Chapter 8
Earth Construction

8.1 General

There is no consensus about the date when man began to use earth for construction purposes. Minke (2006) mentioned that this may have happened over 9,000 years ago, grounding its beliefs on the fact that earth block (adobe)-based dwellings discovered in Turkmenistan dated from a period between 8000 and 6000 BC. Pollock (1999) refers that the use of earth for construction dates from the period of El-Obeid in Mesopotamia (5000–4000 BC). Berge (2009) mention that the oldest examples of adobe blocks, which were discovered in the Tigris river basin date back to 7,500 BC so earth construction could have been used for more than 10,000 years. It is not very relevant, whether the earth construction began more than 9,000 or over 10,000 years ago but it is not far from the truth that the earth construction began with early agricultural societies, a period whose current knowledge dates from 12000 BC to 7000 BC. There are countless cases of earth buildings built thousands of years ago that last to the twenty-first century. Even the Great Wall of China whose construction began about 3,000 years ago has extensive sections built on rammed earth. Evidences also show the use of earth construction by the Phoenicians in the Mediterranean basin including Carthage in 814 BC. The Horyuji Temple in Japan has rammed earth walls built 1,300 years ago (Jaquim 2008). This author refers to the existence of rammed earth-based buildings in the Himalayan region built in the twelfth century. Adobe-based building structures are common in Central America. The ruins of the city of Chanchán in Peru are among the most ancient earth based constructions (Alexandra 2006). The village of Taos in New Mexico is another example of ancient earth constructions (1000–1500 AC). Another good example is the city of Shibam in Yemen with earth buildings up to 11 floors that were built hundred years ago (Helfritz 1937). Currently almost 50% of the world's population lives in earth-based dwellings (Fig. 8.1).

The majority of earth construction is located in less developed countries, however, this kind of construction can also be found in Germany, France or even

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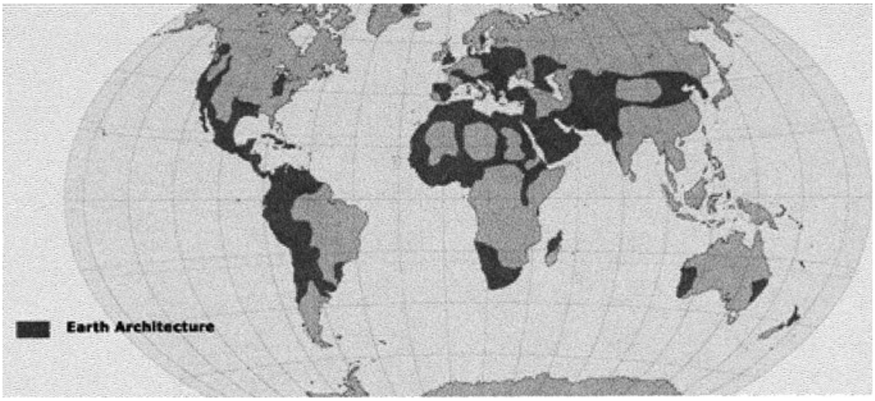


Fig. 8.1 Areas with earth construction

in the UK, a country that has an excess of 500,000 earth-based dwellings. MacDougall (2008) used interviews and site inspections to show that straw-bale construction and rammed-earth construction are gaining growing interest in the UK. The same author reveals that the lack of scientific data and the lack of experience by the mainstream construction industry in using these materials remain barriers to be overcome. Other authors (Desborough and Samant 2009) show that straw construction complies with building regulations and the UK climate, being a feasible option for this country. Williams et al. (2010) also show that thermal performance of earth block masonry meets current UK Building Regulation requirements. Earth construction has also increased substantially in the US, Brazil and Australia, largely due to the sustainable construction agenda, in which earth construction assumes a key role. In France investigations on earth construction were carried out by CRATerre, a laboratory founded in 1979 and linked to the School of Architecture in Grenoble, which acquired an institutional dimension in 1986 trough the recognition of the French Government. Houben et al. (2008) mention the success of an educational project undertaken in CRATerre, consisting of a scientific workshop with over 150 interactive experiences that in just 4 years had been attended by 11,000 visitors. As for Germany, Schroeder et al. (2008a) report the existence of vocational training in earth construction as well as courses that confer the expert title in this area. Three universities offer earth construction courses respectively, the University of Kassel, the University of Applied Sciences in Potsdam and the University of Weimar (Bauhaus). Earth construction is not only dependent on adequate training but also dependent on specific regulations. Several countries already have earth-construction-related standards. In Germany the first Earth Building Code dates back to 1944, but only in 1951 with DIN 18951, these regulations have been put into practice. In 1998 the German Foundation for the Environment disclosed several technical recommendations know as the "Lhmbau Regeln" (Schroeder et al., 2008a). Over the years they have been adopted by all the German states with the exception of Hamburg and Lower-Sáxony. A revised version of the "Lhmbau Regeln" was passed in 2008. Australia was one of the first countries to have specific regulations on earth construction. The Australian regulations were published in 1952 by the Commonwealth Scientific and Industrial Research Organization (CSIRO) under the designation of "Bulletin 5". This document has been revised in 1976, 1981, 1987 and 1992. In 2002 this document has been replaced by the Australian Earth Building Handbook (Maniatidis and Walker, 2003). In 1992 the Spanish Ministry of Transport and Public Works published a document entitled "Bases for design and construction with rammed earth" to support not only rammed earth but also adobe-based buildings (Maniatidis and Walker, 2003). Recently Delgado and Guerrero (2007) stated that earth construction is not yet regulated, posing several drawbacks such as the need to contract a building insurance during a 10 year warranty period. The United States has no specific regulations related to earth construction; but seismic regulations must be addressed by these constructions. Since 1991 New Mexico has a state regulation concerning rammed earth and adobe-based constructions (Maniatidis and Walker 2003). New Zeland has one of the most advanced legal regulations on earth construction which is structured in three distinct parts.

NZS 4297:1998—Engineering Design and Earth Buildings—Establishes performance criteria for mechanical strength, shrinkage, durability, thermal insulation and fire resistance;

NZS 4298:1998—Materials and Workmanship for Earth Buildings—Defines requirements for materials and workmanship;

NZS 4299:1998—Earth Buildings not Requiring Specific Design—This part is applicable for buildings with less than 600 m^2 (or 300 m^2 per floor) and provides constructive solutions for walls, foundations and lintels. In New Zealand the earth building regulations are dependent on the building height. For heights less than 3.3 m there is no need for a specific project, although the earth walls should respect the provisions of NZS 4298:1998. As for the buildings with a height between 3.3 and 6.5 m they shall be designed in accordance with NZS 4297:1998 (Jaquin 2008). Since 2001 Zimbabwe adopted a regulation based on the "Code of Practice for Rammed Earth Structures" (Keable 1996), which is composed by six sections: 1) Materials, 2) Formwork, 3) Foundations, 4) Wall design according to compressive strength, water absorption and erosion, 5) Masonry structural stability and 6) details and finishes. Shittu (2008) mentioned the following constraints of earth construction: lack of skilled craftsmanship; absence of earth-related courses and most of all the fact that earth construction is associated with a low-income status.

