Building with Earth

Gernot Minke

Building with Earth

Design and Technology of a Sustainable Architecture

Birkhäuser – Publishers for Architecture
Basel · Berlin · Boston

Preface

Next page Minaret of the Al-Mihdar Mosque in Tarim, Yemen; it is 38 m high and built of handmade adobes

Written in response to an increasing worldwide interest in building with earth, this handbook deals with earth as a building material, and provides a survey of all of its applications and construction techniques, including the relevant physical data, while explaining its specific qualities and the possibilities of optimising them. No theoretical treatise, however, can substitute for practical experience involving actually building with earth. The data and experiences and the specific realisations of earth construction contained in this volume may be used as guidelines for a variety of construction processes and possible applications by engineers, architects, entrepreneurs, craftsmen and public policy-makers who find themselves attempting, either from desire or necessity, to come to terms with humanity's oldest building material.

Earth as a building material comes in a thousand different compositions, and can be variously processed. Loam, or clayey soil, as it is referred to scientifically, has different names when used in various applications, for instance rammed earth, soil blocks, mud bricks or adobe.

This book documents the results of experiments and research conducted continuously at the Forschungslabor für Experimentelles Bauen (Building Research Institute) at the University of Kassel in Germany since 1978. Moreover, the specialised techniques which the author developed and the practical experience he gathered in the course of designing earth buildings in a number of countries have also found their way into this book.

This volume is loosely based on the German publication *Das neue Lehmbau-Handbuch* (Publisher: Ökobuch Verlag, Staufen), first published in 1994 and now in its sixth edition. Of this publication a Spanish and a Russian edition have also appeared.

While this is first and foremost a technical book, the introductory chapter also provides the reader with a short survey on the history of earth architecture. In addition it describes the historical and future roles of earth as a building material, and lists all of the significant characteristics that distinguish earth from common industrialised building materials. A major recent discovery, that earth can be used to balance indoor climate, is explained in greater detail.

The book's final chapter deserves special mention insofar as it depicts a number of representative earth buildings from various regions of the world. These constructions demonstrate the impressive versatility of earth architecture and the many different uses of the building material earth.

Kassel, February 2006
Gernot Minke

1 The technology of earth building

1 Introduction

1.1

1.1 Storage rooms, temple of Ramses II, Gourna, Egypt

In nearly all hot-arid and temperate climates, earth has always been the most prevalent building material. Even today, one third of the human population resides in earthen houses; in developing countries this figure is more than one half. It has proven impossible to fulfil the immense requirements for shelter in the developing countries with industrial building materials, i.e. brick, concrete and steel, nor with industrialised construction techniques. Worldwide, no region is endowed with the productive capacity or financial resources needed to satisfy this demand. In the developing countries, requirements for shelter can be met only by using local building materials and relying on do-it-yourself construction techniques. Earth is the most important natural building material, and it is available in most regions of the world. It is frequently obtained directly from the building site when excavating foundations or basements. In the industrialised countries, careless exploitation of resources and centralised capital combined with energy-intensive production is not only wasteful; it also pollutes the environment and increases unemployment. In these countries, earth is being revived as a building material.

Increasingly, people when building homes demand energy- and cost-effective buildings that emphasise a healthy, balanced indoor climate. They are coming to realise that mud, as a natural building material, is superior to industrial building materials such as concrete, brick and lime-sandstone.

Newly developed, advanced earth building techniques demonstrate the value of earth not only in do-it-yourself construction, but also for industrialised construction involving contractors.

This handbook presents the basic theoretical data concerning this material, and it provides the necessary guidelines, based on scientific research and practical experience, for applying it in a variety of contexts.

History

Earth construction techniques have been known for over 9000 years. Mud brick (adobe) houses dating from 8000 to 6000 BC have been discovered in Russian Turkestan (Pumpelly, 1908). Rammed earth foundations dating from ca. 5000 BC have been

1.2

1.2 Fortified city, Draa valley, Morocco
1.3 Citadel of Bam, Iran, before earthquake of Dec. 2003

discovered in Assyria. Earth was used as the building material in all ancient cultures, not only for homes, but for religious buildings as well. Illustration *1.1* shows vaults in the Temple of Ramses II at Gourna, Egypt, built from mud bricks 3200 years ago. Illustration *1.2* shows the citadel of Bam in Iran, parts of which are ca. 2500 years old; *1.3* shows a fortified city in the Draa valley in Morocco, which is around 250 years old.
The 4000-year-old Great Wall of China was originally built solely of rammed earth; only a later covering of stones and bricks gave it the appearance of a stone wall. The core of the Sun Pyramid in Teotihuacan, Mexico, built between the 300 and 900 AD, consists of approximately 2 million tons of rammed earth.

