed-earth blocks, largely made without stabilizers, sold for 25 to 35¢ per block.

During sampling, various tests were made on all types of adobe bricks and pressed-earth blocks. Mineralogy and particle-size analyses of the clays and soils, performed at the New Mexico Bureau of Mines and Mineral Resources, show that soil materials used in the adobe-brick and pressed-earth-block industries contain more sand + -size particles than previously reported. Physical-property tests on selected adobe bricks and pressed-earth blocks, performed at the United Nuclear Rock Mechanics Laboratory, New Mexico Institute of Mining and Technology, show that the adobe bricks and particularly the pressed-earth blocks have high physical strength and in all cases meet or surpass the specifications and requirements of the New Mexico Building Code.

The characteristics of the soils, the techniques of production, and the examples of earth-constructed buildings that are detailed in this report show that adobe bricks, pressed-earth blocks, and rammed-earth walls make energy-efficient, durable, attractive dwellings. If problems in radon-prone and seismically active areas are properly recognized and controlled, then earth-constructed buildings are no more dangerous than homes constructed with other materials.

Introduction

In 1980, a study of the adobe-brick industry in New Mexico, *Adobe bricks in New Mexico* (Smith, 1982a), was completed. The study located 48 commercial adobe-brick producers, who in 1980 produced and sold 4,133,000 adobe bricks valued at $1,174,598. The history of adobe use, the geology and mineralogy of adobe soil, the physical properties of adobe bricks, and the current production methods and market trends in the adobe-brick industry were described.

The present 1987—88 study updates and expands the original report. In addition to locating current adobe-brick producers, the 1987—88 study locates manufacturers of pressed-earth-block machines, the producers who use the machines, and the builders of rammed-earth walls (Figs. 1A, 1B). Recent developments in the production techniques for pressed-earth blocks and rammed-earth walls are described and new findings of the geology and mineralogy of adobe soil are documented.

The 1987—88 field investigations show that since 1980 labor-saving power-driven pressed-earth-block machines that add a greater flexibility to pressed-earth-block production have been introduced. During the field investigations, 27 machines were found in operation. Not all machines, however, were engaged in commercial production; most were used by owners for individual, noncommercial building projects. The 27 machines can produce several million blocks per year, a capability that may greatly increase the number of earth homes and commercial buildings constructed in the future. In 1988, five New Mexico manufacturers were actively producing and selling pressed-earth-block machines.

The rammed-earth industry in New Mexico was also investigated. Although several contractors have been active in the past, in 1988 only two contractors were found building rammed-earth walls.

The 1987—88 field investigations also show that in 1987 more than 3,766,000 adobe bricks and pressed-earth blocks were produced for commercial use. A total of 29 adobe-brick producers made 3,124,000 adobe bricks and 16 pressed-earth-block producers made 642,000 pressed-earth blocks. Most adobe bricks used in construction in New Mexico in 1987 were produced by eight major adobe-brick manufacturers who made and sold 2,110,000 semistabilized adobe bricks for 30—35¢ per brick. Approximately 849,000 traditional (untreated) adobe bricks were made and sold for 21—40¢ per brick. Only The Adobe Patch in La Luz, New Mexico, extensively produced the fully stabilized adobe bricks, of which 165,000 were made and sold for 59¢ per brick (Table 1). Several other producers indicated that they could produce stabilized adobe bricks on special order at the average price of 50¢ per brick.

Nearly complete production data for adobe bricks, pressed-earth blocks, and rammed-earth construction in 1988 indicate that the overall production volume in 1988 was nearly the same as in 1987. The amount of adobe bricks produced in 1988 was slightly less than in 1987; in 1988, a little more than 3,000,000 adobe bricks were produced. Producers say that the wet summer of 1988 in northern New Mexico was largely responsible for the slight decrease in adobe-brick production. Pressed-earth-block production, however, rose slightly to about 730,000 blocks because several more new machines were in operation in 1988 than in 1987. Rammed-earth construction remained about the same; in 1988, three homes were built by the state's two rammed-earth construction companies. The similarity in the 1987 and 1988 figures demonstrates that the adobe, pressed-earth, and rammed-earth industries continue to be a viable construction alternative in New Mexico.

Extensive sampling of adobe bricks and pressed-earth blocks in 1987—88 shows that commercial producers use adobe soils with far less clay-size material than expected.

TABLE 1—Total production, price range, and number of producers of New Mexico adobe bricks and pressed-earth blocks in 1987. NA, not available.

Type of adobe	Number of producers	Price per adobe/block	Total production
Adobe brick			
Traditional	20	21—40¢	849,000
Semistabilized	8	30—35¢	2,110,000
Stabilized	1	59¢	165,000
Pressed-earth block			
Traditional	16	25—35¢	642,000
Stabilized	special order	45—55¢	NA

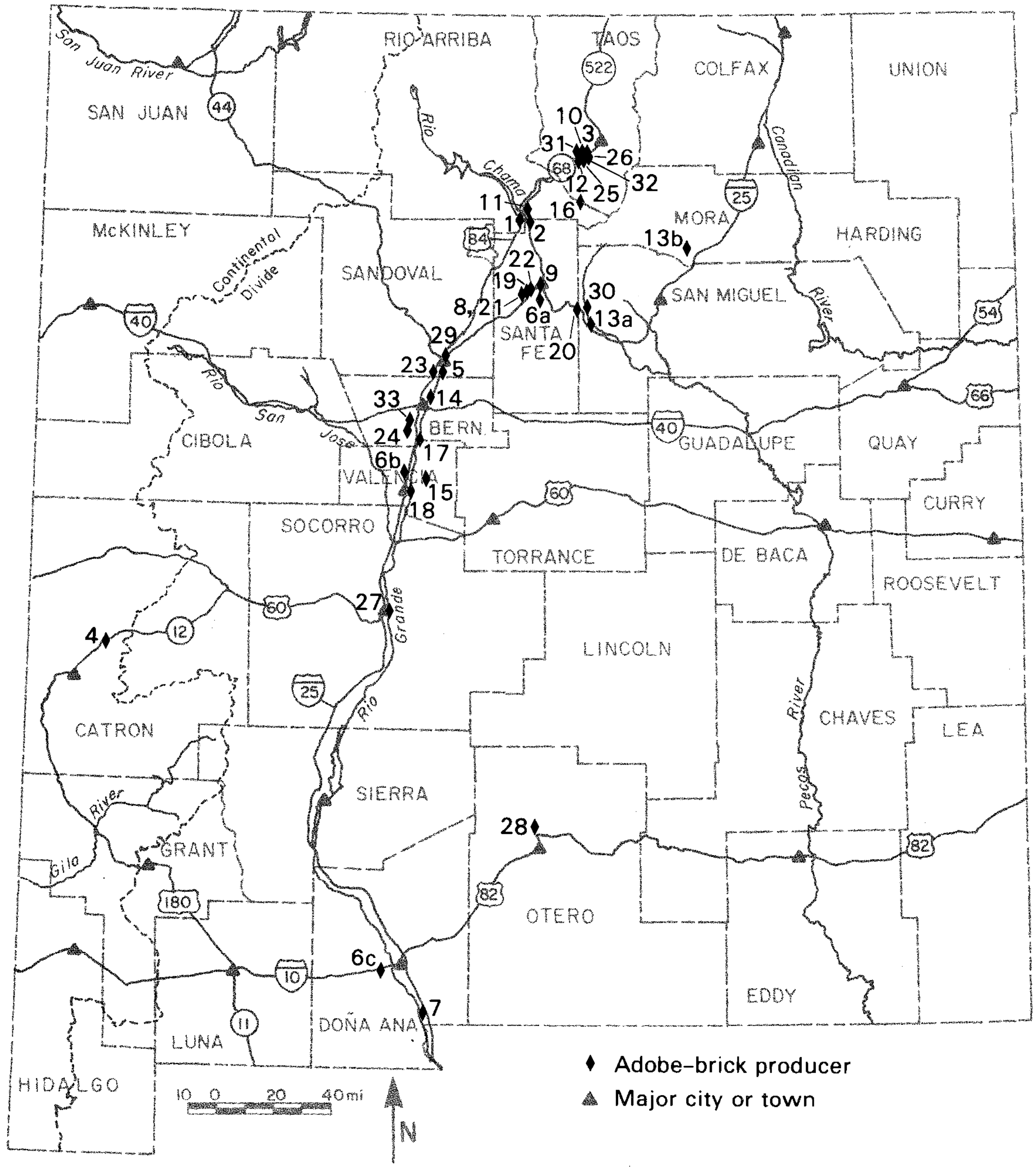


FIGURE 1A—Locations of commercial adobe-brick producers active in New Mexico in 1988. Numbers correspond with listing in Table 4.

Although adobe soils contain about the same amount of silt, the average adobe soil is sandier than expected. The sampling shows that the clay-size (<2 μm) fraction contains a variety of different clay-mineral groups consisting of kaolinite, illite, smectite, mixed-layer illite/smectite (IS), and, rarely, chlorite. As in the previous study (Smith, 1982a), clay minerals tend to be more or less equal in proportion between the expandable clay minerals (smectite and I/S) and the nonexpandable (kaolinite, illite, and chlorite); however, no clay-mineral group dominates the mix and individual samples contain from trace amounts to six parts in ten of nearly all of the groups.

The clay-size fraction also contains significant amounts of nonclay minerals. Clay-size calcite ($CaCO_3$) and quartz (SiO_2) are nearly ubiquitous along with less common occurrences of dolomite ($CaMg(CO_3)_2$), feldspar (sodium, calcium, and potassium aluminosilicates), and gypsum ($CaSO_4 \cdot 2H_20$), in decreasing order of abundance.

The apparent small percentage of clay-size particles indicates that the clay minerals are not the only binding agent in adobe soils. Indeed, the presence of calcite in both the clay-size and coarser fractions suggests that calcite may be the other chief binding agent in adobe soils. Further tests are being made to confirm this finding.

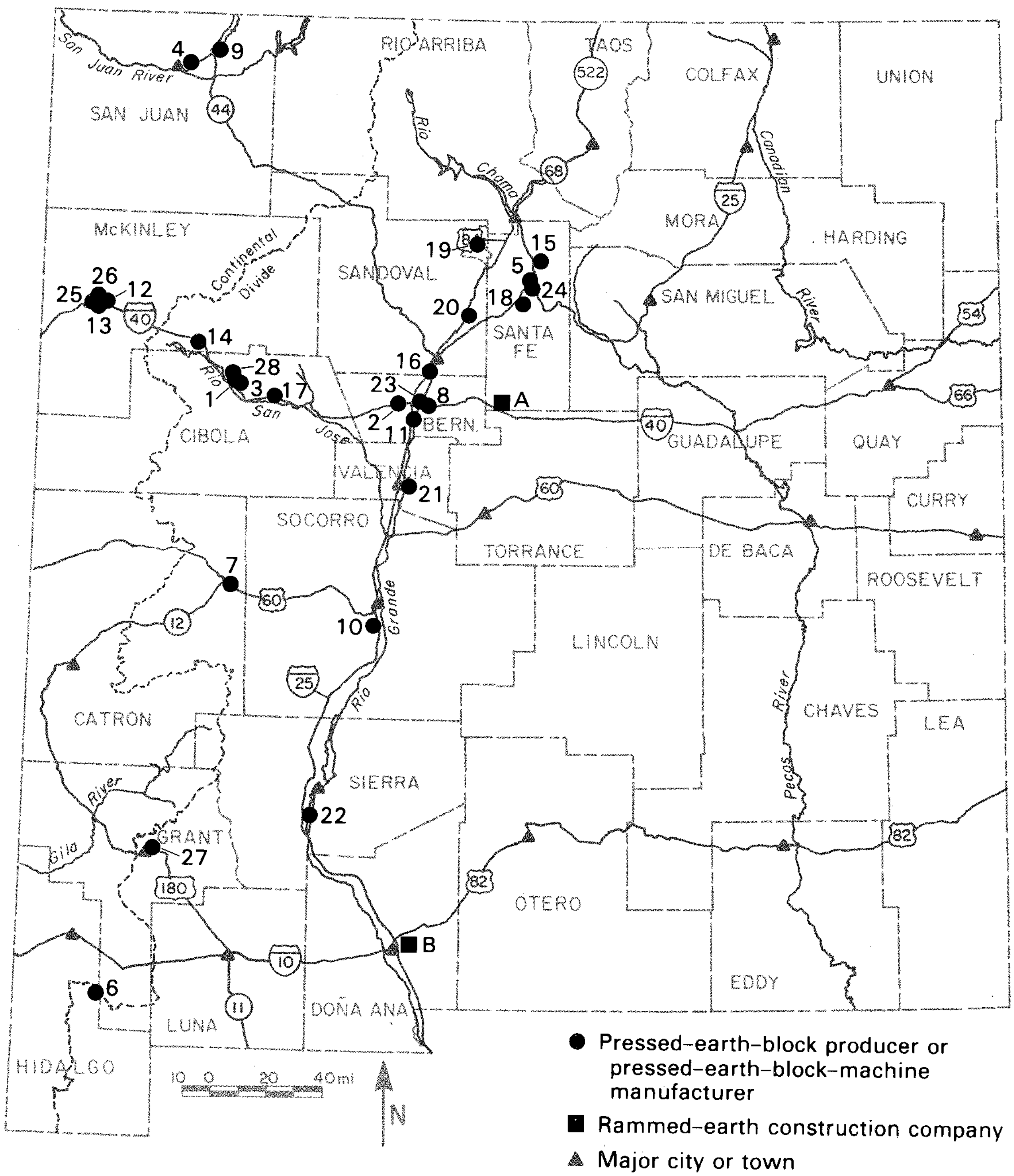


FIGURE 1B—Locations of pressed-earth-block producers, pressed-earth-block-machine manufacturers, and rammed-earth construction companies active in New Mexico in 1988. Numbers correspond with listing in Table 5 and letters correspond with listing in Table 7.

History

The word "adobe" has its roots in an Egyptian hieroglyph denoting brick. The etymological chain of events ultimately yielded the Arabic "at-tob" or "al-tob" (sun-dried brick), which then spread to Spain in the form of the verb "adobar," meaning to daub or to plaster (Lumpkins, 1977). Through Spanish conquests of the New world, the word adobe was brought to the Americas.

Today, adobe is generally used to describe various earth-building materials and techniques and the structures built from them. Most often the term has come to refer to the sun-dried adobe brick, the earth-building material now most widely used in the United States, but adobe can also be applied to puddled structures, adobe-plastered logs or branches, and even to rammed-earth (pisé) construction. Generally, any building that employs soil or mud as a primary material can be considered adobe.

Outlining a clear-cut chronology of the development and spread of the use of adobe in ancient times is difficult because such use probably emerged in many forms. Given the relative abundance of the material, understanding why experimentation with mud buildings was attempted by many ancient peoples is not difficult. The Neolithic Period (10,000-3000 B.C.) marks the gradual replacement of nomadic hunting and foraging with primitive agriculture and the domestication of animals. With this stable, nonmigratory existence came efforts toward building the first relatively permanent adobe structures.

Among the earliest remains of adobe structures are those discovered in the ruins of Neolithic farming villages in Mesopotamia dating as far back as 7000 B.C. (Steen, 1972). Hand-and form-molded bricks from this era are also seen in the ruins of structures throughout Mesopotamia, Crete, Egypt, and India. The use of mud construction spread rapidly east-ward through Asia and westward through North Africa and the Mediterranean Basin and, as the glaciers of the ice age receded, throughout Europe. Meanwhile, the New World was undergoing a similar development. Although not used as early as in the great civilizations of the eastern hemisphere, adobe construction has been dated as early as 3000 B.C. in the Chicama valley in Peru (Steen, 1972).

The first adobe structure in what is now the United States, however, probably does not predate A.D. 900. Since that time the region that now includes the state of New Mexico has undergone much development in adobe architectural styles, incorporating contributions from Indian, Spanish, and Anglo residents to produce a distinct native New Mexican architectural landscape. The evolution of architectural styles in New Mexico can be roughly broken down into four periods (Bunting, 1976): Indian (A.D. 700-1598), Spanish and Mexican Colonial (A.D. 1598-1848), Territorial (A.D. 1848-1880), and later American (A.D. 1880-present). Regardless of period or style, until recently construction of buildings in New Mexico has always revolved around adobe as a primary building material.

What is known as the Indian period actually includes all architecture previous to the 1598 arrival of Spanish settlers in the area and can be broken down along archaeological lines into several distinct periods: Pueblo I (A.D. 700-900), Pueblo II (A.D. 900-1050), Pueblo III (A.D. 1050-1300), and Pueblo IV (A.D. 1300-1598). During Pueblo I, the early Pueblo Indians, the Anasazi, lived in below-ground earth-walled pithouses, some of which had mud-plastered wood partitions and roofs. The floors of the pithouses were often below the depth at which the ground froze so that the temperature of the homes would not drop below freezing. By A.D. 900 (Pueblo II) most of the Anasazi had moved into above-ground rooms often facing south, the walls of which were made of stone masonry and mud mortar. The walls of stone and mud retained the thermal properties of the older pithouses. For interior walls, jacal—a framework of vertical poles and branches covered with mud—was sometimes constructed (Bunting, 1976; Jones and Cordell, 1985).

FIGURE 3—Jacal construction using cedar poles and adobe, old house near Abiquiu.

The architecture of the Great or Classic period of Indian culture (Pueblo III) can be seen at many famous archaeological ruins in the southwest United States, including Pueblo Bonito at Chaco Canyon, old Picuris Pueblo, the site of Sapawe near El Rito, and the Pajarito Plateau sites (Steen, 1977; Bunting, 1976; Fig. 2) within the state of New Mexico. Jacal and stone masonry combined with adobe were the techniques generally employed during this era (Figs. 3, 4).

The rammed-earth technique was also extensively used by the Pueblo Indians during Pueblo III and is represented by such famous structures as the puddled-adobe multi-storied Taos Pueblo housing complex (Fig. 5). With limited primitive wood and stone tools, the Pueblo Indians probably mixed adobe soil with water and carried the mud mixture to building sites, where the mud was shaped and patted by hand to form walls. The puddled-adobe and turtle-back methods are similar to rammed-earth construction except that the mud mixture is laid without the aid of wooden forms. Structures built with puddled-adobe and turtle-back methods have been identified at the excavation site of Sapawe near El Rito, various Pajarito Plateau sites near Bandelier National Monument (Steen, 1977), and at old Picuris Pueblo (Bunting, 1976). At the modern pueblos of Picuris and Taos, examples of old puddled-adobe structures made by patting mud into a wall shape can be seen (Fig. 6).

The Pueblo IV division of the Indian period, spanning the years from A.D. 1300 to A.D. 1598, marks the migration of large numbers of Pueblo Indians into the Rio Grande

FIGURE 2—Puddled-adobe walls near White Rock on Pajarito Plateau. Archaeology site excavated by C. Steen and staff.

FIGURE 4—Old adobe and field-stone structure, San Jose.

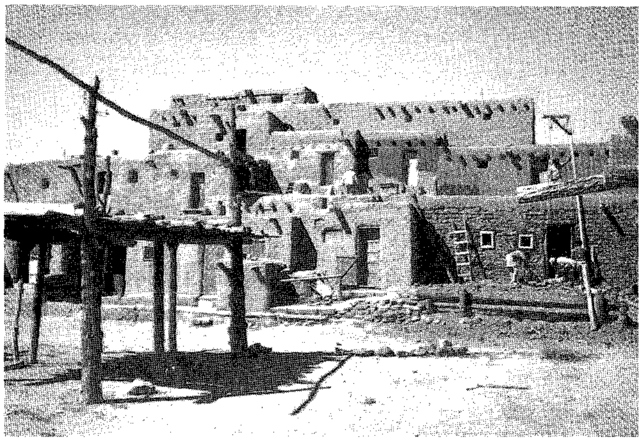


FIGURE 5—Taos Pueblo originally built of puddled adobe. Note mud plastering that is carried out each year to maintain the structure.

valley. Pueblo IV culture was markedly less advanced than that of Pueblo III, as evidenced in the less sophisticated building technology and the smaller and less complex community organization. Ruins dating from this time can be seen at the ancestral villages of Tyounyi (Bandelier National Monument), Hawikuh (Zuni), Kuaua (Coronado State Monument), and Pecos (Bunting, 1976). Only at Taos and Acoma Pueblos have adobe structures dating from before Pueblo IV times been continuously occupied.

The Pueblo V segment of the Indian period began after the 1598 arrival of the Spanish colonists and continues to the present day. Pueblo V overlaps, meshes with, and is overshadowed by Spanish and Mexican Colonial, Territorial, and later American architectural styles. This latter period of Indian style is marked by many rapid architectural changes and a general disintegration of pure Indian structures as the influence of Spanish and later American newcomers encroached upon the pueblo communities.

Upon the arrival of the Spanish colonists in 1598, new building techniques and forms of architecture were introduced to New Mexico. Yet, because of the isolation of the region and the severe survival conditions imposed on the new settlers, the colonial era was characterized by little technical or cultural advancement. In fact, most buildings of this era may have been reduced to the barest essentials, and techniques and materials remained virtually unchanged from what the Indians had used before. A major contribution of the Spanish, however, was the introduction

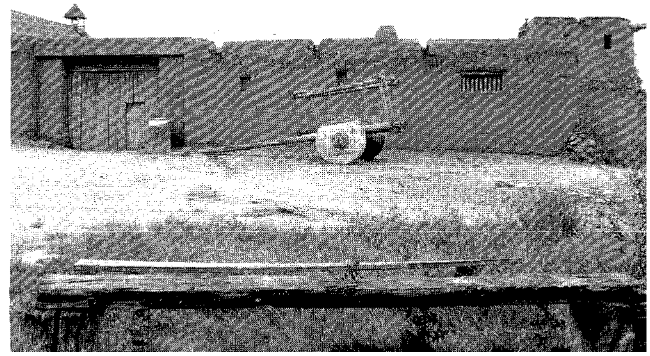


FIGURE 7—Reconstructed Spanish and Mexican Colonial fortress-like structure at el Rancho de las Golondrinas near La Cienega. Note tower (torreòn) used for defense.

of the formed standard adobe brick (Bunting, 1976). In addition, the classic Spanish single-file linear room plan also began to appear, and sometimes homes were constructed around a central plaza area for defense, with fortified round, two-story towers (torreónes) built nearby (Bunting and others, 1964; Bunting, 1976; Fig. 7). Another notable architectural characteristic of the Spanish and Mexican Colonial period were "fortress churches"—solid, rectangular adobe churches that resemble fortresses in their imposing size and lack of fenestration.

With the opening of the Santa Fe Trail in 1821, influences from the east and midwest United States began to trickle slowly westward, and upon annexation of the territory of New Mexico in 1848, the flow of new materials and ideas increased. The Territorial period was one of rapid economic and cultural development that contrasted markedly with the centuries of cultural isolation and preoccupation with warfare and survival that directly preceded it. This change is reflected clearly in the architecture of the period, which went through several phases. However, the new architectural style was in essence nothing more than a transported version of the Greek Revival style that had been popular in the East in the 1820s. The Territorial style is probably best known for its elaborate neo-Classic and Gothic wood trim on windows and doors, the symmetrical floor plan based around a center hall, two-story construction, and columned verandas (Bunting, 1976; Fig. 8). The influx of new technology and materials, such as milled lumber, window glass,

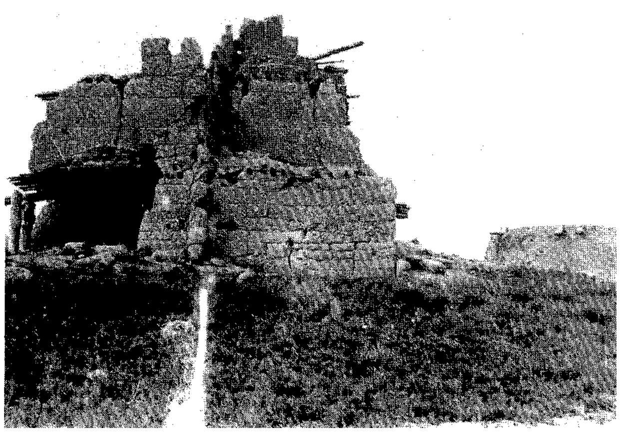


FIGURE 6—Puddled-adobe structure at old Picuris Pueblo, ca 1900. Note size of puddled adobes patted into place by hand. Photo by A. C. Broman.

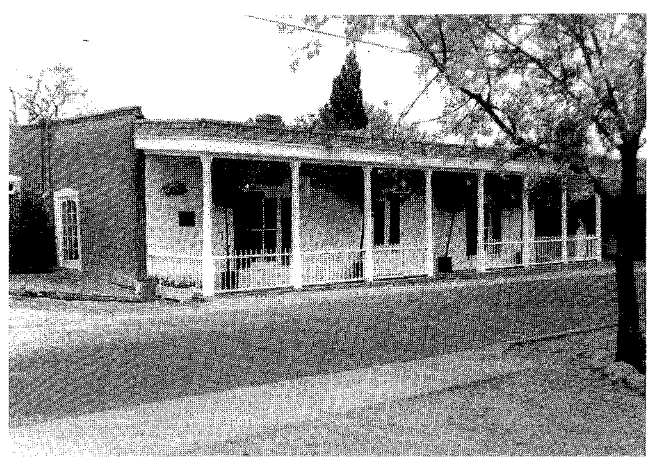


FIGURE 8—Territorial-style adobe building on Canyon Road, Santa Fe. Note neo-Classic (vaguely Doric) columns and portal, exterior woodwork painted white, and burnt bricks on top of adobe walls.

burnt brick (used to trim the tops of adobe walls), and corrugated iron, contributed to the new modern American look of New Mexican architecture. Many people felt traditional adobe architecture was jeopardized during the Territorial period. Some attempt was even made to disguise adobe-building material completely with a lime, sand, or cement coating that was scored or painted to resemble ashlar masonry.

The later American period began with the arrival of the railroad in New Mexico cities in 1880, yet this style did not reach some of the more remote mountain villages until after World War II. During this period, many diverse architectural movements from California and the East were represented simultaneously as New Mexico rushed to catch up with the rest of the country. The availability of iron, improved tools and fittings, and other manufactured items hastened New Mexico's arrival in the 20th century. In addition, pueblo-like architecture was experiencing a rebirth in what became known as the Santa Fe style (Pueblo Revival style), which is now associated in the minds of many people with the soft, earth-tone, curvilinear adobe architecture of the Southwest (Fig. 9).

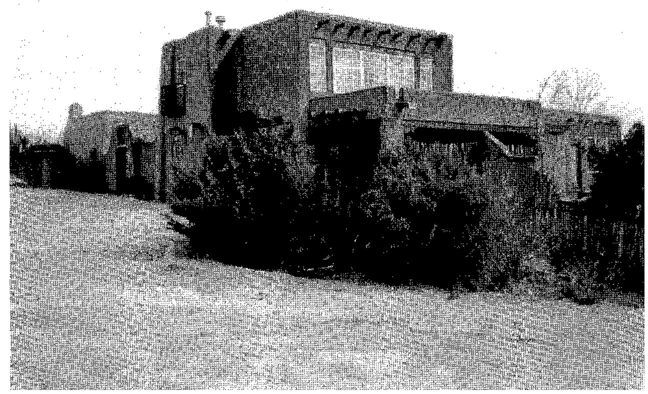


FIGURE 9-Santa Fe-style (Pueblo Revival-style) architecture, Santa Fe.

Also during this time, because of the advent of railroads and the immigration of Anglo settlers mainly from the East who constructed homes made with other materials, the extent of adobe use decreased in New Mexico. From U.S. Bureau of Census reports, Gerbrandt and May (1986) calculated that in 1850, 97% of the homes in New Mexico were adobe; in 1980, only 12% of the homes were adobe (Table 2). Over a period of 130 years, the number of adobe dwellings increased from 13,050 to an estimated 59,000 adobe units; however, during the same period, the population increased from 61,546 to 1,299,968.

In Albuquerque during the last decade, approximately 100 construction permits per year were issued for adobe homes (Gerbrandt and May, 1986). Based on this statistic,

TABLE 2-Estimated numbers and percentages of adobe dwellings in New Mexico from 1850 to 1980 (from Gerbrandt and May, 1986). "Population" and "total dwellings" figures without superscripts are taken from the U.S. Bureau of Census. *, dwellings occupied by "white and free colored" populace (U.S. Bureau of Census); ┼, estimated from 1870 census; -, net reduction.

	Population	**Total dwellings**	**Percentage of dwellings that were adobe**	**Number of adobe dwellings**	**Number of adobe dwellings built per year during decade**	**Percentage of dwellings built per year during decade that were adobe**
1850	61,546	13,453*	97%	13,050		
					690	91%
1860	93,516	21,000┼	95%	19,950		
					----	----
1870	91,874	21,052	94%	19,800		
					360	70%
1880	119,565	26,311	89%	23,400		
					600	72%
1890	160,282	34,671	85%	29,500		
					650	63%
1900	195,310	44,903	80%	35,900		
					1,800	58%
1910	327,301	75,888	71%	53,900		
					----	----
1920	360,350	78,024	63%	49,000		
					----	----
1930	423,317	92,530	50%	46,300		
					270	5%
1940	531,818	145,642	34%	48,900		
					----	----
1950	681,187	199,706	26%	51,100		
					210	4%
1960	951,023	281,976	19%	52,500		
					170	2%
1970	1,019,060	326,762	16%	53,600		
					620	3%
1980	1,299,968	503,676	12%	59,000		

Gerbrandt and May (1986) estimated that 3% of new homes built in New Mexico during the 1970s were adobe. In Albuquerque in 1980, an estimated 7.1% of new homes built were adobe. In 1987–88, adobe bricks continue to be produced in Indian and Spanish-American communities. The majority of adobe bricks are used to construct large-scale, expensive homes throughout the state. Most pressed-earth blocks are being manufactured by Anglo-Americans, whose experience with traditional adobe is relatively recent.

The developments in the use of adobe over hundreds of years has formed the backbone of New Mexico's architectural heritage. The unique and eclectic architectural landscape continues to distinguish the state from the rest of the nation.

Terminology and characteristics

Adobe bricks

Adobe, or sun-dried mud brick, has a long history of widespread use by the Indians, Spanish-Americans, and Anglo-Americans in the southwest United States, where annual precipitation is low. However, the use of adobe need not be restricted to arid and semiarid climates if buildings are properly protected or certain soil stabilizers are used (Hubbell, 1943). In fact, examples of earth-wall construction can be found from New England to South Carolina in climates that are far from arid or semiarid. Modern residences of earth-wall construction have been built since 1920 in Washington, D.C., Illinois, Michigan, Arkansas, Oklahoma, Colorado, North Dakota, Wyoming, Idaho, and in all the southwest states (Long and Neubauer, 1946).

The introduction of the wooden form by the Spanish colonists in the late 1600s permitted the adobero (adobe maker) to control the size and weight of the bricks, which in turn allowed for greater construction flexibility. Many sizes of adobe bricks with considerable variation in weight have been produced in the Southwest. Long and Neubauer (1946) noted brick weights from early California and New Mexico adobe structures that varied from 30 to 100 lbs.

Dimensions (inches)	weight (lbs)
4x 8x16	30
4x 9x18	38
4x12x18	50
5x 9x18	48
5x12x18	60
6x12x14	100

The adobe bricks that are produced today in New Mexico vary from the small mosque-type Egyptian brick of 3 x 5 x 10-inch size, which weighs 8 lbs and is used in the construction of domes and arches, to the Isleta Pueblo terrón brick of 7 x 7 x 14-inch size, which weighs 35 lbs. The principal size manufactured (97%) today by the majority of adobe producers in New Mexico is the 4 x 10 x 14-inch brick that averages 30 lbs in weight. Other sizes of bricks are made that are usually produced only in limited quantities or on special order (Table 3).

Adobe soils

Adobes can be made from a variety of local soils, but the most suitable soil found in the Rio Grande valley is a sandy loam composed of approximately 55–85% sand and 15–45% finer material (generally more silt than clay) and usually containing caliche (pedogenic or formed-in-the-soil calcium carbonate). A balance of particle sizes is essential to ensure a quality adobe. Clay gives strength to the adobe, but in excessive amounts will cause shrinkage; sand or straw is added to decrease the shrinkage and prevent cracking (California Research Corporation, 1963).