8.2 Techniques

Earth construction encompasses several techniques, the most usual being:

- Wattle and daub;
- Rammed earth (including earth projection);
- Earth bricks (adobe) or compressed earth blocks (CEB).

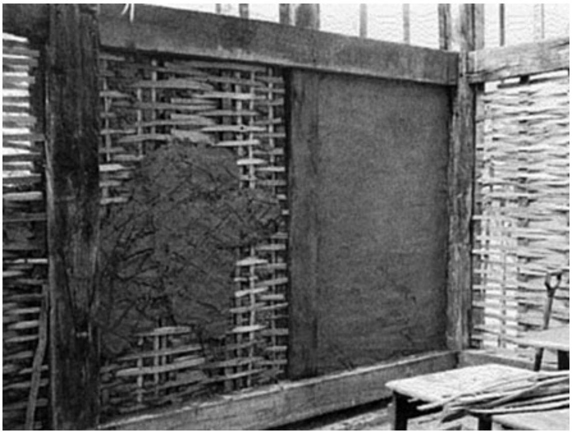


Fig. 8.2 Wattle and daub

In the wattle and daub technique the earth is pressed against a woven lattice of wooden strips (Fig. 8.2).

8.2.1 Rammed Earth

This technique means the compaction of moist earth (stabilized or not) inside a wooden formwork. In the earth projection technique the earth is previously stabilized and then it is projected against an inside formwork layer as happens in shotcrete works (Fig. 8.3).

The rammed earth technique requires a low amount of water, therefore it is suitable for regions where water is scarce. After placing the wooden formwork (Fig. 8.4) it is filled with a 10 cm earth layer followed by a ramming phase and then a new 10 cm layer are added and rammed. Afterwards, the wooden formwork is removed and then placed at a higher level until the desired hall height is reached.

Traditional compaction methods are made manually using heavy wooden tampers (Fig. 8.5a). This process requires quick tampering in order that the compression is performed with moist soil to obtain the desired cohesion. Modern rammed earth uses metal formwork and pneumatic rammers (Fig. 8.5b). Therefore, the time for compaction is shorter than in the traditional processes and is also less tiring. Middleton (1992) suggests the use of pneumatic rammers with circular heads and a diameter between 70 and 150 mm. The foundations of rammed earth walls are made of stone masonry or even concrete to prevent the rise of moisture by capillary action.

Regarding the minimum thicknesses of these walls, different authors suggest different values. According to Schroeder et al. (2008b) the German Earth Code mentioned a minimum of 32.5 cm for rammed earth walls.

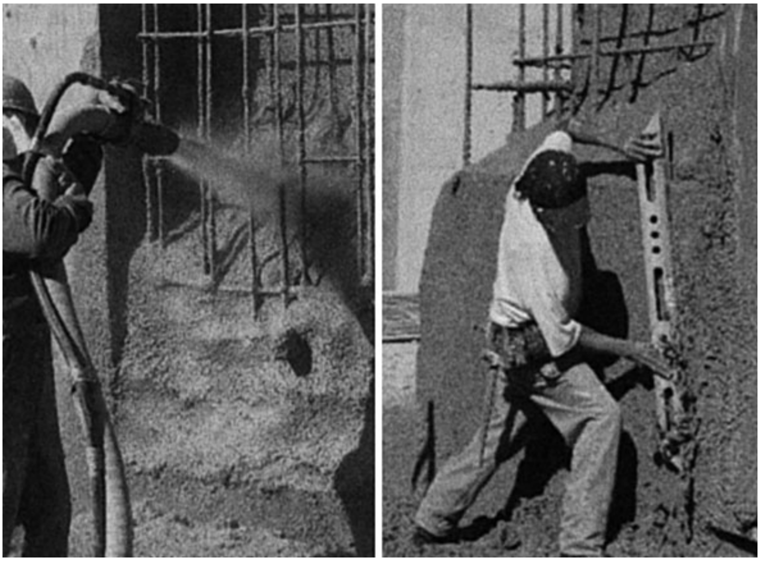


Fig. 8.3 Earth projection

Fig. 8.4 Conventional wooden formwork

8.2.2 Adobe

Adobe is a very simple earth building technique being the most ancient . The word adobe comes from the Arab “attob” which means sun-dried brick (Rogers and Smalley 1995). The production of adobe bricks consists of filling wooden molds with moist earth which are then placed in the sun to dry. When the adobe dries shrinkage cracks could appear in its surface, so some authors (Neumann et al. 1984, Quagliarini and Lenci 2010) suggest the use of straw or other vegetable fibres to prevent this. However, this position is not unanimous because vegetable

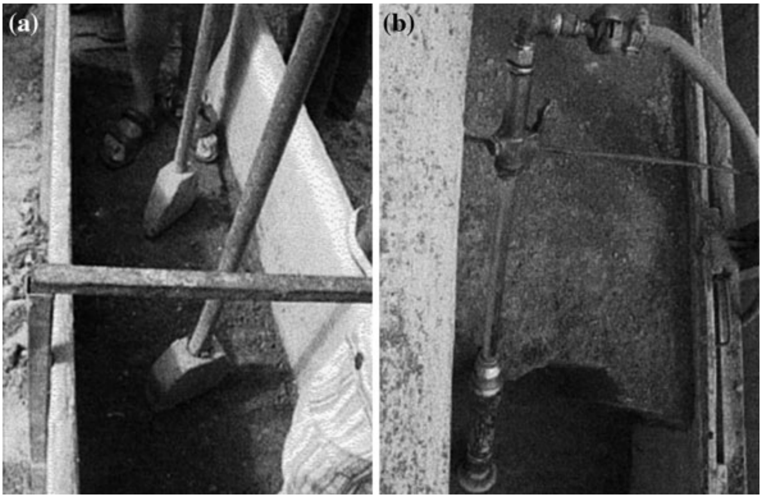


Fig. 8.5 Rammers for earth construction: **a** Manual, **b** Pneumatic

Fig. 8.6 Adobe wall construction

fibres could rot leading to the appearance of fungi. Adobe masonry is very simple to build as it is conventional masonry (Fig. 8.6).

Adobe bricks are usually laid using an earth-based mortar to ensure greater adhesion between the different materials and prevent shrinkage cracks. Afterwards, the adobe masonry can be left plastered with an earth-based mortar or it can be without any covering.

