Building with Earth

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BUILDING WITH EARTH

Design and Technology of a Sustainable Architecture

Fourth and revised edition

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Preface

This handbook was written in response to an increasing worldwide interest in building with earth. While in Europe and North America earthen architecture may never play the dominant role as in warmer regions, we nevertheless find an increasing tendency to build with loam also in cooler climate zones. One reason for this is the growing environmental awareness as well as the desire to live in a balanced and healthy indoor environment. Thus this fourth edition is timely and should encourage architects to explore the potential of this sustainable building material further. The publication provides a survey of all applications and construction techniques of earth as a building material, including the relevant physical data, while explaining its specific qualities and the possibilities of optimising them. On many accounts, earth can offer an interesting alternative to industrialised building materials. The data and expert knowledge contained in this volume may be used as guidelines for a variety of construction processes and possible applications by engineers, architects, builders and clients who seek to use humanity's oldest building material for their purposes.

Earth as a building material comes in many 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 at the Forschungslabor für Experimentelles Bauen (Building Research Institute – BRI) at the University of Kassel in Germany from 1978 to 2011. Moreover, the specialised techniques that 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 *Handbuch Lehmbau* (Publisher: Ökobuch Verlag, Staufen), first published in 1994 and now in its nineth edition (2017). Besides this English edition, the publication was translated into numerous languages such as Spanish, Russian, Japanese, Czech, Farsi, Arabic and Rumanian.

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 this fourth English edition, the relatively recent technology of prefabricated rammed earth elements is introduced and the growing segment of clay panels is documented. The book's final chapter depicts a number of attractive 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. Within this chapter, several older built examples were replaced by 11 new projects.

Kassel, November 2021
Gernot Minke

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

1.1

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1 Introduction

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1.1 Citadel of Bam, Iran, before earthquake of December 2003

1.2 Tulou of the Hakka in Fujian, Nanjing, China: A timber roof construction with a courtyard and rammed earth walls.

1.3 Fortified City, Draa valley, Morocco, 15th century

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

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discovered in Assyria. Earth was used as the building material in all ancient cultures, not only for homes, but for religious buildings as well. Illustrations *1.1* and *1.5* show 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. China has a long tradition of building with earth; well-known are for instance the Tulou ("house of earth") buildings *(1.2; 15.1)* in Fujian, Nanjing (Schittich, 2019). Illustration *1.4* shows vaults in the Temple of Ramses II at Gourna, Egypt, built from mud bricks 3200 years ago. The core of the Sun Pyramid in Teotihuacan, Mexico, built between the 300 and 900 AD, consists of approximately 2 million tonnes of rammed earth.

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. While the splendid Shah Mosque was built from earth bricks *(1.8),* illustration *1.9* shows the bazaar quarter of Sirdjan in Persia, which is covered by such domes and vaults. In China, 20 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 *(1.11)* 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 *1.10* 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 *1.12* shows one from the 12th century, *1.6*, *1.7* and *1.8* 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, François Cointeraux published four booklets on this technique that were translated into German 2 years later (Cointeraux, 1793). The technique came to be known all over Germany and in neighbouring countries through Cointeraux, and through David Gilly who described the rammed earth technique as the most advantageous earth construction method.

In Germany, the oldest inhabited house with rammed earth walls dates from 1795 *(1.13).* 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. The so-called Pisé House (referring to French *piser* or to stamp) by architect Wilhelm Jacob Wimpf was completed in 1828, has six storeys and is still in use today *(1.14).* 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 *1.15* shows the facades of other rammed earth houses at Weilburg, built around 1830.

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1.4 Storage rooms, temple of Ramses II, Gourna, Egypt
1.5 Citadel of Bam, Kerman, Iran, detail
1.6 Large Mosque, Djenne, Mali, built 1935
1.7 Mosque, Kashan, Iran
1.8 Shah Mosque, Isfahan, Iran, 17th century
1.9 Bazaar, Sirdjan, Iran

1.7

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. 37).

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. 38).

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 Institute – BRI) at the University of Kassel, Germany, demonstrated that when the relative humidity in

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1.10 Rammed earth finca, São Paulo, Brazil

1.11 Reconstruction of mud-brick wall, Heuneburg, Germany, 6th century BC

1.12 Mosque at Nando, Mali, 12th century

1.13 Rammed earth house, Meldorf, Germany, 1795

1.14 Rammed earth house (Pisé house), Weilburg, Germany, 1828

1.15 Around 1830, a number of rammed earth houses were built in Weilburg, Germany.

1.16 Section through trachea with sane mucous membrane (left) and dried out one (right) (Beckert, 1986)

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 6 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 8 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. 13).

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.

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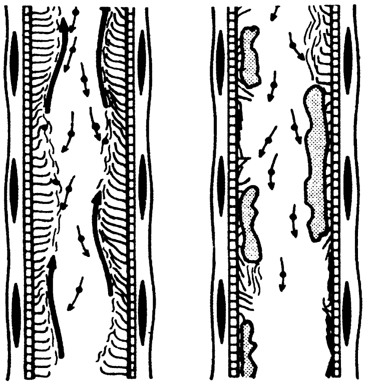

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3 Loam saves energy and reduces environmental pollution

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.

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% (Volz, 2004, p. 60). 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 *10.3*, p. 86).

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.