1.3

Many centuries ago, in dry climatic zones where wood is scarce, construction techniques were developed in which buildings were covered with mud brick vaults or domes without formwork or support during construction. Illustration *1.6* shows the bazaar quarter of Sirdjan in Persia, which is covered by such domes and vaults. In China, twenty million people live in underground houses or caves that were dug in the silty soil.
Bronze Age discoveries have established that in Germany earth was used as an infill in timber-framed houses or to seal walls made of tree trunks. Wattle and daub was also used. The oldest example of mud brick walls in northern Europe, found in the Heuneburg Fort near Lake Constance, Germany (*1.8*) dates back to the 6th century BC. We know from the ancient texts of Pliny that there were rammed earth forts in Spain by the end of the year 100 BC.
In Mexico, Central America and South America, adobe buildings are known in nearly all pre-Columbian cultures. The rammed earth technique was also known in many areas, while the Spanish conquerors brought it to others. Illustration *1.7* shows a rammed earth finca in the state of São Paulo, Brazil, which is 250 years old.
In Africa, nearly all early mosques are built from earth. Illustration *1.9* shows one from

1.4

1.5

1.4 Large Mosque, Djenne, Mali, built 1935
1.5 Mosque, Kashan, Iran
1.6 Bazaar, Sirdjan, Iran

the 12th century, *1.4* and *1.5* show later examples in Mali and Iran.
In the Medieval period (13th to 17th centuries), earth was used throughout Central Europe as infill in timber-framed buildings, as well as to cover straw roofs to make them fire-resistant.
In France, the rammed earth technique, called *terre pisé*, was widespread from the 15th to the 19th centuries. Near the city of Lyon, there are several buildings that are more than 300 years old and are still inhabited. In 1790 and 1791, Francois Cointeraux published four booklets on this technique that were translated into German two years later (Cointeraux, 1793). The technique came to be known all over Germany and in neighbouring countries through Cointeraux, and through David Gilly, who wrote the famous Handbuch der Lehmbaukunst (Gilly, 1787), which describes the rammed earth technique as the most advantageous earth construction method.
In Germany, the oldest inhabited house with rammed earth walls dates from 1795 (*1.10*). Its owner, the director of the fire department, claimed that fire-resistant houses could be built more economically using this technique, as opposed to the usual timber frame houses with earth infill.
The tallest house with solid earth walls in Europe is at Weilburg, Germany. Completed in 1828, it still stands (*1.11*). All ceilings and the entire roof structure rest on the solid rammed earth walls that are 75 cm thick at the bottom and 40 cm thick at the top floor (the compressive force at the bottom of the walls reaches 7,5 kg/cm^2). Illustration *1.12* shows the facades of other rammed earth houses at Weilburg, built around 1830.

1.6

Earth as a building material: the essentials

Earth, when used as a building material, is often given different names. Referred to in scientific terms as loam, it is a mixture of clay, silt (very fine sand), sand, and occasionally larger aggregates such as gravel or stones.
When speaking of handmade unbaked bricks, the terms ”mud bricks”or “adobes” are usually employed; when speaking of compressed unbaked bricks, the term ”soil blocks” is used. When compacted within a formwork, it is called ”rammed earth”.
Loam has three disadvantages when compared to common industrialised building materials:

1 Loam is not a standardised building material
Depending on the site where the loam is dug out, it will be composed of differing amounts and types of clay, silt, sand and aggregates. Its characteristics, therefore, may differ from site to site, and the preparation of the correct mix for a specific application may also differ. In order to judge its characteristics and alter these, when necessary, by applying additives, one needs to know the specific composition of the loam involved.

2 Loam mixtures shrink when drying
Due to evaporation of the water used to prepare the mixture (moisture is required to activate its binding strength and to achieve workability), shrinkage cracks will occur. The linear shrinkage ratio is usually between 3% and 12% with wet mixtures (such as those used for mortar and mud bricks), and between 0.4% and 2% with drier mixtures

(used for rammed earth, compressed soil blocks). Shrinkage can be minimised by reducing the clay and the water content, by optimising the grain size distribution, and by using additives (see p. 39).

3 Loam is not water-resistant
Loam must be sheltered against rain and frost, especially in its wet state. Earth walls can be protected by roof overhangs, damp-proof courses, appropriate surface coatings etc. (see p. 40).