Adobe mortars

During the building of the adobe wall, adobe bricks and pressed-earth blocks are joined together with a water-adobe-soil mixture that hardens and becomes firm upon drying. The New Mexico Building Code allows the use of earth mortar if it is composed of the same materials as the bricks. The majority of adobe-brick and pressed-earth-block producers can furnish this screened adobe soil.

Stabilizers

Moisture re-entering an adobe brick causes clays to swell and release their bonds so that the entire mass disintegrates. To prevent disintegration, various soil stabilizers are added to the basic soil mix to waterproof or increase the weathering resistance of the adobe brick. The most commonly used stabilizers are sand, straw, portland cement, lime, and bituminous and asphalt emulsions (Clifton, 1977), although as many as 20 different materials have been found in use (Wolfskill and others, 1970). In New Mexico, asphalt emul-

TABLE 3—Sizes and weights of adobe bricks and pressed-earth blocks made in New Mexico.

Type of adobe	Dimensions (inches)	Weight (lbs)
Adobe brick		
Egyptian brick	3 x 5 x 10	8
Veneer brick	4 x 4 x 16	26
Half adobe	4 x 4 x 8	23
Quemado (burnt adobe)	$3^1/2$ x 8 x 16	30
New Mexico standard adobe	4 x 10 x 14	30
Adobe (old style)	4 x $5^1/2$ x 16	28
Adobe (old style)	4 x 12 x 18	50
Taos standard adobe	4 x 8 x 12	26
Terrón	7 x 7 x 14	35
Dome brick (mosque)	2 x 10 x 6	8
Mexico standard adobe	$3^1/2$ x 10 x 16	35
Salazar adobe	4 x 10 x $15^1/2$	37
Acoma Mission adobe	3 x 9 x 18	30
Pressed-earth block		
CINVA-Ram pressed block	$3^1/2$ x $5^1/2$ x $11^1/2$	20
Standard pressed-earth block	4 x 10 x 14	40
Medium pressed-earth block	4 x 10 x 12	30
Small pressed-earth block	4 x 8 x 12	25
California/Arizona pressed-earth block	4 x 10 x 16	50

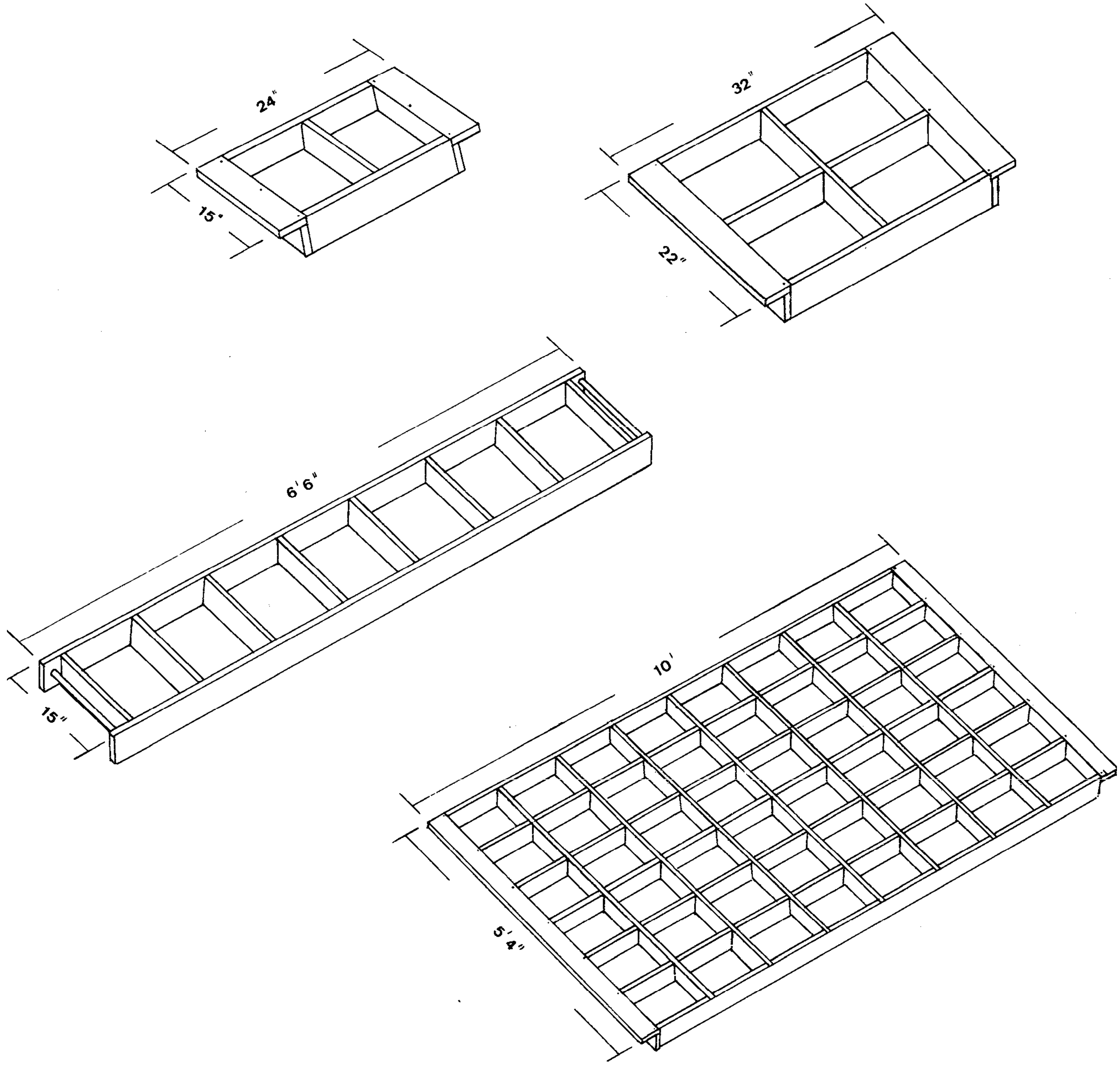


FIGURE 10—Diagrams of typical New Mexico wooden molding forms with approximate overall dimensions.

sion is widely used by the large-scale commercial adobe-brick producers to protect the bricks that are drying in adobe production yards during intense rains.

Molding forms

The construction and design of the metal and wooden molding forms used to make adobe bricks are as numerous and as varied as the makers of adobes themselves. Typical types of molding forms used in the state are illustrated in Fig. 10. The majority of molding forms are made of wood with the sides, ends, and divider members usually 4 inches wide, which produce the standard 4-inch-thick adobe brick. The common use of 2 x 4s to build forms produces a $3^1/2$-inch-thick, lighter adobe averaging 27–30 lbs in weight.

Small-scale adobe producers who make traditional (untreated) adobe bricks generally use a two- or four-mold wooden form, which can be handled by a single individual. Large-scale adobe producers will typically have several hundred wooden molding forms resembling ladders that may vary from seven to ten up to 48 molds per form. Usually two or more persons are required to lift these large molding forms from the drying bricks.

Traditional (untreated) adobe bricks

Often referred to as untreated or standard sun-dried adobe brick, the traditional adobe is made with soil composed of a homogeneous mixture of clay, sand, and silt. Straw is sometimes added to prevent the brick from cracking when curing. Examples of traditional adobe bricks can be found in the majority of cities, villages, and pueblos of New Mexico.

To protect adobe structures made with traditional (untreated) adobe, two methods have been used. Owners have plastered on a simple adobe-mud mixture, which usually requires periodic reapplication (Fig. 11), or have applied a longer lasting wire mesh and cement stucco. In many areas of the state, the owners of adobe structures have added a pitched tin or corrugated iron roof with an overhang to protect the adobe roof and walls from excessive erosion (Fig. 12).

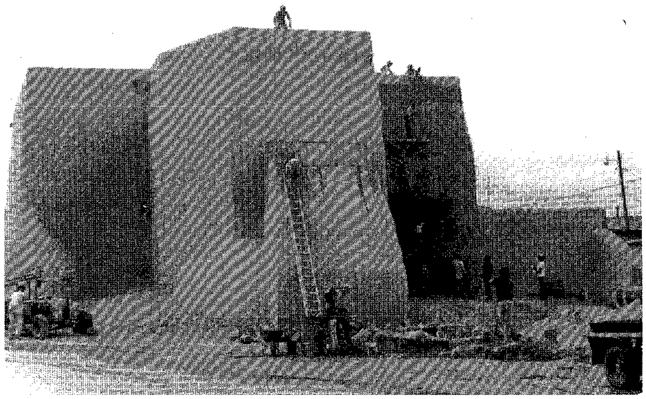


FIGURE 11—Plastering adobe mud on walls of church, Ranchos de Taos.

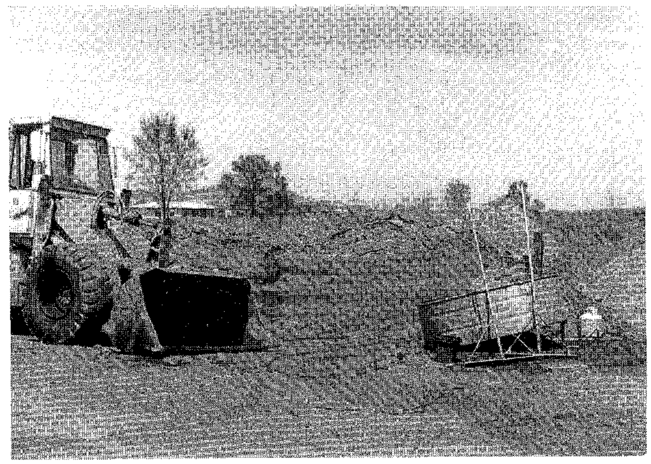


FIGURE 13—Mudpit at the Rio Abajo Adobe Works adobe yard, Belen. Asphalt emulsion from tank on the right and water are added to soil in the center. Mixing is done by the front-end loader.

FIGURE 12—Old adobe home, San Jose. The owner has added a corrugated iron roof to protect the adobe structure.

FIGURE 14—Cutting terrónes from Rio Grande sod, Isleta Pueblo.

The durability of untreated adobe structures that are carefully maintained is well illustrated by the multistoried Taos and Acoma Pueblos, which have been continuously occupied for more than 900 years. Many other examples of historic, traditional (untreated) adobe architecture can be seen in the numerous mountain villages of New Mexico, where some adobe structures are more than 300 years old.

Semistabilized adobe bricks

Developed by the large-scale adobe producers to be somewhat water-resistant, the semistabilized adobe brick is the most widely produced brick in New Mexico. Its name is derived from the practice of adding a small amount of stabilizer to adobe mud to make water-resistant bricks. The primary purpose of the stabilizer is to protect the several thousand bricks that may be drying in an adobe yard from the damage of an intense rain. The semistabilized brick is made essentially the same way as the traditional adobe brick except that 3—5 wt% asphalt emulsion is added to the adobe soil as the soil is mixed in a pugmill or mudpit (Fig. 13).

Stabilized adobe bricks

The fully stabilized adobe brick, referred to by the New Mexico Building Code as a treated adobe, is defined by the addition of a sufficient amount of stabilizer to limit the brick's seven-day water absorption to less than 4 wt%. The fully stabilized adobe brick is usually manufactured with 6—12 wt% asphalt emulsion, which produces a waterproof building material that resists water penetration without a protective coating. The addition of portland cement (5—10 wt%), although not in use as a stabilizer in adobe bricks in 1988, can also produce a good water-resistant brick.

Terrónes

The Spanish word "terrón" meaning "a flat clod of earth" refers to the type of adobe brick made of cut sod or turf material found in boggy river-bottom locations, particularly in the Rio Grande floodplain areas (McHenry, 1985). The terrón is cut from sod in 7 x 7 x 14-inch dimensions using a flat spade and then is stacked in a dry area to sun dry and cure (Fig. 14). Probably because of the sod-root structure and the high clay content of the soil, the terrón has a high compressive strength and modulus of rupture, but has measureable shrinkage during drying.

Quemados

The quemado or burnt adobe is a traditional sun-dried adobe brick that has undergone a modified low-temperature firing process. Combustible materials are burned in a stacked-brick oven that is built to allow air circulation within the kiln. Usually firewood is fed through small doors at each end of the kiln with smoke escaping through holes at the

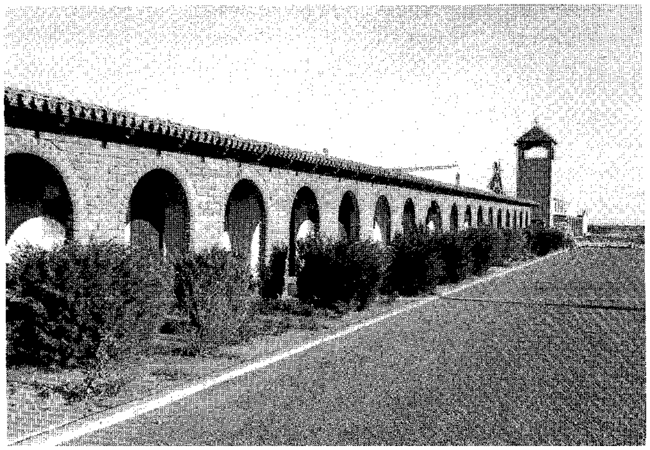


FIGURE 15—Portal made with quemados, airport near Columbus.

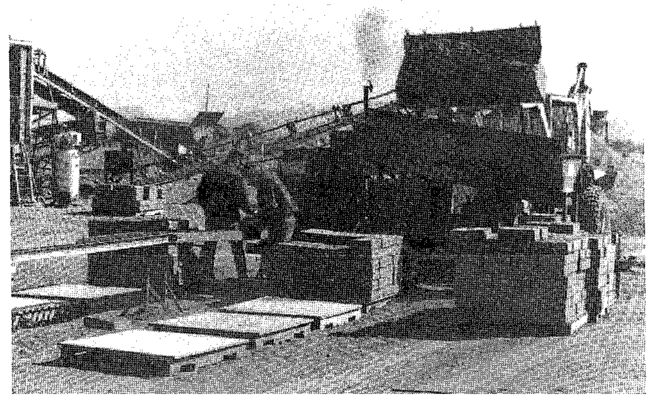


FIGURE 16—Goldbrick "5000" pressed-earth-block machine in operation at the Ridge Adobe production yard, Santa Fe.

top. The firing process usually takes two to four days and approximately 300—500 quemados are produced per firing (Fig. 15).

Pressed-earth blocks

Usually manufactured with traditional (untreated) soil, the pressed-earth block is a type of adobe brick that does not require much curing time. The soil, placed in a steel mold, usually of 4 x 10 x 14-inch size, is pressed into a dense block by a hand-operated press, referred to as a "CINVA-Ram," or a gasoline- or diesel-powered hydraulically operated machine. The powered machines are capable of producing several thousand blocks per day (Fig. 16). Because of the high mechanical pressure applied by the hydraulic press, the pressed-earth block usually tests very high in compressive strength and modulus of rupture.

Rammed-earth walls

The rammed-earth (pisé) wall is built by thoroughly tamping layers of moist soil between wooden, steel, or aluminum concrete forms (Fig. 17). Hand-operated or pneumatic tampers ram the soil until the soil has become dense and firm. When a section of the wall has been rammed, the forms are moved upwards or sideways and the process is repeated until the wall is completed. The density of the wall depends on the soil type and the length of tamping time.

According to Santa Fe architect William Lumpkins (personal communication, 1988), several puddled-earth houses were built north of Santa Fe in the late 1970s. The contractor used a cement mixer to blend soil with a small amount of portland-cement binder and an overload of pea-size gravel, which prevented "gumming up" in the mixer. The mix was moved to the future site of a wall and patted into place. Lumpkins observed that one house was built in seven or eight days by four laborers. Both exterior and interior partition walls were made with the puddled earth.

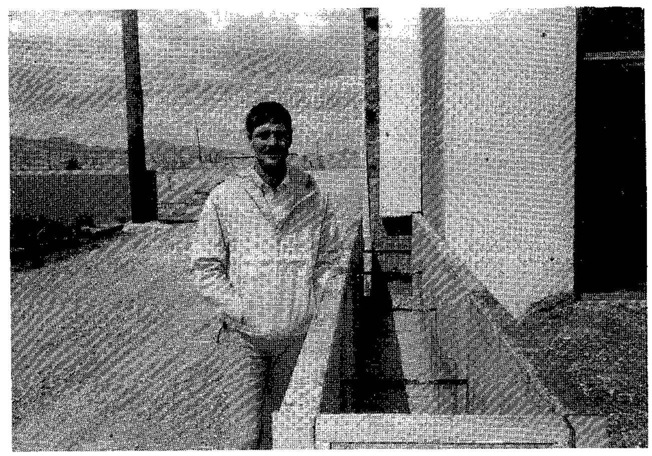


FIGURE 17—Stan Huston of Huston Construction Company standing by rammed-earth forms, Edgewood.

Geology

Usable adobe soils are found in the majority of the Southwest's basins and constitute a virtually inexhaustible supply and reserve in New Mexico. The adobe materials are principally from stream deposits, particularly Holocene (Recent) terrace deposits and older, loosely compacted geologic formations, such as the Santa Fe Group (Tertiary), located throughout the Rio Grande valley. More than 80% of the adobe producers are located between Belen and Taos, New Mexico, and the majority use a sandy loam (50% clay and silt) associated with or derived from the Santa Fe Group.

Although suitable soils for adobe structures are found in almost all areas of New Mexico, a satisfactory soil deposit may not be at or near the proposed manufacturing site. The best method to determine the quality of a soil is to make a series of experimental adobe bricks or pressed-earth blocks, which can be tested for strength, modulus of rupture, and moisture content. To obtain the best adobe material, soils from more than one deposit may be blended.

In many areas, the best sources of adobe material are the local sand and gravel operations where overlying soil or undersized material are sold at $2.00—7.00/yard. Many adobe soils used by large-scale adobe producers are obtained from state, federal, and Indian lands, where the majority of operating sand and gravel pits are presently located. However,

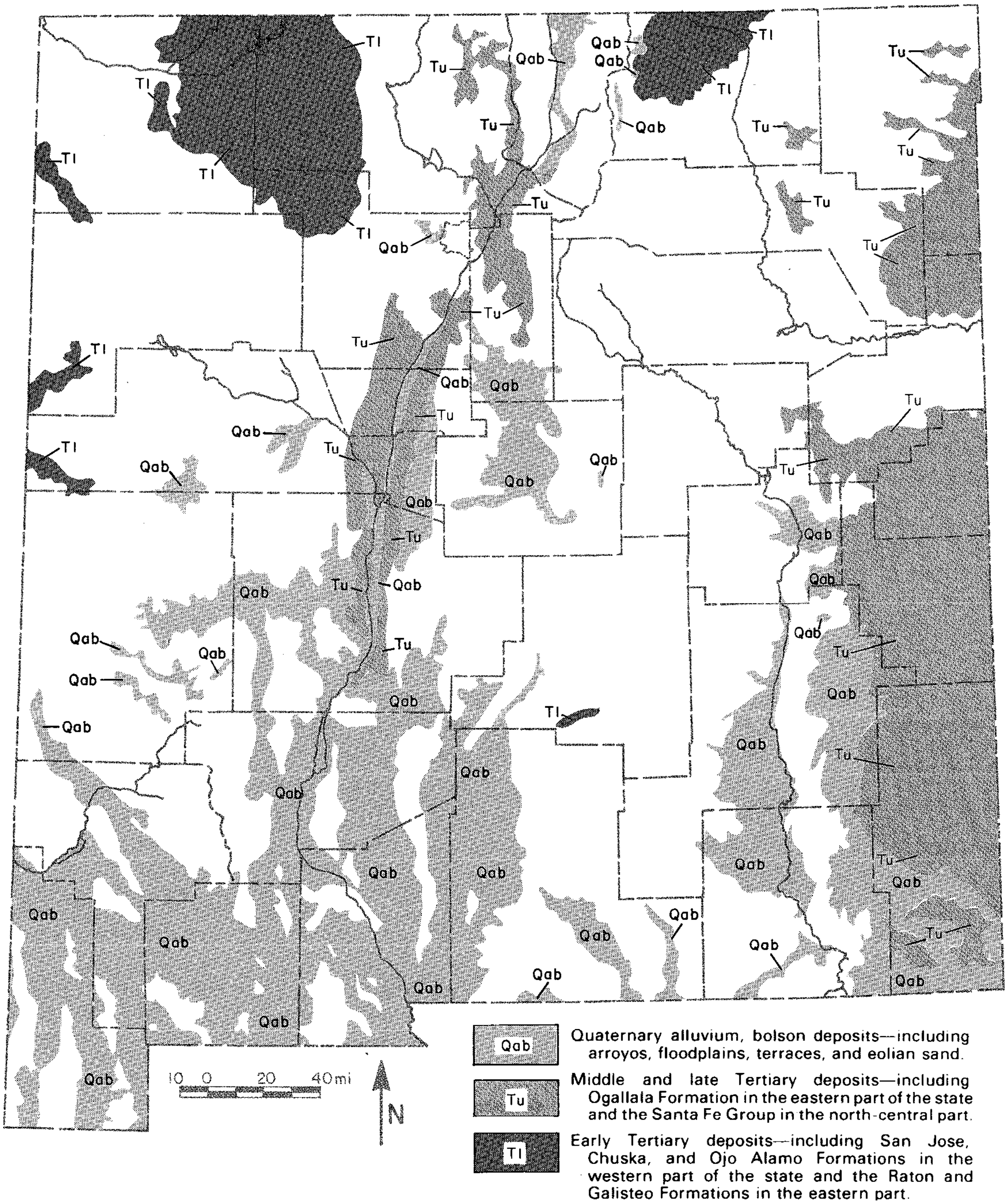


FIGURE 18—Major sources of adobe soil in New Mexico (modified from Carter, 1965).

most small-scale adobe producers haul their adobe soil to the adobe yard from nearby land-leveling operations and from private land sites.

The development and extensive use of pressed-earth-block machines have greatly expanded the geographic locations of the adobe industry throughout the state. Many of the machines are now operating at remote mountain sites and Indian reservations. The soil requirements for pressed-earth blocks are similar to that for adobe bricks, but vary in moisture content.

The locations of the main sources of adobe soil used by most commercial adobe producers have been adapted from the report by Carter (1965) on sand and gravel in New Mexico and are shown in Fig. 18. For detailed geologic data on the major adobe-soil locations, see the geology reports and maps of the Albuquerque and Espanola Basins (Kelley, 1977, 1978). Brief descriptions of the major sources of adobe soil in the state follow.

Channel deposits

Various river deposits and stream or arroyo deposits, which consist of intermixed sand, silt, clay, and gravel in stream beds along present stream courses, are usually a major source of adobe soil. The deposits are accessible during the dry season and the soil can be easily removed by front-end loaders (Fig. 19), loaded into trucks, and hauled to the adobe yard. To remove soil from public land, a permit or lease can be obtained at a relatively low cost.

Terrace deposits

Particularly throughout the Albuquerque and Espanola Basins are extensive terrace deposits that offer excellent sources of sand, gravel, and adobe soil. The terrace deposits border streams, but are located above the level of the present floodplains and are remnants of older floodplains through

FIGURE 19—Stream or arroyo deposit being mined for production of adobes, San Juan Pueblo.

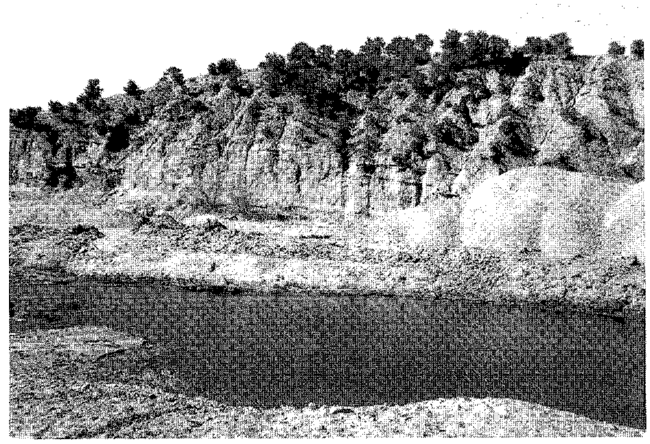


FIGURE 21—Cross section of the alluvial Tesuque Formation (Tertiary), composed of sand and gravel, dipping west towards the Rio Grande. Photo taken near Tesuque River.

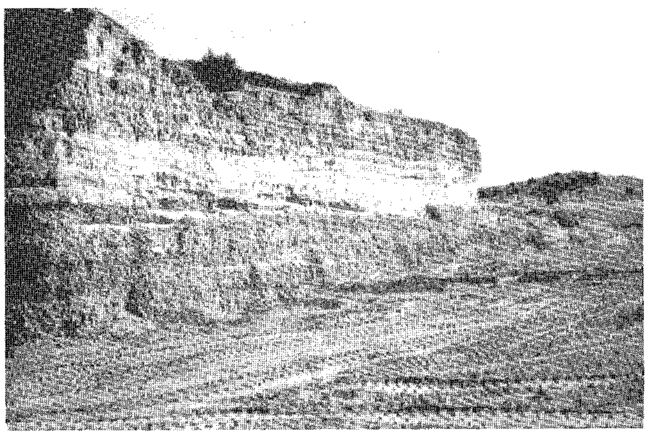


FIGURE 20—Old terrace deposit east of the Rio Grande, San Juan Pueblo. The upper 10—15 ft of fine sandy loam are underlain by coarse gravel.

which a channel has cut. The terrace deposits, especially the lower terrace deposits above the floodplain, are widely mined by sand and gravel operators and adobe producers. Throughout most of the Rio Grande valley, the upper 15—30 ft of overburden covering the terrace deposits are composed of a sandy loam that contains the proper percentage of sand, silt, and clay to produce a quality adobe (Fig. 20).

Alluvial fans—piedmont plains

Throughout New Mexico, gently sloping alluvial fans are found at the mouths of canyons where streams from mountains enter valleys or plains. The flattening slope at the base of the mountains causes cobbles and boulders to be deposited at the apex of the fan-shaped mass and smaller to finer particles toward the sides and toes (Fig. 21). These fans coalesce and form alluvial piedmont plains throughout large areas of the state and are a continuous supply of adobe material. The alluvial fans and piedmont plains are mostly located on public land and are mined by many sand and gravel operators. In the Alamogordo area, the Alamo Canyon alluvial deposit is a major source of sand, gravel, and adobe soil and is presently used by The Adobe Patch in La Luz, New Mexico. With the fine fraction from the alluvial deposit, The Adobe Patch has produced a quality stabilized adobe brick.

Also found in the piedmont plains are gravel, sand, silt, and clay that have been initially cemented by porous caliche. Caliche, a whitish calcium carbonate deposit, forms in the soil from a buildup of the mineral calcite ($CaCO_3$). In the dry Southwest where materials erode much slower, a buildup of calcite (calichification) often accompanies weathering.

Older geologic formations

Many older geologic formations throughout the state contain sources of sand, gravel, and adobe soil. Early Tertiary deposits include the Raton and Galisteo Formations in the eastern part of the state and the San Jose, Chuska, and Ojo Alamo Formations in the northwestern part. The middle and late Tertiary deposits are composed of partially consolidated beds of sandstone, mudstone, arkose, conglomerate, and fanglomerate and include the Ogallala Formation in the eastern part of New Mexico and the Santa Fe Group in the north-central part.

Ditch and aggregate by-products

The extensive irrigation systems throughout the Rio Grande valley require cleaning and removal of soil each year. The fine soils, usually high in clay and silt, are stockpiled adjacent to ditches and can be mixed with other material to make an adobe soil. Permits to remove the soils can usually be obtained from the conservancy districts (Fig. 22).

At most sand and gravel operations with large screening and crusher plants, large quantities of fine soil (crusher fines) are produced. Upper layers of soil are also removed during excavations for gravel and are stockpiled for use as fill. These aggregate by-products (Fig. 23) are sold and can be tested for clay content and for use in adobe production. The fine soils can be blended with other material or can be used directly by large-scale adobe producers to make adobes.

Mineralogy

Adobe soils contain particles of clay, silt, and sand sizes and larger (sand +) sizes. Clay-size particles are less than 2 micrometers (<2 μm or <0.002 mm) in size and are as fine as face powder. Clay-size particles contain no grit and are smooth when ground between teeth. Particles of this size consist chiefly of clay minerals. Silt-size particles are larger than 2 micrometers (>2 μm), but are less than 1/16 mm (<0.0625 mm); sand-size particles are larger than 1/16 mm (>0.0625 mm), but are less than 2 mm (<2 mm), although different organizations have slightly different parameters. Silt-size particles feel gritty between teeth and coarse grains can be seen with the naked eye. Sand-size

FIGURE 22—Stockpile of fine silt and clay removed from a Middle Rio Grande Conservancy District ditch, Corrales.

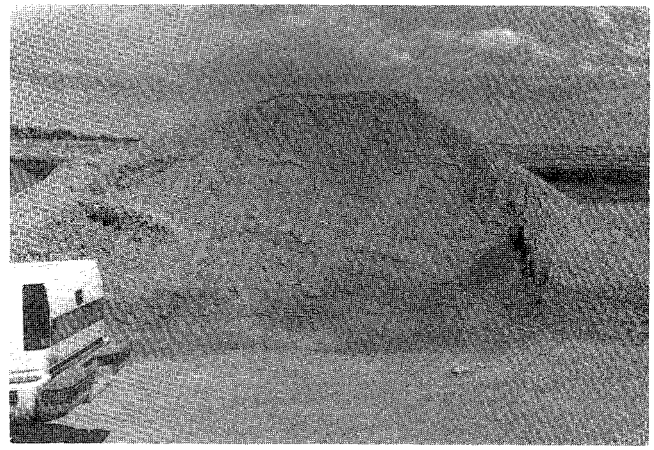


FIGURE 23—Crusher fines that are suitable for the construction of rammed-earth walls on property owned by Huston Construction Company, Edgewood.

particles are easily visible with the naked eye. The silt-sand dividing line in terms of U.S. Standard Sieve Mesh Numbers is mesh 230.

Silt- and sand-size particles can be thought of as bits of pre-existing rock. Although many different minerals make up silt- and sand-size particles, the most common are quartz (SiO_2) and feldspar (calcium, sodium, and potassium aluminosilicates). Quartz and feldspar are abundant in other rocks and are hard and chemically resistant. Clay minerals are also present in silt and sand, but in small amounts as the finest silt-size fragment or as indurated (hardened) aggregates of shale or mudstone, which have properties more akin to fragments of rock than to clay minerals or clay-size particles. The "sharpness" of aggregates and sand-size particles may increase the strength and reduce the quantity of binder material necessary to produce an acceptable adobe. Architect P. G. McHenry, Jr., (personal communication, 1988) says that the shape of sand-size particles in adobe soils is significant and that rounded particles, as found in "blow sand," need more clay-silt binder than other soils.

During this project, particle-size analyses of adobe soils have unearthed several new findings. First, all samples tested contain far more sand + -size particles than previously reported (Smith, 1982a). Typical adobe materials are 60–80%, and as high as 89%, sand + -size particles; 15–40%, but as low as 8% and as high as 68%, silt-size particles; and 4–11%, but as low as 1%, clay-size particles. Second, the particle-size analyses indicate that clay minerals cannot be the only, or perhaps even the chief, binding agent.

Smith (1982a) discussed the presence of calcite in the majority of adobe soils tested in 1980. The present investigation shows that calcite is present in the clay-size fraction in 99% of the samples tested. Calcite is not limited to clay size; it is present in the silt- and sand + -size fractions as well. However, the presence of calcite is more extensive than expected and its predominantly clay size indicates the calcite is undoubtedly of pedogenic or formed-in-the-soil origin.

Inorganic calcite as found in the Southwest is identified as caliche. Caliche can make or break the quality of an adobe soil. Recently deposited sediments have relatively dispersed, fibrous to powdery calcite as a common constituent. When these soils are wetted, the calcium carbonate is partly mobilized. When dried, the dissolved calcium carbonate deposited in pores binds particles together.

Processing adobe soils into a form with a hydraulic ram or a pressed-earth-block machine further binds particles together. Indeed, pressed-earth-block producers, particularly users of pressed-earth-block machines, state that caliche soils make the best pressed-earth block. However, caliche builds an impermeable barrier over relatively long time intervals. If the calichification process has proceeded to the point that the caliche is very hard and massive, then caliche acts as an aggregate, making particle mobilization and recrystallization difficult and binding insufficient for adobe soils.