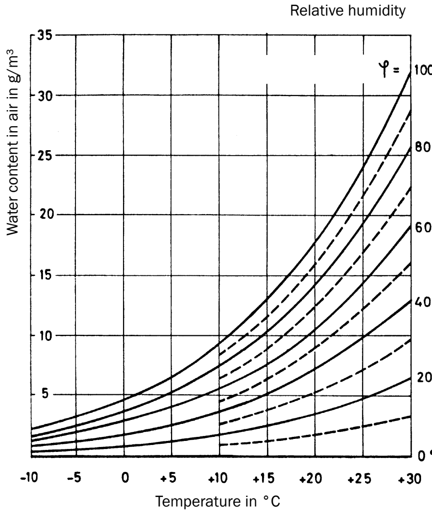
Improving indoor climate

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 (1973) and Beckert (1986) has shown that a relative humidity of less than 40% over a long period may dry out the mucous membrane, which



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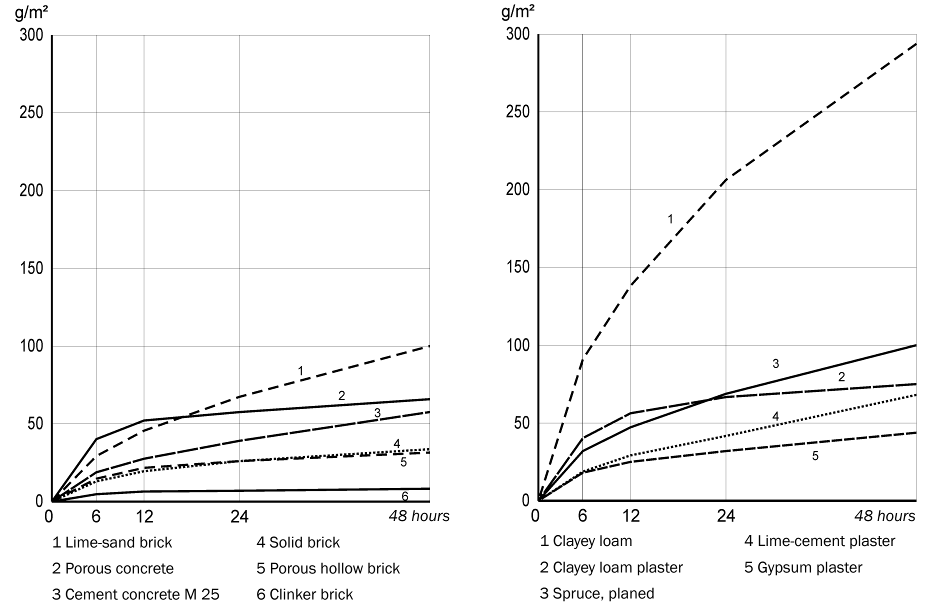

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can decrease resistance to colds and related diseases. This is so because normally the mucous membrane of the epithelial tissue within the trachea absorbs dust, bacteria, viruses etc. and returns them to the mouth by the wavelike movement of the epithelial hair. If this absorption and transportation system is disturbed by drying, then foreign bodies can reach the lungs and may cause health problems *(1.16).* 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.

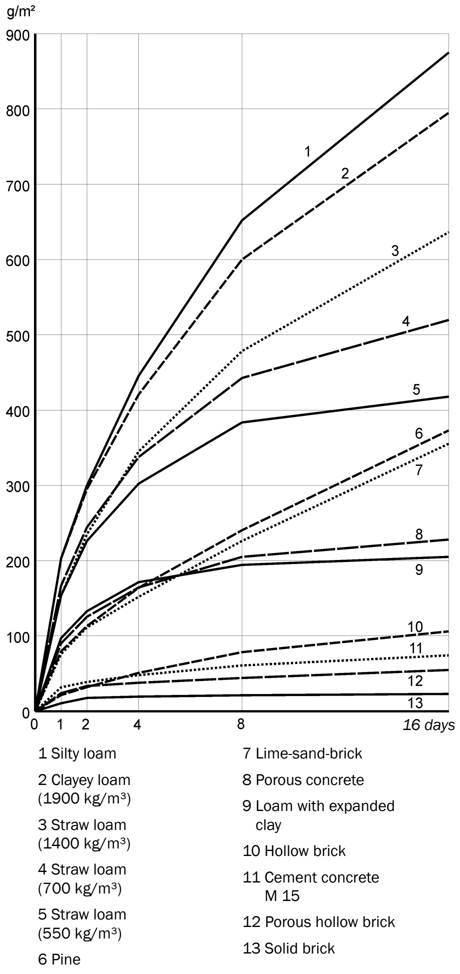
A relative humidity of more than 70% is normally experienced as unpleasant, probably because of the reduction of oxygen intake by the blood in warm-humid conditions. Increasing rheumatic pains are observed in cold humid air. Fungus formation increases significantly in closed rooms when the humidity rises 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%.

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 *(1.17).*

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 *2.29*, p. 28). The effectiveness of this balancing process also depends upon the speed of the absorption or desorption.