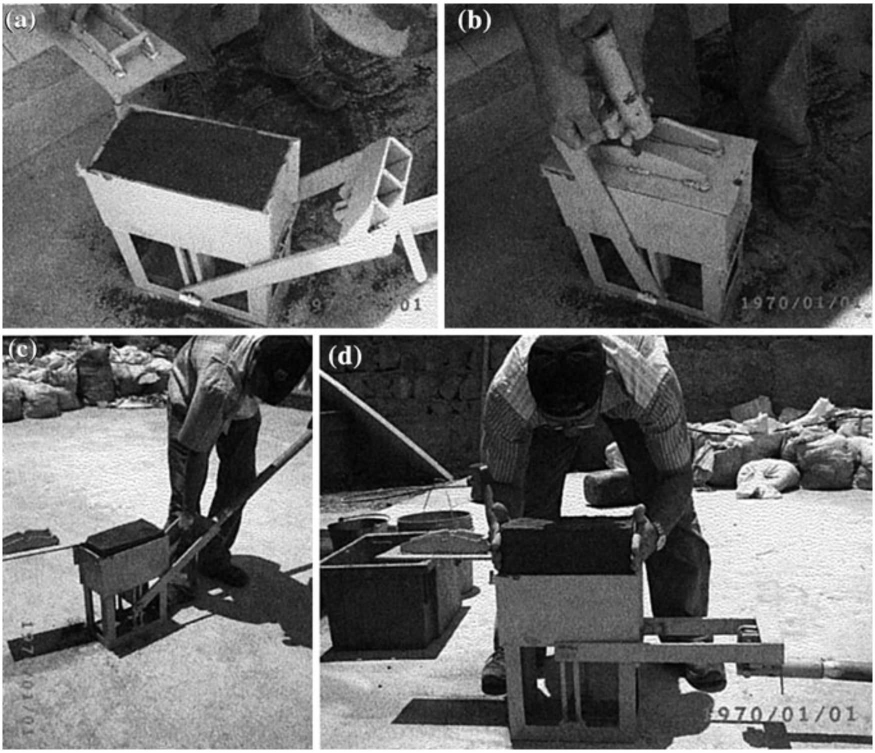


Fig. 8.7 Execution of a CEB with the Cinva-ram: **a** Filling the mold, **b** Compression of the earth, **c** Elevation of the block, **d** Removing the block

8.2.3 Compressed Earth Blocks

CEB represents an evolution of adobe bricks by using a specific device to compress the earth inside a mold. The pressure can be carried out manually or mechanically. The earth consistency is similar to that used in rammed earth allowing for the production of earth blocks that are heavier and more resistant than adobe bricks. The first machine used to make CEB was the CINVA-Ram created by Raul Ramirez in the International American Housing Centre (CINVA) in 1956 (Mukerji 1986). Figure 8.7 shows how to make a CEB with the CINVA-Ram.

Several other block making machines are also used like the Astram machine, developed in the mid 1970s at the Centre for Application of Science and Technology for Rural Areas in India, the CETA-Ram which is a modified CINVA-Ram developed in 1976 at the Centre of Appropriate Technical Experimentation in Guatemala (Mukerji 1986), the multi-block Brepak developed in 1980 at Building Research Establishment at Watford, England (Webb 1983), the CTA Triple-Block Press developed in 1982 at the Centre for Appropriate Technology in Paraguay and many others (Mukerji 1986). CEB produced manually require more manpower and

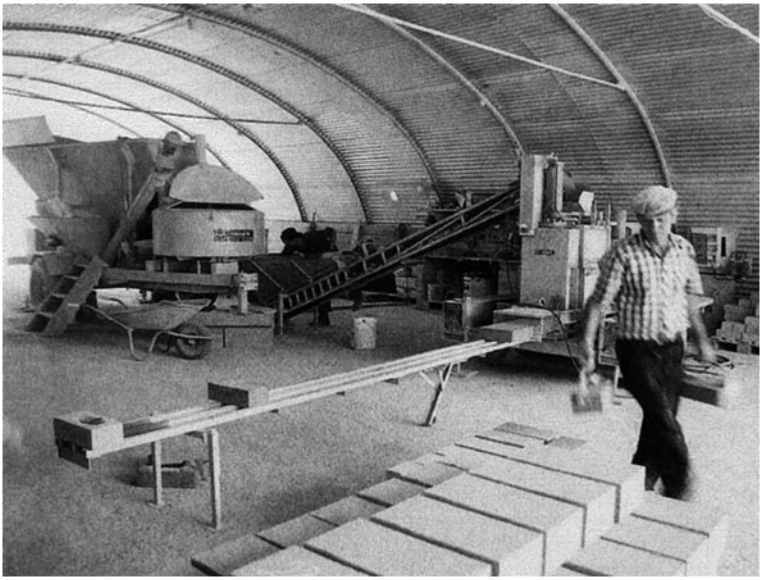


Fig. 8.8 Hydraulic machine for CEB production

are more time-consuming, however, they are cost-effective and could be made on-site reducing transportation costs. According to Shittu (2008) the success of the Cinva-Ram depends on the type of soil and sometimes the compression just expels the water leading to the disintegration of the earth block. When using a hydraulic machine (Fig. 8.8) the process is faster especially on machines that compress several blocks at once. These blocks show a higher mechanical resistance than the blocks made with Cinva-Ram and they also show a high resistance to water exposure. The mobility of hydraulic machines also allows for on-site production reducing transportation costs.

8.3 Earth Stabilization

The soil used in earth construction consists only in its mineral phase excluding the organic phase usually present in the first layers. This phase consists of mineral particles including clays, silts and sandy material, which are mixed together in varying proportions. The behavior of a soil depends not only on the amount of clay, silt and sand but also on the amount of water present in soil. This water encompasses the free water beneath the freatic level, the capillary water which is retained in the vicinity of the contact points of solids and finally the adsorbed water, i.e. the water held on the surface of the particles (with less than 0.002 mm) by electrochemical forces (Correia 1995). In order to understand the properties of the soil one must first characterize it using specific tests. The characterization of the mineral phase of a soil is carried out through tests that allow quantifying different types of properties, including its dimensions, its mechanical behavior and its deformation behavior for a certain level of humidity. These tests can be subdivided into two major groups, expedite tests to be held on-site that have a low level of confidence and laboratory tests made according to standard procedures.