On the other hand, loam has many advantages in comparison to common industrial building materials:

1 Loam balances air humidity
Loam is able to absorb and desorb humidity faster and to a greater extent than any other building material, enabling it to balance indoor climate. Experiments at the Forschungslabor für Experimentelles Bauen (Building Research Laboratory, or BRL) at the University of Kassel, Germany, demonstrated that when the relative humidity in a room was raised suddenly from 50% to 80%, unbaked bricks were able, in a two-day period to absorb 30 times more humidity than baked bricks. Even when standing in a climatic chamber at 95% humidity for six months, adobes do not become wet or lose their stability; nor do they exceed their equilibrium moisture content, which is about 5% to 7% by weight. (The maximum humidity a dry material can absorb is called its "equilibrium moisture content").
Measurements taken in a newly built house in Germany, all of whose interior and exterior walls are from earth, over a period of eight years, showed that the relative humidity in this house was a nearly constant 50% throughout the year. It fluctuated by only 5% to 10%, thereby producing healthy living condition with reduced humidity in summer and elevated humidity in winter. (For more details, see p. 15).

2 Loam stores heat
Like all heavy materials, loam stores heat. As a result, in climatic zones with high diurnal temperature differences, or where it becomes necessary to store solar heat gain by passive means, loam can balance indoor climate.

3 Loam saves energy and reduces environmental pollution
The preparation, transport and handling of loam on site requires only ca. 1% of the energy needed for the production, transport and handling of baked bricks or reinforced concrete. Loam, then, produces virtually no environmental pollution.

1.7

1.8

1.9

1.7 Rammed earth finca, São Paulo, Brazil
1.8 Reconstruction of mud-brick wall, Heuneburg, Germany, 6th century BC
1.9 Mosque at Nando, Mali, 12th century

1.11

1.12

1.10 Rammed earth house, Meldorf, Germany, 1795
1.11 Rammed earth house, Weilburg, Germany, 1828
1.12 Rammed earth houses, Weilburg, Germany, about 1830

4 Loam is always reusable
Unbaked loam can be recycled an indefinite number of times over an extremely long period. Old dry loam can be reused after soaking in water, so loam never becomes a waste material that harms the environment.

5 Loam saves material and transportation costs
Clayey soil is often found on site, so that the soil excavated for foundations can then be used for earth construction. If the soil contains too little clay, then clayey soil must be added, whereas if too much clay is present, sand is added.
The use of excavated soil means greatly reduced costs in comparison with other building materials. Even if this soil is transported from other construction sites, it is usually much cheaper than industrial building materials.

6 Loam is ideal for do-it-yourself construction
Provided the building process is supervised by an experienced individual, earth construction techniques can usually be executed by non-professionals. Since the processes involved are labour-intensive and require only inexpensive tools and machines, they are ideal for do-it-yourself building.

7 Loam preserves timber and other organic materials
Owing to its low equilibrium moisture content of 0.4% to 6% by weight and its high capillarity, loam conserves the timber elements that remain in contact with it by keeping them dry. Normally, fungi or insects will not damage such wood, since insects need a minimum of 14% to 18% humidity to maintain life, and fungi more than 20% (Möhler 1978, p. 18). Similarly, loam can preserve small quantities of straw that are mixed into it.
However, if lightweight straw loam with a density of less than 500 to 600 kg/m^3 is used, then the loam may lose its preservative capacity due to the high capillarity of the straw when used in such high proportions. In such cases, the straw may rot when remaining wet over long periods (see p. 83).

1.10

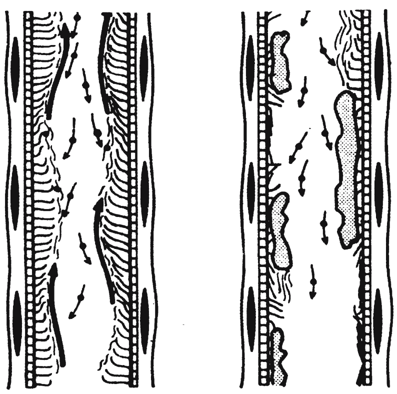
8 Loam absorbs pollutants
It is often maintained that earth walls help to clean polluted indoor air, but this has yet to be proven scientifically. It is a fact that earth walls can absorb pollutants dissolved in water. For instance, a demonstration plant exists in Ruhleben, Berlin, which uses clayey soil to remove phosphates from 600 m^3 of sewage daily. The phosphates are bound by the clay minerals and extracted from the sewage. The advantage of this procedure is that since no foreign substances remain in the water, the phosphates are converted into calcium phosphate for reuse as a fertiliser.