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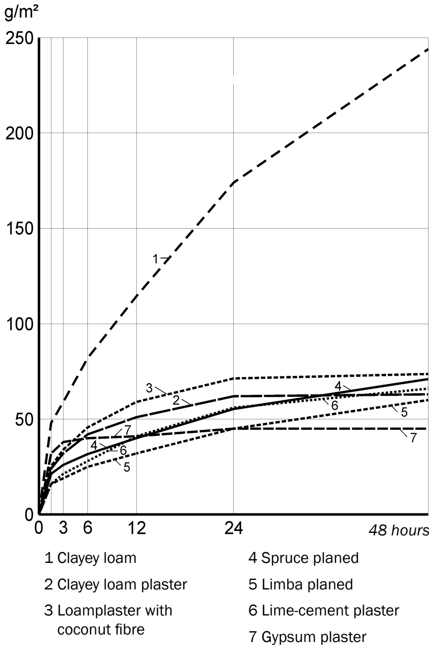

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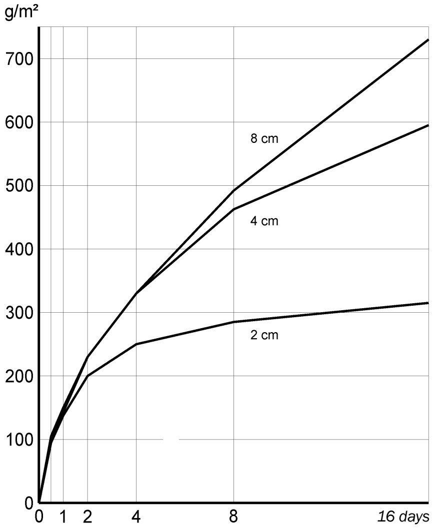


1.21

1.17 Water vapour content of the air in relation to temperature

1.18 Absorption of samples, 15 mm thick, at a temperature of 21 °C and a sudden increase of humidity from 50% to 80%

1.19 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%

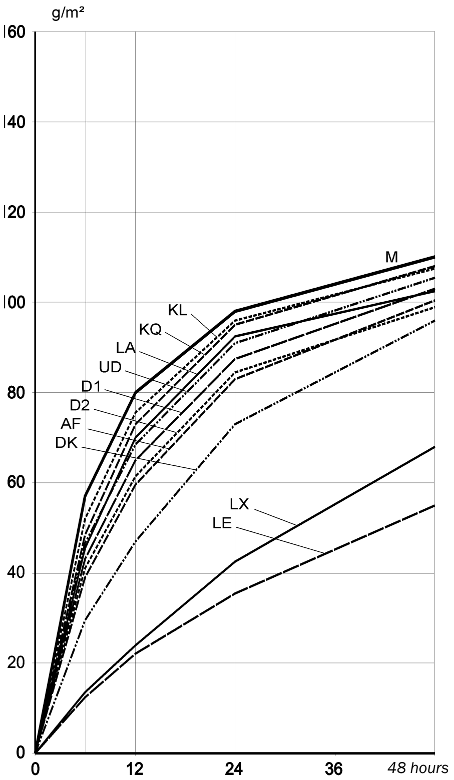
1.20 Absorption curves of 15-mm-thick samples, one side exposed, at a temperature of 21 °C after a sudden rise in humidity from 30% to 70%

1.21 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%

Experiments conducted at the BRI show, for instance, that the first 1.5-cm-thick layer of a mud brick wall is able to absorb about 300 g of water per m^2 of wall surface in 48 hours if the humidity of the ambient air is suddenly raised from 50% to 80%. However, limesandstone and pinewood of the same thickness absorb only about 100 g/m^2, plaster 26 to 76 g/m^2, and baked brick only 6 to 30 g/m^2 in the same period *(1.18).* The absorption curves from both sides of 11.5-cm-thick unplastered walls of different materials over 16 days are shown in *1.19.* 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 *1.20.*

The influence of the thickness of a clayey soil on absorption rates is shown in *1.21.* 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 4 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 *1.22.* In a room with a floor area of 3 × 4 m, a height of 3 m, and a wall area of 30 m^2 (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 5 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.



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

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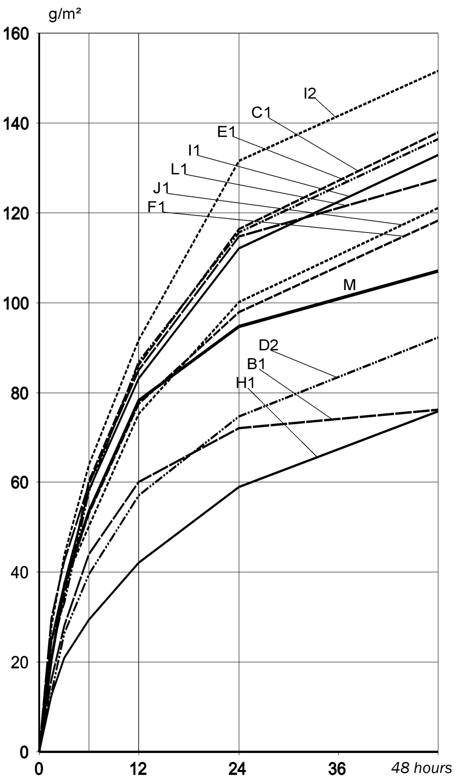


M	Loam plaster without aggregate
I2	with 2.0% coconut fibres
C1	with 2.0% cellulose fibres
E1	with 2.0% water glass
I1	with 1.0% coconut fibres
L1	with 3.0% saw dust
J1	with 2.0% wheat straw
F1	with 3.0% cement
D2	with 2.0% boiled rye flour
B1	with 0.5% cellulose glue
H1	with 6.0% casein/lime++