Clay mineralogy

The clay-size (<2 μm or <0.002 mm) fraction of soil is made up of different minerals in varying proportions. The most abundant minerals in the clay-size fraction are clay minerals. Kaolinite, illite, smectite, chlorite, and vermiculite are the principal clay-mineral groups or types, each with their own chemical and physical properties. Nonclay minerals, such as quartz, feldspar, and calcite, may also be present.

Appendix 1 shows that the amount of clay minerals in adobe soils varies greatly and is less than previously considered (Smith, 1982a). Although the abundance of clay minerals is relatively low (1–15% of adobe soils sampled), the amount of the clay-size fraction in an adobe soil and the presence or absence of a particular clay-mineral group affect the physical properties of an adobe product. To understand the effect of one clay-mineral group relative to another in an adobe soil, it is necessary to understand the structures of clay minerals. Diagrams of the silicon-oxygen tetrahedron and aluminum-hydroxyl octahedron—the fundamental building blocks of most clay minerals—and the schematic representations of crystal structures of major clay-mineral types are illustrated in Fig. 24 (Harrison and Murray, 1964; Austin, 1975).

Four clay-mineral groups are commonly represented in the clay-size fraction of adobe soils in New Mexico: kaolinite, illite, smectite, and mixed-layer illite/smectite (Appendix 1; Fig. 24). The high-aluminum kaolinite and high-potassium illite generally make up about 50% of the clay minerals in the 41 samples tested. Both groups are nonexpandable; they will expand only slightly in the presence of water. The calcium- or sodium-rich smectite and mixed-layer illite/smectite (I/S) also make up about 50% of the clay minerals in the adobe soils analyzed. They are expandable and will swell in the presence of water. I/S is generally represented by interstratification of both illite and smectite layers. I/S will expand somewhat but not as much as pure smectite. Chlorite was found in only two samples, and vermiculite was not represented in this study.

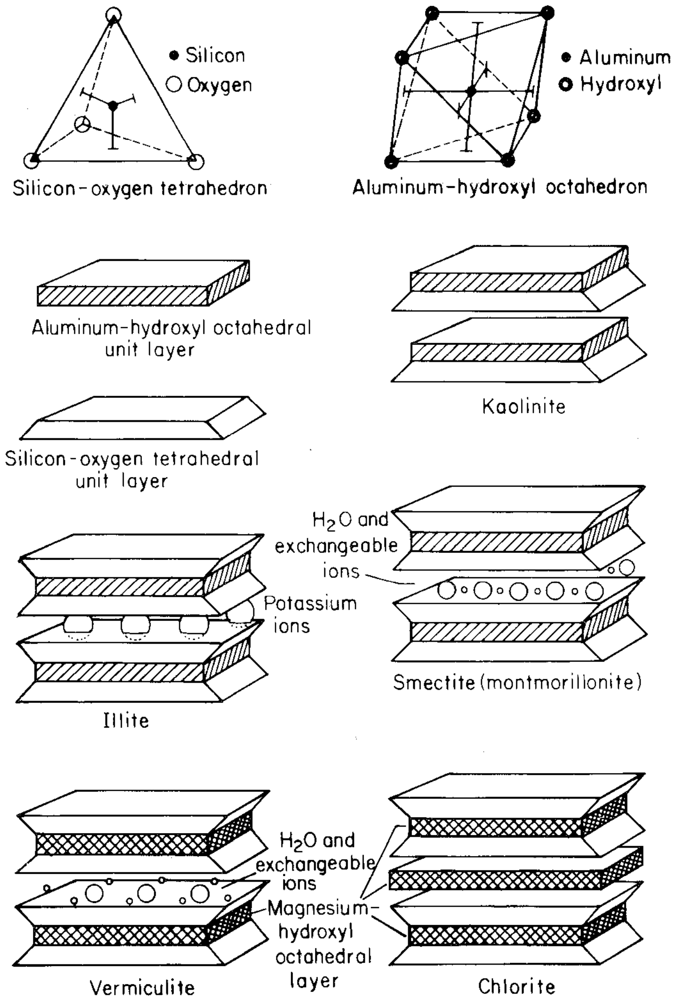


FIGURE 24—Diagrams of major clay-mineral types. The silicon-oxygen tetrahedron and the aluminum-hydroxyl octahedron are the fundamental building blocks of most clay minerals (modified from Harrison and Murray, 1964; Austin, 1975).

The proportions of expandable/nonexpandable clay minerals and the amount of the clay-size fraction in adobe soils help to control the quality of adobe bricks, pressed-earth blocks, and rammed-earth walls. Clay-size fractions high in expandable clay minerals relative to nonexpandable clay minerals increase the compressive strengths of adobe materials. That is, a soil with a small clay-size fraction high in smectite will make an adobe product as high in compressive strength as a soil with a larger clay-size fraction low in smectite. Generally, inclusion of expandable clay minerals (especially smectite and I/S groups) in an adobe soil results in greater compressive strength than inclusion of nonexpandable minerals; however, too much smectite in the soil may make a poor adobe product. In such soils, depending on the presence or absence of water, expansion and contraction of the smectite-rich clay may cause excessive cracks in the adobe product. More silt, sand, or straw can be added to the soil to dilute the effect of the expandable clay minerals.

Quemados (burnt adobe bricks) are similarly affected by the mineralogy of adobe soils. Moderate heat applied to a brick increases compressive strength. Although temperature is not closely controlled in quemado kilns, it is clear that clay minerals are responsible for the increased strength. A standard brick is normally heated to approximately 1,800°F or 1,000°C before incipient vitrification (melting) of the clay minerals occurs, binding more resistant aggregates together. However, if calcite is present in the brick, the calcium ion of calcite acts as a flux, lowering the incipient vitrification temperature as much as several hundred degrees.

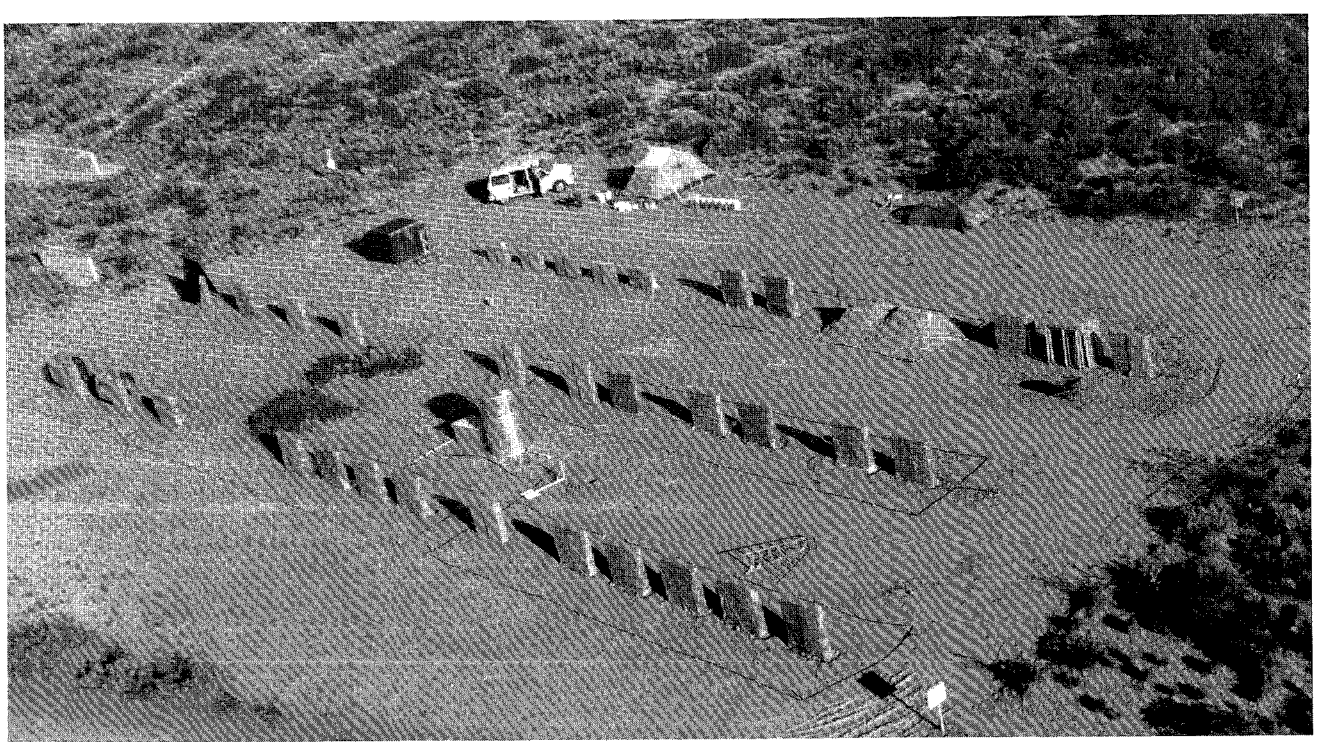


FIGURE 25—Adobe test walls, Fort Selden State Monument, May 1988.

Preservation of adobe structures

The deterioration of adobe walls at historical sites in New Mexico has spurred interest in improving conservation techniques. The best maintenance and repair strategy at present is to replaster weathering and crumbling ruins with like material, to cap walls with mud, and to build basal supports of untreated adobe bricks and mortar for unstable walls that have wasted at the base. These efforts, however, may be impractical for abandoned structures and are certainly costly. The Getty Conservation Institute (GCI), in collaboration with the New Mexico State Monuments, a unit of the Museum of New Mexico, has designed and is testing chemical and nonchemical treatments of deteriorating adobe structures to determine which preservation methods are most effective in the Southwest and throughout the world. The field testing is being carried out at Fort Selden State Monument, an abandoned mid–19th-century adobe fort near Las Cruces, New Mexico.

As part of the project, adobe test walls were constructed by the staff of the New Mexico State Monuments near the Fort Selden State Monument. The test walls were applied with various mixtures of mud plasters and preservatives, including commercial sprays, that have been used at other monuments in New Mexico, throughout the Southwest, or universally to protect adobe structures (Fig. 25). Other test walls were built and capped with cement, adobe brick, or fired brick, with and without drip edges. The bases of some test walls were constructed with different materials to determine the best type of foundation. Included in the experiments are historic and modern preservation techniques, some of which may actually accelerate the erosion of adobe structures (Taylor, 1987a, b).

Other conservation techniques that may minimally alter the historic fabric of a site are being tested by GCI. Simulated reburial under "nonwoven geotextiles" and the use of "aerotextile" shelters and "geotextile" drains are some of the tests that are being conducted to assess the protective efforts of reburying archaeological sites (Agnew and others, 1987; Taylor, 1987a).

For these experimental purposes, more than 50 adobe test walls have been constructed about 450 ft from Fort Selden State Monument. Some of the walls were allowed to cure and undergo weathering for several months before preservative plasters and sprays were applied (Fig. 26). To achieve rapid results, and to allow comparison of the various techniques together with that of natural exposure, a spray system to artificially accelerate the weathering of GCI adobe test walls is being used.

The project, begun in 1985 and due to be concluded in 1995, should give conservationists the best preservation methods to use for adobe structures in the Southwest. However, no testing of occupied dwellings and the effects on inhabitants are scheduled. The results are available in status reports from the New Mexico State Monuments, Museum of New Mexico, and will be presented in detail in Las Cruces, New Mexico, in October 1990 at the 6th International Meeting of Experts on the Conservation of Earthen Architecture.

FIGURE 26—Neville Agnew of the Queensland Museum, Australia, working in cooperation with the Getty Conservation Institute, is applying chemicals to adobe test walls at Fort Selden State Monument, May 1988.

Radon

The identification of radon gas as a potential health hazard in homes has prompted adobe homeowners to wonder whether they are exposed to greater danger than other homeowners. Concern about elevated indoor concentrations of radon first arose in the late 1960s when homes that had been built with aggregate from uranium tailings were found high in radon. Studies by the U.S. Environmental Protection Agency and the State of New Mexico Environmental Improvement Division showed that low concentrations of radon gas are naturally present in the atmosphere. High indoor radon levels may be caused by natural concentrations of uranium in the soil beneath houses as well as in adobe bricks. Although concentrations are known to exist in some particular soils and rock types, no area is free from the possible accumulation of radon.

Radon is a colorless, odorless, heavier-than-air radioactive gas that is derived directly from the breakdown of an isotope of radium, ^{126}Ra, one in a chain of radioactive daughter elements produced from the radioactive decay of the most abundant isotope of uranium, ^{238}U. The most stable of radon isotopes, ^{222}Rn, has a half-life of 3.8 days (Wilkening, 1980). The half-life is the time it takes one-half of the parent isotope to change to daughter products; the less stable the isotope, the shorter the half-life. Radon is extremely unstable so it decays to daughter products in a relatively short amount of time. Each time a radioactive element decays to daughter products, radiation in the form of particles is emitted. Whereas most radioactive elements are relatively immobile solids, radon is a mobile gas that can find its way into homes. If gaseous radon decays in air that is breathed, the fine-grain solid particles that are emitted can cause lung cancer. The combination of mobility, decay, and emission of fine-grain solid particles, which can become trapped in the respiratory tract, makes radon hazardous.

Few adobe homes have basements where radon can constantly move into the home; thus adobe homes may not have as great a radon problem as other homes. Most radon enters homes from soils through cracks in basements or slabs, drains, and other openings (Fig. 27). Devices such as clothes dryers, fireplaces, and furnaces that reduce air pressure within a home increase the amount of air (and radon) moving into the home by pulling the soil gas, which comes from the ground beneath the house, through openings into areas of lower air pressure.

Remedial actions to prevent the accumulation of radon in a home are relatively inexpensive (Green, 1988). The simplest way to prevent the accumulation of radon in a

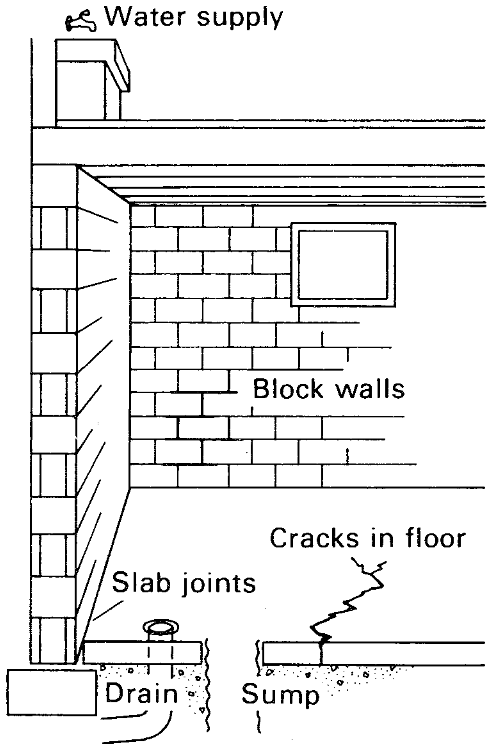


FIGURE 27—Common radon entry points.

home is to keep the home well ventilated. Positive air pressure in the home prevents radon from being pulled in from outside soils. In the summertime, positive air pressure is relatively easy to maintain in the home because evaporative coolers (swamp coolers) are in use; homes with refrigerated air conditioners require other methods. In the winter, a positive air pressure is more difficult to achieve because heat is kept in and the cold out. However, external sources of air for furnaces, fireplaces, and clothes dryers can cut down the movement of radon into the home during winter. Finally, keeping the adobe home in good repair by filling cracks and openings in concrete slabs, repairing cracks in walls, and sealing adobe blocks with plaster and paint, especially inside the house, greatly decreases the chance that gaseous radon will accumulate in the home.

The U.S. Environmental Protection Agency and the State of New Mexico Environmental Improvement Division can provide information about radon concentrations in homes. Although the results of most homes tested in New Mexico have located only a few problem areas, the State of New Mexico Environmental Improvement Division, Radiation Protection Bureau, continues to test homes upon request. Test canisters are also available from many drugstores.

Adobe construction in seismically active areas

Adobe structures are sometimes hazardous in seismically active areas because of the low-strength materials used; with heavy earthen roofs supported by low-strength walls, adobe structures can collapse during earthquakes. However, studies conducted at the Richmond Field Station of the University of California, Berkeley, on nearly full-size adobe structures (Scawthorn, 1986) showed that low-strength adobe structures can be strengthened with inexpensive methods to a point where adobe structures are no more hazardous in earthquakes than structures constructed with other commonly used building materials.

Tests were performed on structures built with walls of 4 x 12 x 16-inch unstabilized adobe blocks and mud mortar on a 20 x 20-ft Earthquake Simulator Laboratory shaking table. The first test structure contained a window opening and door with lintel beams and 4 x 6-inch wooden roof beams bolted into the top three adobe courses, which carried the weight of a simulated earthen roof. The second test structure was installed with a wooden bond beam (Fig. 28). Subsequent test structures were also constructed with a bond beam and walls were reinforced inside and out with welded wire mesh and stucco netting. As a result of the tests, structural improvements of adobe structures to reduce hazards related to earthquakes have been suggested (Tibbets, 1986):

(1) A simple wire enclosement of an adobe structure, inside and out, can be used to greatly strengthen adobe walls.
(2) Inexpensive stucco netting or chicken wire is equal, or nearly so, to more expensive welded wire mesh.
(3) New adobe structures commonly use stucco netting or chicken wire as a stucco attachment system nailed to outside walls at little additional cost. (The wire enclosure system used in the tests had wire both inside and outside the home anchored with $^{7}/8$-inch staples.)
(4) If wire mesh is not preferred, internal reinforcement must be designed and overlapping steel rebar, bent to curve around wall corners, can be used.
(5) Wooden or concrete bond beams (tie beams) are important in strengthening adobe structures and are required by the New Mexico Building Code to be a minimum of 6 inches thick. Thinner, well-reinforced bond beams perform better than massive, less well-reinforced ones because of the need for horizontal and vertical flex.
(6) Buttresses at certain points on walls can add additional strength. Although not required by the New Mexico Building Code for adobe and pressed-earth construction, such strengthening structures will nonetheless provide increased safety and peace of mind, which can be translated into financial benefit at resale time.

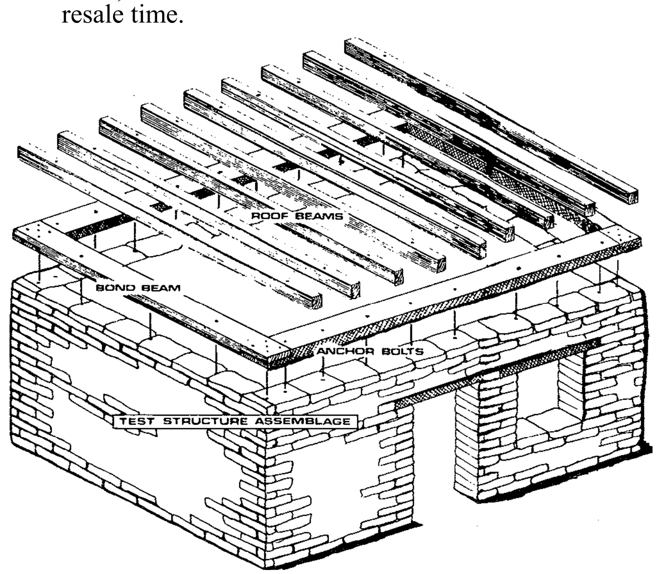


FIGURE 28—Nearly full-size adobe structure that was tested for strength during a simulated earthquake (from Tibbets, 1986).

Thermal properties

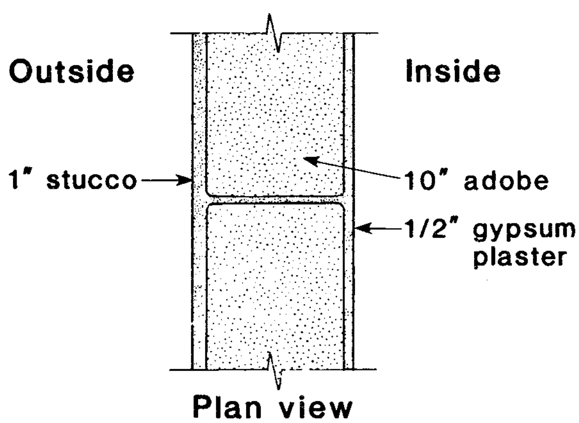
In New Mexico, thermal specifications for building materials are covered in the 1988 New Mexico Energy Conservation Code as adopted from the Uniform Building Code and the New Mexico Building Code. Portions of the New Mexico Building Code relating to adobe appear in Appendix 3.

Traditionally, materials are evaluated for thermal performance based on measurements known as R- and U-values. The R-value is an indicator of the ability of a wall to insulate effectively. Insulation is nothing more than the resistance of a material to the transfer of heat, and naturally the higher that resistance, or R-value, the more the material insulates. The R-value is calculated by dividing the thickness of the wall by the wall's thermal conductivity, the amount of heat per ft^2/hr flowing from the hotter to the cooler side of the wall. The U-value, sometimes referred to as the value of conductance, is the reciprocal of the R-value and reflects the rate at which heat is conducted through a material. Total R-value may be calculated for a given wall by adding up the sum of the values of each of the individual components of the wall structure; for example, all insulation, interior sheathing, framing, air-space resistance, or masonry must be taken into consideration.

R- and U-values do not, however, tell the full story in determining what constitutes a high-quality, thermally efficient wall (Fine, 1976). Both of these values reflect the rate at which heat passes through a wall only after the steady state of heat flow (the state when heat energy is passing uninterrupted from one side of the wall to the other at a constant rate) has been achieved. What is not taken into consideration, and what is of critical importance in the case of masonry-mass walls such as adobe, is the heat storage capacity of the wall, which determines the length of time that passes before a steady state of heat flow is achieved. The higher the heat storage capacity of the wall, the longer period of time it will take for heat flow to reach a steady state. In real situations, external and internal temperatures are changing constantly so that a true steady-state condition is rarely achieved. What does occur, in the case of a wall with a high-heat storage capacity such as adobe, is outlined below.

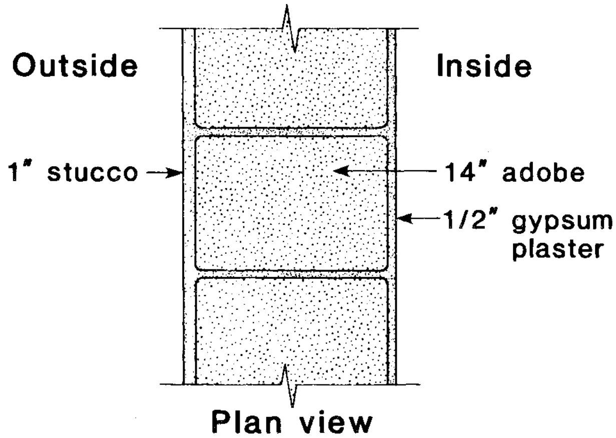
In the morning, when the sun rises, heat from the warmer, exterior side of the wall begins to move through the adobe mass. Depending not only on the resistance (R-value) of adobe, but also on the heat storage capacity of the wall (a factor both of the specific heat capacity of adobe and the thickness of the wall), the heat takes a certain length of time to reach the cooler, interior side of the wall where the heat is released into the atmosphere. In adobe walls of sufficient thickness and of sufficient R-values (perhaps supplemented by other insulation), the normal daily fluctuations of temperature never allow much heat to pass through the wall at a steady state. At night, when the warmer side of the wall drops in temperature, heat already absorbed into the adobe wall continues to flow, not just in one direction, but to both sides of the wall until a temperature equilibrium has been reached. This cycle is repeated in what is known as the flywheel effect and is responsible for the comfort well known to those who inhabit properly designed adobe homes.

Thermal properties of masonry materials in general, and adobe in particular, have often been unjustly maligned because only R-values and steady-state U-values were considered when evaluating thermal performance. For mass materials such as adobe, a more accurate representation of average thermal performance than R-values and steady-state U-values is given by what is known as the effective U-value (Figs. 29A, 29B). This value is determined as a factor both of the resistance of a wall to the transfer of heat and of its capacity to hold heat. The inside wall temperature approximates the average of the high/low ambient exterior temperatures and the time delay affected by the thickness of the wall. Therefore, in actual home use, optimum comfort may be achieved by a mass wall with a moderate R-value and high-heat storage capacity (adobe with a small amount of insulation), as well as by a highly resistant wall with little or no heat storage capacity (traditionally highly insulated frame wall).



Wall type 1	ASHRAE steady-state U-value: 0.240			BTU / $ft^2 \cdot hr \cdot °F$
Heating effective U-value				
Wall orientation / Wall color	Climatic region 1	2	3	4
East — light	0.226	0.217	0.222	0.211
East — medium	0.194	0.176	0.178	0.158
East — dark	0.161	0.135	0.133	0.106
South — light	0.218	0.208	0.206	0.197
South — medium	0.174	0.152	0.136	0.123
South — dark	0.131	0.096	0.067	0.050
West — light	0.232	0.224	0.229	0.218
West — medium	0.208	0.193	0.194	0.178
West — dark	0.185	0.162	0.160	0.137
North — light	0.238	0.234	0.241	0.231
North — medium	0.223	0.217	0.224	0.210
North — dark	0.208	0.201	0.207	0.188

FIGURE 29A—Effective U-values for different orientations and colors of a 10-inch adobe wall in the four climatic regions of New Mexico (from Robertson, 1981). Climatic regions determined by solar radiation, dry-bulb temperature, and wind velocity. Low-number climatic regions (regions 1 and 2) tend to be rugged areas of high elevation, whereas high-number climatic regions (regions 3 and 4) tend to be desert areas of low elevation. Note generally higher ASHRAE steady-state U-value of 0.240.



Wall type 2	ASHRAE steady-state U-value: 0.189	BTU / ft²·hr·°F			
Heating effective U-value					
Wall orientation	Wall color	Climatic region 1	2	3	4
East	light	0.181	0.174	0.178	0.168
	medium	0.155	0.141	0.142	0.126
	dark	0.129	0.108	0.106	0.084
South	light	0.175	0.166	0.165	0.157
	medium	0.140	0.122	0.109	0.098
	dark	0.105	0.077	0.063	0.040
West	light	0.186	0.179	0.183	0.174
	medium	0.167	0.155	0.155	0.142
	dark	0.148	0.130	0.128	0.109
North	light	0.191	0.187	0.193	0.185
	medium	0.179	0.174	0.179	0.167
	dark	0.167	0.161	0.165	0.150

FIGURE 29B—Effective U-values for different orientations and colors of a 14-inch adobe wall in the four climatic regions of New Mexico (from Robertson, 1981). Climatic regions determined by solar radiation, dry-bulb temperature, and wind velocity. Low-number climatic regions (regions 1 and 2) tend to be rugged areas of high elevation, whereas high-number climatic regions (regions 3 and 4) tend to be desert areas of low elevation. Note generally higher ASHRAE steady-state U-value of 0.189.

The New Mexico Energy Research and Development Institute has determined effective U-values for many different wall types (including adobe), which have been incorporated into the New Mexico Energy Conservation Code for building materials. The effective U-values may be used in lieu of traditional R-values and steady-state U-values for cases where a design relying primarily on passive solar gain and masonry-mass materials will not normally pass code standards (Robertson, 1981). The State of New Mexico has prepared information that details the method of calculating effective U-values for the climatic zones in the state (Scheuch and Busch, 1988).

Adobe-brick production

Adobe-brick production varies from a labor-intensive, traditional hoe-shovel-and-wheelbarrow technique to a mechanized large-scale operation capable of producing 5,000—20,000 bricks per day. The production of adobe bricks is seasonal and is usually limited by the number of available frost-free days for a particular adobe yard. In general, the production season lasts from five to nine months, depending on climate and weather conditions.

The bricks are made in various sizes according to their intended use. The principal standard-size adobe brick used in the state measures 4 x 10 x 14 inches. An average of 1 yard' of adobe soil is used to produce approximately 70—80 standard-size bricks. In 1987, 29 adobe-brick manufacturers produced 3,124,000 bricks (Table 4): 849,000 traditional (untreated) bricks, 2,110,000 semistabilized bricks, and 165,000 stabilized bricks. The bricks were produced by three different methods: the handcrafted (traditional), semimechanized, and mechanized techniques. The adobe-making procedures used by producers representative of each technique are described below.

Handcrafted (traditional) technique

The handcrafted technique was used by 15 adobe-brick producers visited in 1988, of whom 11 produced only 252,000 traditional (untreated) adobe bricks in 1987. This figure does not represent the total production of handcrafted traditional (untreated) adobe bricks in the state; bricks handcrafted for noncommercial use by individuals for their own construction projects were not included in the survey. Daily production rates of handcrafted bricks varied considerably. One-person commercial adobe yards produced 100—300 bricks per day, whereas commercial adobe yards utilizing two or three adobe makers produced 300—500 bricks per day. Prices for adobe bricks at the adobe yards varied from 21 to 400 per brick.

Eloy Montano Sand & Gravel (Santa Fe)

Eloy Montano Sand & Gravel, located by the airport road in the southwest (Agua Fria) section of Santa Fe, is a typical adobe yard that uses the traditional (handcrafted) method of production. The adobe yard produced 140,000 traditional (untreated) adobe bricks in 1987. Workers at the adobe yard excavate soil for the adobe bricks from nearby federal land leased through the Bureau of Land Management (BLM) and stockpile the material adjacent to a mudpit.

With two or three employees, Eloy Montano Sand & Gravel makes adobe bricks as follows:

(1) The adobe soil from the stockpile is used to build a mudpit into which is placed the adobe soil and water. The soil and water are mixed by hoe and shovel until the proper adobe-mud mixture has formed. Depending upon the type of soil used, straw is usually added to prevent the adobe bricks from cracking excessively.

(2) The prepared adobe mud is shoveled into a wheelbarrow and is delivered to several four-mold wooden forms that have been laid out on the leveled ground of the adobe yard. The mud is then dumped into the molding forms, tamped by hand into the corners, and

TABLE 4—Commercial adobe-brick producers active in New Mexico in 1988. For locations see Fig. 1A. NA, not available.