Improving indoor climate

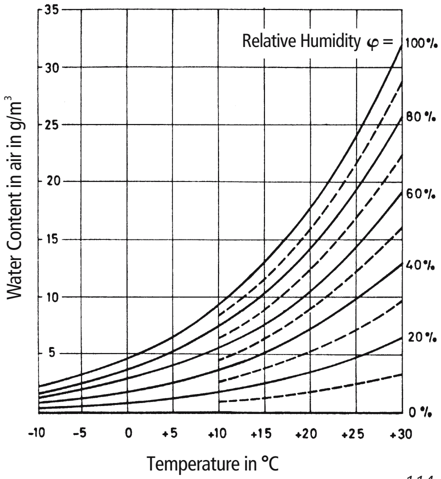
In moderate to cold climates, people usually spend about 90% of their time in enclosed spaces, so indoor climate is a crucial factor in well-being. Comfort depends upon the temperature, movement, humidity, radiation to and from surrounding objects, and pollution content of the air contained in a given room.
Although occupants immediately become aware when room temperatures are too high or too low, the negative impacts of excessively elevated or reduced humidity levels are not common knowledge. Air humidity in contained spaces has a significant impact on the health of inhabitants, and earth has the ability to balance indoor humidity like no other building material. This fact, only recently investigated, is described in detail later in this section.

Air humidity and health

Research performed by Grandjean (1972) and Becker (1986) has shown that a relative humidity of less than 40% over a long period may dry out the mucous membrane, which can decrease resistance to colds and related diseases. This is so because normally the mucous membrane of the epithelial tissue within the trachea absorbs dust, bacteria, viruses etc. and returns them to the mouth by the wavelike movement of the epithelial hair. If this absorption and transportation system is disturbed by drying, then foreign bodies can reach the lungs and may cause health problems (see *1.13*).
A high relative humidity of up to 70% has many positive consequences: it reduces the fine dust content of the air, activates the protection mechanisms of the skin against microbes, reduces the life of many bacteria and viruses, and reduces odour and static charge on the surfaces of objects in the room.
A relative humidity of more than 70% is normally experienced as unpleasant, probably because of the reduction of oxygen intake by the blood in warm-humid conditions. Increasing rheumatic pains are observed in cold humid air. Fungus formation increases significantly in closed rooms when the humidity rises above 70% or 80%. Fungus spores in large quantities can lead to various kinds of pain and allergies. From these considerations, it follows that the humidity content in a room should be a minimum of 40%, but not more than 70%.



1.13



1.14

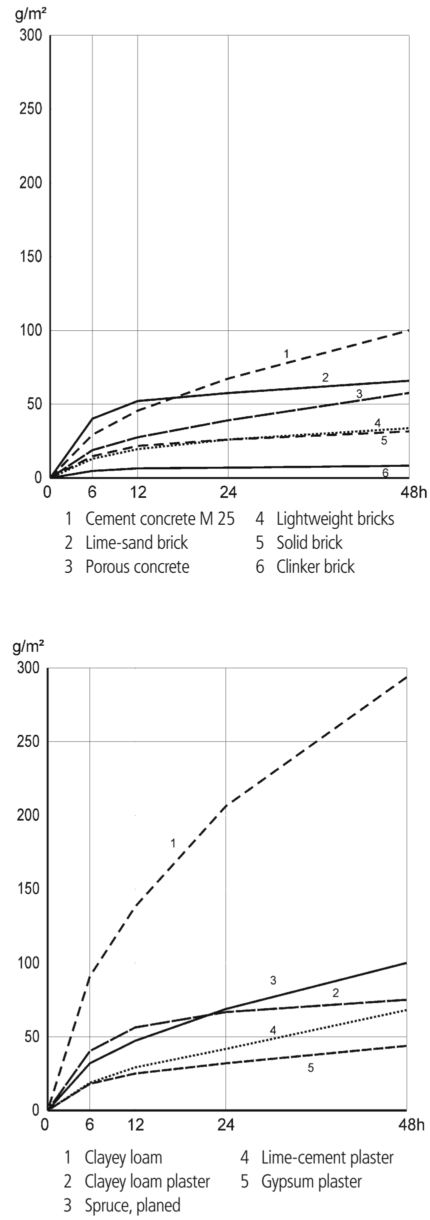
The impact of air exchange on air humidity

In moderate and cold climates, when the outside temperatures are much lower than inside temperatures, the greater degree of fresh air exchange may make indoor air so dry that negative health effects can result. For example, if outside air with a temperature of 0°C and 60% relative humidity enters a room and is heated to 20°C, its relative humidity decreases to less than 20%. Even if the outside air (temperature 0°C) had 100% humidity level and was warmed up to 20°C, its relative humidity would still drop to less than 30%. In both cases, it becomes necessary to raise the humidity as soon as possible in order to attain healthy and comfortable conditions. This can be done by regulating the humidity that is released by walls, ceilings, floors and furniture (see *1.14*).