1.23

1.22 Influence of coatings on 1.5-cm-thick, oneside-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.

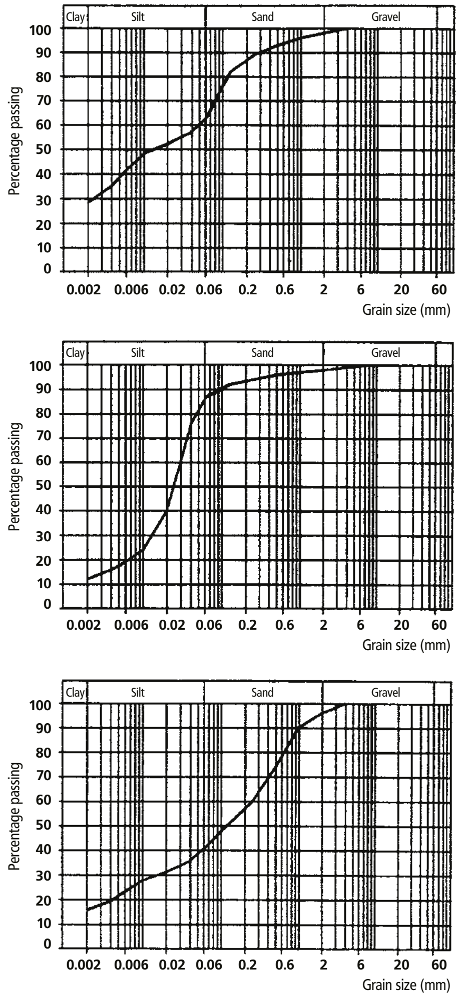
1.23 Influence of different aggregates on the absorption of humidity. Same conditions as mentioned in *1.22*

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 nonabrasive. As explained on p. 129, bathrooms with earth walls are more hygienic than those with glazed tiles, since earth absorbs high humidity quickly, thereby inhibiting fungus growth.

2

The properties of earth as a building material



2.1

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

Composition

General

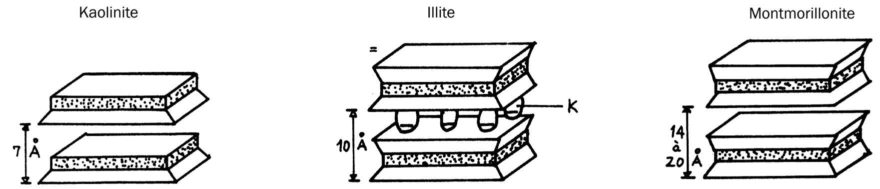
Loam is a product of erosion from rock in the earth's crust. This erosion occurs mainly through the mechanical grinding of rock via the movement of glaciers, water and wind, or through thermal expansion and contraction of rock, or through the expansion of freezing water in the crevices of the rock. Due 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 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



2.2

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 *(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 percentage of clay, silt and sand can be plotted on the three axes of a triangle and read accordingly. For example, the loam indicated by an asterisk in this graph is composed of 22% clay, 48% silt and 30% sand.

Organic constituents

Soil dug from depths of less than 40 cm usually contains plant matter and humus (the product of rotting plants), which consists mainly of colloidal particles and is acidic (pH-value less than 6). Earth as building material should be free of humus and plant matter. Under certain conditions, plant matter like straw can be added, provided it is dry and there is no danger of later deterioration (see *10.3*, p. 86).

Water

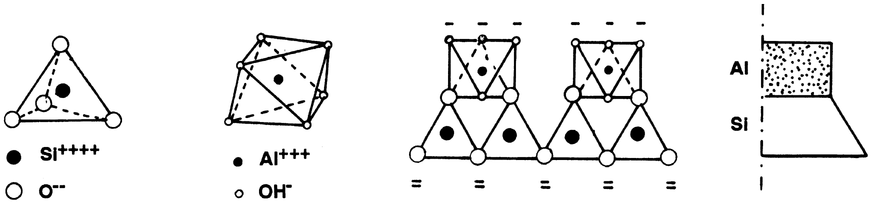
Water activates the binding forces of loam. Besides free water, there are three different types of water in loam: water of crystallisation (structural water), absorbed water, and water of capillarity (pore water). Water of crystallisation is chemically bound and is only distinguishable if the loam is heated to temperatures between 400 °C and 900 °C. Absorbed water is electrically bound to the clay minerals. Water of capillarity has entered the pores of the material by capillary action. Absorbed and capillary water are released when the mixture is heated

2.2 Structure of the three most common clay minerals (Houben and Guillaud, 1984)

2.3 Lamellar structure of clay minerals (Houben and Guillaud, 1984)

2.4 Soil grain size distribution depicted on a triangular grid (Voth, 1978)

2.5 Soil grain size distribution of two loams tested in the sedimentation test



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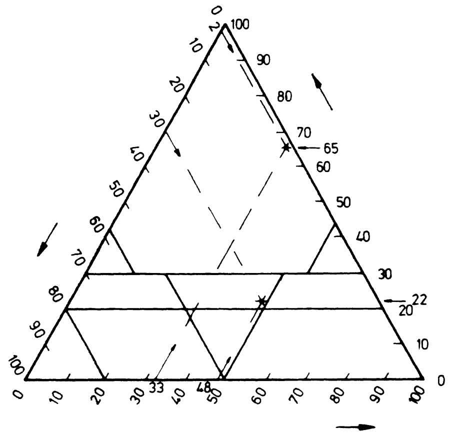