8.3.1 On-Site Tests

These types of tests allow some initial conclusions about the type of soil available on-site, without the need for laboratory testing which is always expensive. The following tests are an adaptation of the tests used by the French group CRATerre and cited by Eusébio (2001):

a. Color observation: Soils with a high content of organic matter have a dark color. Pale soils mean the presence of feldspar or quartz sand. Red soils may be due to the presence of iron oxides.
b. Smell test: Soils with a high content of organic matter have a strong smell of humus, which is enhanced by heating or moistening of the soil.
c. Touch test: When rubbing a sample of soil between the hands, one perceives the presence of a sandy soil if it is rough. Plastic soils (when moist) indicate a high amount of clays.
d. Brigthness test: A ball of soil slightly moist and cut by a knife, will have opaque surface if there is a predominance of silt or will have a shiny surface if there is a predominance of clay.
e. Adherence test: In this test a ball of soil slightly moist is penetrated by a spatula. If the penetration is difficult and the earth sticks to the spatula, it is a clay soil. If the spatula enters and gets out easily is a sandy soil.
f. Sedimentation test: This test is an easy way to measure the sand, silt and clay content in a soil sample. First a bottle with 1 l of volume is filled up to ¼ of its capacity with soil and then it is filled with water. The bottle is shaken and allowed to stand for an hour, the procedure is repeated twice. After this procedure it is possible to measure the thickness of the layers of sand, silt and clay with a ruler.
g. Expedite sieving followed by visual test: This test uses loose dry soil and two sieves series ASTM, No. 200 (0.074 mm) and No. 10 (2 mm). The soil sample is passed on sieve No. 200 and the retained portion is passed on sieve No. 10. Comparing the volume of the soil that passed in each sieve it is possible to give a rough characterization: If the volume of the soil that passes sieve No. 200 is larger than the retained soil we are in a presence of a clayey soil. If the inverse situation occurs the soil is sand based. When using sieve No. 10, if the volume of the soil passed is lesser than the volume of the soil retained, the soil is a coarser one. When the inverse occurs the soil is sandy based.

h. Water retention test: A sample of soil is passed trough a sieve with a mesh of 1 mm. With a little volume of water a soil ball with a size of an egg is made. The soil ball is held in one hand and struck repeatedly with the other hand until the water appears on its surface. In a sandy soil ball the water appears on the surface after 5–10 strikes. A clayey soil or a silty clay requires 20–39 strikes. When there is no reaction the soil has a high clay content.

8.3.2 Laboratory Tests

Water content: In this test the mass of a sample of soil is compared before and after being dried in an oven at 105°C.

Organic matter: In order to estimate the organic matter content in the soil it must be heated at 400°C. Then one has to compare the mass differences before and after heating.

Particle size analysis: The test identifies the mass percentages of sandy soil above 0.074 mm (ASTM sieve No. 200), obtained by sieving it through a series of standard sieves. To identify the different constituents of the soil below 0.074 mm (silt and clay) it is necessary to use the sedimentation test. The soil is placed in a liquid suspension to determine the settling velocity which is dependent on the diameter of the particles through the Stokes law.

Atterberg limits: These limits allow knowing the behavior of a soil fraction below 0.4 mm according to their water content. They include the SL, the liquid limit (LL), the plastic limit (PL). The plasticity index (PI) is obtained by the difference PI = LL−PL. The shrinkage limit (SL) is the water content where further loss of moisture will not result in any more volume reduction. The LL is the water content obtained on the Casagrande device, a metal cup with a clay sample. In this test a groove was cut through the clay sample with a spatula, and the cup is repeatedly dropped 10 mm onto a hard rubber base during which the groove closes up gradually as a result of the impact. The moisture content at which it takes 25 drops of the cup to cause the groove to close over a distance of 13.5 mm (0.53 in) is defined as the liquid limit (LL). The PL is the water content that leads an earth cylinder with 3 mm diameter to crumble. If the cylinder crumbles with less than 3 mm it has too much water.

Proctor compactation test: The Proctor test is used to determine the water content that leads to the maximum density. This test uses a soil sample with less than 4.76 mm (Sieve No. 4) to which an increasing water content is added. The soil sample is compressed into three layers with 25 blows per layer, with a manual or mechanical device (with a mass of 2.49 kg falling by 30.5 cm). The soil density and the water content are registered allowing the determination of the minimum water content that leads to the maximum density. However, some authors argue that the Proctor test has a low compaction energy leading to a higher optimum water content than that recommended for rammed earth with a pneumatic

Table 8.1 Dry density after the Proctor compaction test (Doat et al. 1979)

Dry density (kg/m^3)	Soil classification
1,650–1,760	Mediocre
1,760–2,100	Very satisfactory
2,100–2,200	Excellent
2,200–2,400	Exceptional

Table 8.2 Atterberg limits of the soil used for earth construction (Doat et al. 1979)

	Recommended	Maximum and minimum
PI	7–18	7–29
LL	30–35	25–50
PL	12–22	10–25
SL	Optimum water content	8–18

Table 8.3 Soil plasticity classification (Doat et al. 1979)

Plasticity	PI
Week	5–10
Medium	10–20
High	>20

tamper. Maniatidis and Walker (2003) refer to an expedite way to obtain the optimum water content using a "drop test". A soil ball with a certain water content is dropped from a height of 1.5 m. If the ball does not break, the water content is excessive, if it breaks into several pieces then the water content is low.

Compressive strength test: This test is similar to the test used to assess the compressive strength of concrete or bricks. An earth specimen is submitted to an axial load until the rupture occurs.

8.3.3 Properties and Soil Classification

The CRATerre group classifies the soil according to its dry density after the Proctor compaction test (Table 8.1).

The same authors make some recommendations concerning the Atterberg limits of the soil used for earth construction (Table 8.2).

According to Michel (1976), the most suitable soils to be stabilised present low PI values. Doat et al. (1979) present a classification for the PI of a soil (Table 8.3).

The activity (A) of a soil or Skempton index is the PI divided by the percentage of clay-sized particles (lesser than 2 μm). A higher (A) means a higher deformability (Table 8.4).

Table 8.5 shows the characteristics of two soils used for earth construction.

Bahar et al. (2004) recommend that the optimum water content should be between 9.5% and 11%. According to the standard NZS 4298 the water content to be used in rammed earth should be located between 3% below the optimum water

Table 8.4 Clay activity (Doat et al. 1979)

Clay type	A = PI/(% clay < 0.002 mm)
Low activity	Ac < 0.75
Medium activity	0.75 < Ac < 1.25
Active	1.25 < Ac < 2.0
High activity	Ac > 2.0

Table 8.5 Characteristics of two soils used for earth construction

	Bahar (2004)	Guettala et al. (2006)
Clay and silt (%)	62	36
Sand (%)	38	64
LL (%)	39	31
PI	15	14
Optimum water content (%)	11	11.8
Dry density (kg/m^3)	1,760	1,877

content and 5% above (Hall and Djerbib 2004). The soils more suitable for earth construction should have a sand content between 50% and 70%. For adobe bricks Doat et al. (1979) recommend the following composition: sand (55% to 75%); silt (10% to 28%); clay (15 to 18%) and less than 3% of organic matter. Delgado and Guerrero (2007) mentioned that soils with a clay content between 10% to 20% should be used in CEB, and 10% to 15% in rammed earth. These authors also mentioned that independent of the technique used (rammed earth, adobe or CEB) the soils must have a minimum of 5% clay content. Jayasinghe and Kamaladasa (2007) mentioned high reductions in the compressive strength of lateritic soils stabilized with cement, when the fines percentage (clay and silt) exceeds 40%. Perera and Jayasinghe (2003) suggest that this percentage should not exceed 30%. Burroughs (2008) analyzed 104 soil types, compacted and stabilized with lime or cement in a total of 219 mixtures. According to this author a soil could be considered suitable for stabilization if its compressive strength exceeds 2 MPa (Fig. 8.9).