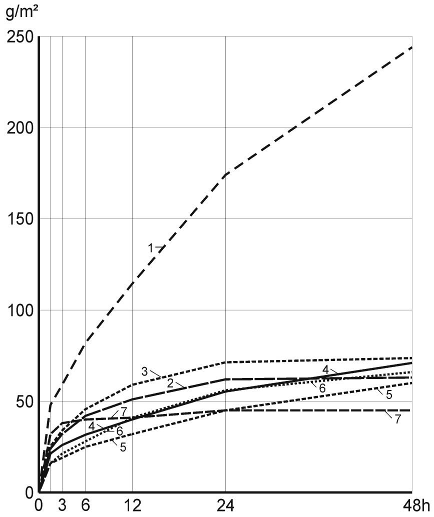
The balancing effect of loam on humidity

Porous materials have the capacity to absorb humidity from the ambient air and to desorb humidity into the air, thereby achieving humidity balance in indoor climates. The equilibrium moisture content depends on the temperature and humidity of the ambient air (see p. 29) and illustration *2.29*). The effectiveness of this balancing process also depends upon the speed of the absorption or desorption. Experiments conducted at the BRL show, for instance, that the first 1.5-cm-thick layer of a mud brick wall is able to absorb about 300 g of

1.13 Section through trachea with sane mucous membrane (left) and dried out one (right) (Becker, 1986)
1.14 Carrier Diagram
1.15 Absorption of samples, 15 mm thick, at a temperature of 21°C and a sudden increase of humidity from 50% to 80%



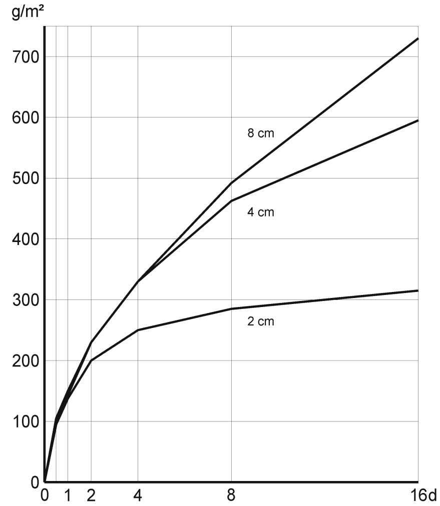
1.15



1 Spruce, planed
2 Limba, planed
3 Clayey loam
4 Clayey loam plaster
5 Loam plaster with coir
6 Lime-cement plaster
7 Gypsum plaster

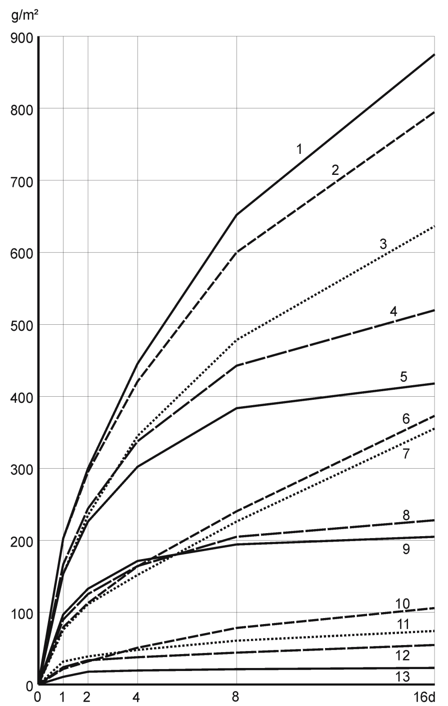
1.17

1.16 Absorption curves of 11.5-cm-thick interior walls with two sides exposed at a temperature of 21°C after a sudden rise in humidity from 50% to 80%
1.17 Absorption curves of 15-mm-thick samples, one side exposed, at a temperature of 21°C after a sudden rise in humidity from 30% to 70%
1.18 Effect of the thickness of loam layers at a temperature of 21°C on their rate of absorption after a sudden rise in humidity from 50% to 80%