2.4

Sample	Content	by vision		Real
		% (vol.)	% (mass)	% (mass)
K1	Clay	45	14	6
	Silt	18	26	38
	Sand	37	60	56
K2	Clay	36	17	2
	Silt	24	19	16
	Sand	40	64	82

2.5

to 105 °C. If dry clay gets wet, it swells because water creeps in between the lamellary structure, surrounding the lamellas with a thin film of water. If this water evaporates, the interlamellary distance is reduced, and the lamellas arrange themselves in a parallel pattern due to the forces of electrical attraction. The clay thus acquires a “binding force” (see p. 30), if in a plastic state, and compressive and tensile strength after drying.

Porosity

The degree of porosity is defined by the total volume of pores within the loam. More important than the volume of the pores are the dimensions of the pores. The larger the porosity, the higher the vapour diffusion and the higher the frost resistance. Specific surface The specific surface of a soil is the sum of all particle surfaces. Coarse sand has a specific surface of about 23 cm^2/g, silt about 450 cm^2/g and clay, from 10 m^2/g (Kaolinite) to 1000 m^2/g (Montmorillonite). The larger the specific surface of clay, the higher the internal cohesive forces which are relevant for binding force as well as compressive and tensile strength.

Density

The density of soil is defined by the ratio of dry mass to volume (including pores). Freshly dug soil has a density of 1000 to 1500 kg/m^3. If this earth is compressed, as in rammed earthworks or in soil blocks, its density varies from 1700 to 2200 kg/m^3 (or more, if it contains considerable amounts of gravel or larger aggregates).

Compactability

Compactability is the ability of earth to be compacted by static pressure or dynamic compaction so that its volume is reduced. To attain maximum compaction, the earth must have a specific water content, the so-called “optimum water content”, which allows particles to be moved into a denser configuration without too much friction. This is measured by the Proctor test (see p. 42).

Tests used to analyse the composition of loam

To determine the suitability of a loam for a specific application, it is necessary to know its composition. The following section describes standardised laboratory tests and simple field tests that are used to analyse loam composition.

Combined sieving and sedimentation analysis

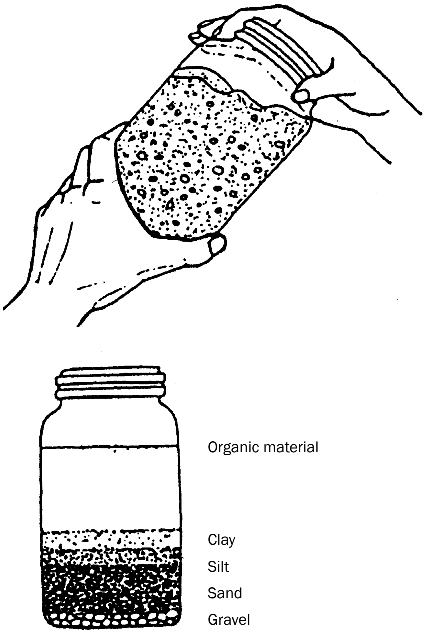
The proportion of coarse aggregates (sand, gravel and stones) is relatively easy to distinguish by sieving. However, the proportion of fine aggregates can only be ascertained by sedimentation. This test is specified in detail in the German standard DIN 18123.

Water content

The amount of water in a loam mixture can be easily determined by weighing the sample and than heating it in an oven to 105 °C. If the weight stays constant, the mixture is dry, and the difference of the two weights gives the weight of all water not chemically bound. This water content is stated as a percentage of the weight of the dry mixture.

Simple field tests

The following tests are not very exact, but they can be performed on site relatively quickly, and are usually exact enough to estimate the composition of loam and ascertain if the mixture is acceptable for a specific application.



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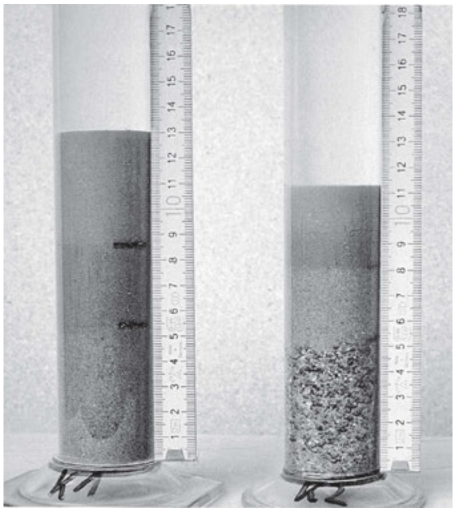


2.7

2.6 Sedimentation test (CRATerre, 1979)

2.7 Sedimentation test

2.8 Grain size distribution of test loams

2.9 Loam balls after the dropping test

2.10 Ribbon test

2.11 Cohesion test developed at the BRI

Smell test

Pure loam is odourless, however it acquires a musty smell if it contains deteriorating humus or organic matter.

Nibble test

A pinch of soil is lightly nibbled. Sandy soil produces a disagreeable sensation as opposed to silty soil, which gives a less objectionable sensation. Clayey soil, on the other hand, gives a sticky, smooth or floury sensation.