8.3.4 Particle Size Correction

When the soil does not exhibit the more favorable characteristics for earth construction it must be mixed with other soils in order to obtain the required characteristics.

If the soil is too clayey and very plastic, it must be mixed with sand or with a sandy-like soil, however, if it is very sandy it must be corrected through the addition of fine particles. If the soil contains a high amount of coarse particles, it must it be passed by a sieve with the proper mesh. If the soil has too many fine particles, the solution may undergo washing, however, this operation may remove all the fines, so it is preferable to mix it with a sandy soil.

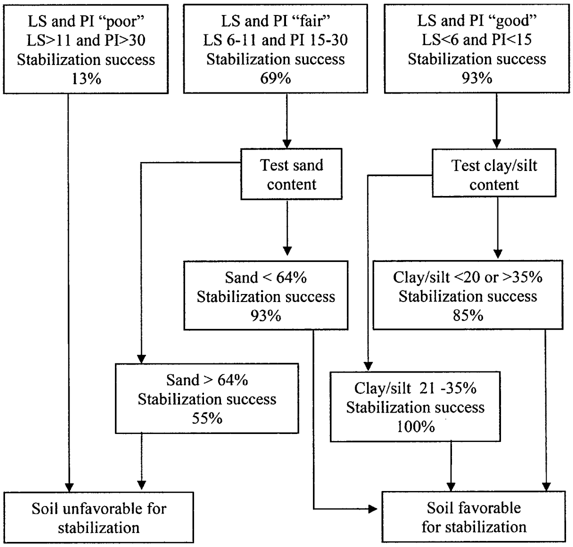


Fig. 8.9 Procedures for determining soil favorability for stabilisation (Burroughs 2008)

8.3.5 Soil Stabilization

The soil stabilization means changing the soil characteristics in order to improve its mechanical or physical behavior. The stabilization process aims at the reduction of the soil plasticity, the improvement on its workability and the deflocculation resistance and also the resistance to erosion. The methods for soil stabilizing can be subdivided into:

- Mechanical stabilization which seeks to improve the characteristics of the soils through a higher density.
- Chemical stabilization with lime, cement or other additions.

Anger et al. (2008) studied the cohesion mechanism of the earth. According to these authors, water is one of the main factors responsible for earth cohesion, due to its surface tension. As to the clay matrix it consists of lamellar microscopic particles whose cohesion is due to the nanoscale capillary connections. The optimum stabilization process encompasses two different stages: the first related to the dispersion of clay induced by electrostatic repulsion that minimizes the water content and reduces the final porosity, and the second, consisting of a binding mechanism. These authors report the existence of various cements available in nature, such as "silcrete" resulting from the dissolution and hardening of silica, "ferricrete" resulting from the agglomeration of sand and other aggregates through the action of iron oxide due to the oxidation of percolating solutions containing iron salts. The stabilization of soils for earth construction can include vegetable fibres (Ghavami et al. 1999), artificial fibres (Binici et al. 2005) or even animal droppings (Ngowi 1997). More recently Silva et al. (2010) studied the nests of andorinha-dos-beirais birds concluding that a mixture of clay and polysaccharide/ sugar is responsible for its high strength and high durability.

8.3.5.1 Stabilization with Lime

Mixing lime into a moist soil generates various chemical reactions which cause the agglutination of the soil particles and the modification of their characteristics. The most important reactions during the lime stabilization process are as follows:

- Ion exchange and flocculation;
- Cementing action (or pozzolanic reaction);
- Carbonation.

The ion exchange causes the Ca^{2+} cations to adsorb into the surface of the particles decreasing their electronegativity and promoting flocculation. The action of calcium ions begins immediately after the addition of lime to the soil, leaving a loose moist mixture in a curing process (a process also named as rotting due to its smell), a decrease in the plasticity of the soil occurs, which then becomes brittle and easily breaks up. To achieve these benefits all that is needed is a small amount of lime. The cementing action requires considerable time and is therefore a slow reaction, being responsible for long-term action of lime stabilization. It is designated as pozzolanic reaction and occurs under hot weather and can be accelerated by using suitable additives. Through the reaction between lime, silica and aluminum present in the clay particles promote the formation of calcium silicate hydrates and/or calcium aluminates. The interaction between lime and clay dissolves the silica and aluminum particles under the high pH created by the molecules of $Ca(OH)_2$. The dissolved materials combine with calcium ions, forming cementitious products that connect the clay particles. Finally, the carbonation reaction is the reaction of lime with the carbon dioxide from the atmosphere. It consists in the chemical alteration of clay minerals due to the reaction of atmospheric carbonate ions with calcium ions to form calcium carbonate. This is the reverse reaction that occurs in the production of lime from limestone, and should be avoided since the formed calcium and magnesium carbonates affect the pozzolanic reaction, preventing the required soil strength. The identification of physical and chemical properties of lime is essential for its use in soil stabilization. One of the main properties to consider is its particle size, since it affects various properties of the soil–lime mixture, such as the hydration speed, the density and also the homogeneity. The particle size of lime is conditioned by the particle size of the limestone rock, by the calcination process, by the final product (slaked lime) and even by possible additional mill operations. The knowledge of the lime fineness may be useful for the evaluation of the degree of homogenization and the reaction between lime, soil and water, because larger areas of contact give rise to more balanced mixtures. The porous structure of the lime particles causes its outer surface to be in contact with water. Through absorption and adsorption phenomena, a part of its interior surface is also surrounded by water. The high reactivity shows the high speed of the lime action after being mixed with the soil and the efficiency of its stabilizer action. This property allows to anticipate the duration of the reactions and if they are exothermic, the increase in the temperature. The production of soil–lime mixtures for soil stabilization needs appropriate lime content. The optimum lime content depends on the future application of the stabilized soil. These may aim at the decrease of the plasticity and workability increase—improvements—making permanent changes that alter the strength of the mixture—stabilization. For the composition of soil–lime mixtures the Atterberg limits are determined, the particle size and the soil classification. Afterwards, compaction tests and resistance and durability tests take place. In cold climates, durability constitutes a major requirement. The content of lime to be used in soil stabilizing, should be the in the range of 1 to 10%, however, the exact percentage must be determined for each case. The use of higher amounts would not be economical nor necessary, but one should never use less than 3%, because even if in the laboratory the mixture with a lower percentage has achieved the desired properties, one must remember that the mixing conditions on-site are somehow different. The lime stabilization process is suitable for soils with a fine fraction very plastic and very expansive. The material initiates the cementing process, strengthens and becomes more granular and then it can be regarded as a material with particles of larger size and greater friction angle. Millogo et al. (2008) studied the effect of adding lime to clay soils for the manufacture of adobe bricks, mentioning that the use of a lime content of 10% maximizes the compressive strength and minimizes the water absorption of the bricks. According to these authors, the addition of increasing percentages of lime induces the formation of calcite and CSH phases generated by the reaction between lime and quartz (silica) of the soil. But when the lime percentage rises to 12% the formation of portlandite also occurs.