Map no. (Fig. 1A)	Name and mailing address	Telephone	County	Approximate annual production (1987)	Production equipment
1	A. D. Adobe Co. Box 489 Santa Cruz, NM 87567 Audelio Romero, Owner	753-9377	Rio Arriba (yard) Santa Fe (home)	40,000	Transit cement mixer, front-end loader, ladder forms, and delivery truck
2	Adobe Bricks of New Mexico Box 733 Santa Cruz, NM 87567 Dennis Duran, Owner	753-6189	Santa Fe	150,000	Front-end loader, ready-mix truck, self-propelled adobe layer, and delivery trucks
3	Aguires Services P.O. Box 475 Ranchos de Taos, NM 87557 Ismael Aguires, Owner	758-9181	Taos	10,000	Wheelbarrows, wooden forms, and shovels
4	Juan Aragon, Contractor General Delivery Aragon, NM 87820	533-6411	Catron	0	Backhoe, wooden forms, grader, and dump truck
5	Big "M" Sand & Cinder Box 33 Bernalillo, NM 87004 Randy Montoya, Owner	867-5498	Sandoval	60,000	Front-end loaders, pugmill, aluminum forms, and delivery trucks
6	Corrections Industries State of New Mexico 1422 Paseo de Peralta Santa Fe, NM 87501 James C. Leopold, Director	827-8670	Santa Fe	Santa Fe (6a): 1988: 180,000 Los Lunas (6b): 1987: 180,000 Las Cruces (6c): 1988:180, 000	Wooden forms, front-end loaders, mixing hods, shovels, hoes, and dump-and-water truck
7	DeLaO Adobe Brick Mfg. 300 Warthen Rd. Anthony, NM 88021 Antonio DeLaO, Owner	882-5278	Doña Ana	70,000	Backhoe, pugmill, front-end loader, wooden forms, and delivery truck
8	Eloy Montano Sand & Gravel 14 Calle Chuparosa Santa Fe, NM 87505 Eloy Montano, Owner	471-4747	Santa Fe	140,000	Hoes, shovels, wheelbarrows, front-end loader, wooden forms, and delivery truck
9	Gallegos Sand & Gravel Rt. 6, Box 212 Santa Fe, NM 87501 Abe Gallegos, Owner	471-8579	Santa Fe	3,000	Front-end loader, wooden ladder forms, and delivery truck
10	Paul Martinez Rt. 3, Box 197 Ranchos de Taos, NM 87557	758-8280	Taos	0 1988: 10,000	Wooden forms, wheelbarrows, and shovels
11	Medina's Adobe Factory Box 651 Alcalde, NM 87511 Mel Medina, Owner	852-4131	Rio Arriba	500,000	Front-end loader, pugmill, Hans Sumpf—type mechanical adobe layer, and delivery trucks
12	Ralph Mondragon Box 199 Ranchos de Taos, NM 87557	758-3644	Taos	2,000	Wooden forms, hoes, shovel, and mud pickup
13	National Park Service 1220 S. St. Francis Dr. Santa Fe, NM 87501 Terry Morgart, Project Leader	988-6730 988-6796	Santa Fe	2,000 Pecos (13a) Fort Union (13b) (stabilized, untreated, and half adobes)	Wooden forms, hoes, shovels, and wheelbarrows
14	New Mexico Earth P.O. Box 10506 Alameda, NM 87184 Richard Levine, Owner	898-1271	Bernalillo	600,000	Front-end loaders, pugmill, wooden ladder forms, and delivery trucks
15	Otero Brothers Rt. 2, Box 774 Los Lunas, NM 87031	864-4054	Valencia	40,000	Front-end loader, wooden ladder forms, and delivery truck
16	Picuris Pueblo Box 127 Peñasco, NM 87553	587-2519	Taos	15,000	Front-end loader, wooden forms, and delivery truck

TABLE 4 (continued)

Map no. (Fig. 1A)	Name and mailing address	Telephone	County	Approximate annual production (1987)	Production equipment
17	Pueblo of Isleta Adobe and Cinder Enterprise Box 500 Isleta, NM 87022 Dave Harris, Manager	869-6433	Bernalillo	60,000	Front-end loader, pugmill, Hans Sumpf—type adobe layer, and delivery truck
18	Rio Abajo Adobe Works 105 W. Aragon Belen, NM 87002 Jerry Sanchez, Owner	864-6191	Valencia	250,000	Front-end loader, wooden ladder forms, and delivery truck
19	Archie Rivera Box 425 Santa Fe, NM 87501	983-1930	Santa Fe	0 1988: 10,000	Steel forms, wheelbarrows, and shovels
20	Jim Rivera Rt. 1, Box 4 Glorieta, NM 87505	471-1380	Santa Fe	14,000	Front-end loader, wooden forms, and shovels
21	Rodriguez Brothers Rt. 6, Box 22 Santa Fe, NM 87501 George and Jim Rodriguez, Owners	471-7570	Santa Fe	150,000	Front-end loader, wooden forms, and shovels
22	Steve Romero 200 Camino Rio Santa Fe, NM 87501	983-1304	Santa Fe	35,000	Wooden forms, hoes, shovel, and wheelbarrows
23	Manuel Ruiz Box 104 Corrales, NM 87048	898-2218	Sandoval	150,000	Front-end loader, wooden forms, and delivery truck
24	Ernest Sanchez 6000 Powers Way SW Albuquerque, NM 87105	873-1065	Bernalillo	20,000	Front-end loader, wooden forms, and delivery truck
25	Henry C. Sandoval Box 383 Ranchos de Taos, NM 87557	758-3836	Taos	10,000	Wooden forms, hoes, shovel, and wheelbarrows
26	Roman Sandoval Box 423 Ranchos de Taos, NM 87557	758-3856	Taos	5,000	Wooden forms, hoes, shovel, and delivery truck
27	Candelario Saucedo P.O. Box 1572 Socorro, NM 87801	NA	Socorro	NA	Wooden forms, shovels, and wheelbarrows
28	The Adobe Patch Rt. 1, Box 240 Alamogordo, NM 88310 Robert and Christina Duran Godby, Owners	437-9932	Otero	165,000	Front-end loader, transit mixer, mechanical adobe layer, forklifts, and delivery truck
29	Tim's Adobes Box 1534 Bernalillo, NM 87004 Tim Montoya, Owner	867-4847	Sandoval	60,000	Front-end loader, wooden forms, and dump and delivery trucks
30	Sabino R. Varela Rt. 2, Box 57 Pecos, NM 87552	757-6252	San Miguel	5,000	Wooden forms, shovels, and delivery truck
31	Elias Vargas Lower Ranchitos Rd. Taos, NM 87571	758-2489	Taos	8,000	Transit cement mixer, wooden ladder forms, and front-end loader
32	Trini Velarde Box 726 Ranchos de Taos, NM 87557	758-4185	Taos	30,000	Transit cement mixer, front-end loader, wooden forms, and delivery truck
33	Western Adobe 7800 Tower Rd. SW Albuquerque, NM 87105 Dean Leach, Owner	836-1839	Bernalillo	350,000	Front-end loader, pugmill, Hans Sumpf—type mechanical adobe layer, and delivery trucks

FIGURE 30—Packing the adobe mud into a four-mold wooden form. Eloy Montano Sand & Gravel adobe yard, Santa Fe.

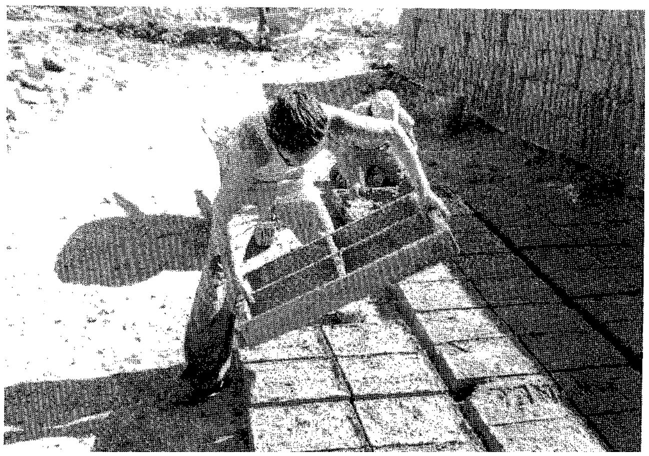


FIGURE 31—Lifting the four-mold wooden form to permit the adobe bricks to dry for two or three days before they are turned on edge. Eloy Montano Sand & Gravel adobe yard, Santa Fe.

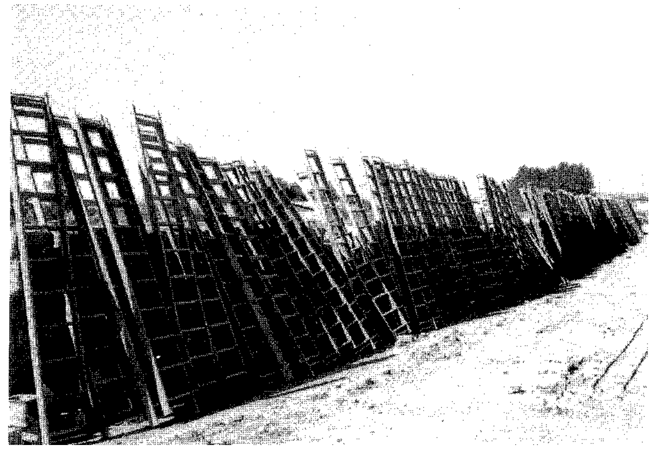


FIGURE 32—Stacked adobe bricks and ladder molding forms. New Mexico Earth adobe yard, Alameda.

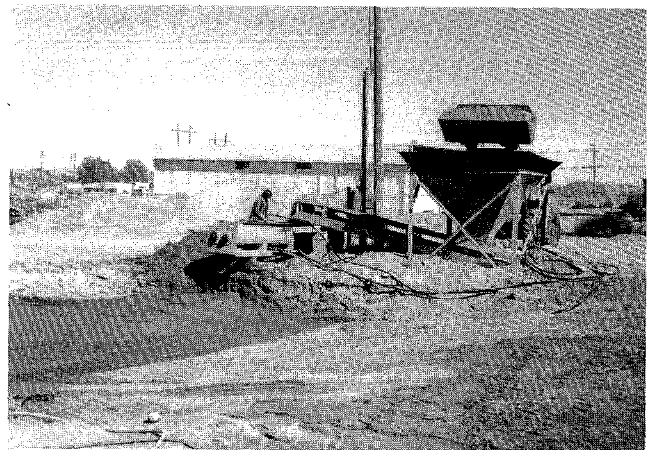


FIGURE 33—Front-end loader placing soil mixture into pugmill, where the adobe mud is mixed and then dumped into the mudpit by the conveyer system. New Mexico Earth adobe yard, Alameda.

brushed clean of excess material (Fig. 30).

(3) The molding forms are removed by hand, with care taken to retain the shape of the four adobe bricks, and the excess mud is washed from the forms prior to replacing them on the level ground (Fig. 31).

(4) After two or three days of drying, the bricks are turned on edge and are trimmed of excess material and any rough edges. The bricks are then allowed to sun cure for three to four weeks before they are stacked for delivery.

Semimechanized technique

The semimechanized method of adobe-brick production is similar to the traditional handcrafted method except that front-end loaders and mixing equipment—pugmills, plaster mixers, and cement mixers—are usually used. The semimechanized method is also the lowest capital-investment (equipment) type of operation capable of large-scale adobe-brick production. Adobe-brick producers using the semimechanized method can make 1,000,000 or more bricks per year.

In 1988, 14 adobe-brick producers were found who manufactured 1,797,000 adobe bricks (traditional (untreated), semistabilized, and stabilized) in 1987 using the semimechanized method. Their annual production totals varied from 3,000 to 600,000 adobe bricks, the majority of which were of the standard 4 x 10 x 14-inch size and were semistabilized. Prices for semistabilized bricks varied from 30 to 35¢ per brick at the adobe yard. Three different and representative examples of the semimechanized method of production are described below.

New Mexico Earth (Alameda)

The largest producer of adobe bricks in the state is New Mexico Earth, a company established in 1972 and managed by Richard Levine of Alameda, New Mexico. The operation is located on four acres in Alameda on the north side of Albuquerque, where over 600,000 adobe bricks were produced in 1987. The adobe site has an average elevation of 4,800 ft and a semiarid climate. The average annual rainfall is 10–14 inches and the mean annual temperature is 57°F. The adobe season usually extends from March through November and normally has a frost-free period of 203 days.

Equipment at the adobe yard includes two front-end loaders, a pugmill, a storage and conveyer system, and 700–800 ten-mold wooden ladder forms (Fig. 32). The adobe soil is obtained from a local sand and gravel operation, where the overburden (15–30 ft) of the alluvial piedmont plain and Quaternary terrace deposits from the Albuquerque Basin are mined. The sandy loam is typical of the material used by the majority of Rio Grande valley adobe producers.

The method used by the company for the large-scale production of adobe bricks is as follows:

(1) The soil, perhaps sand as well, is delivered to the adobe yard and stockpiled adjacent to the hopper. The material is moved from the stockpile by a front-end loader (1-yard^3 capacity) and placed into the 8 x 8-ft pugmill hopper (Fig. 33).

FIGURE 34—Front-end loader working the mudpit. Note conveyer system from pugmill on the right. New Mexico Earth adobe yard, Alameda.

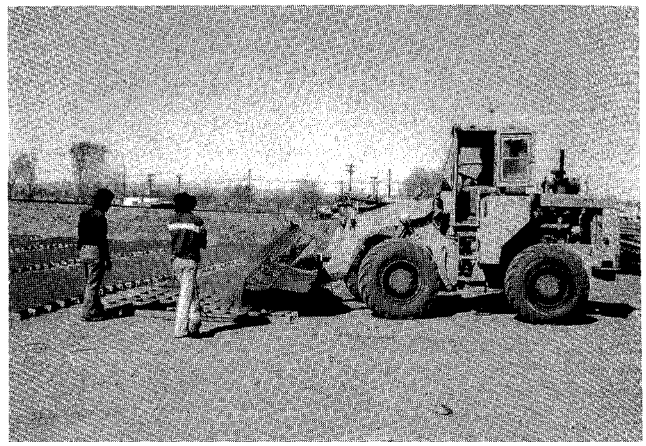


FIGURE 35—Front-end loader dumping the adobe mud into the ladder molding forms. New Mexico Earth adobe yard, Alameda.

(2) The soil mixture, water, and asphalt emulsion are added simultaneously in the pugmill. Two shafts studded with paddles rotate in the trough of the pugmill and continuously mix the adobe material as the mud works its way to the open end of the trough. The mud drops into a large mudpit (30 x 80 ft), and a front-end loader removes and carries the mud to the adobe-laying yard (Fig. 34).

(3) Located in the leveled adobe yard are usually 500—600 ten-mold wooden forms. The adobe mud is dumped into the forms and then raked and leveled (Fig. 35). The newly laid bricks are allowed to dry for several hours or until they have started to shrink from the form sides. The molding forms are then lifted and moved to a new area.

(4) The adobe bricks are allowed to sun dry for two or three days, after which time they are turned on edge, trimmed, and remain in the adobe yard for delivery or are stacked to cure. This operation, with a crew of 8—10 employees, produces an average of 5,000—6,000 adobe bricks per day, and, with available yard space, the daily production total can double.

(5) The delivery system at New Mexico Earth consists of several 2½-ton flatbed trucks with a local delivery capability of approximately 5,000 adobe bricks per day. The number of trucks requires a shop mechanic and dispatcher to coordinate the schedules. An effective delivery system is essential to maintain the company's production goals because the four-acre adobe yard can only hold a maximum of 65,000 bricks.

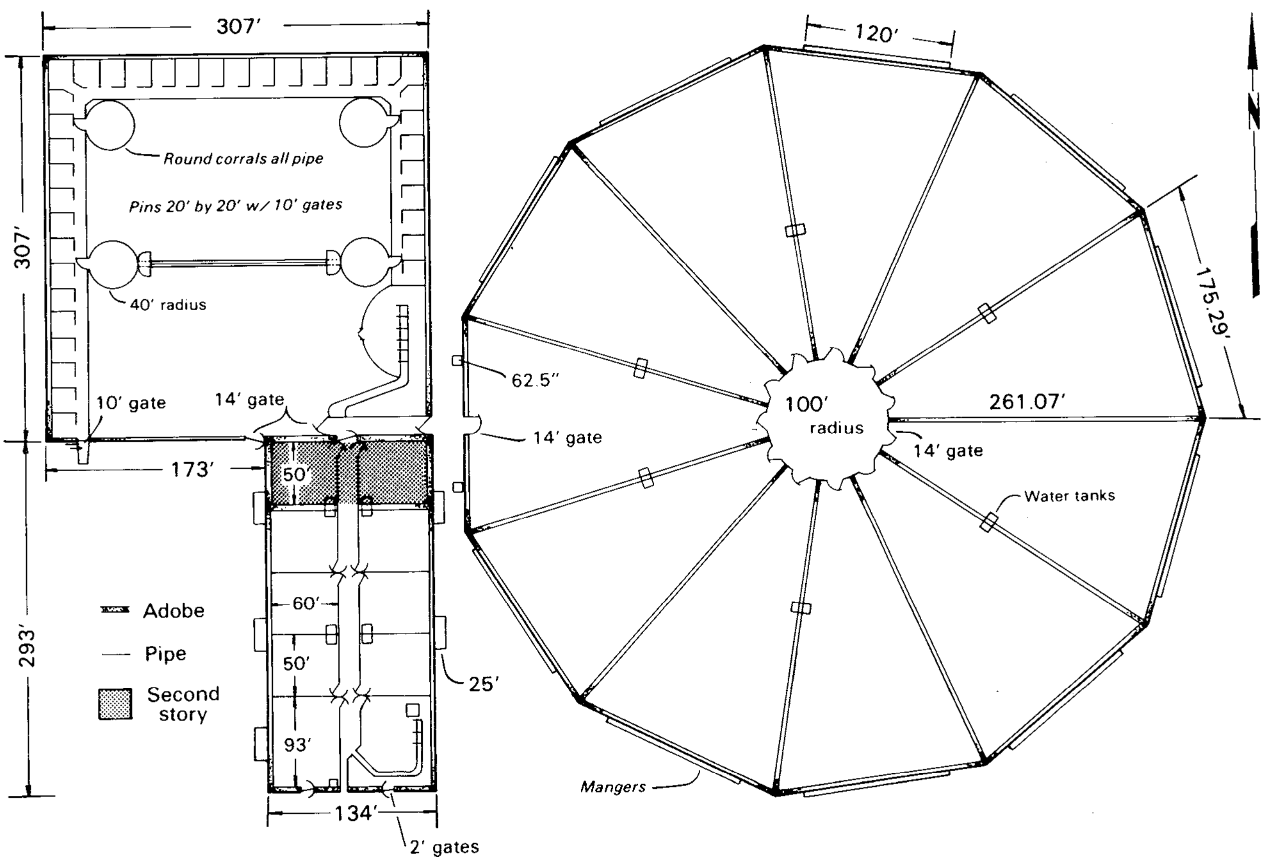


FIGURE 36—Drawing of the wild-horse corrals on NM–14 near Santa Fe. Adobe Corrals Project, Corrections Industries, Santa Fe.

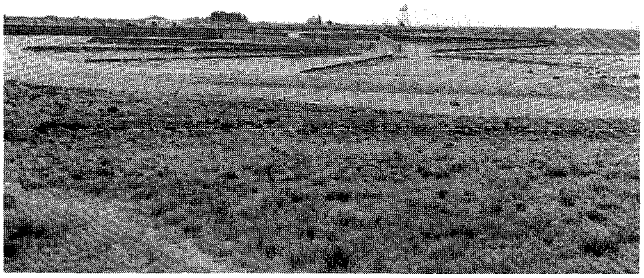


FIGURE 37—View of the wild-horse corrals under construction during the summer of 1988. The walls are 7 ft high, 261 ft long, and 16 inches thick. Adobe Corrals Project, Corrections Industries, Santa Fe.

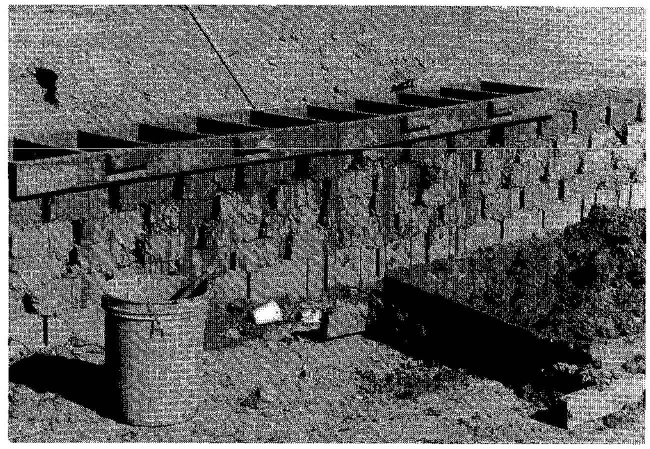


FIGURE 38—Close-up of an adobe corral wall under construction. Adobe Corrals Project, Corrections Industries, Santa Fe.

Adobe Corrals Project, Corrections Industries (Santa Fe)

In July 1987, a unique adobe operation, the Adobe Corrals Project, was initiated by the State of New Mexico Corrections Industries. Funded by the State of New Mexico Corrections Industries, the project manufactures and uses adobe bricks to construct stables for wild horses. At the medium-security correctional facility near Los Lunas, New Mexico, nine corrals and holding pens were built by 60 inmates in 1987. An estimated 180,000 adobe bricks were produced and used to construct the corrals and pens. In the spring and summer of 1988, more stables were under construction at the Las Cruces and Santa Fe correctional facilities.

At the Santa Fe site 12 miles south of Santa Fe on the west side of NM—14, the ten corrals under construction (Fig. 36) were being bound by adobe walls 7 ft high, 261 ft long, and 16 inches thick (Fig. 37). Lloyd McClendon (production manager), Don Timberman, and David Falance of the Corrections Industries were supervising the eight crews of four inmates, who worked on assigned sections of the corrals and pens.

Mechanized equipment at the site includes two front-end loaders and a combination dump-and-water truck. The soil used to make the adobe bricks is obtained from the building site by land leveling. The native vegetation is scraped from the surface and the upper 2—10 inches of soil are removed and stockpiled.

In general, the following production procedure is used by the local construction crews:

(1) Sand (used as a stabilizer to prevent cracking of the adobes) is delivered to the building site and stockpiled by each corral wall under construction. Initially, adobe soil was moved by a front-end loader from its stockpile to a mudpit, where the front-end loader mixed the soil and then delivered it to a mixing hod located adjacent to the walls under construction. However, crews now use hoes and shovels to mix the sand and soil (at a rate of one shovelful of sand to eight shovelfuls of soil) directly into the mixing hod, where water and a drying/hardening agent, XLR-8, are added (Fig. 38).

(2) The adobe-mud mixture is shoveled from the mixing hod into a five-mold wooden form that has been set on a wall. The five-mold wooden form measures 4 x 18 x 57½ inches and produces five 4 x 10 x $15^1/2$-inch bricks. Usually two wooden forms are assigned to each crew so that ten adobe bricks are made before the forms are lifted and moved further along the wall (Fig. 39). No mud mortar is used because the placement of the wooden forms and the moisture content of the adobe material allow the bricks to bond and interblock with the lower bricks, which have been drying for several hours (Fig. 40).

FIGURE 39—Two five-mold wooden forms set on corral wall under construction and ready for filling. Adobe Corrals Project, Corrections Industries, Santa Fe.

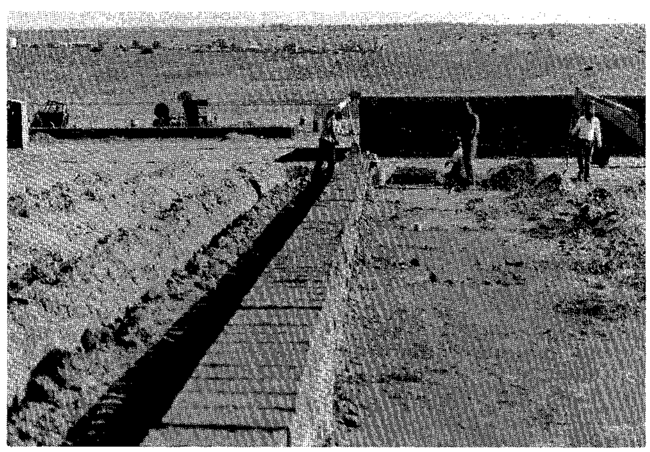


FIGURE 40—Packing adobe mud into the five-mold wooden forms to produce bricks directly on the wall. Adobe Corrals Project, Corrections Industries, Santa Fe.

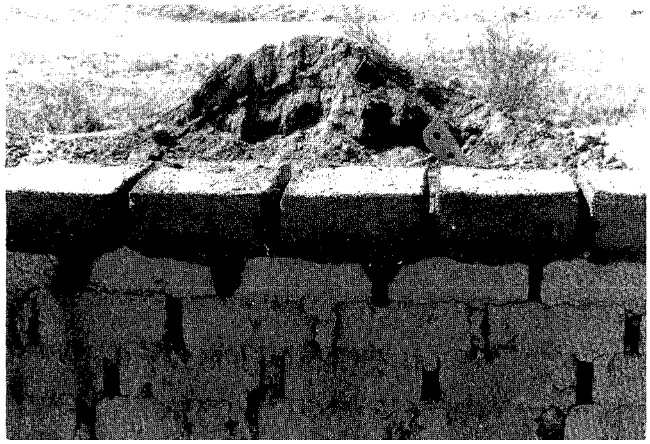


FIGURE 41—Close-up of adobe bricks after removal of five-mold wooden form. Note interlocking of bricks and lack of mortar (unlike normal sun-dried adobe-brick construction). Adobe Corrals Project, Corrections Industries, Santa Fe.

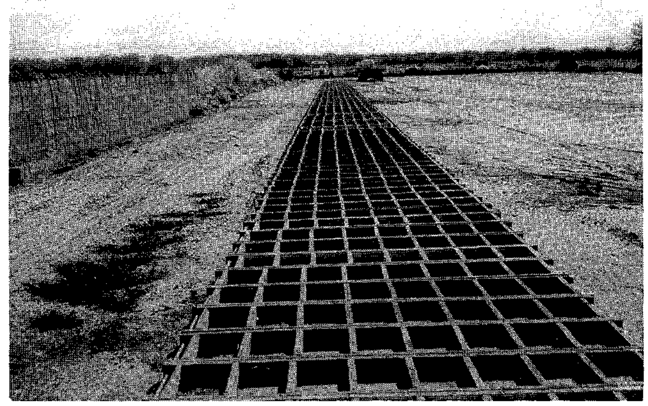


FIGURE 42—Ladder molding forms ready for filling. Rio Abajo Adobe works adobe yard, Belen.

(3) The forms, after removal from the wall, are brushed by wet brooms and reset for the next set of adobe bricks. This process continues until three wall courses have been completed and permitted to dry.

(4) After the two to three courses of adobe bricks have been allowed to dry for several hours, the next series of courses is ready for construction. Upon completion of each wall to its full length and height, the crews wire the walls with commercial stucco netting and add a cement and stucco coat for final finish and protection of the adobe bricks.

According to the Corrections Industries officials, David Salazar of Santa Fe, New Mexico, developed the technique of adobe-brick production and wall construction used at the corral sites. The formula that quickly dries and hardens the adobes (identified as XLR-8) was developed by chemist Kenneth Salazar. The system permits the adobe bricks to be produced directly on the wall and eliminates the need for the traditional method of sun drying the bricks in an adobe yard. The technique can be compared with that used to make rammed-earth buildings except that the adobe soil is not mechanically tamped in the corral-wall forms (Fig. 41).

Bricks produced by David Salazar were delivered in March and April 1988 to the United Nuclear Rock Mechanics Laboratory, New Mexico Institute of Mining and Technology. Test results indicated that the soil consisted of 5% clay-, 36% silt-, and 59% sand + -size particles. The mineralogy of the clay-size fraction was three parts mixed-layer I/S, three parts illite, two parts kaolinite, and two parts calcium smectite, plus minor calcite and quartz. The traditional (untreated) adobe bricks, which were dried and hardened with the XLR-8 formula, had a compressive strength of 499—621 psi for a mean of 525 psi. The modulus of rupture was 55—76 psi for a mean of 61 psi.

Rio Abajo Adobe Works (Belen)

An outstanding and well-organized adobe operation observed during this study is the Rio Abajo Adobe works, owned by Jerry Sanchez of Belen, New Mexico. The operation is located on three acres, where over 250,000 semi-stabilized adobe bricks were produced in 1987. The company also produces fully stabilized adobe bricks on special order. All adobe bricks are 3½ x 10 x 14 inches in size. The adobe-yard site has an average elevation of 4,700 ft and a semiarid climate. The average annual rainfall is 10 inches and the average annual temperature is 57°F. The adobe season usually extends from March through November and normally has a frost-free period of 200 days.

Equipment in the adobe yard includes a 2-yard^3-capacity Michigan Model 75 front-end loader, 200 eight-mold wooden forms (Fig. 42), a portable mud vat, a portable oil tank, and a 2½-ton flatbed truck. The adobe soil is taken from nearby Quaternary terrace deposits and Santa Fe Group (Tertiary) sediments and is hauled to the adobe yard, where the soil is stockpiled adjacent to the irrigation ditch and mudpit. The sandy loam and clay soil is typical of the adobe material used by most Rio Grande producers.

The method used by Sanchez and a crew of two or three employees for the large-scale production of adobe bricks is detailed as follows:

(1) The sandy loam and clay are removed by the front-end loader from the soil stockpile and are blended in a large mudpit that measures approximately 30 x 65 ft and slopes to a maximum 3-ft depth at one end. Water from an adjacent irrigation ditch is added to the adobe soil (8 yards^3), which is then allowed to soak overnight in order to break down the clay mixture. A measured amount of asphalt emulsion (33 gal) is added to the adobe mud, which is worked by the front-end loader in the pit until a uniform mixture is achieved.

(2) The adobe mud is removed from the pit by the front-end loader and is delivered to the adobe-laying yard where oil-sprayed wooden molding forms have been placed next to each other. The mud is poured into the molding forms and the excess material is raked and leveled (Fig. 43). The adobe bricks are allowed to dry in the molding forms for several hours, depending on the weather. When the adobe bricks have shrunk from the form sides, the forms are lifted and moved to an adjacent location for the next pouring of adobe mud.

(3) The bricks are allowed to dry for two or three days, at which time they are turned on edge, trimmed, and later, after drying for two to three weeks, are stacked ready for delivery. This method of production with a crew of two or three employees is capable of producing 1,500—3,000 adobe bricks per day.

(4) In addition to the adobe-brick delivery system using a 2½-ton flatbed truck, Sanchez has designed and constructed a portable mud vat that is mounted on

FIGURE 43—Pouring and raking the adobe-mud slurry into the ladder molding forms. Rio Abajo Adobe works adobe yard, Belen.

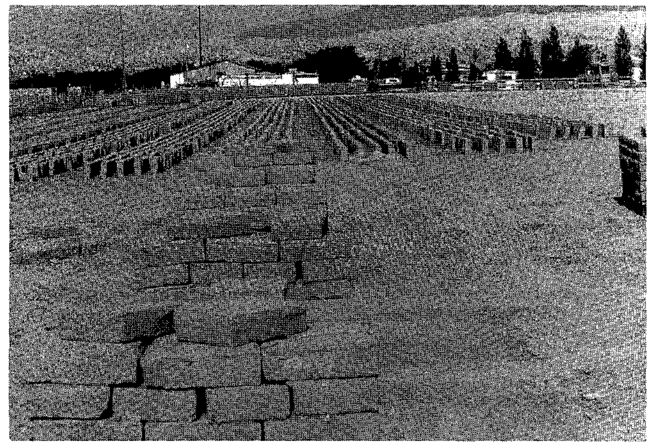


FIGURE 44—Stacked and drying adobe bricks. Medina's Adobe Factory adobe yard, Alcalde.

the truck. The adobe mud mixed in the yard is transferred by the front-end loader to the mud vat which is then delivered to the construction site. Once at the site, a valve on the mud vat is opened and the mud is poured into a wheelbarrow. The mud mortar is then transported to the workers laying the bricks for adobe walls or other structures.

Mechanized technique

The mechanized technique of adobe-brick production is usually associated with large-scale manufacturing of adobe bricks and maximum use of mechanical equipment. Four mechanized operations found in New Mexico in 1987 were using front-end loaders, pugmills or ready-mix cement trucks, and machine-powered mechanical adobe layers.

Mechanized operations use several thousand yards^3 of adobe soil per year and can produce over 1,000,000 bricks per yard annually. The soil is usually obtained from the adobe yards or is purchased from local sand and gravel operations. The size of the adobe yards varies from one to eight acres and the yards are capable of handling a daily production of 5,000—7,000 adobe bricks. In 1987, 1,075,000 semistabilized and stabilized adobe bricks of the standard 4 x 10 x 14-inch size were produced by the four fully mechanized New Mexico manufacturers.

Medina's Adobe Factory (Alcalde)

The largest producer of adobe bricks in northern New Mexico is Medina's Adobe Factory, owned and managed by Mel Medina of Alcalde, New Mexico (Fig. 44). A total of 500,000 semistabilized adobe bricks of 4 x 10 x 14-inch size were produced in 1987 using the following procedures:

(1) Local sandy loam is obtained by land leveling nearby alluvial or pediment deposits. The sandy loam is hauled to the adobe yard and stockpiled adjacent to the pug-mill mixer. The soil is removed from the stockpile by a 1.5-yard^3 front-end loader and is dumped onto a 1-inch-maximum particle-size screen located over the pugmill (Fig. 45).

(2) Approximately 3 yards^3 of adobe soil are screened and placed in the pugmill, where water and asphalt emulsion are added to the mixing process. The two pugmill shafts, studded with paddles, rotate in the trough of the 4 x 6-ft pugmill and mix the adobe mud for 15—20 minutes (Fig. 46). The mud is then dumped into a large 33 x 75 x 7-ft mudpit. The production crew mix and dump a sizable amount of adobe mud throughout the morning.