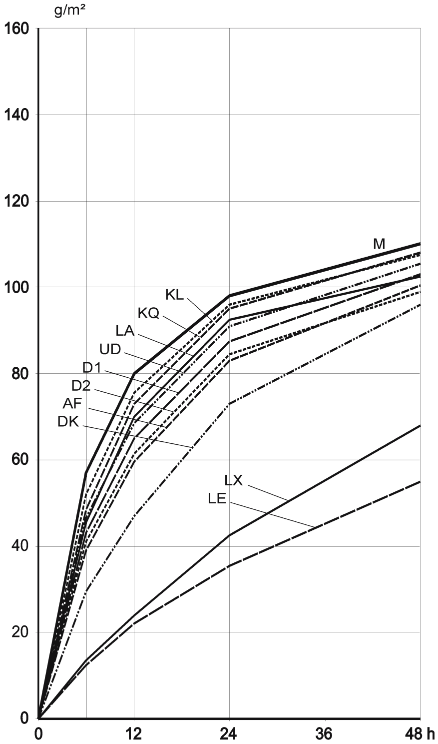
1.18

water per m² of wall surface in 48 hours if the humidity of the ambient air is suddenly raised from 50% to 80%. However, lime-sandstone and pinewood of the same thickness absorb only about 100 g/m², plaster 26 to 76 g/m², and baked brick only 6 to 30 g/m² in the same period (*1.15*).
The absorption curves from both sides of 11.5-cm-thick unplastered walls of different materials over 16 days are shown in *1.16*. The results show that mud bricks absorb 50 times as much moisture as solid bricks baked at high temperatures. The absorption rates of 1.5-cm-thick samples, when humidity was raised from 30% to 70%, are shown in *1.17*.
The influence of the thickness of a clayey soil on absorption rates is shown in *1.18*. Here we see that when humidity is raised suddenly from 50% to 80%, only the upper 2 cm absorbs humidity within the first 24 hours, and that only the upper layer 4 cm in thickness is active within the first four days. Lime, casein and cellulose glue paints reduce this absorption only slightly, whereas coatings of double latex and single linseed oil can reduce absorption rates to 38% and 50% respectively, as seen in *1.19*.
In a room with a floor area of 3 x 4 m, a height of 3 m, and a wall area of 30 m² (after subtracting doors and windows), if indoor air humidity were raised from 50% to 80%, unplastered mud brick walls would absorb about 9 litres of water in 48 hours. (If the humidity were lowered from 80% to 50%, the same amount would be released). The same walls, if built from solid baked bricks, would absorb only about 0.9 litres of water in the same period, which means they are inappropriate for balancing the humidity of rooms.
Measurements taken over a period of five years in various rooms of a house built in Germany in 1985, all of whose exterior and interior walls were built of earth, showed that the relative humidity remained nearly constant over the years, varying from 45% to 55%. The owner wanted higher humidity levels of 50% to 60% only in the bedroom. It was possible to maintain this higher level (which is healthier for people who tend to get colds or flues) by utilising the higher humidity of the adjacent bathroom. If bedroom humidity decreased too much, the door to the bathroom was opened after showering, recharging the bedroom walls with humidity.



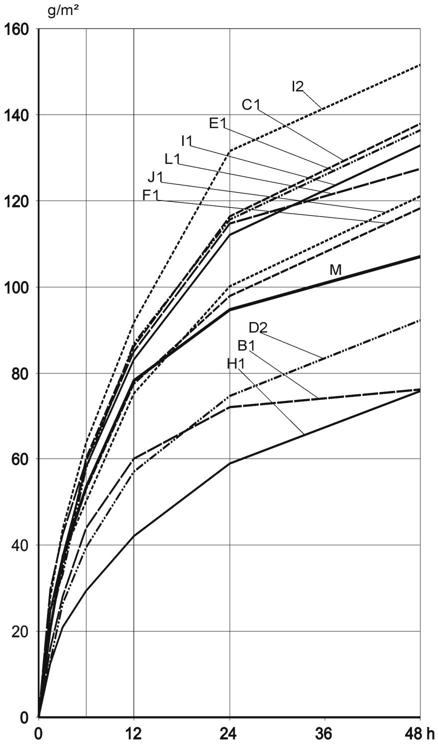
1 Silty loam
2 Clayey loam (1900)
3 Straw loam (1400)
4 Straw loam (700)
5 Straw loam (550)
6 Pine
7 Porous concrete (400)
8 Expanded clay loam (750)
9 Expanded clay loam (1500)
10 Porous bricks (800)
11 Solid brick (1800)
12 Cement concrete (2200)
13 Cement concrete M 15

1.16



M Silty loam, 2 Sand without coating
KQ 2x 1 Lime : 1 Quark : 1.7 Water
KL 2x Chalk cellulose glue paint
LE 1x Double-boiled linseed oil
D2 2x Biofa dispersible paint
LA 1x Biofa glaze with primer
AF 2x Acrylic paint
DK 2x Synthetic dispersion paint exterior
LX 2x Latex
UD 2x Dispersion paint without solvent
D1 2x Dispersion paint for interior

1.19



M Loam plaster without aggregate
I2 with 2.0% coconut fibres
C1 with 2.0% cellulose fibres
E1 with 2.0% water glass
I1 with 1.0% coconut fibres
L1 with 3.0% saw dust
J1 with 2.0% wheat straw
F1 with 3.0% cement
D2 with 2.0% boiled rye flour
B1 with 0.5% cellulose glue
H1 with 6.0% casein/lime

1.20

1.19 Influence of coatings on 1.5-cm-thick, one-side-exposed loam plasters at a temperature of 21°C (clay 4%, silt 25%, sand 71%) after a sudden rise in humidity from 50% to 80%. Thickness of coating is 100 ± 10 µm.
1.20 Influence of different aggregates on the absorption of humidity. Same conditions as mentioned in *1.19*

Prejudices against earth as a building material

Owing to ignorance, prejudices against loam are still widespread. Many people have difficulty conceiving that a natural building material such as earth need not be processed and that, in many cases, the excavation for foundations provides a material that can be used directly in building.
The following reaction by a mason who had to build an adobe wall is characteristic: "This is like medieval times; now we have to dirty our hands with all this mud." The same mason, happily showing his hands after working with adobes for a week, said, "Have you ever seen such smooth mason's hands? The adobes are a lot of fun to handle as there are no sharp corners."