8.3.5.2 Soil Stabilization with Cement

Stabilization with cement involves two different mechanisms on the cement content that is added to the soil (Cruz and Jalali 2009). When low cement contents are used a modification of the clay fraction of the soil takes place. This phenomenon decreases its plasticity, and sometimes it can lead to an increase in the mechanical strength, because the hydration of cement particles will contribute to form independent nuclei. During the hydration process some calcium hydroxide will be formed reacting with the clay particles to form CSH, however, its volume will be a low one. The hydration of cement particles will increase with time leading to increased soil strength. The particle size and plasticity leads to different stabilization mechanisms (cementing action or modifying action) that depends on the cement content being simultaneous or not. In soils with a relevant sand fraction the cement will not be enough to fill all the empty spaces. For these soils the cement will link the contact areas of the soil particles. Since these areas depend on the soil particle size, maximizing the number of contact points, lowers the cement

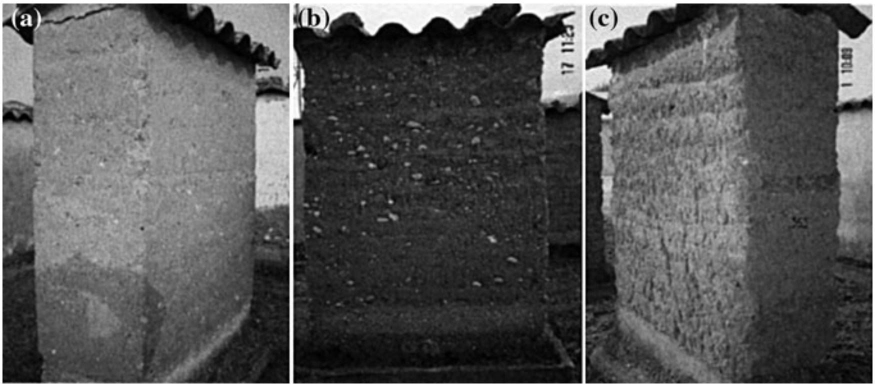


Fig. 8.10 Rammed earth masonry sections exposed during 20 years to natural climatic conditions. **a** Wall made with soil stabilized with 5% lime, **b** Wall made with soil without stabilization (mixed soil), **c** Wall made with soil without stabilization (Bui et al. 2008)

content required to reach a certain strength level. It is worth remembering that soil stabilization with cement is strongly affected by the presence of organic matter in the soil, this slows or inhibits the cementing action preventing the release of calcium ions. As for the volume of water necessary for soil–cement mixtures it matches the optimum water content for maximum compaction, obtained in the Proctor test. The water needed for cement hydration is less than the amount needed for maximum compaction, so that the water necessary for the hydration process is ensured as long as no loss occurs during the curing period. The water content of soil–cement mixtures, should be in the range of 0.95 to 1.10 times the water content for maximum compaction (Pereira 1970).

8.4 Durability

What is known in terms of the durability of earth construction comes from the fact that some of these buildings last for hundreds of years. Durability has also been assessed by accelerated aging tests and more recently from monitoring experimental sections of earth masonry sections built a dozen years ago. The main mechanism responsible for the erosion of earth walls have to do with the kinetic energy of the impact of rainfall (Heathcote 1995). This justifies the worst durability behavior of earth walls oriented to the South, a direction usually associated with wind-based rain. Other authors (Ogunye and Boussabaine 2002) mentioned that rain does not always have a erosive effect on the earth walls which only happens for rain intensities above 25 mm/m. Bui et al. (2008) evaluated the performance of 104 sections of rammed earth masonry sections with and without stabilization, which were exposed for 20 years to natural climatic conditions (Fig. 8.10).

The durability of earth buildings is also dependent on appropriate maintenance and repairs that are compatible with the original construction (Little and Morton,

Table 8.6 Assessment of the durability of earth constructions (Heathcote 2002)

Test	Types of tests		
	Indirect	Simulation	Accelerated erosion
Compressive strength	x		
Superficial strength	x		
Permeability	x		
Erosion	x		
Drip tests	x	x	
Spray tests			x

Table 8.7 Accelerated erosion spray tests (Maniatidis and Walker 2003)

	Distance (mm)	Pressure (kPa)	Nozzle	Time (min)
Israel (Cytryn, 1955)	250 vertical	50	Spray	33
Austrália-CSIRO	470 vertical	50	Spray	60
Dep. Housing Washington	175 horizontal	137	Shower	120
Norton	180 horizontal	137	Shower	120
Houben and Guillaud	200 horizontal	140	Shower	120

2001). The assessment of the durability of earth constructions can be made indirectly through the analysis of the compressive strength and permeability of earth specimens. It can also be made using erosion tests by mechanical impact or water falling in a drop by drop mode (Table 8.6).

Geelong test—this test was specially designed for adobe specimens (Walker 2000). The test consists to drip water at a controlled rate onto earth bricks (inclined 30°) from a height of 400 mm. The test ends when the volume of dripped water reach 100 ml, this should happen after 30 min. The degree of erosion is given by the depth of the erosion caused by the drop of water. A depth greater than 15 mm means that the earth bricks must be rejected.

Accelerated erosion test (SAET)—this test also uses a similar inclined 30° earth specimen but uses a jet of water rather than individual drops used in the Geelong test. The SAET results are obtained from the pitting depth caused by the falling water, and the specimens with a depth of over 30 mm are considered unsuitable for earth construction.

In the last 50 years several accelerated erosion tests based on spraying water horizontally onto earth specimens were developed (Table 8.7).

Bulletin 5 accelerated erosion test—this test was developed in Australia in the early 1980s and was named after the document in which it is contained. This test consists of spraying water horizontally onto an earth specimen during 1 h or until the water penetrates the earth specimen. The test uses a water pressure of 50 kPa which corresponds to a velocity of 10 m/s. After 15 min the test is interrupted for the assessment of the erosion rate. The final erosion assessment is given in millimeter per minute and the maximum acceptable erosion assessment is 1 mm/min.