(3) In the afternoon, a front-end loader moves the adobe mud from the mudpit to the mud hopper on the Hans Sumpf—type adobe-layer machine (Fig. 47). The ma-

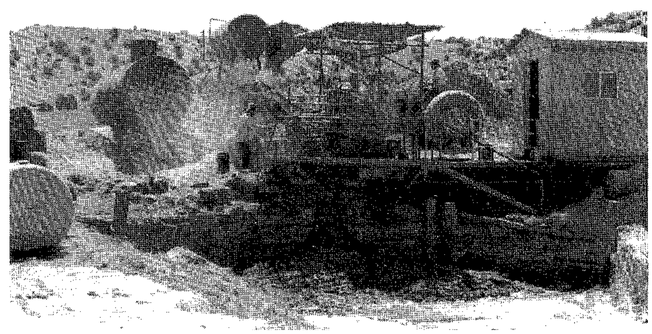


FIGURE 45—Dumping soil into the pugmill. Note mud accumulating in the mudpit. Medina's Adobe Factory adobe yard, Alcalde.

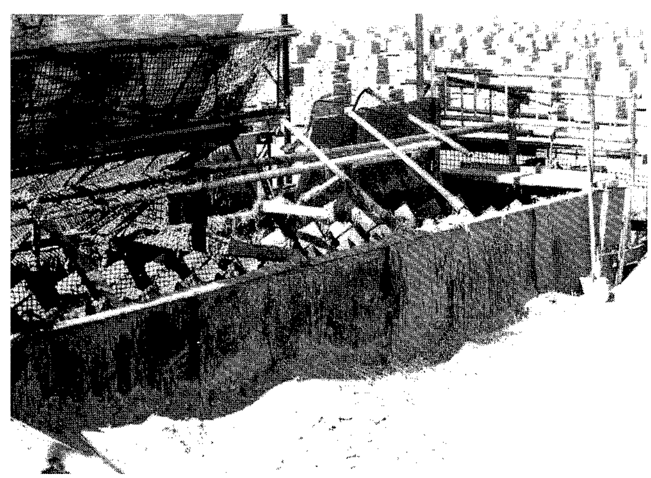


FIGURE 46—Close-up of the large 4 x 6-ft pugmill. Medina's Adobe Factory adobe yard, Alcalde.

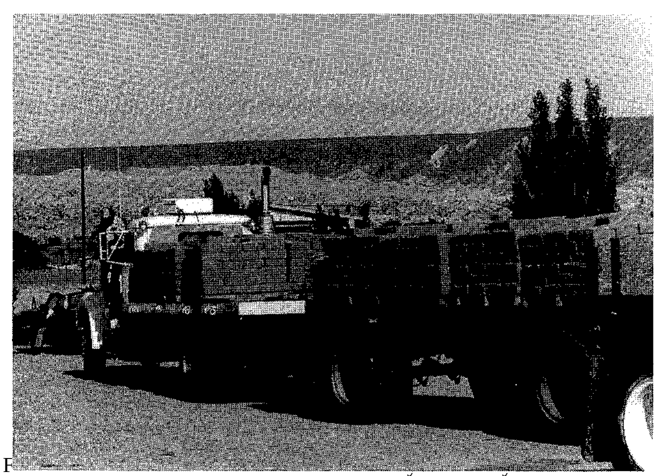
FIGURE 47—Hans Sumpf—type adobe layer that produces 25 standard-size adobe bricks per laydown. Medina's Adobe Factory adobe yard, Alcalde.

chine, called a self-propelled adobe layer, is operated by one person who maneuvers it across the level adobe yard depositing 25 standard 4 x 10 x 14-inch adobe bricks at a time. The steel adobe form is then hydraulically lifted by the machine operator and the adobe layer is moved ahead for the next batch. A continuous straight line of adobe bricks that are ready for drying is produced in the yard.

(4) The newly laid bricks, which cover a large area of the adobe yard and which may total several thousands, are then allowed to dry for two or three days, de-pending on the weather. They are then hand-turned on their side by the adobe crews, trimmed of any excess material, and allowed to dry for a minimum of three weeks under normal conditions.

(5) When the bricks have cured sufficiently, they are stacked directly on the semi-flatbed trucks for delivery or are placed on wooden pallets that hold 70 bricks per pallet. The stacked pallets are lifted onto a truck by a forklift, which is also hauled to the purchaser's building site, permitting placement of the stacked adobe bricks adjacent to the construction project (Fig. 48).

Medina's Adobe Factory has several different size adobe molds available that can be mounted on the mechanical adobe layer to produce many different adobe-brick shapes



F
Factory adobe yard, Alcalde.

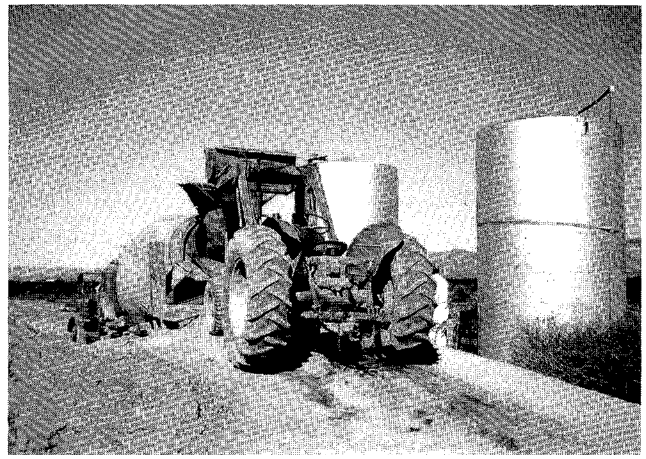


FIGURE 49—Loading adobe soil into the hopper of the ready-mix truck. The Adobe Patch adobe yard, La Luz.

and dimensions. With good weather conditions and a minimum of mechanical breakdowns, the operation can pro-duce an average of 5,000—7,000 adobe bricks per eight-hour day with a crew of three employees.

In July 1988, 15 semistabilized adobe bricks were delivered to the Professional Services Industries, Inc. Albuquerque Testing Laboratory. Tests showed the bricks had a compressive strength of 390—450 psi for an average of 430 psi. The modulus of rupture was 70—150 psi for an average of 80 psi and the moisture content varied from 1.2 to 7.0 wt% for an average of 3.78 wt%. A seven-day water absorption test that was also performed showed only 1.3 wt% water absorption.

The Adobe Patch (La Luz)

The Adobe Patch is located approximately one mile north of Alamogordo and is owned by Robert and Christina Duran Godby of La Luz, New Mexico. The Adobe Patch is the only large-scale producer of stabilized adobe bricks in the eastern part of New Mexico; more than 165,000 bricks were made during the 1987 season.

The geographic location of The Adobe Patch permits an adobe-production season of approximately 300 frost-free days. Adobe soil (crusher fines) is purchased from a sand and gravel operation located north of Alamogordo, New Mexico.

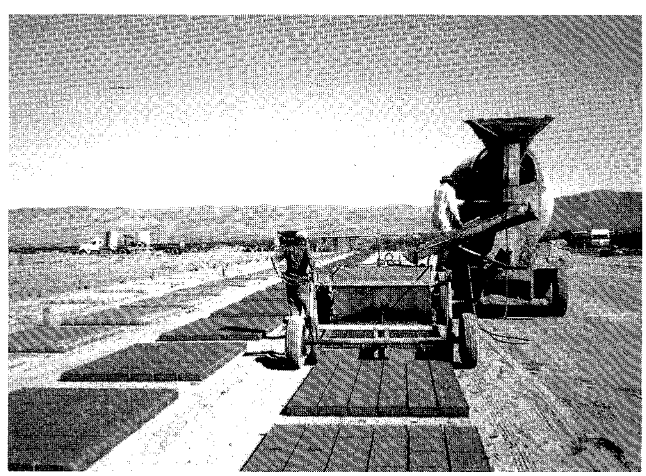


FIGURE 50—The ready-mix truck dumping the mixed adobe mud into the hopper of the adobe layer, which produces 42 standard-size adobe bricks per laydown. The Adobe Patch adobe yard, La Luz.

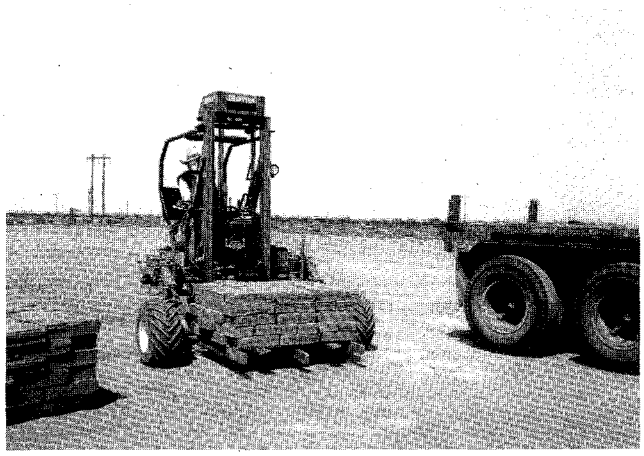


FIGURE 51—Spyder forklift loading adobe bricks onto flatbed of truck. The Adobe Patch adobe yard, La Luz.

FIGURE 52—Use of the Spyder forklift requires only one employee for delivering and unloading the adobe bricks at the building site. The Adobe Patch adobe yard, La Luz.

The equipment used at the adobe yard includes one front-end loader, three 7.5-yard^3 ready-mix trucks, one mechanical adobe layer, one sand spreader, one 5,000-gal water tank, one 5,000-gal asphalt-emulsion tank, and one diesel semi-flatbed truck, trailer, and forklift for deliveries.

The Adobe Patch produces adobe bricks as follows:

(1) Seven yards^3 of adobe soil and a mixture of 340 gal of water and 80 gal of asphalt emulsion are added to a ready-mix truck (Fig. 49). The mud, water, and asphalt emulsion are mixed for an average of 45 minutes and then are conveyed to a special mechanical adobe layer that is attached to the rear of the ready-mix truck. The adobe layer is operated hydraulically and is powered by the truck.

(2) The mixer on the truck empties the adobe mud into the hopper of the adobe layer, which feeds into a steel mold that produces 42 bricks at a time. The scrapers attached to the mud hopper level the top of the mud mix, and the mold is raised, leaving the formed bricks on the ground (Fig. 50).

(3) The ready-mix truck and the attached adobe layer are moved forward. The mold is sprayed with water and is lowered for the next filling. The procedure is repeated until the ready-mix truck has been emptied (after producing approximately 630 bricks per load). The operation at La Luz produces 2,000—3,000 adobe bricks per day with a crew of two employees.

(4) After two or three days of drying, the bricks are turned on edge and are cleaned and scraped. They remain on edge to dry thoroughly (15—20 days) or until needed for shipment. The dried or drying adobe bricks are then stacked on pallets that have a holding capacity of 77 bricks. The loaded pallets are lifted by a Spyder forklift onto the flatbed of the company truck (Figs. 51, 52). The forklift is then fitted into a cradle built into the end of the flatbed, where it is carried to the construction site to unload the adobe bricks. The Spy-der forklift weighs 2,350 lbs and requires only 3—5 minutes to load and unload from the carrying cradle.

The Godbys' fully mechanized and quality-control method of adobe production has manufactured a superior adobe brick that is fully stabilized and meets all the state's building codes. The soil is alluvial-fan material, usually consisting of 2% clay-, 18% silt-, and 80% sand + -size particles. The larger sand + -size particles were only those that pass through a ¼-inch screen. The clay-size fraction consisted of five parts illite, three parts kaolinite, two parts mixed-layer I/S, and a trace of calcium smectite, with minor calcite, dolomite, and quartz.

Pressed-earth-block production

In the published 1980 survey, *Adobe bricks in New Mexico* (Smith, 1982a), pressed-earth blocks were identified as pressed adobes and were manufactured using the hand-operated CINVA-Ram or a hydraulically operated, gasoline-powered machine that made one block at a time. The 1982 and subsequent revisions of the New Mexico Building Code identify pressed-earth blocks as "hydraulically pressed units." In 1987—88, however, most equipment manufacturers and block producers use the general term pressed-earth block.

In 1980, production of all types of pressed-earth blocks was limited; an estimated 15,000 blocks were manufactured statewide. The prices for the blocks varied from 30 to 35¢ each at the producer's yard. During the 1980 survey (Smith, 1982a), the machines that made pressed-earth blocks pro-duced traditional (untreated), semistabilized, and stabilized standard 4 x 10 x 14-inch blocks. The hand-operated CINVA-Ram press, however, produced a 3½ x 5½ x11½-inch block. The major machines used to produce the pressed-earth blocks included (1) Adobe Farm's Hydra-BrikCrete Press; (2) David Griego's Porta Press; (3) W. S. Carson's CINVA-Ram; (4) Al Niblack's Sun Mountain Adobe Press; and (5) Bill David-son's Soil-Crete Solar Company Press.

In 1987, more than 642,000 traditional (untreated), semi-stabilized, and stabilized (with portland cement and lignite sulfate) pressed-earth blocks were produced statewide (Table 5). Traditional (untreated) 4 x 10 x 14-inch blocks that were produced using local or hauled-in soil at a builder's home-site sold for 25 to 350 each.

Extensive and rapid development of greatly improved types of portable (trailer-mounted) pressed-earth-block ma-chines and accessory equipment occurred in the early 1980s. In 1987—88, five manufacturers in New Mexico were making

TABLE 5—Pressed-earth-block producers and pressed-earth-block-machine manufacturers active in New Mexico in 1988. For locations see Fig. 1B. NA, not available.

Map no. (Fig. 1B)	Name and mailing address	Telephone	County	Approximate annual production (1987)	Pressed-earth-block machine
1	Adobe International Box 1284 Grants, NM 87020 Henry Elkins, Owner	287-2961	Cibola	Manufacturer and producer 200,000	Earth Press II, III, IV
2	Adobes Unlimited 10820 Cruz Place SW Albuquerque, NM 87105 Richard Marquez, Owner	831-4656	Bernalillo	25,000	Goldbrick "5000"
3	Alternative Block, Inc. Box 7397 Grants, NM 87020	285-5468	Cibola	200,000	Goldbrick "5000"
4	George and Shauna Bennett Box 1264 Farmington, NM 87499	325-7765	San Juan	0 (noncommercial)	Earth Press II
5	Coyote Adobe, Inc. 247 Rosario Blvd. Santa Fe, NM 87501 Robert W. Higginson and Paul Romero, Owners	989-7224	Santa Fe	0	Earth Press III
6	Josue Flores Box 246 Playas, NM 88009	436-2698	Hidalgo	8,000	Earth Press III
7	Gringo Adobes Box 24 Datil, NM 87821 Vernon Mullins, Owner	772-5757	Catron	0	Earth Press III
8	John E. Irick, Jr. 14305 Central Ave. NW Albuquerque, NM 87105	883-4443	Bernalillo	40,000	Earth Press III
9	Jaquez Construction P.O. Box 27, Rd. 3285 Aztec, NM 87410	334-2491	San Juan	0	Terra Rammed Block
10	Gary Johnson P.O. Box 700 Socorro, NM 87801	835-2140	Socorro	10,000 (noncommercial)	Earth Press II
11	Lyon Enterprises Ltd. 3308 Coors Blvd. SW Albuquerque, NM 87105 J. L. Romero, President	877-2187	Bernalillo	5,000	Goldbrick "5000"
12	J. Howard Menapace 501-23 West Coal Ave. Gallup, NM 87301	722-2271	McKinley	0 (noncommercial)	Earth Press III
13	Munoz Enterprise 120 S. Boardman St. Gallup, NM 87301 Edward (Jr.) and Joyce Munoz, Owners	722-5488	McKinley	0	Earth Press III
14	Navajo Tribe, Baca Chapter Prewitt, NM 87045 Roy Vandever, Council Delegate	876-4025	McKinley	0	Earth Press II
15	Northern Pueblo Housing Authority P.O. Box 3502 Pojoaque, NM 87501 David Perez, Director	455-2246	Santa Fe	14,000	Goldbrick "5000"
16	Overview Consulting & Manufacturing Box 1363 Corrales, NM 87048 David Lineau, Owner	898-6609	Sandoval	Manufacturer	Impact 1000
17	Fred & Mary Raje Box 100 San Fidel, NM 87049	552-6738	Cibola	8,000	Earth Press III

TABLE 5 (continued)

Map no. (Fig. 1B)	Name and mailing address	Telephone	County	Approximate annual production (1987)	Pressed-earth-block machine
18	Ridge Adobe Box 4396 Santa Fe, NM 87502 Chester Berridge, Owner	983-7624	Santa Fe	72,000	Goldbrick "5000"
19	Rustech 163 Piedra Loop Los Alamos, NM 87544 Ken Rust, Owner	672-9692	Los Alamos	Manufacturer	Rustech
20	Santo Domingo Pueblo Box 99 Santo Domingo Pueblo, NM 87052 Bennie Atencio, Manager	NA	Sandoval	NA	Earth Press II
21	Carl & Lorraine Steiner 19 Lazy Lane Star Route 7, Box 142C Belen, NM 87002	864-0104	Valencia	8,000	Earth Press II
22	T. D. Adobe Works Box 315 Arrey, NM 87930 Guy Bennett, Owner	267-9277	Sierra	2,000	Goldbrick "5000"
23	Terra Manufacturing Co. % Western Metal Works 8325 Washington NE Albuquerque, NM 87113 Mike Riddle, Owner	892-4865	Bernalillo	Manufacturer	Terra Rammed Block
24	The Adobe Farm Rt. 6, Box 30 Santa Fe, NM 87501 Gilbert Garcia, Owner	473-4571	Santa Fe	1,000	Earth Press III
25	The Adobe Machine % Merrill Fence Co. P.O. Box 681 Gallup, NM 87301 Perry Merrill and Kevin Mowrer, Partners	722-9206 722-3079	McKinley	8,000	Earth Press III
26	Michael Vanderwagen P.O. Box 4269 Yahtahey, NM 87375	722-3859	McKinley	35,000 (noncommercial)	Earth Press II
27	Paul E. Wilmeth P.O. Box 2862 Silver City, NM 88062	538-3559	Grant	6,000	Earth Press III
28	Worldwide Adobe, Inc. P.O. Box 7397 Grants, NM 87020 John Wright, President	285-5468	Cibola	Manufacturer	Goldbrick "5000"

and selling various machines that can produce several thou-sand blocks per day. The blocks that are produced are usually of the standard 4 x 10 x 14-inch size and weigh an average 38—40 lbs. The major machines made by the five active manufacturers are (1) Adobe International's Earth Press II, III, and IV; (2) Worldwide Adobe, Inc.'s Goldbrick "5000"; (3) Rustech's Rustech; (4) Overview Consulting & Manufacturing's Impact 1000; and (5) Terra Manufacturing Co.'s Terra Rammed Block machine. The manufacturers and owners of the pressed-earth-block machines are listed in Table 5, and the machines are compared in Table 6. Six Goldbrick "5000" and seven Earth Press II and III machines made most of the 642,000 pressed-earth blocks produced in 1987. In the spring and summer of 1988, the prices for the machines varied from $9,000 for the Impact 1000 to $72,000 for the Goldbrick "5000" FOB. Certain optional and accessory equipment are priced separately.

A major advantage to using pressed-earth blocks for construction is that they have a higher average compressive strength and modulus of rupture than sun-dried adobe bricks. According to the procedures outlined by the New Mexico Building Code, various tests were performed on sample pressed-earth blocks at the United Nuclear Rock Mechanics Laboratory, New Mexico Institute of Mining and Technology, and at other private laboratories. The tests showed that the blocks have an unusually good modulus of rupture of 46—279 psi and a compressive strength of 512—3,702 psi. However, unless a stabilizer, such as portland cement, polymer, lime, or asphalt emulsion, is added to the soil mixture, the blocks must be protected from moisture at all times.

TABLE 6—Comparison of pressed-earth-block machines manufactured in New Mexico in 1988.

	Earth Press II	**Earth Press III**	**Earth Press IV**	**Goldbrick "5000"**	**Rustech**	**Impact 1000**	**Terra Rammed Block**
Weight	6,700 lbs	2,720 lbs	4,200 lbs	9,500 lbs	2,200 lbs	1,760 lbs	11,000 lbs
Dimensions	6 ft wide, 6 ft, 8 inches high, 21 ft long	5 ft wide, 8 ft high, 16 ft long	5 ft wide, 8 ft high, 20 ft long	8 ft wide, 8 ft high, 16 ft, 6 inches long	7 ft wide, 6 ft, 6 inches high, 8 ft long	5 ft, 4 inches wide, 3 ft, $8\frac{1}{2}$ inches high, 5 ft, 4 inches long	8 ft wide, 10 ft high, 16 ft long
Power	4-cyl—72-hp John Deere, liquid-cooled, diesel engine	2-cyl—18-hp Tecumsech, air-cooled, gasoline engine	Two 2-cyl—20-hp Koehler, air-cooled, diesel engines	6-cyl—115-hp Onan L634, liquid-cooled, diesel engine	2-cyl—24-hp Koehler, air-cooled, diesel engine	4-cyl—8-hp Koehler, air-cooled,, gasoline engine; other power sources possible	6-cyl—110-hp Deutz, air-cooled, diesel engine
Controls	manual or automatic	manual or automatic	manual or automatic	automatic (Rexroth Worldwide hydraulics with programmable controller)	automatic	manual	automatic
Press force	7-inch-diameter hydraulic cylinders, double RAM producing 2,500 psi	2—4-inch-diameter hydraulic cylinders, double RAM, producing 2,500 psi	2—5-inch-diameter hydraulic cylinders, double RAM, producing 2,500 psi	8-inch-diameter hydraulic cylinder producing 5,000 psi, up to 250,000 lbs on bricks	7-inch-diameter hydraulic cylinder producing 3,000 psi, up to 115,000 lbs on bricks	2—6-inch-diameter hydraulic cylinders pro-ducing 2,000 psi to 132,000 lbs thrust on brick	10-inch-diameter hydraulic cylinder producing 1,750 psi, up to 250,000 lbs on brick
Production	14 blocks/minute	4 blocks/minute	6 blocks/minute	14 blocks/minute	3 blocks/minute	2 blocks/minute (1,000/8-hr day)	6—7 blocks/minute
Trailer	tandem axles, electric brakes, & towing signals	tandem axles, electric brakes, & towing signals	tandem axles, electric brakes, & towing signals	tandem axles, electric brakes, & towing signals	single axle	single axle	tandem axles, electric brakes, & towing signals
Block sizes	4 x 10 x 16 inches 4 x 10 x 14 inches 4 x 10 x 12 inches	4 x 8 x 12 inches 4 x 8 x 8 inches	4 x 10 x 16 inches 4 x 10 x 14 inches 4 x 10 x 12 inches	4 x 10 x 14 inches 4 x 7 x 14 inches other sizes available	4 x 10 x 14 inches (standard) 4 x 7 x 14 inches (optional)	$3\frac{1}{2}$ x $5\frac{1}{2}$ x 12 inches	4 x 10 x 14 inches optional sizes available
Price	$35,000 FOB Grants, NM	$13,500 FOB Grants, NM	$25,000 FOB Grants, NM	$72,000 FOB Grants, NM	$14,500 FOB Los Alamos, NM	$9,000—9,800 FOB Corrales, NM	$65,000—70,000 FOB Albuquerque, NM

Without a stabilizer or other protection, the blocks rapidly disintegrate when subjected to intense rains.

Another major advantage to using pressed-earth blocks for construction is the convenient method of production. The pressed-earth-block machines are portable; they can produce blocks using local soils at the construction site. The finished blocks are uniform in at least two directions and can be conveyed directly from the machine to a wall or stockpiled for later use. The blocks are commonly placed into the wall without further drying. A thin mud slurry or the lightly wet block surfaces bind the blocks together.

Pressed-earth-block production techniques using the var-ious machines, including the Porta Press, still in use in 1987—88, and the hand-operated CINVA-Ram, are described below.

Porta Press

The first Porta Press was manufactured in 1966 by Vern and N. N. Huffaker of Santa Fe, New Mexico. The Porta Press is mounted on a single-axle, two-wheel trailer that weighs approximately 3,000 lbs and is powered by a seven-hp Briggs and Stratton, air-cooled engine. According to the manufacturer, the Porta Press is capable of producing 600—800 pressed-earth blocks per day with a crew of two. Al-though no longer manufactured, the unit was priced in 1966 at an average of $2,700 per machine. Approximately 15—20 machines were produced and sold throughout the South-west and Latin America.

Two Porta Press machines were in use in New Mexico during the summer of 1980 (Smith, 1982a). With a Porta Press machine, David Griego of Ledoux, New Mexico, pro duced pressed-earth blocks that he used for an addition to his adobe house or sold for local projects. He produced 7,000 pressed-earth blocks on a part-time basis at the construction sites of several adobe buildings. The blocks sold for an average of 35¢ per block.

A second machine at Tierra Amarilla, New Mexico, was used by A. Ulibarri in 1980. In the 1960s, the machine, owned by Dr. Dabbs, had been originally operated to pro-duce pressed-earth blocks for the construction of La Clinica

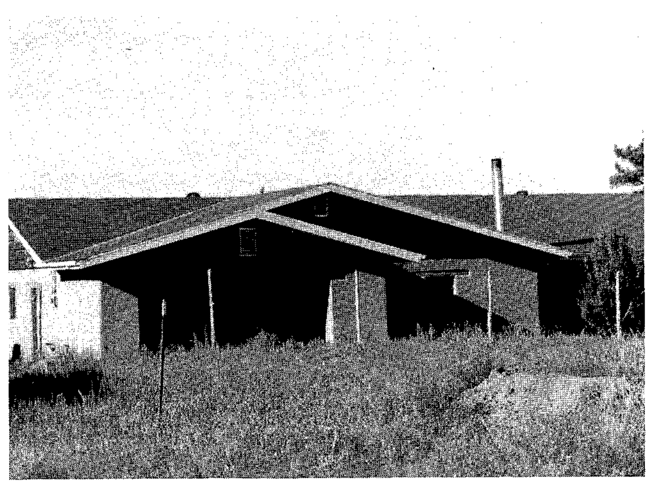


FIGURE 53—Narciso Garcia house built of 10,000 Porta Press pressed-earth blocks, Cedar Crest.

FIGURE 54—Porta Press in operation during the summer of 1980. David Griego building site, Ledoux.

FIGURE 55—Cleaning Porta Press pressed-earth blocks prior to stacking in the yard to dry. David Griego building site, Ledoux.

del Pueblo. In 1987—88, the present owner of the Porta Press, Brenda Martinez of Cedar Crest, New Mexico, purchased the machine from Narciso Garcia, a neighbor who used the equipment to construct a large home. The 1,950-ft^2 house was built over a three-year period on a part-time basis by Garcia, who produced a total of 10,000 pressed-earth blocks (Fig. 53).

In 1980, with a crew of two at the adobe yards of David Griego of Ledoux and A. Ulibarri of Tierra Amarilla, the production procedure used is as follows:

(1) The Porta Press is set up adjacent to a stockpile of local soil. The soil is shoveled into a storage hopper from which a measured amount is pushed into the loading slot between two wooden oiled plates.
(2) Water is then added to produce a moist mixture and the slot door is closed and locked.
(3) A lever activates the hydraulic ram to apply approximately 20,000 lbs of pressure to the adobe soil.
(4) A second lever permits the same ram to eject the 3½ x 10 x 14-inch pressed-earth block from the machine (Figs. 54, 55).
(5) The pressed-earth blocks are then placed in the adobe yard to sun dry for several days.

Soil and test results—At Ledoux, New Mexico, the soil contained a relatively high percentage of clay—silt (20—30%). Test results on samples of the standard pressed-earth blocks in 1980 indicated a very high compressive strength of 1,036—1,071 psi and a modulus of rupture of 46—58 psi.

CINVA-Ram

The CINVA-Ram was developed in 1955 by Chilean engineer Raoul Ramirez working in conjunction with the National University of Chile and the University of Illinois Housing Mission to Colombia. The CINVA-Ram is a small portable press made of steel with a molding box in which a hand-operated piston compresses the moistened mixture of adobe soil (Fig. 56). The press has been used in over 40 countries and has been used by the Peace Corps throughout the developing nations of the world. In 1988, no CINVA-Ram press was found in operation in New Mexico. However, because of its past use in the state and widespread use in other countries, the CINVA-Ram has been included in this report. As outlined in the Volunteers for International Technical Assistance publication, *Making building blocks with the CINVA-Ram* (VITA, 1966), the overall equipment specifications are as follows:

Weight	140 lbs
Height and base width	10 x 16 x 26 inches
Application force of lever	80 lbs
Bearing strength (cured block)	200-500 psi
Size of blocks	3½ x 5½ x 11½ inches
Size of tiles	1½ x 5½ x 11½ inches
Average weight of blocks	20 lbs
Average number of blocks per 100 lbs of cement	150
Average number of blocks per 5 gal of asphalt emulsion and water mixture	40

In 1980, W. S. Carson of Columbus, New Mexico, had hired a work crew to produce CINVA-Ram pressed-earth blocks and to construct a 3,000-ft^2 two-story house near the Columbus airport (Smith, 1982a). During a normal eight-hour work day at the building site, an average of 180 pressed-earth blocks of 3½ x 5½ x 11½ -inch size were produced. The Carson crew of two used a cement mixer to add asphalt emulsion to the soil mix to produce a semistabilized pressed-earth block. Other stabilizers such as lime or portland cement are also commonly used for waterproofing.

The equipment used at the Carson site included the CINVA-Ram press, a gravel screen, front-end loader, cement mixer, and various water and asphalt-emulsion containers. The adobe soil, sand, and gravel were obtained from a nearby arroyo and hauled to the construction site. Blended soil was placed in the cement mixer and the water and asphalt emulsion was added to dampen the soil (10 wt% moisture). After mixing, the material was dumped next to the CINVA-Ram, which had been mounted on a nine-ft board to provide stability. The procedure used to produce the pressed-earth blocks is as follows:

(1) The cover on the press is opened and the piston is moved to the bottom of the mold box. A flat 1/8-inch steel 5½ x 11½ -inch plate is set in the mold. The soil mixture is added to the mold, tamped, and leveled off (Fig. 57). The operator wets the bottom of the press cover and places it over the mold box.
(2) The mold lever is moved to the vertical position which permits the rollers to fall into place. The lever latch is disengaged and the lever is moved to a horizontal position on the side opposite the lower rollers for the compressive cycle (Fig. 58). The lever is moved down with two or three pushes to the vertical position and the lever latch is engaged. The lever then is returned to the resting position on the lower rollers and the cover is removed.
(3) The lever is depressed at a steady rate to eject the block and the block is lifted from the machine by hand

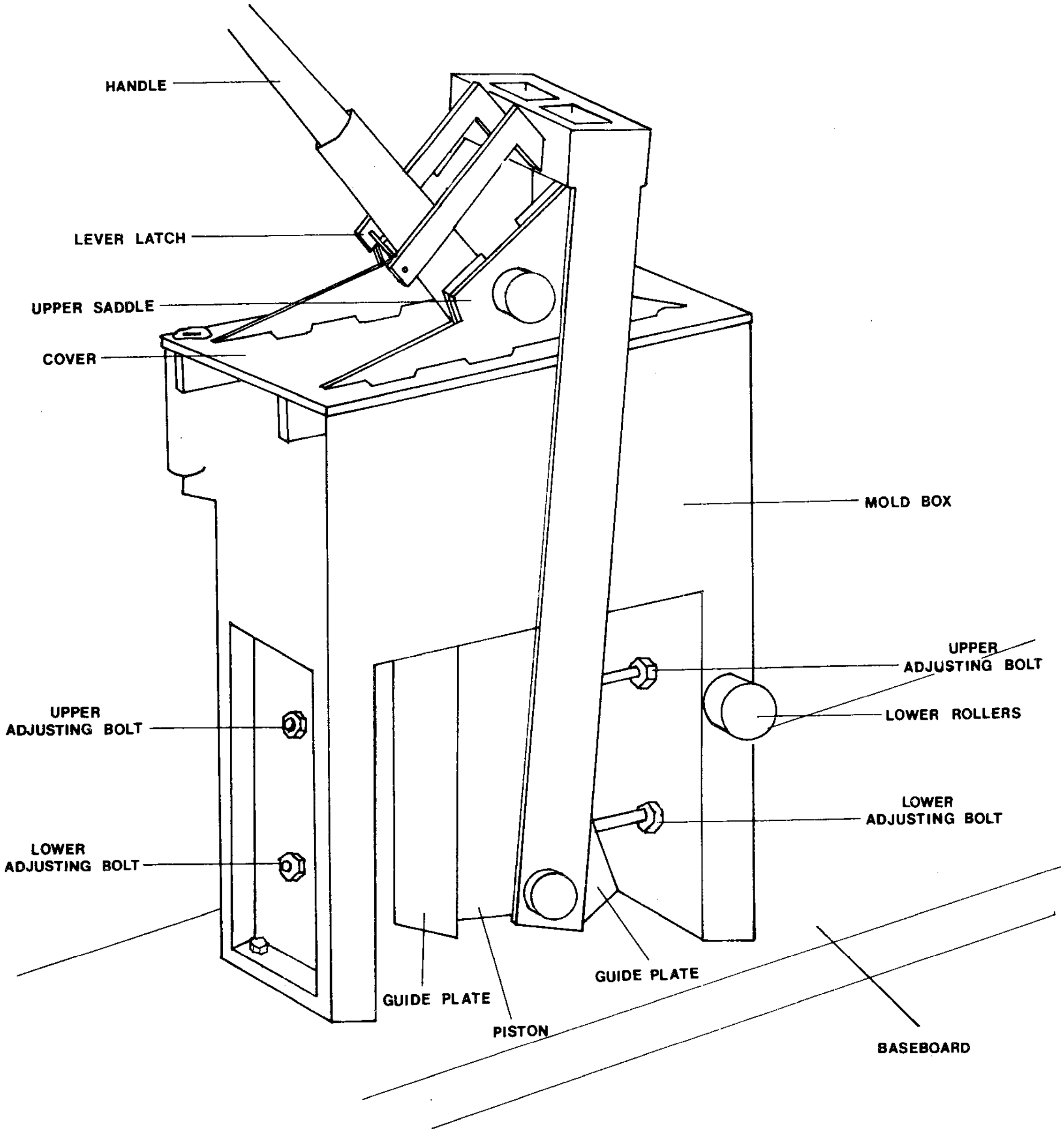


FIGURE 56—Diagram of CINVA-Ram press and its parts.