Wash test

A humid soil sample is rubbed between the hands. If the grains can be distinctly felt, it indicates sandy or gravelly soil. If the sample is sticky, but the hands can be rubbed clean when dry, this indicates silty soil. If the sample is sticky, so that water is needed to clean the hands, this indicates clayey soil.

Cutting test

A humid sample of the earth is formed into a ball and cut with a knife. If the cut surface is shiny, it means that the mixture has high clay content; if it is dull, it indicates high silt-content.

Sedimentation test

The mixture is stirred with a lot of water in a glass jar. The largest particles settle at the bottom, the finest on top. This stratification allows the proportion of the constituents to be estimated. It is a wrong to assert that the height of each layer corresponds to the proportion of clay, silt, sand and gravel, as is claimed by many authors (e.g. CRATerre, 1979, p. 180; International Labour Office, 1987, p. 30; Houben and Guillaud, 1984, p. 49; Stulz and Mukerji, 1988, p. 20; United Nations Centre for Human Settlements, 1992, p. 7) *(2.6).*

Several experiments at the Building Research Institute – BRI, University of Kassel, showed that the margin of error could be higher than 1000%, see *2.5.* The clay content in sample K2 appears to be 36% by vision, but in reality was only 2%. In fact, one can only distinguish successive strata at sudden changes of grain-size distribution, and these may not coincide with the actual defined limits between clay and silt, and between silt and sand *(2.7).*

Ball dropping test

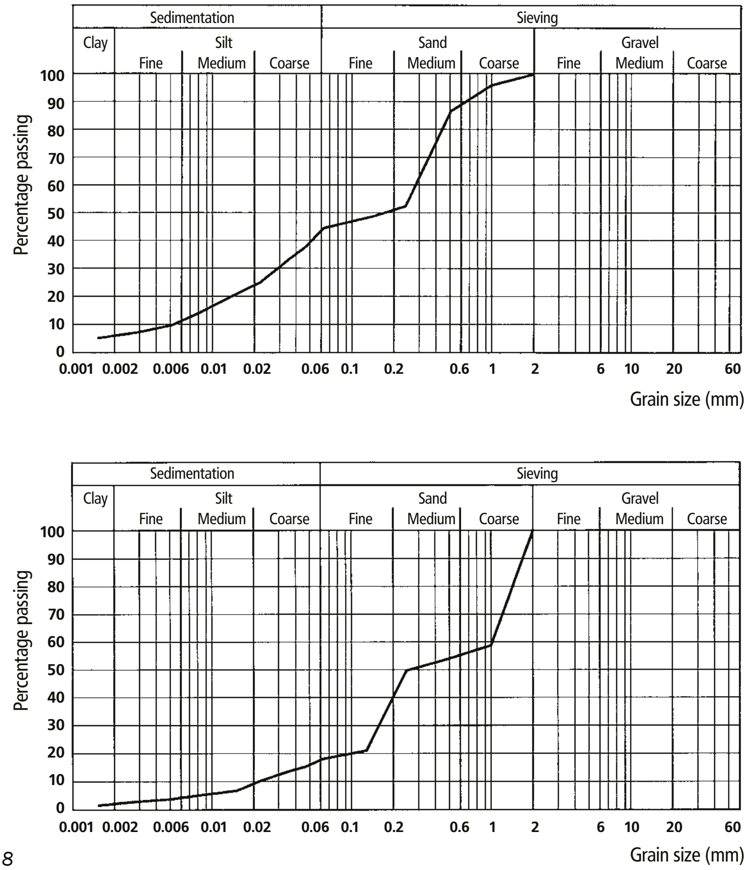
The mixture to be tested has to be as dry as possible, yet wet enough to be formed into a ball 4 cm in diameter. When this ball is dropped from a height of 1.5 m onto a flat surface, various results can occur, as shown in *2.9.* If the ball flattens only slightly and shows few or no cracks, like the sample on the left, it has a high binding force due to high clay content. Usually this mixture must be thinned by adding sand. If the test looks like the sample on the right, it has very low clay content. Its binding force is then usually insufficient, and it cannot be used as a building material. In the case of the third sample from the left, the mixture has a relatively poor binding force, but its composition usually enables it to be used for mud bricks (adobes) and rammed earth.

Consistency test

Moist earth is formed into a ball 2 to 3 cm in diameter. This ball is rolled into a thin thread 3 mm in diameter. If the thread breaks or develops large cracks before it reaches 3 mm diameter, the mixture is slowly moistened until the thread breaks only when its diameter reaches 3 mm. This mixture is then formed into a ball. If this is not possible, then the sand content is too high and the clay content too low. If the ball can be crushed between the thumb and forefinger only with a lot of force, the clay content is high and has to be thinned by adding sand. If the ball crumbles very easily, then the loam contains little clay.