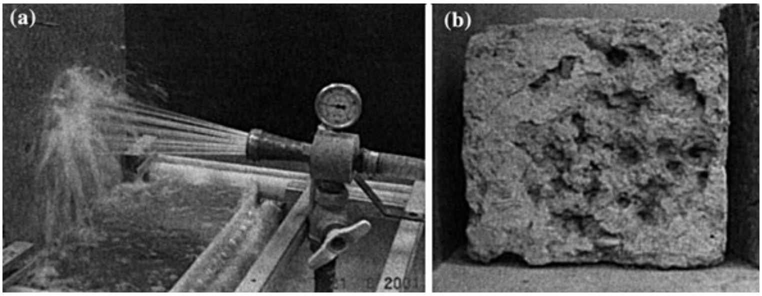


Fig. 8.11 Bulletin 5 accelerated erosion test: **a** Spray, **b** Specimen after Bulletin 5 test (Heathcote and Moore 2003)

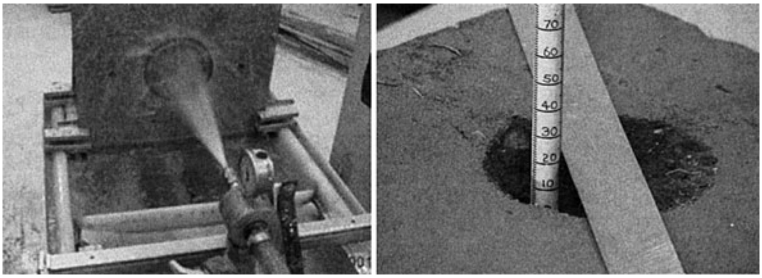


Fig. 8.12 UTS spray test: Left spray, right erosion assessment (Heathcote and Moore 2003)

According to Heathcote and Moore (2003) this test can hardly reproduce the action of rainfall because it has a very intense effect leaving bore holes in the earth specimens (Fig. 8.11b).

University of Technology Sydney (UTS)—the UTS spray test is a refinement of the Bulletin 5 test, it uses a higher water pressure (70 kPa) producing an even more erosive effect, that is less concentrated due to the use of a specific kind of nozzle capable of producing a turbulent flow with a velocity similar to the wind velocity (9 m/s) that occur in Sydney on rainy days (Fig. 8.12).

8.5 Eco-Efficiency Aspects

8.5.1 Economic Advantages

For less-developed countries the cost-efficiency aspect remains of paramount importance. Zami and Lee (2010) quote several authors for whom “earth construction is economically beneficial”, nevertheless one cannot take this as a guaranteed truth because the economics of earth construction depend on several aspects such as: construction technique, labour costs, stabilization process, durability and repair needs. Williams et al. (2010) mentioned that the materials used in earth construction in UK have no significant impact in the final cost. These authors state that the production and construction costs represent the most important part because earth construction is labor intensive. However, this is not the case in less-developed countries in which labor is available for a very low cost. According to Sanya (2007) this is very important to create decentralized job creation. In these countries the cost-efficiency is dependent on the nature and the amount of the binder used in the stabilization process. Recent investigations (Zami and Lee 2010) show that soil stabilization with gypsum shows to be much more cost-effective than with Portland cement.

8.5.2 Non-Renewable Resource Consumption and Waste Generation

The use of soil for earth construction cannot be regarded as the use of a renewable resource; however, one must recognize that it is very different from the extraction of raw materials needed for the construction materials used in conventional masonry. This is because generally the soil used in earth construction is located immediately below the organic layer of the soil. Therefore, earth extraction generally involves the removal of the top layer of the soil, an operation without high energy needs since it can be done manually. If we assume that the building is made with soil located in its vicinity there is no pollution associated with its transportation. This is very different from conventional masonry in which concrete blocks and fired-clay bricks are always very distant from construction sites thus implying high transport distances responsible for the emission of GHGs. Regarding earth construction wastes they can simply be deposited at the site of its extraction without any environmental hazard involved. Even when the soil is stabilized with cement or lime, it can be reused in this type of construction, so we may consider that earth construction hardly generates any waste. As a comparison the traditional fired-clay brick masonry implies a relevant amount of waste because the use of broken pieces takes place quite often in this kind of masonry. According to Morton (2008) earth construction could reuse the 24 million tones of waste soil produced every year in UK.

8.5.3 Energy Consumption and Carbon Dioxide Emissions

Some authors compared the carbon dioxide emissions of earth blocks and the emissions of the construction materials used in conventional masonry, showing the good environmental performance of the former (Fig. 8.13).

For a house with three rooms and an area of 92 m^2 made with earth walls the values in Fig. 8.13 represent a reduction of 7 tons of CO_2 compared to fired clay

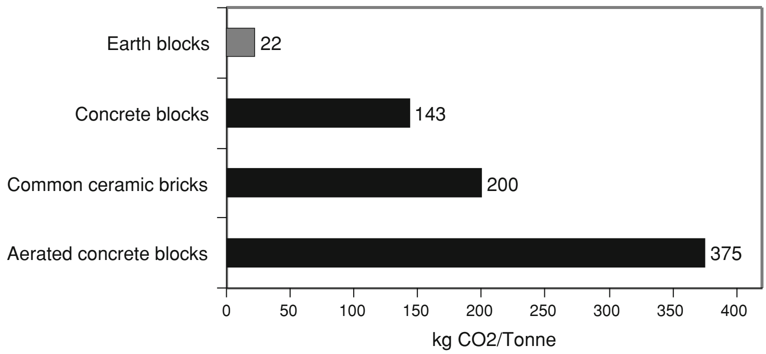
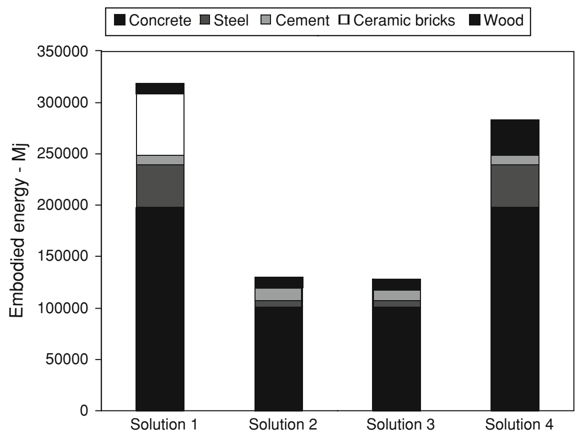


Fig. 8.13 Embodied carbon in different masonry materials (Morton et al. 2005)

Fig. 8.14 Embodied energy for four different scenarios (Lourenço 2002)



brick and a reduction of 14 tons of CO_2 if aerated concrete blocks were used. Lourenço (2002) studied the embodied energy (wood, concrete, steel, fired-clay bricks and cement) of a single floor building comprising the following variants:

- Solution 1: Building with a reinforced concrete structure, fired-clay bricks masonry and roof slab using precast reinforced concrete beams and fired-clay hollow elements;
- Solution 2: Building with CEB masonry with top concrete beams and wooden roof;
- Solution 3: Building with exterior walls made on rammed earth, interior walls made on adobe and wooden roof;
- Solution 4: Building with a reinforced concrete structure and adobe walls.