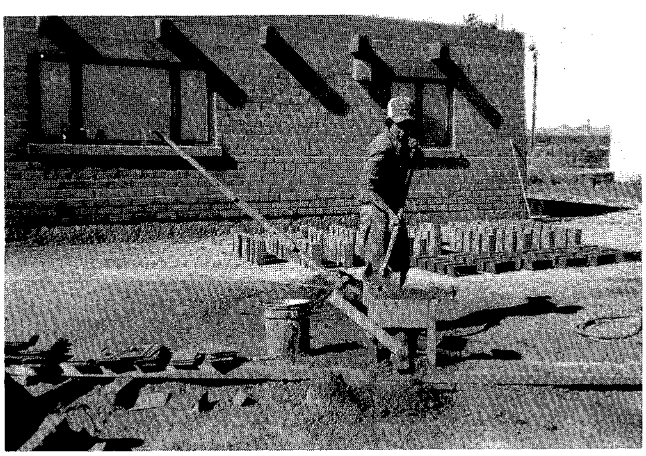


FIGURE 57—Loading the CINVA-Ram mold. Note drying pressed-earth blocks near building. W. S. Carson building site near Columbus.

FIGURE 58—Applying pressure to the soil mixture to produce the pressed-earth block from the CINVA-Ram. W. S. Carson building site near Columbus.

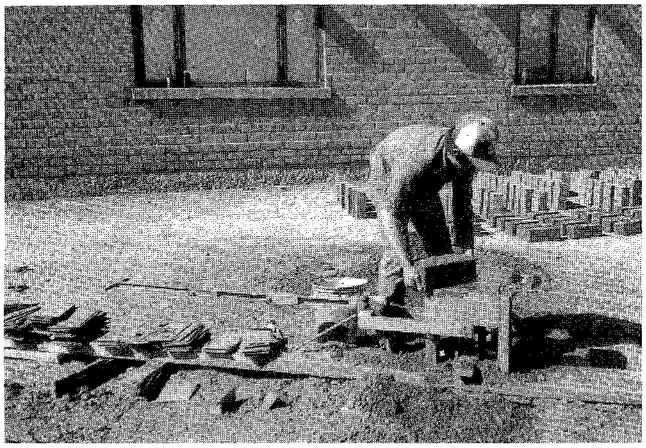


FIGURE 59—Removing the pressed-earth block from the CINVA-RAM mold. The pressed-earth block is then placed in the yard to dry. W. S. Carson building site near Columbus.

FIGURE 61—Henry Elkins standing in front of Earth Press II (left) and Earth Press III (right) pressed-earth-block machines, manufactured by Adobe International, Grants.

and carried to the drying yard (Fig. 59). Blocks are sun dried for five to ten days before being placed into the walls (Fig. 60).

Soil and test results—The CINVA-Ram manufacturer recommended that soils contain 33—66% coarse particles after screening through a 1/4-inch sieve and that 5—10 wt% cement or 10—20 wt% lime be added to make enough moisture to hydrate the mixture. The curing time is approximately eight days.

Testing of the W. S. Carson untreated and semistabilized pressed-earth blocks in 1980 showed a high compressive strength of 512—769 psi and a modulus of rupture of 46—69 psi.

Several other individuals, including Carl Steiner of Belen, now own CINVA-Ram block presses, which were used in the 1970s to produce blocks for building projects. In each case, the blocks were stabilized with portland cement (5—10 wt %), which produced a water-resistant and durable block.

Earth Press II, III, and IV

In 1969, Henry Elkins, the owner of Adobe International, began to manufacture pressed-earth-block equipment for use on building projects at his ranch in Grants, New Mexico. After ten years of research, Elkins developed his first commercial machine, which cost $40,000 and attracted few buyers.

Machine production today is largely limited to three models identified as Earth Press II, III, and IV. Prices for the equipment vary from $13,500 to $35,000 FOB Grants, New Mexico. The most popular model is the Earth Press III machine developed in 1986. The new model Earth Press IV was developed in 1988 and produces a 16-inch block, targeted largely for the Arizona and California market.

In the summer of 1988, nine Earth Press II and twelve Earth Press III machines (Fig. 61) were located and in operation in New Mexico. Most machines were used by individual owners on their own construction projects (Fig. 62). However, several of the machine owners had formed small companies and were producing blocks, under a contract arrangement, at the customer's building site. One ma-chine owner also rented his Earth Press equipment on a monthly basis. Elkins also contracts the use of his equipment to various builders who produce blocks at building sites. Elkins (Adobe International) produced a total of 200,000 pressed-earth blocks for customers in 1987 under this arrangement.

In general, the three Earth Press machines (Earth Press II, III, and IV) produce blocks at the rate of 4—14 per minute. Several block sizes are available varying from the Mexico

FIGURE 60—W. S. Carson CINVA-Ram pressed-earth-block house under construction in 1980 near Columbus. Note vertical steel reinforcements.

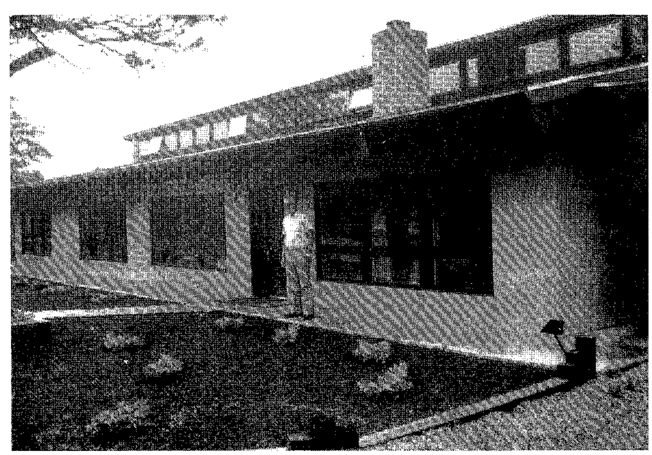


FIGURE 62—Hal Fouts of Gallup, with four untrained helpers and an Earth Press III machine, produced the walls of his solar pressed earth-block house in five months beginning in November 1985.

4 x 8 x 8-inch block, the New Mexico standard 4 x 10 x 14-inch block, to the 4 x 8 x 12-inch block. Other sizes are also available on special order or as optional equipment. Weight of the machines also varies from 2,720 lbs to 6,700 lbs for the earlier Earth Press II machine (Table 6).

Soil and test results—According to Elkins, an ideal soil that contains about 50% sand-and-larger particles and 50% clay and silt produces the best pressed-earth block. A sample taken from soil at the Adobe International plant in June 1988, which Elkins said produced a very acceptable brick, contained 9% clay-, 22% silt-, and 69% sand + -size particles. The clay-size fraction consisted of five parts kaolinite, three parts calcium smectite, two parts illite, and a trace of mixed-layer I/S, plus minor amounts of calcite and quartz. Elkins also recommended a moisture content of 8—10 wt%. He stated that blocks can also be stabilized with 5—10 wt% portland cement to produce a high-strength, water-resistant block.

Test results performed by a private testing laboratory in Albuquerque in January 1986 on traditional (untreated) pressed-earth blocks made using the Earth Press II machine showed a modulus of rupture of 50—70 psi for an average of 60 psi and a compressive strength of 900—940 psi for an average of 920 psi. The tests showed that water absorption varied from 1.3 to 2.7 wt% for an average of 1.9 wt%.

Coyote Adobe, Inc. (Santa Fe)

The Coyote Adobe, Inc. operation is owned by Robert W. Higginson and Paul Romero of Santa Fe, New Mexico. They move their Earth Press III machine to various building sites as contracted by the construction needs of each customer. Their equipment was purchased in 1987 from Adobe International. During the spring of 1988, the equipment was set up in the Velarde area, where approximately 25,000 pressed-earth blocks were produced by a crew of two and were placed in an extensive wall project (Figs. 63, 64). By the end of 1988, the company will have produced an estimated 75,000 blocks.

The blocks produced are all 4 x 8 x 12-inch in size and are traditional (untreated). The company has been most aggressive in developing a sizable market in northern New Mexico by contracting the services of its block-making machine. At the majority of production sites, local adobe soil is used to produce blocks at an average charge of 250 per block.

At the Velarde wall-building construction site, the adobe soil is dug from the owner's acreage and stockpiled by the

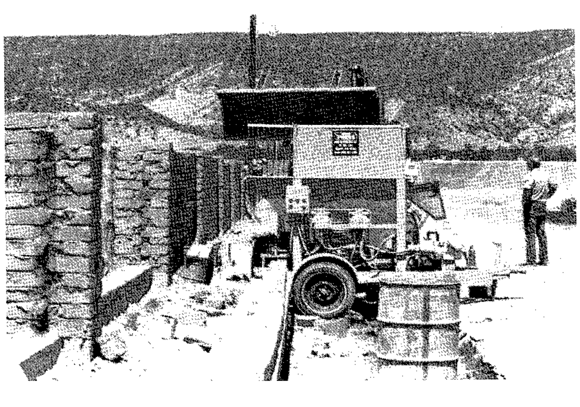


FIGURE 63—Earth Press III machine set up near a wall undeonstruction. Coyote Adobe, Inc. building site, Velarde.

screening equipment. Production accessory equipment includes a front-end loader, block conveyers, and a small screen for screening the adobe soil for use in mud-slurry mortar.

(1) The dry soil is stockpiled by the screening equipment.
(2) The soil mixture is dampened (6—12 wt% or less) and directly loaded into the Earth Press III hopper.
(3) The blocks are pressed and conveyed directly for stacking into the adjacent wall.
(4) The blocks are mortared with a screened mud-slurry mixture that is poured and spread on the block surfaces. Adhesion of the blocks takes only a few minutes and produces a strong bond.

Soil and test results—A sample of the mixture at the Velarde site consisted of 4% clay-, 24% silt-, and 72% sand + - size material. The clay-size particles consisted of three parts calcium smectite, three parts mixed-layer I/S, two parts illite, and two parts kaolinite, plus calcite, quartz, and feldspar.

Goldbrick "5000"

John Wright of Worldwide Adobe, Inc., developer of the Goldbrick "5000" pressed-earth-block machine, is the second manufacturer of portable hydraulic pressed-earth-block equipment in Grants, New Mexico. The first machine was produced in 1981 at the present sales-and-service center at 2500 North Highway 53, Milan, New Mexico.

The Goldbrick "5000" machine has a gravity-fed hopper with a capacity of 2 yards^3 and is usually loaded by a front-end loader that has removed soil from a nearby stockpile (Fig. 65). The soil is then funneled into a 4 x 10 x 14-inch mold welded into a revolving wheel where it is pressed into a block.

The diesel-powered unit also has a 5,000-watt belt-driven generator 120/240 volt, of which 60 or 50 hz supplies power to the machine's programmable controller; the excess wattage is used for operating power tools and a block conveyer system.

The machine presses a standard 4 x 10 x 14-inch block, with a 4 x 7 x 14-inch block available as an option, and has a production capacity of 750—850 blocks per hour. The basic Goldbrick "5000" machine was priced at $72,000 FOB Grants, New Mexico, in the spring of 1988. Other sizes of block molds and accessories, including power conveyers, straight gravity-roller conveyers, and portable block cutters, are also available.

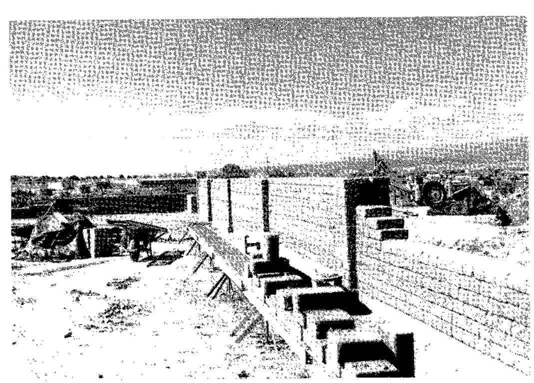


FIGURE 64—Partly wired pressed-earth-block wall ready for scratch-coat cover. Coyote Adobe, Inc. building site, Velarde.

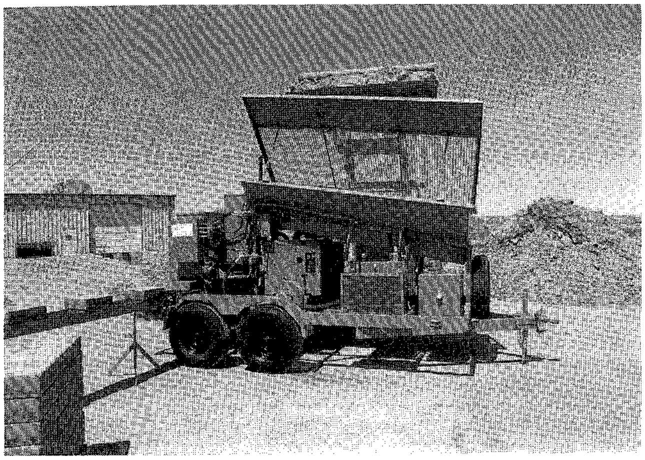


FIGURE 65—Goldbrick "5000" pressed-earth-block machine developed by John Wright and manufactured by Worldwide Adobe, Inc., Grants.

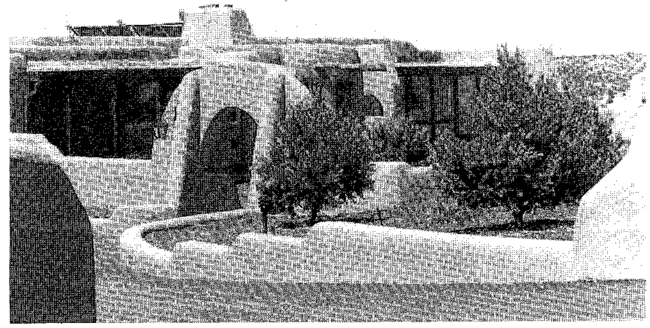


FIGURE 67—Large pressed-earth-block home built with Ridge Adobe pressed-earth blocks made by the Goldbrick "5000" machine, La Tierra area near Santa Fe.

Ridge Adobe (Santa Fe)

The Ridge Adobe operation, owned by Chester Berridge of Santa Fe, New Mexico, is located on the 1–25 frontage road off NM–14 south of Santa Fe. The Goldbrick "5000" pressed-earth-block equipment was purchased from World-wide Adobe, Inc. in 1987 and is set up at Berridge's three-acre production yard (Fig. 66). A total of 72,000 blocks were produced in 1987 with an estimated 300,000 under production in 1988. With a crew of three, the company is producing traditional (untreated), semistabilized, and stabilized pressed-earth blocks in the 4 x 10 x 14-inch and 4 x 7 x 14-inch sizes. In 1988, the traditional (untreated) blocks were priced at 30¢ each and the stabilized blocks were 45¢ each at the producer's yard. Examples of a large pressed-earth-block home and guest house under construction near Santa Fe, New Mexico, are shown in Figs. 67, 68.

Local soil from the nearby area and arroyos is delivered to the Ridge Adobe yard and is stockpiled by the screening equipment. The soil material is dampened (6 wt% or less) and blended with clay and sand as needed with the use of a front-end loader. Production accessory equipment, in addition to the block machine, includes the screening equipment on the conveyer and a pugmill for the mixing of portland-cement stabilizer. Other items include a 14-yard^3 dump truck, two forklifts, the front-end loader, and a 2½ -ton flatbed truck for the delivery of the finished blocks.

(1) The soil is stockpiled by the screening equipment.
(2) The front-end loader blends clay and sand with the moistened soil material.
(3) From the pugmill, the material is conveyed to the hopper located above the hydraulic press.
(4) The blocks are pressed and conveyed directly for stacking on pallets. The stacked pallets are hoisted by a forklift onto a flatbed truck for delivery.

Soil and test results—Particle-size analyses of the mixture used in April 1988 showed it consisted of 5% clay-, 24% silt-, and 71% sand + -size material. The clay-size fraction consisted of four parts kaolinite, three parts illite, three parts mixed-layer FS, a trace of calcium smectite, plus minor quartz, feldspar, and calcite.

A shipment of over 40 blocks was delivered in May and June 1988 to the United Nuclear Rock Mechanics Laboratory, New Mexico Institute of Mining and Technology. The traditional (untreated) pressed-earth blocks showed a compressive strength of 1,218–1,612 psi and a modulus of rupture of 70–88 psi. The semistabilized blocks containing 5 wt% portland cement showed a compressive strength of 2,614–3,978 psi, with a mean of 3,071 psi, and a modulus

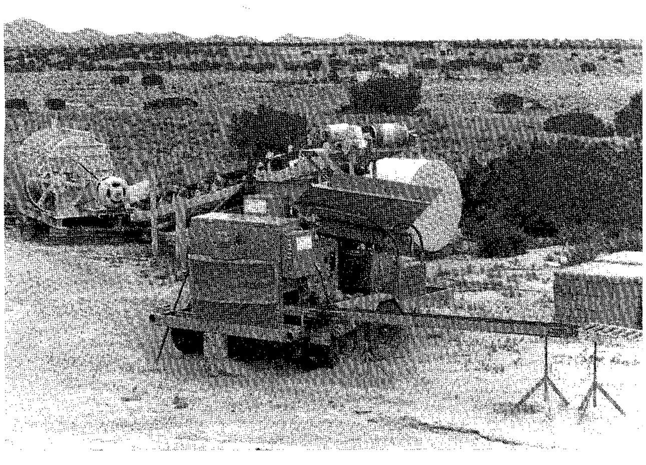


FIGURE 66—Goldbrick "5000" pressed-earth-block machine equipped with pugmill mixer in operation. Ridge Adobe production yard, Santa Fe.

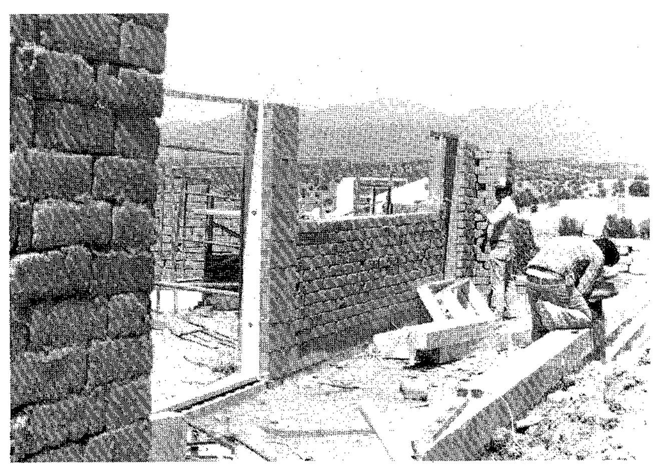


FIGURE 68—Guest house under construction using pressed-earth blocks from the Goldbrick "5000" machine. Note use of adobe-mud slurry as mortar for the blocks. Ridge Adobe building site, La Tierra area near Santa Fe.

of rupture of 172–233 psi, with a mean of 194 psi. The moisture content varied from 6.47 to 7.72 wt% and the seven-day water absorption varied from 9.37 to 10.17 wt%, with a mean of 9.75 wt%. The fully stabilized pressed-earth blocks containing approximately 10 wt% portland cement had a compressive strength of 3,448—3,702 psi and a modulus of rupture of 227–279 psi. The moisture content varied

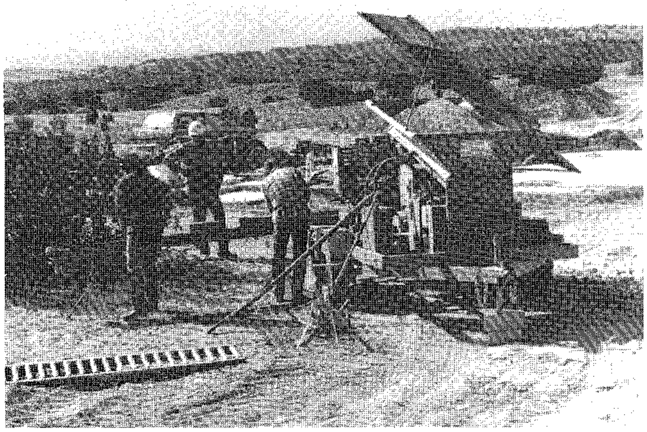


FIGURE 69—Pressed-earth-block production using the Goldbrick "5000" machine. HUD building site, Nambé Pueblo.

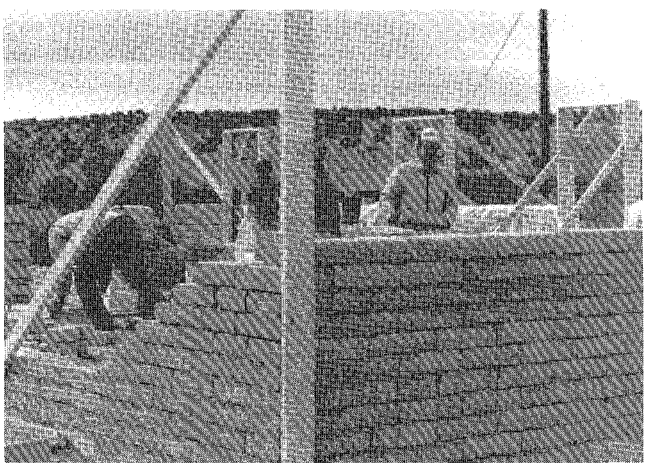


FIGURE 70—Pressed-earth-block house under construction. HUD building site, Nambé Pueblo.

from 6.77 to 6.95 wt% and the seven-day water absorption varied from 8.88 to 9.84 wt%.

Northern Pueblo Housing Authority

Also in full-time use in 1988 was the Goldbrick "5000" machine owned by the Northern Pueblo Housing Authority at Nambé Pueblo, New Mexico. The machine, with a crew of three, was producing 75,000 blocks at building sites in Nambé and Pojoaque Pueblos, where 15 new HUD housing units were under construction. The equipment was moved to each housing pad where the blocks were pressed and stockpiled (Fig. 69). Each house requires approximately 5,000 blocks that are laid with a mud slurry and are wired and stuccoed (Fig. 70). An example of a HUD-approved pressedearth-block house is shown in Fig. 71.

Soil and test results—Tests performed at the United Nuclear Rock Mechanics Laboratory, New Mexico Institute of Mining and Technology, in September 1988 on pressed-earth blocks from the Pojoaque Pueblo project showed the pressed-earth blocks had a compressive strength of 664—819 psi, with a mean of 751 psi, and a modulus of rupture of 39—51 psi, with a mean of 44 psi.

Rustech

The Rustech hydraulic pressed-earth-block machine was developed in 1984 by Ken Rust of Los Alamos, New Mexico. This unique and simple machine contains two hydraulic cylinders and only three other moving parts. The machine is equipped with a gravity-fed hopper system. Its compact size and weight of 2,200 lbs allows easy towing and placement at various tight building sites (Fig. 72).

Soil and test results—According to the developer, a soil containing 70% sand and 30% clay and silt produces a strong pressed-earth block. The moisture content of the soil should be 6—12 wt%. Untreated blocks should be protected by a standard cement coat and stucco. Blocks can also be stabilized with 6—12 wt% portland cement. The blocks should then be wet cured for seven days under black plastic. With a 20% clay mixture, a strong block can be made with a modulus of rupture exceeding 70 psi and a compressive strength over 600 psi. The addition of a small amount of portland cement (3—6 wt%) produces a stronger block with a modulus of rupture of 200 psi. The blocks can be mortared into the wall directly from the machine or can be stockpiled at the building site.

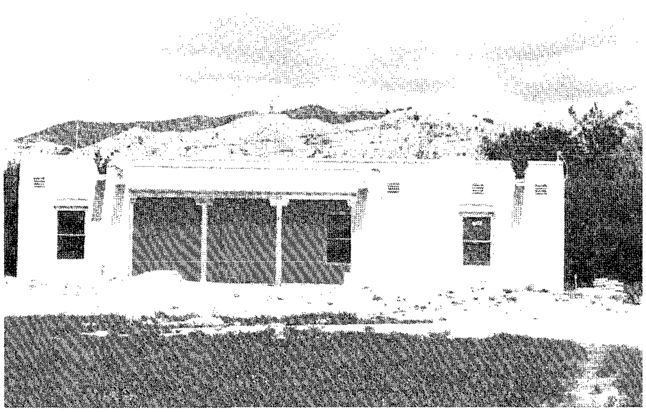


FIGURE 71—Completed HUD pressed-earth-block house built with the Goldbrick "5000" machine, Nambé Pueblo.

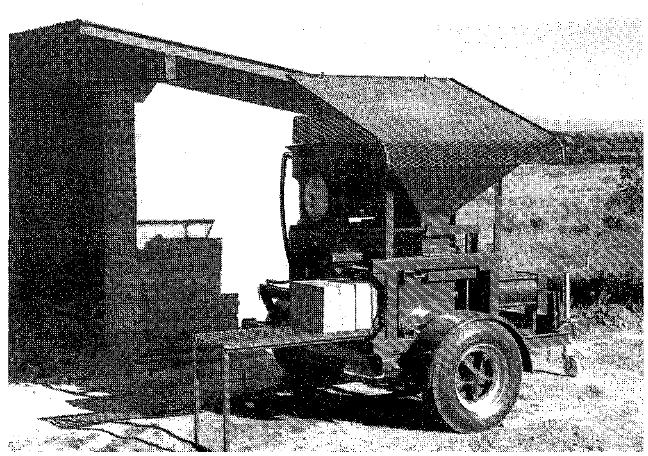


FIGURE 72—Rustech pressed-earth-block machine developed by Ken Rust and manufactured by Rustech, Los Alamos. Note storage building constructed with Rustech pressed-earth blocks.

Impact 1000

The Impact 1000 pressed-earth-block machine was introduced in 1987 by David Lineau of Overview Consulting & Manufacturing, Corrales, New Mexico, as an efficient and inexpensive method of producing pressed-earth blocks (Fig. 73). According to the developer, the light weight and small size allow the Impact 1000 to be easily towed by a small vehicle or by horse, oxen, or other animals.

Soil and test results—A soil mixture of 60% clay and silt and 40% sand are recommended for making the pressed-earth blocks. The developer also stated that the Impact 1000 pressed-earth blocks require only 4—7 wt% moisture. The blocks can be used immediately after they are made; no wet curing or sun drying is required. The untreated blocks require protection by a standard cement coat and stucco. The blocks may also be stabilized with 6—12 wt% portland cement or other stabilizers.

Test data furnished by David Lineau on the Impact 1000 pressed-earth blocks showed a compressive strength of 600—1,000 psi for an average of 850 psi and a modulus of rupture of 77—84 psi for an average of 80 psi.

Terra Rammed Block

Mike Riddle developed and built his first pressed-earth-block machine in 1982. The present Terra Rammed Block machine (Fig. 74) was built in 1985 at the Western Metal Works facility in Albuquerque. The unit is capable of pressing several size blocks, including the standard 4 x 10 x 14-inch block and optional blocks of various sizes. The basic Terra Rammed Block machine was priced at $65,000—70,000 FOB in the summer of 1988.

(1) The machine is mounted on a 16-ft tandem-axle, gooseneck trailer equipped with electric brakes and signals for towing.

(2) The 5½-yard^3 hopper is usually loaded by a front-end loader that moves soil from a local stockpile.

(3) The soil is screened, removing the greater-than-1-inch rocks at the hopper, and is then conveyed into the mixer, where water may be sprayed depending on the moisture content of the soil. At this stage, a stabilizer located by the mixer may also be added.

(4) The material is then moved automatically into the mold, where it is pressed by the platen into a block.

Soil and test results—Test data on 15 samples furnished by Riddle for blocks manufactured in 1982 showed a compressive strength of 1,000—5,050 psi and a modulus of rupture of 47—384 psi, with the moisture content varying from 2.7 to 7.5 wt%. The soil mixture was composed of clay, silt, sand, and C-grade fly ash.

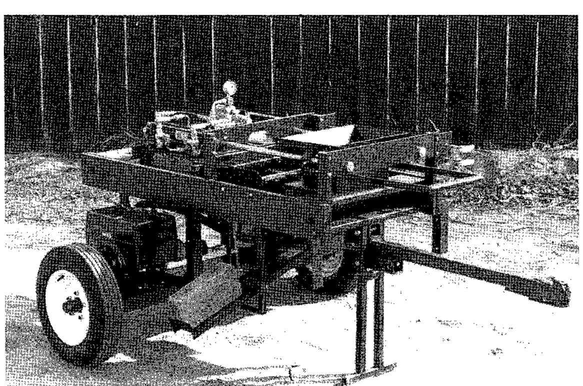


FIGURE 73—Impact 1000 pressed-earth-block machine developed by David Lineau and manufactured by Overview Consulting & Manufacturing, Corrales.

Jaquez Construction (Aztec)

Chris Jaquez of Aztec, New Mexico, purchased the Terra Rammed Block machine from the manufacturer in 1985. In the summer of 1988, the machine was moved to and set up in the Flora Vista area approximately three miles east of Farmington, New Mexico. The machine and a crew of two or three workers produced 10,000 pressed-earth blocks of 3½ x 10 x 14-inch size to build a 3,350-ft^2 home (Fig. 75).

The portable machine is moved to and set up adjacent to the house pad (Fig. 76). A stockpile of soil is hauled to the homesite from a pit near the La Plata and Animas river area. Production accessory equipment include a front-end loader, block conveyers, and several 55-gal water barrels that supply the water for the soil material.

(1) The front-end loader is used to move the dry soil from the stockpile to the machine's 5½-yard^3 hopper, where the soil is screened down to less than one inch.

(2) The screened soil is automatically conveyed from the hopper to a mixing trough, where water is added to produce a damp (8—10 wt %) soil mixture. A stabilizer of 10 wt% portland cement is added to produce sev-

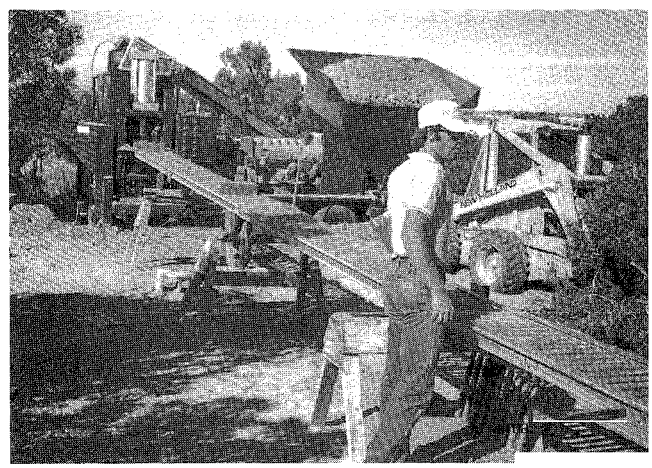


FIGURE 74—Terra Rammed Block pressed-earth-block machine developed by Mike Riddle and manufactured by Terra Manufacturing Co., Albuquerque.