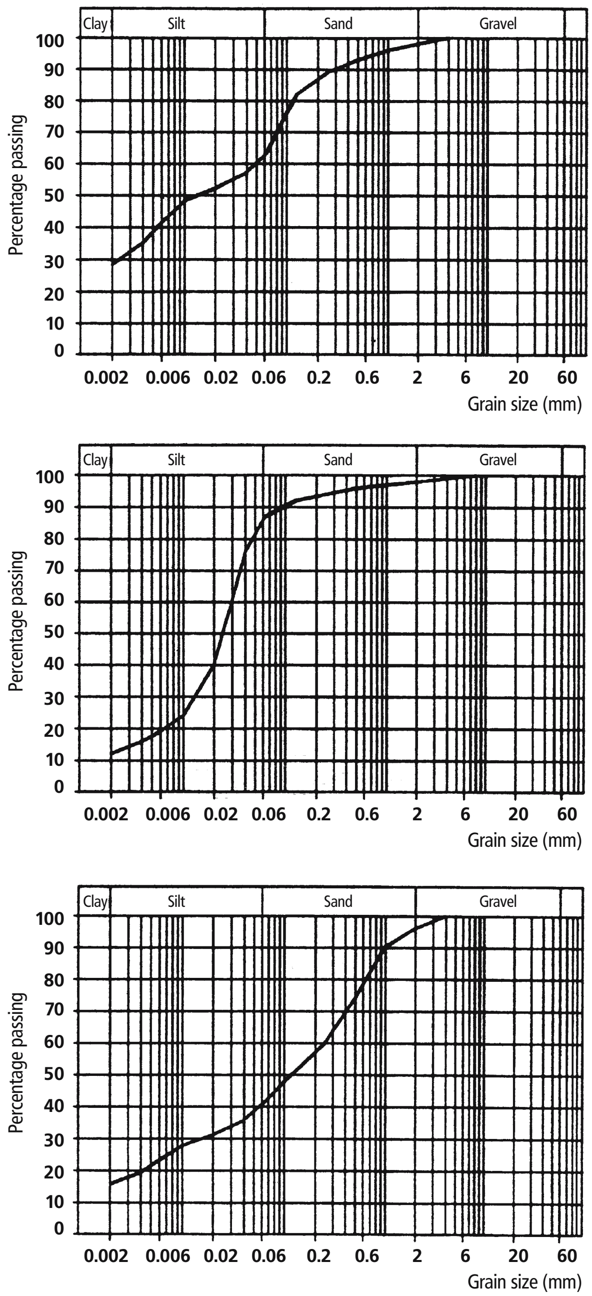
The anxiety that mice or insects might live in earth walls is unfounded when these are solid. Insects can survive only provided there are gaps, as in "wattle-and-daub" walls. In South America, the Chagas disease, which leads to blindness, comes from insects that live in wattle-and-daub walls. Gaps can be avoided by constructing walls of rammed earth or mud bricks with totally filled mud mortar joints. Moreover, if the earth contains too many organic additives, as in the case of lightweight straw clay, with a density of less than 600 kg/m^3, small insects such as wood lice can live in the straw and attack it.
Common perceptions that loam surfaces are difficult to clean (especially in kitchens and bathrooms) can be dealt with by painting them with casein, lime-casein, linseed oil or other coatings, which makes them non-abrasive. As explained on p. 132, bathrooms with earth walls are more hygienic than those with glazed tiles, since earth absorbs high humidity quickly, thereby inhibiting fungus growth.

Note
For the conversion of metric values into imperial ones, see page 197.