This author shows that the embodied energy of earth buildings (Solutions 2 and 3) is half the embodied energy of a conventional construction (Fig. 8.14).

According to Morton (2008) the replacement of only 5% of concrete blocks used in the UK masonries by earth masonry would mean a reduction in CO_2 emissions of approximately 100,000 tons. Shukla et al. (2008) studied adobe-based buildings observing an embodied energy of 4.75 GJ/m^2. Nevertheless, compressed-stabilized earth blocks are more eco-friendly than fired-clay and their manufacture consumes less energy (15 times less) and pollutes less than fired-clay bricks (8 times less) Zami and Lee (2010). Reddy and Kumar (2010) show that the embodied energy in cement-stabilized rammed earth walls increases linearly with the increase in cement content and is in the range of 0.4 to 0.5 GJ/m^3 for a cement content in the range of 6% to 8%. Lax (2010) assessed the LCA of rammed earth showing that the stabilization with cement makes the embodied carbon to raise from 26 Kg CO^2 to 70 Kg CO^2.

8.5.4 Indoor Air Quality

Earth construction is not associated with the adverse effects of indoor air volatile organic compounds (VOCs) so the occupants of these buildings will have a superior air quality (Wargocki et al. 1999). Another advantage of the indoor air quality of earth buildings relates to its ability to control the relative humidity (Minke 2000). Some investigations show that the earth blocks are capable of absorbing ten times more weight moisture than fired-clay bricks (Fig. 8.15). Earthen structures act as a relative humidity flywheel, equalizing the relative humidity of the external environment with that of the pores within the walls (Jaquin 2008; Allison and Hall 2010). According to Morton (2008) the hygroscopic behavior of construction materials can be more effective in reducing the indoor air relative humidity than the use of ventilation. This author mentioned a study conducted in Britain where it was noticed that earth construction is capable of keeping the relative humidity of indoor air between 40% and 60%, this range being the most suitable for human health purposes. Recently, Allison and Hall (2010) showed that earth walls have a high potential to stabilize the relative humidity of indoor air. High levels of humidity above 70% are responsible for the appearance of molds which can trigger allergic reactions (Arundel et al. 1986). Relative humidity values above 60% are associated with the presence of mites and also asthmatic diseases (Howieson 2005).

On the other hand, a relative humidity below 40% is linked to the syndrome of "sick buildings" typical of very dry indoor air. This leads to a drying of the respiratory mucosa, resulting in respiratory diseases such as tonsillitis, pharyngitis or bronchitis. Therefore, it is easily understood that public health statistics in recent decades show an increase of almost 50% in the occurrence of health problems from respiratory conditions such as asthma (Heerwagen 2000). Berge (2009) mentioned that the Hospital of Feldkirch in Austria in which a 180 m gallery was built with long sections coated with rammed earth (in some cases up to 6 m high), with the sole aim of achieving the stabilization of the relative humidity without using conventional mechanical devices (Fig. 8.16).

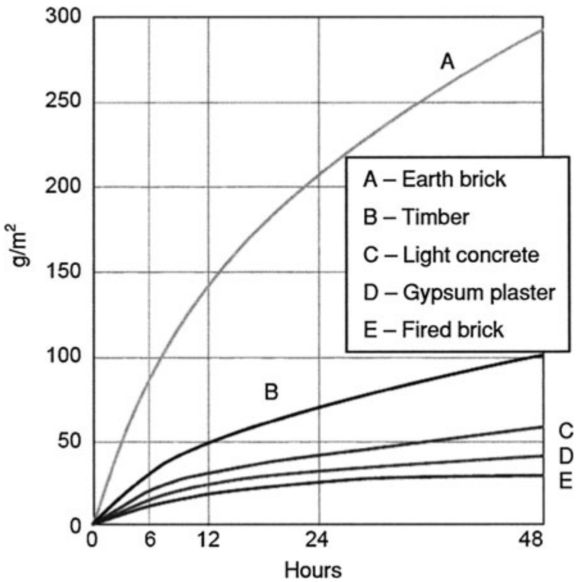


Fig. 8.15 Weight of moisture absorbed by different materials when relative humidity increases from 50% to 80% (Minke 2000)

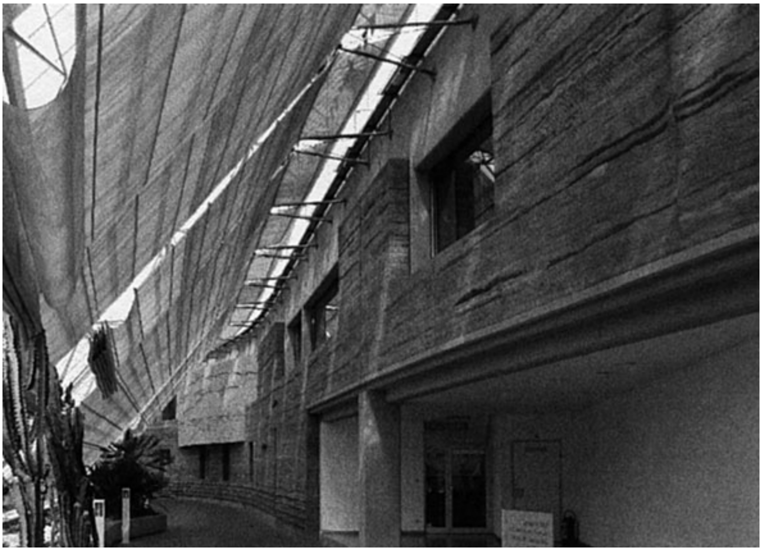


Fig. 8.16 Rammed earth wall, Hospital of Feldkirch, Áustria (Berge 2009)

8.6 Conclusions

Earth construction exists since the early agricultural societies, a period whose current knowledge dates from 12000 to 7000 BC. There are countless cases of earth constructions built thousand years ago that made it to the twenty-first century.

Nowadays, the majority of earth construction is located in less-developed countries. Unfortunately, the fact that earth construction is associated with low-income status is probably one of the most important reasons explaining why less-developed countries try to emulate the use of polluting construction techniques based on reinforced concrete and fired-clay bricks. Earth construction can also be found in developed countries, where a growing awareness on the importance of this type of construction can be witness nowadays. Although this construction technique is cost-effective its economic advantages are dependent on the nature and the amount of the binder used in the stabilization process. Soil stabilization with gypsum shows to be much more cost-effective than that with Portland cement. Earth construction is associated with low-embodied energy, low carbon dioxide emissions and very low-pollution impacts. The use of cement for soil stabilization increases embodied energy. Therefore further studies about the environmental performance of earth construction stabilized with non-Portland cement binders are needed. The use of pozzolanic potential aluminosilicate wastes could also be analyzed. Earth construction is also responsible for an indoor air relative humidity beneficial to the human health; therefore, earth construction has clear competitive advantages in the field of eco-efficiency over conventional construction assuring it a promising future in the years to come.

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