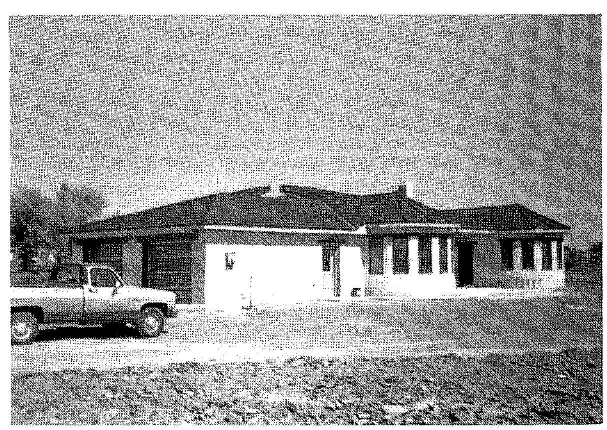


FIGURE 75—Completed pressed-earth-block house built by Jaquez Construction with the Terra Rammed Block machine, Aztec/Farmington area.

FIGURE 76—Terra Rammed Block pressed-earth-block machine being moved to a Jaquez Construction building site, Aztec/Farmington area.

eral hundred waterproof blocks for the first wall course. However, for the rest of the walls, most blocks are made without stabilizers.

(3) The soil-water material is conveyed from the mixer to a mold where it is pressed into a 3½ x 10 x 14-inch pressed-earth block that weighs an average of 38 lbs.

Soil and test results—The senior author randomly selected five blocks from the stacked-block stockpile in July 1988 and delivered them to the New Mexico Institute of Mining and Technology for testing. The pressed-earth blocks showed a compressive strength of 1,022–1,519 psi for a mean average of 1,324 psi.

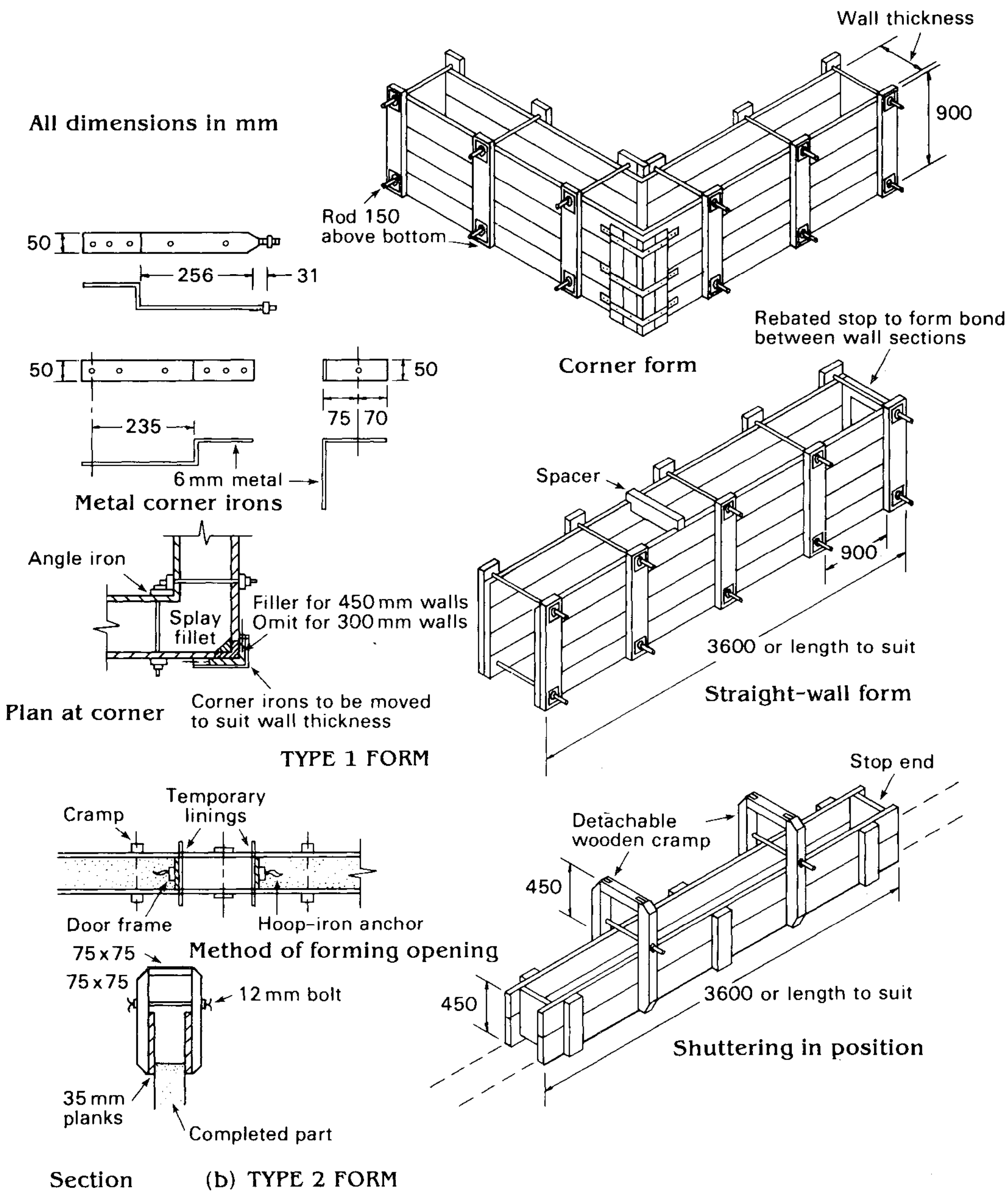


FIGURE 77—Types of rammed-earth forms developed in Australia (from Middleton, 1987).

Rammed-earth production

Building with rammed earth (pisé de terre) is not a new invention. Pliny mentions it in his *Natural History* and the Romans introduced it into what is now France. Various rammed-earth buildings have been constructed in England, Africa, Australia, New Zealand, Mexico, and California, representing a wide range of climates and soil types (Read, 1939). Although building with rammed earth has been practiced for many centuries in many countries, the process is still widely unknown and limited in usage.

Rammed-earth construction has also been used by "do–it-yourself"–type owners who prefer to use their own soil and labor to construct buildings. The rammed-earth technique can be used to build substantial structures, which include houses, barns, commercial buildings, walls, and stables. Rammed-earth walls are similar to pressed-earth blocks, but because of size, type equipment, and forms used to construct the walls, the production method differs.

Rammed-earth walls are built by thoroughly tamping layers of moist soil between wooden, steel, or aluminum forms to form a layer several inches deep (Fig. 77). When a section of wall has been tamped, the forms are moved upwards or sideways and the process is repeated until the wall is completed. The ramming is done with hand-operated or pneumatic tampers that reduce the volume of the soil material 25–30% to a dense and firm compaction (Wolfskill and others, 1970; Fig. 78). The forms require accurate setting and must be held in place so that the rammed-earth wall will be straight and true. Density of the wall depends on the soil type and the ramming. The tamping procedure works in two ways:

(1) repeated vertical blows of the rammer press the soil and
(2) the blows of the rammer, which seldom strike the same place, tend to work the soil particles back and forth horizontally, thus working the material into a dense pattern (DeLong, 1959).

Rammed earth is best adapted for use in side walls and major interior partitions. Exterior walls are commonly stuccoed and finished interior walls are usually plastered and painted. Rammed earth should not be used for below-grade foundations that do not meet New Mexico building Code requirements. Running water in contact with rammed-earth walls (without stabilizers) will cause excessive erosion. Well-made rammed-earth walls are durable and can last hundreds of years, especially if the soils have been carefully selected and construction codes followed.

Rammed earth is a stable building material that has many advantages in the construction of homes, commercial buildings, garages, and barns. The walls, if thick enough (16–24 inches), have certain insulation and thermal characteristics that provide well-known comfort. According to McHenry (1984), the strength of the soil (8–10 wt% moisture content) at initial compaction is approximately 30 psi or more and, within a few weeks of drying in the wall, will achieve a dry strength of 300 psi or more. Investigations by Clough (1950) showed that the compressive strength of rammed earth varies from 462 psi to a high of 850 psi. The compressive strength increases with age (Patty, 1939).

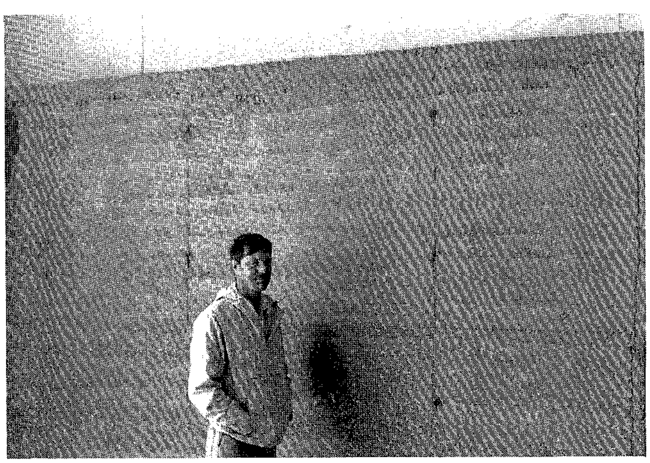


FIGURE 78—Close-up of tamped wall. Note layering produced by tamping. Huston Construction Company building site, Edgewood.

More important than the compressive strength of rammed earth is the ability of the rammed-earth wall to resist deterioration from weathering. Five factors that may affect the weathering ability of the entire rammed-earth wall, rather than just its surface, were listed by DeLong (1959) in his study of mechanical abrasion and water erosion.

(1) Freezing and thawing when the moisture content of the wall is high loosen the structure and cause it to crumble. Rammed earth must be thoroughly dried prior to the set in of cold weather.
(2) Shrinkage while drying out from a moisture content of 9–13 wt% causes cracks and pulverization. Surface cracks appear soon after ramming, because the surface dries out first. Later these cracks lessen or even disappear, proving that the rest of the wall is also internally shrinking. (Eventually a test block attained a maximum shrinkage of near 3% for a stable moisture content.)
(3) A high sand content prevents excessive wall shrinkage and cracking. (A test wall containing 50–75% sand and otherwise suitable soil did not deteriorate due to the initial or continued effect of shrinkage.)
(4) "Colloids," which include all the clay and silt particles, are a second cause of shrinkage variation. The particles have more surface area than sand particles of equal weight. Therefore it takes more water to make the soil semiplastic for proper ramming, resulting in more drying and greater shrinkage.
(5) Various stabilizers affect the weathering ability. Lime, portland cement, and asphalt emulsion generally improve the wall, but all additional materials should always be well blended with the earth before ramming.

Rammed-earth construction companies

Although several individuals and rammed-earth contractors have been active in the past in New Mexico, the only companies active in 1987–88 were the Huston Construction Company of Edgewood and the Soledad Canyon Earth Builders of Mesilla (Table 7). The production techniques used by the two construction companies are outlined below.

Huston Construction Company (Edgewood)

The Huston Construction Company has been engaged in the production of rammed-earth systems since 1983 and has constructed approximately five homes and commercial buildings. The company, owned by Don and Stan Huston, is located on 420 acres in Edgewood, New Mexico, approximately 30 miles east of Albuquerque.

To build the Huston house (Fig. 79), which was their first project, Don and Stan Huston used local soil adjacent to the construction site. The soil was screened and stockpiled. To secure the proper moisture content, a sprinkler, placed on the top of the pile, wetted the soil. The material was then removed and used to construct the walls.

Historically, traditional rammed-earth forms were made of planks and bracing. In 1987-88, rammed-earth builders are using a variety of steel, plywood, and aluminum concrete-pouring systems that are available in the construction market. For their building projects, the Hustons use a modified concrete-pouring form that they made out of 4-ft-wide plywood and steel-reinforced panels. A crew of four worked on the rammed-earth walls of the Huston house.

(1) The forms are stacked for an 8-ft-high and 16-inchwide wall and are locked together at the corners to permit the walls to be rammed without a break (Figs. 80–82) .
(2) A Bobcat front-end loader is used to place the adobe soil in the forms in 6–8-inch layers.

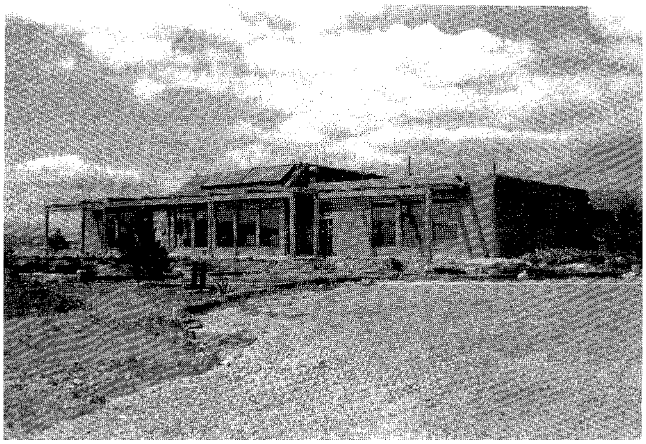


FIGURE 79—Huston house built with 16-inch-thick interior and 36-inch-thick exterior rammed-earth walls, Edgewood.

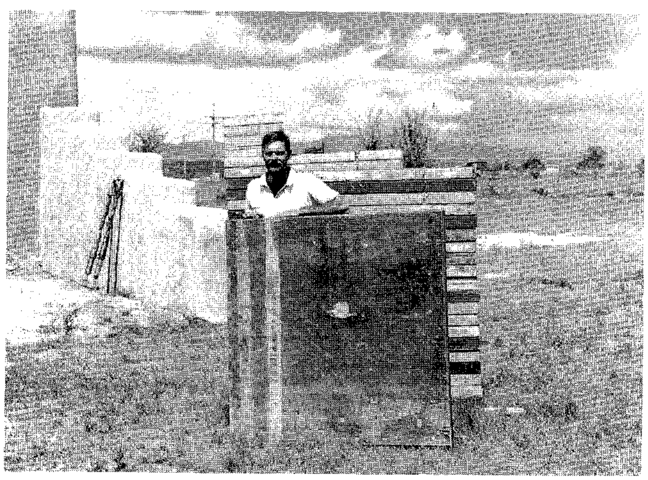


FIGURE 80—Stan Huston displaying the 4 x 4-ft wooden forms used in rammed-earth construction. Huston Construction Company building site, Edgewood.

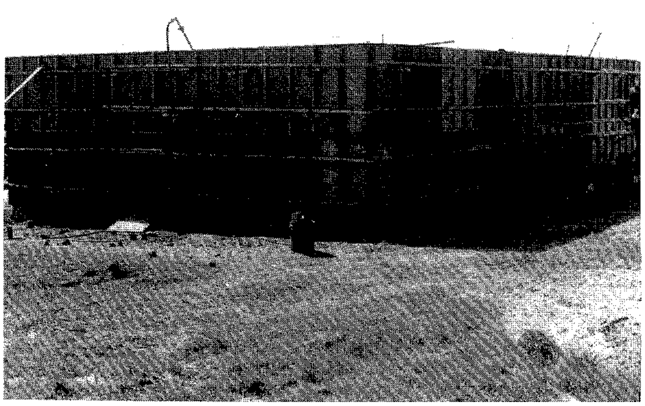


FIGURE 81—Setting of the wooden forms for construction of the rammed-earth walls, Huston Construction Company building site, Edgewood.

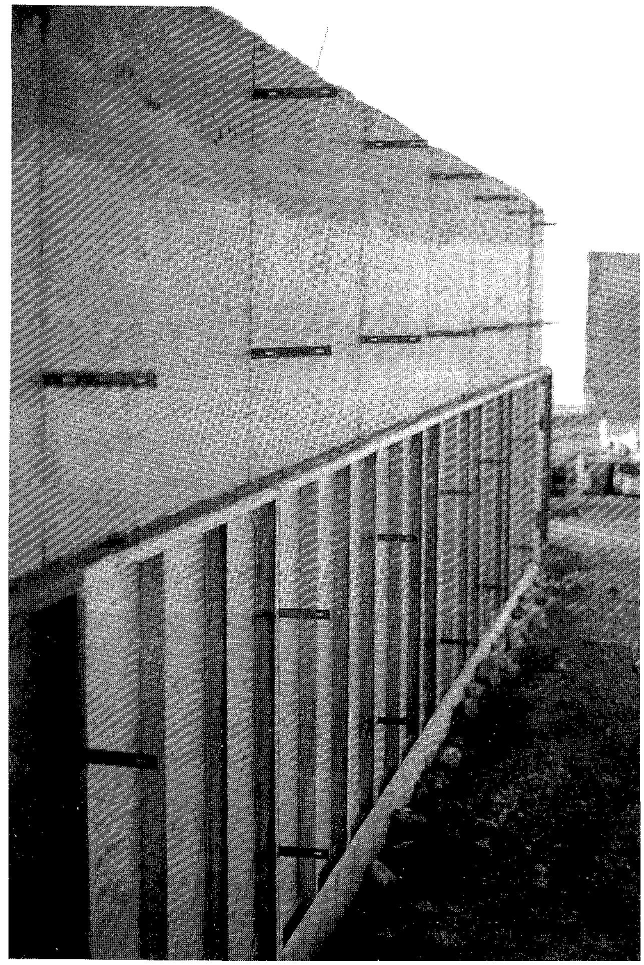


FIGURE 82—Removal of top forms exposing the metal form fasteners that are later cut off at the wall surface. Huston Construction Company building site, Edgewood.

FIGURE 83—Stan Huston holding one of the Ingersoll Rand 341 backfill tampers that are hooked up to a 125 Schramm compressor for tamping rammed-earth walls. Huston Construction Company building site, Edgewood.

TABLE 7—Rammed-earth construction companies active in New Mexico in 1988. For locations see Fig. 1B. NA, not available.

Map no. (Fig. 1B)	Name and mailing address	Telephone	County	Approximate annual production (1987)	Production equipment
A	Huston Construction Company Box "A" Edgewood, NM 87015	281-9006	Santa Fe	NA	Front-end loaders, backfill tampers, and plywood and steel reinforced panels
B	Soledad Canyon Earth Builders P. O. Box 274 Mesilla, NM 88046	642-5175	Doña Ana	NA	Hydraulic tampers and cement forms of metal with wood inserts

(3) Two Ingersoll Rand 341 backfill tampers, hooked up to a 125 Schramm compressor (125 cfm, 110 psi), are used to tamp the 6–8-inch layers to $4\frac{1}{2}$ - 5inches (Fig. 83).
(4) The bottom row of forms is set for a given wall section, filled with adobe soil, and then rammed until the forms are three-quarters full. Then the top layer of the forms is stacked, the walls are rammed to their full 8-ft height, and a concrete bond beam is poured (Figs. 84, 85).

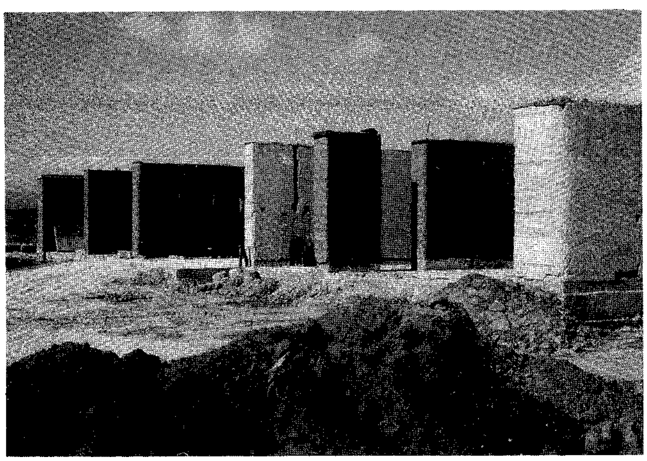


FIGURE 84—Huston house under construction, Edgewood. Note thickness of exterior walls (36 inches) and interior walls (16 inches) after removal of wooden forms.

In general, the moisture content varies from 8 to 10 wt% and the clay content from 10 to 15 wt%. No stabilizer other than sand and crusher fines are added to the soil mixture. Samples collected in the summer of 1988 from Huston stock-piles proved to contain 6% clay-, 25% silt-, and 69% sand + - size particles. The mineralogy of the clay-size fraction was four parts VS, two parts kaolinite, two parts smectite, and two parts illite, plus calcite and quartz.

Soledad Canyon Earth Builders (Mesilla)

The only rammed-earth contractor in southern New Mexico is Soledad Canyon Earth Builders, owned by Mario Bellestri. Soledad Canyon Earth Builders has produced four rammed-earth homes near Las Cruces since 1983. Walls are typically 2-ft thick, but can be up to 3-ft thick. The soil material commonly consists of three parts crusher fines to one part clay soil. Bellestri uses Ingersoll Rand backfill tampers and a compressor to tamp down each layer of about 8 inches of soil to about 5 inches. The forms used are metal frames with wooden insets. A 5 wt% portland-cement stabilizer is commonly used with as much as 10 wt% in the lowest one or two layers for enhanced stability. Concrete bond beams, window and door lintels, and reinforced concrete window sills add further strength (Figs. 86, 87). A compressive strength of about 450 psi is achieved after the walls cure for seven days.

Some interior walls are constructed of frame materials, but most are also of rammed earth. Soledad Canyon Earth Builders specializes in custom homes with passive solar designs.

soil colors and the layering produced by tamping. Huston Construction Company building site, Edgewood.

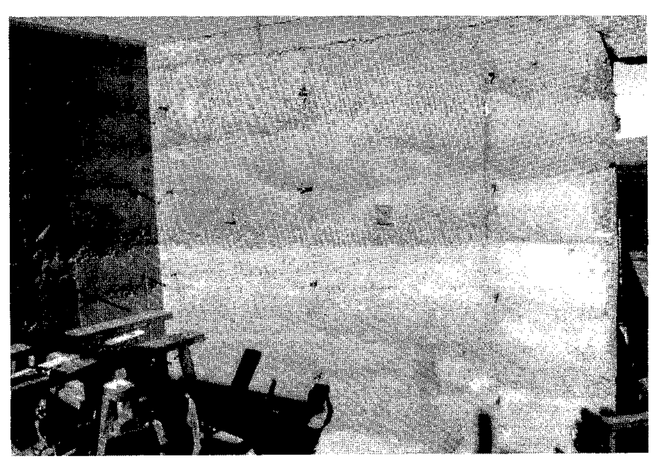


FIGURE 86—Exterior 2-ft-thick rammed-earth wall of home under construction. Note concrete bond beam topped by wooden frame. Soledad Canyon Earth Builders building site, Mesilla.

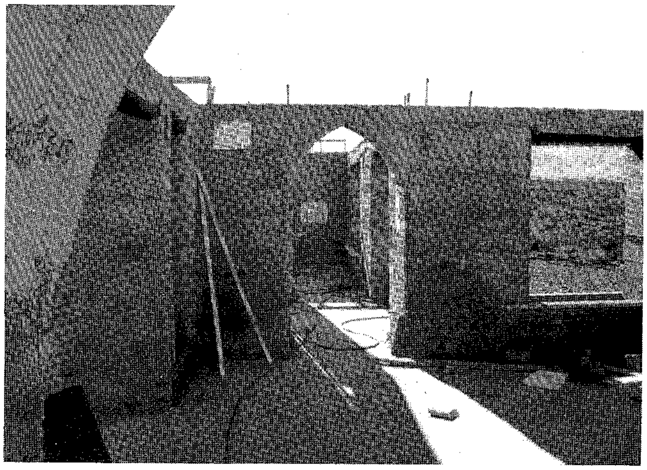


FIGURE 87—Rammed-earth walls with arches and windows. Note concrete bond beam and form for concrete window sill at lower right. Soledad Canyon Earth Builders building site, Mesilla.

Advantages in using native soils

Results of this study and various geologic reports indicate that there is an unlimited supply of adobe soil throughout New Mexico. Extensive deposits are found throughout the local floodplains, streams, arroyos, terraces, and alluvial fans. The deposits are widely used at present as sources of adobe soil by most commercial adobe-brick and pressed earth-block producers in the Albuquerque and Española Basins of the Rio Grande valley.

Other major advantages in using adobe bricks, pressed-earth blocks, and rammed-earth walls for the construction of buildings include the following:

(1) **Cost is reasonable**—The cost of the adobe bricks and pressed-earth blocks are most reasonable prices in 1987 and 1988 are about the same as in 1980. In 1988, adobe bricks and pressed-earth blocks sold for 21 to 59¢ each at the local production yards.

(2) **Soil stabilizers**—The adobe soils can be stabilized at reasonable costs to produce tough water-resistant or waterproof adobe bricks and pressed-earth blocks. Major stabilizers include asphalt emulsion, portland cement, and lime.

(3) **Water resistance**—Fully stabilized adobe bricks and pressed-earth blocks are most resistant to water penetration. A properly stabilized adobe brick will usually absorb less than 4 wt% water, which is much better than several of the other construction materials (after Ferm, 1985):

	Water absorption (wt%)
Light weight cement bricks	20-25
Burnt brick	8-12
Cement stucco	8-11
Wood	4- 8
Stabilized adobe brick	½ - 4
Stabilized pressed-earth block	8- 9

(4) **Durability**—The durability and resistance to weathering and erosion from wind, rains, and sandstorms are well demonstrated by the 19 Indian Pueblos located throughout the state. In particular, the five-storied Taos Pueblo has been occupied and in continued use for over 900 years. Many other examples of durability are the large number of adobe Spanish churches, old haciendas, and homes built in the state in the 1500s and 1600s that are still standing today. Another reason the historic pueblos and other homes still exist is that the people inhabiting the adobe structures realized that a good cyclical maintenance program using like materials was essential for preservation.

(5) **Good thermal qualities**—Where adobe bricks, pressed-earth blocks, and rammed-earth walls remain dry, buildings retain heat well in winter. In summer, they are comfortably cool because the inside daytime temperature is usually lower than the outside temperature.

(6) **Termite-proof**—Adobe walls are unaffected by dry rot, termites, and other destructive insects.

(7) **Fireproof**—Walls made with adobe are not fire hazardous and structures can be made fireproof.

(8) **Painting is easily accomplished**—Adobe structures may be painted any color or shade desired. Latex paints usually adhere well to adobe surfaces. A small-scale test should be made before any paint is used.

(9) **Design and architecture**—Adobe construction permits design flexibility and uniqueness; it is a southwestern architectural style that is environmentally and sculpturally compatible with the western landscape.

(10) **Energy-efficient building material**—Adobe is an energy-efficient building material in manufacturing because it is a sun-dried, rather than fired, brick, not produced with high temperatures as is cement or masonry brick. Architect David Wright (1978) stated that it takes over 300 times more commercial energy to produce a concrete block equal in volume to a sun-dried adobe block. Adobe is also energy-efficient because in many cases the soil can be mined at the building site, further eliminating transportation costs.

(11) **Resistance to bullet penetration**—A CINVA-Rammade adobe wall (ten parts soil, one part portland cement), built with average-size adobes that measured 3½ x 5 /2 x 11½ inches, was subjected to a Galil (Israeli) machine gun test. Five shots at a 20-meter distance penetrated the adobe wall only 1½-2 inches (Lola, 1981).

Summary and conclusions

The use of adobe in construction has evolved in several of the arid and semiarid regions of the world as early as 7000 B.C. To this day, mud and soil are the primary building materials for the housing of at least 50% of the world's 5-billion population (Ferm, 1985). In the urban areas of developing countries, more than half the population has inadequate housing. The situation is worse in the rural areas where seven out of ten dwellings are substandard (Ferm, 1985).

In the southwest area of the United States, the Indian and Spanish populations have long used adobe to construct homes. This historic and cultural use of native soils has developed into the largest adobe industry in this country. New Mexico's adobe industry continues to maintain an average production rate of 3 to 4 million adobe bricks and pressed-earth blocks per year. A large segment of the local population, particularly the Indians and Spanish-Americans, continue to desire to build adobe houses of traditional architectural style. Interest in solar adobe construction has also made the adobe industry grow. It has been estimated that approximately 3% of the new homes built in New Mexico are adobe; an average of 500 to 600 new adobe homes are built each year (Gerbrandt and May, 1986). The majority of the new housing is in the Rio Grande valley and includes the major cities of Albuquerque, Santa Fe, Española, and Taos.

During the 1987 and 1988 field investigations in New Mexico, 33 commercial adobe-brick producers, 28 owners of pressed-earth-block machines, and 2 rammed-earth contractors were located. In 1987, 3,124,000 adobe bricks and 642,000 pressed-earth blocks were produced. Prices for the traditional (untreated) adobe bricks varied from 21 to 40¢ each, the semistabilized from 30 to 35¢ each, and the fully stabilized from 50 to 59¢ each at the adobe yard. The prices for the traditional (untreated) pressed-earth blocks varied from 25 to 35¢ each using the owner's local soil on site or a soil mixture delivered to the construction site or production yard. Most adobe bricks and pressed-earth blocks were of the standard 4 x 10 x 14-inch size.

In general, the pressed-earth blocks tested have higher compressive strength and modulus of rupture than adobe bricks made the traditional way with or without stabilizers; however, if stabilizers were not used, pressed-earth blocks were also as sensitive as the traditional adobe brick to water damage.

Mineralogy analyses of the clay-size fraction of the soils used in adobe bricks, pressed-earth blocks, and rammed-earth walls indicated that although the mineralogy varies greatly, expandable clay minerals (smectite and I/S) and nonexpandable clay minerals (kaolinite, illite, and chlorite) each constitute about 50% of the fraction. In addition, quartz and particularly calcite are very common.

Particle-size analyses of soils used by the adobe, pressed-earth, and rammed-earth industries indicated that the soils used by all three groups are about the same, but that the sand-and-larger–size (sand + -size) fraction is far more abundant than previously thought. Acceptable blocks can be made from material containing up to 89% sand + -size, and as little as 1% clay-size, particles. The soils used have a significant amount of calcite in all size ranges, and the water used to make the adobe mud contains a large amount of dissolved calcium salts that precipitate when the mud dries. The results show that highly competent bricks, blocks, and walls are used throughout the adobe, pressed-earth, and rammed-earth industries.

Environmental hazards related to the concentration of radon and the effects of earthquakes on homes do not appear to be significantly greater for adobe buildings than buildings constructed of other material, provided that adobe buildings are built to withstand these problems and are kept in good repair. In both cases, planning for and attention to possible problems preclude difficulties.

The continued growth of the adobe, pressed-earth, and rammed-earth industries in the state depends on the following: (1) ability of the adobe construction industry to compete with "stick" construction presently estimated at \$50 to \$60 per ft^2; (2) support and continued acceptance by HUD and other federal, state, and local governmental agencies of using native soils for construction; (3) availability of low-cost adobe soils near the major commercial adobe-brick yards and pressed-earth-block-production and rammed earth-construction sites; (4) development of better and less expensive stabilizers for producing water-resistant and waterproof adobe bricks and pressed-earth blocks; and (5) establishment of a strong adobe, pressed-earth, and rammed-earth organization that will improve specifications and promote the industry.