Cohesion test (ribbon test)

The loam sample should be just moist enough to be rolled into a thread 3 mm in diameter without breaking. From this thread, a ribbon approximately 6 mm in thickness and 20 mm wide is formed and held in the palm. The ribbon is then slid along the palm to overhang as much as possible until it breaks *(2.10).* If the free length before breakage is


Sedimentation
Sieving
Clay
Silt
Fine
Medium
Coarse
Sand
Fine
Medium
Coarse
Gravel
Fine
Medium
Coarse
Percentage passing
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.006
0.01
0.02
0.06
0.1
0.2
0.6
1
2
6
10
20
60
Grain size (mm)
Sedimentation
Sieving
Clay
Silt
Fine
Medium
Coarse
Sand
Fine
Medium
Coarse
Gravel
Fine
Medium
Coarse
Percentage passing
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.006
0.01
0.02
0.06
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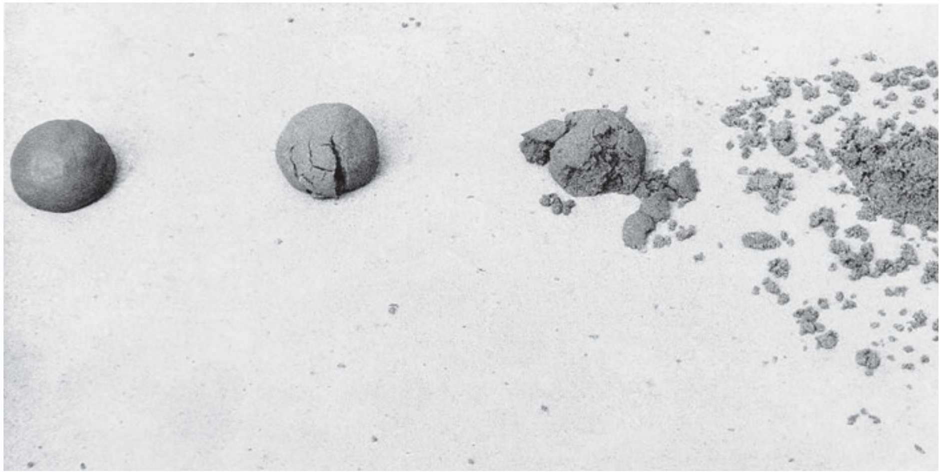
0.2
0.6
1
2
6
10
20
60
Grain size (mm)

2.8



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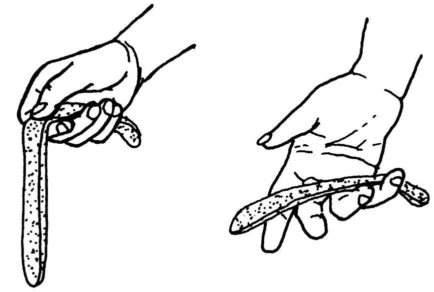

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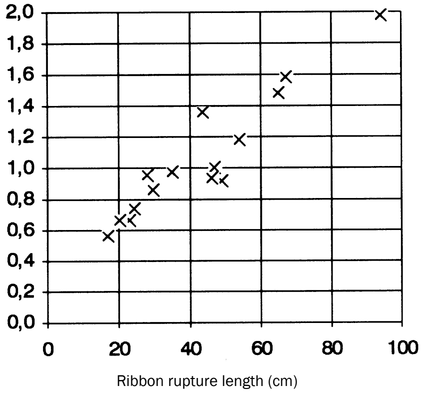
2.11



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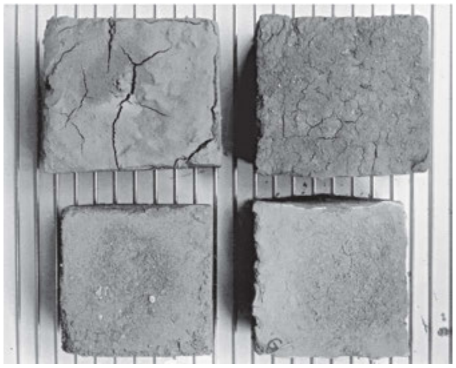


2.13

more than 20 cm, then it has a high binding force, implying a clay content that is too high for building purposes.

If the ribbon breaks after only a few centimetres, the mixture has too little clay. This test is inaccurate, and at the BRI it was known to have margins of errors of greater than 200% if the loam was not well-kneaded and the thickness and width of the ribbon varied.

For this reason, a new, more precise test was developed in which a 20-mm-wide and 6-mm-high profile was produced by pressing the loam with the fingers into the groove between two ledges. The surface is smoothened by rolling with a bottle *(2.11).* To prevent the loam profile from sticking, the base is lined with a thin strip of plastic or oilpaper. The length of the ribbon, when it breaks under its own weight, is measured by pushing it slowly over a rounded edge with a radius curvature of 1 cm *(2.11, right).* For each type of soil, five samples were taken and ribbon lengths measured at the point of rupture.

The longest rupture lengths from each set have been plotted in *2.12,* against the binding force according to the standard DIN 18952 test (see p. 30), with a slight change: here the maximum strength of five samples was also considered.

This is because it was found that the lower values were usually due to insufficient mixing, inaccurate plasticity or other preparation mistakes. In order to guarantee that different loam mixtures are comparable, the chosen consistency of the samples was defined by a diameter of 70 mm (instead of 50 mm) of the flat circular area, which forms if a test ball of 200 g weight is dropped from a height of 2 m. (With sandy loam mixtures with little clay content, a diameter of 50 mm is not attainable.)