2 The properties of earth as a building material

2.1 Soil grain size distribution of loams with high clay content (*above*), high silt content (*middle*), and high sand content (*below*)

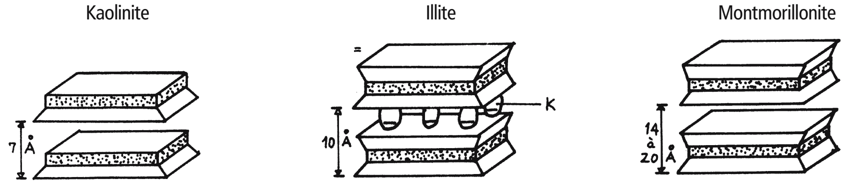
2.1



Composition

General

Loam is a product of erosion from rock in the earth's crust. This erosion occurs mainly through the mechanical grinding of rock via the movement of glaciers, water and wind, or through thermal expansion and contraction of rock, or through the expansion of freezing water in the crevices of the rock. Due to organic acids prevalent in plants, moreover, chemical reactions due to water and oxygen also lead to rock erosion. The composition and varying properties of loam depend on local conditions. Gravelly mountainous loams, for instance, are more suitable for rammed earth (provided they contain sufficient clay), while riverside loams are often siltier and are therefore less weather-resistant and weaker in compression.
Loam is a mixture of clay, silt and sand, and sometimes contains larger aggregates like gravel and stones. Engineering science defines its particles according to diameter: particles with diameters smaller than 0.002 mm are termed clay, those between 0.002 and 0.06 mm are called silt, and those between 0.06 and 2 mm are called sand. Particles of larger diameter are termed gravels and stones.
Like cement in concrete, clay acts as a binder for all larger particles in the loam. Silt, sand and aggregates constitute the fillers in the loam. Depending on which of the three components is dominant, we speak of a clayey, silty or sandy loam. In traditional soil



2.2

mechanics, if the clay content is less than 15% by weight, the soil is termed a lean clayey soil. If it is more than 30% by weight, it is termed a rich clayey soil. Components that form less than 5% of the total by weight are not mentioned when naming the soils. Thus, for instance, a rich silty, sandy, lean clayey soil contains more than 30% silt, 15% to 30% sand, and less than 15% clay with less than 5% gravel or rock. However, in earth construction engineering, this method of naming soils is less accurate because, for example, a loam with 14% clay which would be called lean clayey in soil mechanics, would be considered a rich clayey soil from the point of view of earth construction.

Clay

Clay is a product of the erosion of feldspar and other minerals. Feldspar contains aluminium oxide, a second metal oxide and silicon dioxide. One of the most common types of feldspar has the chemical formula $Al_2O_3 \cdot K_2O \cdot 6SiO_2$. If easily soluble potassium compounds are dissolved during erosion, then clay called Kaolinite is formed, which has the formula $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$. Another common clay mineral is Montmorillonite, whose formula is $Al_2O_2 \cdot 4SiO_2$. There also exists a variety of less common clay minerals such as Illite. The structure of these minerals is shown in *2.2*.
Clay minerals are also found mixed with other chemical compounds, particularly with hydrated iron oxide ($Fe_2O_3 \cdot H_2O$) and other iron compounds, giving the clay a characteristic yellow or red colour. Manganese compounds impart a brown colour; lime and magnesium compounds give white, while organic substances give a deep brown or black colour.
Clay minerals usually have a hexagonal lamellar crystalline structure. These lamellas consist of different layers that are usually formed around silicon or aluminium cores. In the case of silicon, they are surrounded by oxygenations; in the case of aluminium, by hydroxyl (ions) groups (-HO). The layers of silicon oxide have the strongest negative charge, which endows them with a high interlamellary binding force (see *2.3*). Because each layer of aluminium hydroxide is connected to a layer of silicon oxide, the double-layered Kaolinite has a low ion-binding capacity, whereas with the three-layered mineral Montmorillonite, one aluminium hydroxide layer is always sandwiched between two layers of silicon oxide, thereby displaying a higher ion binding capacity. Most of the clay minerals have interchangeable cations. The binding force and compressive strength of loam is dependent on the type and quantity of cations.

Silt, sand and gravel

The properties of silt, sand and gravel are totally different from clay. They are simply aggregates lacking binding forces, and are formed either from eroding stones, in which case they have sharp corners, or by the movement of water, in which case they are rounded.

Grain size distribution

Loam is characterised by its components: clay, silt, sand and gravel. The proportion of the components is commonly represented on a graph of the type shown in *2.1*. Here, the vertical axis represents weight by percentage of the total of each grain size, which in turn is plotted on the horizontal axis using a logarithmic scale. The curve is plotted cumulatively, with each grain size including all the fine components.
The upper graph characterises a rich clayey loam with 28% clay, 35% silt, 33% sand and 4% gravel. The middle graph shows rich silty loam with 76% silt, and the bottom graph a rich sandy loam containing 56% sand. Another method for graphically describing loam composed of particles no larger than 2 mm is shown in *2.4*. Here the

2.2 Structure of the three most common clay minerals (according to Houben, Guillaud, 1984)
2.3 Lamellar structure of clay minerals (according to Houben, Guillaud, 1984)
2.4 Soil grain size distribution depicted on a triangular grid (after Voth, 1978)