APPENDIX 1
Particle-size and clay-size-mineralogy analyses

Particle sizes (sand + , silt, and clay) and minerals of the clay-size fraction (particles less than 2 micrometers or <2 of adobe bricks, pressed-earth blocks, and rammed-earth production materials in New Mexico. Clay-mineral analyses are semiquantitative (parts in 10). FS, mixed-layer illite/smectite; tr, trace amount; –, not present,

Producer	Table no.	Map no. (Fig. 1A or 1B)	Particle-size percentages Sand +	Silt	Clay	Clay minerals Smectite	I/S	Illite	Kaolinite	Chlorite	Other minerals in clay-size fraction in order of abundance
A. D. Adobe Co.	4	1	85%	13%	2%	4	1	3	2	–	quartz and calcite
Adobe International	5	1	69%	22%	9%	3	tr	2	5	–	calcite and quartz
Adobe Bricks of New Mexico	4	2	81%	16%	3%	6	1	2	1	–	calcite
Adobes Unlimited	5	2	67%	31%	2%	1	2	3	4	–	calcite
Aguires Services	4	3	52%	45%	3%	1	3	2	3	1	quartz and calcite
Big "M" Sand & Cinder	4	5	34%	60%	6%	3	2	2	3	–	quartz and calcite
Corrections Industries	4	6	54%	40%	6%	–	3	3	4	–	quartz
(resample)	4	6	59%	36%	5%	2	3	3	2	–	calcite and quartz
Coyote Adobe, Inc.	5	5	72%	24%	4%	3	3	2	2	–	calcite, quartz, and feldspar
DeLaO Adobe Brick Mfg.	4	7	71%	21%	8%	1	4	3	2	–	calcite and quartz
Eloy Montano Sand & Gravel	4	8	61%	35%	4%	2	2	3	3	–	calcite and quartz
Gallegos Sand & Gravel	4	9	84%	10%	6%	2	4	1	3	–	calcite
Huston Construction Company	7	A	68%	25%	7%	1	4	3	2	–	calcite
(resample)	7	A	69%	25%	6%	2	4	2	2	–	calcite and quartz
Jaquez Construction	5	9	69%	26%	5%	2	2	1	5	–	calcite and quartz
Paul Martinez	4	10	55%	36%	9%	1	4	2	3	–	quartz and calcite
Medina's Adobe Factory	4	11	76%	9%	15%	1	5	2	2	–	quartz and calcite
Ralph Mondragon	4	12	54%	42%	4%	1	5	1	3	–	calcite and quartz
New Mexico Earth	4	14	78%	18%	4%	2	4	1	1	2	quartz and calcite
Northern Pueblo Housing Authority											
Nambe Pueblo	5	15	40%	55%	5%	2	2	4	2	–	quartz and calcite
Pojoaque Pueblo	5	15	57%	37%	6%	3	4	2	1	–	calcite
Picuris Pueblo	4	16	41%	55%	4%	3	3	2	2	–	calcite and quartz
Pueblo of Isleta Adobe and Cinder Enterprise	4	17	89%	10%	1%	2	3	2	3	–	calcite and quartz
(resample)	4	17	89%	10%	1%	2	3	2	3	–	calcite and quartz
Ridge Adobe	5	18	71%	24%	5%	tr	3	3	4	–	quartz, feldspar, and calcite
Rio Abajo Adobe Works	4	18	77%	21%	2%	1	1	2	6	–	quartz and calcite
Archie Rivera	4	19	83%	15%	2%	1	3	3	3	–	quartz, calcite, and feldspar
Jim Rivera	4	20	60%	31%	9%	1	2	1	6	–	quartz
Rodriguez Brothers	4	21	63%	30%	7%	1	4	3	2	–	quartz and calcite
Steve Romero	4	22	77%	19%	4%	4	2	2	2	–	calcite and quartz
Manuel Ruiz	4	23	73%	20%	7%	2	4	2	2	–	calcite, quartz, and feldspar
Roman Sandoval	4	26	27%	68%	5%	1	3	3	3	–	quartz
Candelario Saucedo	4	27	66%	26%	8%	2	2	2	4	–	calcite and quartz
Carl & Lorraine Steiner	5	21	55%	37%	8%	1	4	2	3	–	quartz and calcite
The Adobe Farm	5	24	50%	41%	9%	2	3	2	3	–	quartz
The Adobe Patch	4	28	80%	18%	2%	tr	2	5	3	–	calcite, dolomite, and quartz
Tim's Adobes	4	29	81%	8%	11%	1	4	3	2	–	calcite and quartz
Elias Vargas	4	31	83%	16%	1%	1	4	4	1	–	quartz and calcite
Trini Velarde	4	32	48%	47%	5%	2	3	2	3	–	calcite and quartz
Western Adobe	4	33	83%	13%	4%	2	4	1	3	–	calcite and quartz

APPENDIX 2
Physical properties of adobe bricks and pressed-earth blocks

For any building project, certain minimum requirements or specifications have been developed regarding the durability, strength, thermal characteristics, and fire safety of the construction materials (Long and Neubauer, 1946). In New Mexico, the building of adobe structures is regulated by specifications adopted from the Uniform Building Code and the New Mexico Building Code. The section on unburned clay masonry (Section 2412) of the New Mexico Building Code is detailed in Appendix 3 and lists the basic requirements for adobe bricks, pressed-earth blocks, and rammed-earth walls. Included are standards of compressive strength, modulus of rupture, and water resistance, as well as construction specifications.

The New Mexico Building Code requires that adobe bricks have an average compressive strength of 300 psi (pounds per square inch). This standard assures that all units from the tested-brick batch will resist a compressive force equal to 300 lbs for each square inch of surface area. The importance of this test for a relatively heavy material such as adobe is apparent when considering the great amount of weight a typical wall unit must resist.

Another major test required on all types of adobe bricks, pressed-earth blocks, and rammed-earth walls is the modulus of rupture test. This test helps indicate the relative cohesion of the materials that make up the various earth blocks and walls and the ability of those materials to resist the tension or shear forces that may result from settling of foundations, earthquakes, or wind forces.

Other tests used on semistabilized and stabilized adobe bricks and pressed-earth blocks determine the water-resistance quality of the bricks. The New Mexico Building Code requires that, for a treated (stabilized) adobe brick, the moisture content and the water absorption not exceed 4 wt%.

The code requires that samples of all bricks to be tested should be selected at random at a ratio of 5 units/25,000 bricks. Usually the selected bricks are from the same production batch, to assure a more representative range of values. The major tests that are usually completed by various commercial testing companies or by the United Nuclear Rock Mechanics Laboratory at the New Mexico Institute of Mining and Technology, Socorro, New Mexico, are described below.

Compressive strength

In order to provide the necessary at and smooth loading planes for this test, the adobes are capped with plaster of pans. Upon drying the adobe samples are placed in a standard hydraulically operated testing machine between two flat loading plates (Fig. 88). A loading rate of approximately 500 psi per minute is then applied to the plates. The compressive strength is calculated from the maximum load sustained before the brick shows evidence of failure.

Modulus of rupture

To establish the rupture strength of the adobe, a three-points loading method is used. A dry brick is placed symmetrically on two supporting parallel pipes two inches in diameter that extend across the full width of the adobe. A third two-inch pipe is placed on top of the brick midway between and parallel with the lower supports (Fig. 89). The load is applied to the top pipe at a rate of 500 psi per minute using a static loading device until the rupture occurs.

Water absorption

Four-inch^3 adobe specimens are cut from all the bricks being tested and are dried at 140°F (60°C) to a constant weight. Upon cooling the specimens are placed on a water-saturated surface in the moisture cabinet (Fig. 90). The weight gain from the absorbed water after seven days is determined and recorded as a percentage of the dry weight.

Moisture content

Four-inch^3 adobe specimens are first weighed and then dried to a constant weight. Moisture content is then calculated as the percentage of weight change relative to the dry weight (Fig. 91).

Simple field tests

In New Mexico, generally the small-scale adobe producers and builders have developed several simple techniques to evaluate the physical properties of adobes:

(1) For the compressive-strength test, various owners of adobe yards have been known to drive their cars,

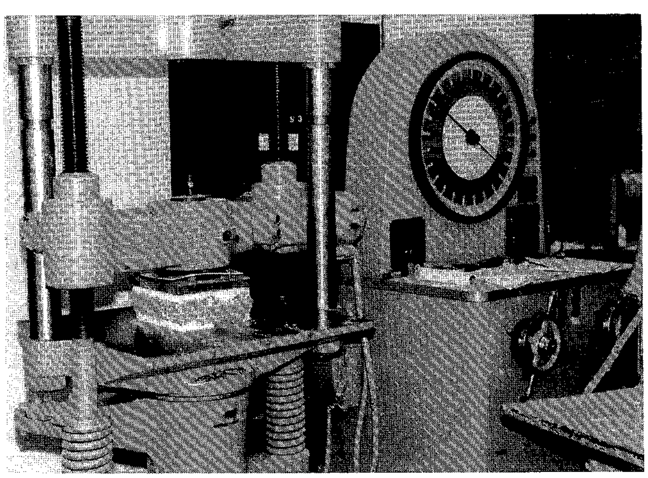


FIGURE 88—Adobe brick loaded between fixed and hemispherical mounting of hydraulically powered machine for compressive-strength test.

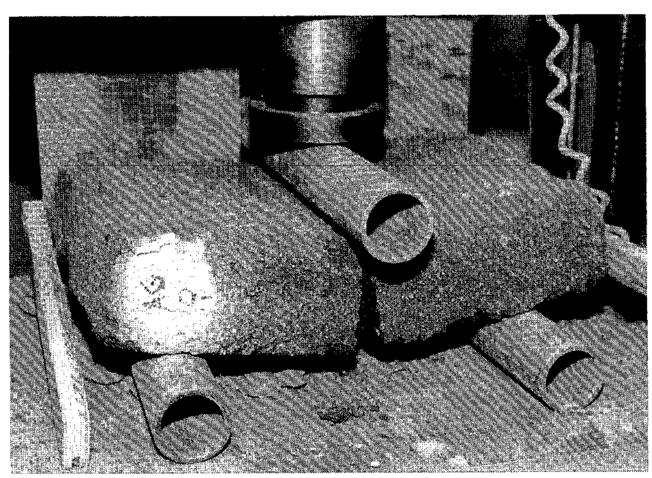


FIGURE 89—Three-points loading method used on typical adobe brick to establish rupture strength.

FIGURE 90—Four-inch^3 adobe-brick samples on wet, porous surface in moisture cabinet for water-absorption test.

FIGURE 91—Four-inch^3 adobe-brick samples drying for moisture-content determination.

pickups, and, in some cases, their front-end loaders atop a series of adobes.

(2) The drop test or modular of rupture test is outlined in McHenry's (1984) publication and consists of drop-ping a dry brick, on its corner, onto the ground from a height of three ft. A good brick will sustain little damage.

(3) The test for water absorption can be determined by using the blade of a common pocket knife to penetrate a brick. An easy penetration by the blade will indicate a poor quality or not completely dry brick.

Any or all of these tests can be performed in the field to determine the general character of soil materials. Many soils that appear to be poor performers can be upgraded by adding the proper materials.

APPENDIX 3
New Mexico Building Code, Section 2412

In most regions of the United States where adobe is widely used in construction, locally adopted amendments to the Uniform Building Code establish standard building specifications. In New Mexico, specifications for adobe are covered in Section 2412 of the 1988 New Mexico Building Code; an older version was approved and adopted by the Construction Industries Committee of the New Mexico Construction Industries Division on July 22, 1977. Prior to this 1977 version, which was developed under the auspices of the adobe industry and written by a team of four New Mexican adobe experts, the section on adobe had been regarded as severely limited and inconsistent in its coverage of the material and its specifications.

The method by which building codes in general are put together combines objective data gathering with the subjective interpretation of that data. Information derived from extensive engineering and construction experience and statistics collected from standardized laboratory tests all contribute to the store of practical and scientific knowledge about how a material behaves under a variety of conditions. However, the transition from raw data and information to a meaningful and workable building code relies on an interpretive and analytical process and ultimately on the quality of judgment of those individuals who produce the final written code.

Adobe codes have traditionally suffered from deficiencies in both areas of objective data gathering and subjective interpretation of the data. Until 1982, the amount of "official" data concerning adobe had been quite small relative to that of many other building materials.

Among the major revisions in the 1977 edition of the New Mexico Building Code were the legalization of untreated (traditional) adobes, already used throughout the state, and the removal of the requirement that buildings constructed with sufficiently stabilized adobe and mortar be coated with some other protective substance. In addition, many other minor revisions were included, such as the allowance of the use of wooden "gringo" blocks and soil for mortar, as well as changes in the required thicknesses of load-bearing walls.

The second revision of the adobe code was approved in 1983. This revision recognized stabilized adobes, untreated adobes, hydraulically pressed units (pressed-earth blocks), terrònes, burned adobes (quemados), and rammed earth. In the 1988 revision, characteristics of hydraulically pressed units (pressed-earth blocks) were qualified; a curing period of 14 days and physical-property tests were recommended. In addition, the allowed percentage of water absorption for stabilized adobes was increased from 2½ to 4 wt%.

Section 2412 of the New Mexico Building Code (Construction Industries Division, 1988) is reprinted below in its entirety. Any further questions concerning the code should be addressed to the Construction Industries Division, Bataan Memorial Building, Santa Fe, New Mexico 87503 (telephone: 505/827-6251).

CHAPTER 24—MASONRY

Sec. 2412.-Unburned Clay Masonry.

A. *General:* Masonry of unburned clay units shall not be used in any building more than two (2) stories in height. The height of every wall of unburned clay units without lateral support shall be not more than ten (10) times the thickness of such walls. *Exterior* walls, which are laterally supported with those supports located no more than 24 feet apart, are allowed a minimum thickness of 10 inches for single story and a minimum thickness of 14 inches for the bottom story of a two story with the upper story allowed a minimum thickness of 10 inches.

Interior bearing walls are allowed a minimum thickness of 8 inches. Upward progress of walls shall be in accordance with acceptable practices.

B. *Soil:* The best way to determine the fitness of a soil is to make a sample brick and allow it to cure in the open, protected from moisture. It should dry without serious warping or cracking. A suitable adobe mixture of sand and clay shall contain not more than 2% of water soluble salts.

C. *Classes of Earthen Construction:*

(1) *Stabilized Adobes.* The term "stabilized" is defined to mean water resistant adobes made of soils to which certain ad-mixtures are added in the manufacturing process in order to limit the adobe's water absorption. Exterior walls constructed of stabilized mortar and adobe require no additional protection. Stucco is not required. The test required is for a dried four-inch (4") cube cut from a sample unit and shall absorb not more than four percent moisture by weight when placed upon a constantly water saturated porous surface for seven (7) days. An adobe unit which meets this specification shall be considered "stabilized."

(2) *Untreated Adobes.* Untreated adobes are adobes which do not meet the water absorption specifications. Use of untreated adobes is prohibited within 4 inches above the finished floor grade. Stabilized adobes and mortar may be used for the first 4 inches above finished floor grade. All untreated adobe shall have an approved protection of the exterior walls.

(3) *Hydraulically Pressed Units.* Sample units must be prepared from the specific soil source to be used and may be cured for a period of fourteen (14) days. The building official may require additional test procedures outlined in paragraphs D, G, H, and I at his discretion.

(4) *Terrónes.* The term terrón shall refer to cut sod bricks. Their use is permitted if units are dry and the wall design is in conformance with this code [(Section 2412(a) of this code)].

(5) *Burned Adobe.* The term "burned adobe" shall refer to mud adobe bricks which have been cured by low temperatures kiln firing. This type of brick is not generally dense enough to be "frost proof" and may deteriorate rapidly with seasonal freeze-thaw cycles. Its use for exterior locations is discouraged in climate zones with daily freeze-thaw cycles.

(6) Rammed Earth.

(a) Soils: See Section 2412(b).
(b) Moisture Content: Moisture content of rammed earth walls shall be suitable for proper compaction.
(c) Forms: Suitable forms shall be used.
(d) Lifts and Compaction: Uncompacted damp soil shall be compacted in lifts not to exceed 6 until suitable compressive strength is achieved.
(e) Tests: Testing of rammed earth construction shall be in accordance with approved standards.
(f) Curing: The building officials may allow continuous construction of rammed earth prior to the full curing process, provided proper compaction methods are followed.

D. *Sampling:* Each of the tests prescribed in this section shall be applied to sample units selected at random at a ratio of 5 units/ 25,000 bricks to be used or at the discretion of the building official.

E. *Moisture Content:* The moisture content of untreated units shall be not more than four percent by weight.

F. *Absorption*: A dried four (4) inch cube cut from a sample unit shall absorb not more than four percent moisture by weight when placed upon a constantly water saturated porous surface for seven (7) days. An adobe unit which meets this specification shall be considered "stabilized."

G. *Shrinkage Cracks: No* units shall contain more than three shrink-age cracks, and no shrinkage crack shall exceed two (2) inches in length or one-eighth (1/8) inch width.

H. *Compressive Strength:* The units shall have an average compressive strength of 300 pounds per square inch when tested. One sample out of five may have a compressive strength of not less than 250 pounds per square inch.

I. *Modulus of Rupture:* The unit shall average 50 pounds per square inch in modulus of rupture when tested according to the following procedures:

(a) A standard 4 x 10 x 14 cured unit shall be laid over (cylindrical) supports two (2) inches from each end, and extending across the full width of the unit.
(b) A cylinder two (2) inches in diameter shall be laid mid-way between and parallel to the supports.
(c) Load shall be applied to the cylinder at the rate of 500 pounds per minute until rupture occurs.
(d) The modulus of rupture is equal to [$3WL/2Bd^2$] W= Load of rupture

L = Distance between supports
B = Width of brick
d = Thickness of brick

J. *Mortar:* The use of earth mortar is allowed if earth mortar material is of same type as the adobe bricks. Conventional lime/ sand/cement mortars of Types M, S, N are also allowed.

Mortar "bedding" joints shall be full SLUSH type, with partially open "head" joints allowable if surface is to be plastered. All joints shall be bonded (overlapped) a minimum of 4 inches.

K. *Use: No* adobe shall be laid in the wall until fully cured.

L. *Foundations:* Adobes shall not be used for foundation or basement walls. All adobe walls, except as noted under Group M Buildings, shall have a continuous concrete footing at least eight (8) inches thick and not less than two (2) inches wider on each side that support the foundation walls above. All foundation walls which support adobe units shall extend to an elevation not less than six (6) inches above the finish grade.

Foundation walls shall be at least as thick as the exterior wall. Where perimeter insulation is used, a variance is allowed for the stem wall width to be two (2) inches smaller than the width of the adobe wall it supports. Alternative foundation systems shall be approved by the building official.

All bearing walls shall be topped with a continuous belt course or tie beam (except patio walls less than six (6) feet high above stem).

M. *Tie Beams:*

(a) Concrete: Shall be a minimum of six (6) inches thick by width of top of wall. A bond beam centered to cover 2/3 of the width of the top of the wall by 6 inch thick shall be allowed for walls wider than 24 inches. All concrete tie beams shall be reinforced with a minimum of two No. 4 reinforcing rods at each floor and ceiling plate line. All bond beam construction shall be in accordance with accepted engineering practices.
(b) Wooden Tie Beam: Shall be a minimum of 6 inch wall thickness except as provided for walls thicker than 10" above. Wood tie beams may be solid in the six (6) inch dimension or may be built up by applying layers of lumber. No layer shall be less than one (1) inch. The building official shall approve all wooden tie beams for walls thicker than ten (10) inches.

N. *Wood Lintels:* Shall be minimum in size six (6) inches by wall width. All ends shall have a wall bearing of at least twelve (12) inches. All lintels, wood or concrete, in excess of nine (9) feet shall have specific approval of the building official.

O. *Anchorage:* Roof and floor structures will be suitably anchored to tie beams. Wood joists, vigas or beams shall be spiked to the wood tie beams with large nails or large screws.

Fireplaces shall be secured to the wall mass by suitable ladder reinforcement such as "durowall" or equivalent.

Partitions of wood shall be constructed as specified in Chapter 25 of the 1988 Uniform Building Code, wood and metal partitions may be secured to nailing blocks laid up in the adobe wall or by other approved methods.

P. *Plastering*: All untreated adobe shall have all exterior walls plastered on the outside with portland cement plaster, minimum thickness 7/8". Protective coatings other than plaster are al-lowed, provided such coating is equivalent to portland cement plaster in protecting the untreated adobes against deterioration and/or loss of strength due to water. Metal wire mesh minimum 17 gauge by one (1) inch opening shall be securely attached to the exterior adobe wall surface by nails or staples with minimum penetration of one and one-half ($1^1/2$) inches. Such mesh fasteners shall have a maximum spacing of sixteen (16) inches from each other. All exposed wood surfaces in adobe walls shall be treated with an approved wood preservative before the application of wire mesh. Alternative plastering systems shall be approved by the building official.

EXCEPTION:

(1) Exterior patio, yard walls, etc. need not have portland cement coating.

Q. *Floor Area:* Allowable floor area shall not exceed that specified under Occupancy. Adobe construction shall be allowed the same area as given in Type V-N construction.

R. *Wall Insulation:* All methods of wall insulation shall comply with the manufacturer's recommendations.

S. *Stop Work:* The building inspector shall have the authority to issue a stop work order if the provisions of this Section are not complied with. (See Section 202(b) of this code.)

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Glossary

adobe brick—a sun-dried mud brick extensively used throughout the southwest United States.

adobe layer (mechanical)—a self-propelled and hydraulically operated machine developed by the Hans Sumpf Company of California for molding adobe bricks; the mechanical adobe layer uses various metal molds to produce adobe bricks of different sizes.

adobe soil—a mixture of clay, silt, and sand deposits found in the basins of the southwest United States and used to produce sun-dried bricks, pressed-earth blocks, and rammed-earth walls.

adobero--(from the Spanish) a person engaged in the production of adobe bricks and the construction of adobe buildings.

alluvial—pertaining to particular types of, or mineral associated with, deposits made by flowing water.

alluvial fan—a fan-shaped deposit of gravel, sand, and fine materials (clay and silt) dropped by a stream where the gradient lessens abruptly.

alluvium—soil material (clay, silt, sand, and gravel, or similar unconsolidated detrital material) deposited on land by streams and local wash.

arroyo—a channel or gully of an ephemeral stream, usually dry but can change into a temporary watercourse for a short-lived torrent after a rainfall.

asphalt emulsion—asphalt globules of microscopic size which are surrounded by and suspended in a water medium (International Institute of Housing Technology and California State University, Fresno Foundation, 1972).

basin—in the southwest United States, a depression on the surface of the land (a broad topographic low between mountain ranges), usually caused by subsidence, which may contain extensive sedimentary deposits of adobe soil.

bolson—an extensive flat alluvium-floored basin, into which drainage from surrounding mountains flows toward a central depression; a basin with internal drainage.

British thermal unit (Btu)—a measurement representing the amount of heat necessary to raise 1 lb of water (1 pint) 1°F.

caliche—a secondary (in-place) accumulation of calcium carbonate found in many soils of the southwest United States.

chlorite—a group of platy, usually greenish minerals characterized by magnesium and iron aluminosilicate compositions; can occur in clay sizes as well as in coarsely crystalline masses.

clay—a fine-grained, natural, earthy material composed primarily of hydrous aluminosilicates with grain diameters less than 0.002 mm (<2 micrometers or $<2\ \mu m$).

cohesion—the ability of various particles to stick together (Wolfskill and others, 1970).

colloid—a subdivision of suspended matter in which the particle size ranges between 5 and 200 millionths of a mm (Bateman, 1951).

compressive strength—a physical property of a material that indicates its ability to withstand compressive forces, usually expressed in *psi*.

crusher fines—finely crushed or powdered material (gravel, silt, and clay), but not necessarily in the correct ratio for adobe-brick production; an engineering term for the clay-and silt-sized soil particles (diameters less than 0.074 mm) passing U.S. Standard Sieve Mesh Number 200.

curing—a time period during which the action of water in a stabilized soil mass causes the mass to be cemented together by the stabilizer (Wolfskill and others, 1970).

detrital—pertaining to or formed from detritus; the term is often used to indicate a source from outside the depositional basin.

dry-bulb temperature—a measure of the air's cooling capacity.

durability—the resistance of a material to weathering and erosion.

earthquake—a sudden motion or trembling in the earth caused by abrupt release of slowly accumulated strain (by faulting or by volcanic activity).

effective U-value–value determined (in masonry-mass walls) as a factor of the resistance to the transfer of heat and of the capacity to hold heat.

eolian—pertaining to the wind.

erosion—the physical and chemical processes by which a material is removed, including the processes of weathering, mechanical wear, and transportation of the material.

gypsum—common evaporite mineral used in making plaster of paris ($CaSO_4 \cdot 2H_2O$).

Hans Sumpf brick-molding machine—patented by H. C. Sumpf of Fresno, California, in 1946; the self-propelled, hydraulically operated adobe layer is capable of producing 25 4 x 10 x 14-inch adobe bricks per laydown; five machines were in use in New Mexico in 1988.

Holocene (Recent)—the interval of geologic time since the retreat of the last intercontinental ice sheets from North America and Eurasia, roughly 10,000 years ago to the present; also, the rocks and deposits formed during that time.

illite—a general name for a group of three-layer, mica-like clay minerals, relatively high in potassium with no expanding lattice characteristics.

impermeable—the ability of a material to restrict the flow or seepage of water to a negligible amount (Wolfskill and others, 1970).

jacal—a framework of vertical wooden poles and branches covered and bound together with mud.

kaolinite—a common two-layered aluminum-rich clay mineral and group ($Al_2Si_2O5(OH)_4$).

kiln—an oven, furnace, or heated enclosure used for processing bricks by burning or firing.

loam—a rich, permeable soil composed of a crumbly mixture of relatively equal and moderate proportions of clay, silt, and sand particles, and usually containing organic matter; it usually implies fertility; topsoil.

mechanized technique of adobe-brick production—the use of powered mixers, front-end loaders, and mechanical adobe layers to produce adobe bricks on a large scale.

micrometer—a unit of length equal to one-thousandth of a millimeter; symbol Rm.

mineralogy—the science of the. study of minerals. mixed-layer clay minerals—a random or ordered interstratification of clay-mineral groups; generally interstratification of nonexpanding and expanding layer lattices such as illite and smectite (I/S) or chlorite and smectite.

modulus of rupture—a physical-property measure indicating the relative cohesion of the materials that make up the adobe and the ability of the material to resist tension or shear forces, usually expressed in *psi*.

moisture content—the amount of water contained in soil material expressed as the weight of the water divided by the weight of the dry soil material in percent (Wolfskill and others, 1970).

molding forms—a single or multiple mold of a particular size usually made of wood into which the mixed adobe soil is placed to produce a uniform brick.

mortar—a material used in a plastic state which can be troweled and which becomes hard in place to bond together building blocks.

mosque—a temple of worship in the religion of Islam.

New Mexico Building Code—used in conjunction with the broad principles outlined in the *Uniform Building Code;* this set of, amendments was adopted in its most recently revised form by the New Mexico Construction Industries Division in 1982 and 1988; the local code addresses construction concerns about building materials and conditions specific to the State of New Mexico; regulations concerning the use of adobe are handled in Section 2412 of the most recent code.

pallet—a flat wooden board base used to stack and store adobe bricks, designed to permit a forklift to lift the adobes and pallet on and off a flatbed truck.

pediment—a gently sloping plain at the foot of a mountain range in an arid region, usually covered with a veneer of *alluvium*.

pedogenic—pertaining to soil formation.

piedmont plain—a broad, continuous slope or gently inclined detrital surface extending along and from the base of a mountain range out, into, and around a basin, formed by the coalescence of a series of separate but confluent alluvial fans; a bajada.

pisé—(from the French) "pisé-de-terre" meaning rammedearth–type adobe construction (Wolfskill and others, 1970).

plasticity—the ability of a moist soil to be deformed and hold its shape; this indicates that the soil has cohesion and contains clay-size particles (Wolfskill and others, 1970).

Pleistocene—the older of two epochs in the *Quaternary*, from about 2 million years to 10,000 years ago; also, the rocks and deposits formed during that time.

pressed-earth block—a type of adobe brick made from *traditional or stabilized adobe* material pressed into dense bricks of various sizes using either a hydraulically operated gasoline- or diesel-powered machine or a hand-operated press (the CINVA-Ram).

psi—pounds per square inch (lbslinch^2).

puddled adobe—adobe mud patted by hand into a wall shape without the use of wooden forms.

pugmill—a machine in which materials (such as clay and water) are mixed, blended, or kneaded into a desired consistency.

Quaternary—the interval of geologic time from about 2 mil-lion years ago to the present, consisting of the *Pleistocene* and *Holocene (Recent)* epochs; also, the rocks and deposits formed during that time.

quemado (burnt adobe)—a sun-dried adobe brick that has undergone a modified low-firing process.

radon—a colorless, odorless, heavier-than-air, radioactive gas that is derived directly from the breakdown of radium-126 (^{126}Ra), one in a chain of radioactive elements produced from the radioactive decay of uranium-238 ('U).

rammed earth—damp or moist earth that is tamped into a wall between temporary, movable forms (Middleton, 1987); also known as *pise* construction.

R-value—a measure of the ability to retard heat flow, rather than the ability to transmit heat; R is the numerical reciprocal of U, thus R 1/U; R is used in combination with numerals to designate thermal-resistance units (R-11 equals 11 resistance units); the higher the R, the higher the insulating factor; all insulation products having the same R-value, regardless of material and thickness, are equal in insulating value (New Mexico Energy Institute, 1977).

sand—individual rock or mineral fragments in a soil that range in diameter from 0.05 to 2 mm (Folks, 1975); in this report, the sand size ranges in diameter from 0.0625 to 2 mm.

sand +—individual rock or mineral fragments coarser than 0.0625 mm (sand-and-larger–size particles).

seismically active area—a region that may be affected by earthquakes or earth vibrations.

semimechanized technique of adobe-brick production—a method similar to the traditional handcrafted method of adobe-brick production except for the use of some mechanical equipment—usually a front-end loader and a series of ladder molding forms.

semistabilized adobe—classified as a water-resistant adobe brick because of the addition of a small amount of asphalt emulsion (4 wt% or less).

shrinkage—the decrease in volume of soil material caused by evaporation of water (Wolfskill and others, 1970).

silt—individual mineral particles in a soil that range in diameter from the upper limit of clay (0.004 mm) to the lower limit of fine sand (0.05 mm; Folks, 1975); in this report, the silt size ranges in diameter from 0.002 mm (2 μm) to 0.0625 mm.

slurry—a mixture of soil and water that results in a soupy liquid that is easily poured into wooden molding forms or is used as mortar.

smectite—a common clay-mineral group consisting of three-layer units with high expanding interunit positions and large cation exchange capacity.

stabilization—the improvement of soil properties by the addition of materials which will either cement the soil, waterproof the soil, or reduce volume changes (Wolfskill and others, 1970).

stabilized adobe—the fully stabilized adobe (referred to by the *New Mexico Building Code* as a "treated adobe"); de-fined as containing a sufficient amount of stabilizer to limit a brick's water absorption to less than 4 wt% in seven days.

stabilizer—a material such as asphalt emulsion, portland cement, lime, or one of many other chemicals that is added to *adobe soil to* waterproof or increase the weathering resistance of an adobe brick, pressed-earth block, or rammed-earth wall.

steady-state condition—the state when heat energy is passing uninterrupted from one side of the wall to the other at a constant rate.

strength—the ability of a material to resist applied forces; the strength of a soil mix is normally considered the strength in shear stress and is expressed in *psi* (Wolfs" and others, 1970).

terrace—one of a series of level surfaces in a stream valley, elongated parallel to the stream channel, representing the dissected remnant of an abandoned floodplain or valley floor produced during a former state of erosion or deposition.

terròn—(from the Spanish) meaning "a flat clod of earth"; the type of adobe brick made of cut sod or turf material found in the floodplain areas of the Rio Grande.

Tertiary—the interval of geologic time from about 65 to 2 million years ago; also, the rocks and deposits formed during that time.

traditional adobe—an untreated, sun-dried adobe made with soil composed of a uniform mixture of clay, sand, and silt; usually straw is added to the *adobe soil*.

traditional handcrafted, technique of adobe-brick production—the process of making adobe bricks by hand, with-out the use of any mechanized equipment.

turtle-back adobe—adobe mud formed by hand into turtle-like shapes on the ground, allowed to dry, and then placed into a wall.

U-value--coefficient of heat transmission expressed in units of btu per ft'/hr/°F (the time rate of heat flow); the U-value applies to combinations of different materials used in a series along ,the heat-flow path, such as single materials that comprise a building station, the air-space cavities, and the surface-air film on both sides of the building element (New Mexico Energy Institute, 1977).

Uniform Building Code--a standard code of building specifications established by the International Conference of Building Officials and adopted by local construction regulating agencies in most states; the code is founded on broad-based performance principles and is dedicated to the development of better building construction and greater public safety through the establishment of uniform building laws.

water absorption—the taking in of water into a soil mass (Wolfskill and others, 1970).

Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CONVERT	MULTIPLY BY	TO OBTAIN
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide* by the factor number to reverse conversions.
Exponents: for example 4.047×10^3 (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

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