Acid test

Loams that contain lime are normally white in appearance, exhibit a low binding force and are therefore inappropriate for earth construction. In order to define the lime content, one drop of a 20% solution of HCl is added using a glass or a timber rod. In the case of loam with lime content, CO_2 is produced according to the equation $CaCO_3 + 2HCl = CaCl_2 + CO_2 + H_2O$. This CO_2 production is observable because of the efflorescence that results; if there is no efflorescence, the lime content is less than 1%. If there is a weak, brief efflorescence, the lime content is between 1% and 2%; if the efflorescence is significant though brief, the lime content is between 3% and 4%; and if the efflorescence is strong and long lasting, the lime content is more than 5% (Voth, 1978, p. 59).

It should be noted that a dark lime-free loam with a high content of humus could also exhibit this phenomenon.

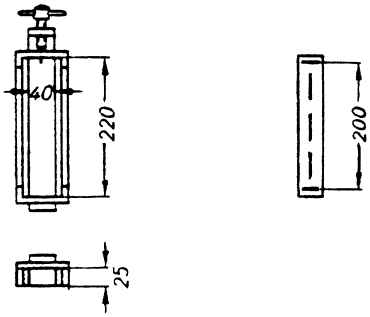
Effects of water

If loam becomes wet, it swells and changes from a solid to a plastic state.

Swelling and shrinking

The swelling of loam when in contact with water and its shrinkage through drying is disadvantageous for its use as a building material. Swelling only occurs if loam comes into direct contact with so much water that it loses its solid state. The absorption of humidity from the air, however, does not lead to swelling.

The amount of swelling and shrinkage depends on the type and quantity of clay (with Montmorillonite clay this effect is much larger than with Kaolinite and Illite), and also on the grain distribution of silt and sand. Experiments were conducted at the BRI using 10 × 10 × 7 cm samples of different loam mixtures that were soaked with 80 cm^3 of water and then dried in an oven at 50 °C in order to study shrinkage cracks *(2.13).* Industrially fabricated unbaked blocks *(2.13, top left),* whose granularity curve is shown in *2.1* (upper left), display shrinkage cracks. A similar mixture with the same kind and amount of clay, but with “optimised” distribution of silt and sand, exhibited hardly any cracks after drying out *(2.13, top right).* The mud brick made of silty soil *(2.13, bottom right)* (granularity curve shown in *2.1, middle*) shows several very fine cracks, whereas the mud brick of sandy soil *(2.13, bottom left)* (granularity



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2.15

2.12 Binding force of different loams of equal consistency in relation to their rupture lengths, tested according to the BRI cohesion test

2.13 Swelling and shrinkage test

2.14 Tools to distinguish the linear shrinkage according to the German standard DIN 18952

2.15 Apparatus to obtain the liquid limit, according to Casagrande method

curve shown in *2.1, bottom*) shows no cracks at all. On p. 37 it is explained how shrinkage might be minimised by changing grain distribution.

Determining linear shrinkage

Before the shrinkage ratio of different loam samples can be compared, they must have comparable plasticity.

The German standard DIN 18952 describes the following steps required to obtain this standard stiffness:

1. The dry loam mixture is crushed and sieved to eliminate all particles with diameters larger than 2 mm.
2. About 1200 cm^3 of this material is slightly moistened and hammered on a flat surface to produce a continuous piece (like a thick pancake).
3. This is then cut into 2-cm-wide strips, placed edge-to-edge touching each other, then hammered again. This procedure is repeated until the lower part shows an even structure.
4. Loam with high clay content must then rest for 12 hours, and one with low clay content for about 6 hours, so that the water content is equally distributed throughout the sample.
5. From this mixture, 200 g are beaten, to compact into a sphere.
6. This ball is dropped from a height of 2 m onto a flat surface.
7. If the diameter of the flattened surface thus formed is 50 mm, standard stiffness is said to be reached. The difference between the largest and smallest diameters of this disc should not be more than 2 mm. Otherwise the whole process must be repeated until the exact diameter in the drop test is reached. If the disc diameter is larger than 50 mm, then the mixture has to be dried slightly and the whole process repeated until the exact diameter is attained.
8. If the diameter of the disc is less than 50 mm, then a few drops of water should be added.

With this standard stiffness, the shrinkage test is to be executed as follows:

1. The material is pressed and repeatedly rammed by a piece of timber about 2 × 2 cm in section into the form shown in *2.14*, which rests on a flat surface.
2. Three samples have to be made and the form has to be taken off at once.
3. Template marks at a distance of 200 mm are made with a knife.
4. The three samples are dried for three days in a room. They are then heated to 60°C in an oven until no more shrinkage can be measured. The DIN mentions that they are to be dried on an oiled glass plate. The BRI suggests lining the plate with a thin layer of sand to make the drying process more even and avoiding friction.
5. The average shrinkage of the three samples in relation to the length of 200 mm gives the linear shrinkage ratio in percentages. If the shrinkage of one sample differs more than 2 mm from the other two, the sample has to be remade.

Plasticity

Loam has four states of consistency: liquid, plastic, semisolid and solid. The limits of these states were defined by the Swedish scientist Atterberg.

Liquid limit

The liquid limit (LL) defines water content at the boundary between liquid and plastic states. It is expressed as a percentage and is determined by following the steps explained below using the Casagrande instrument shown in *2.15:*

1. The mixture must remain in water for an extended period (up to 4 days if the clay content is high) and then pressed through a sieve with 0.4 mm meshes.
2. 50 to 70 g of this mixture in a pasty consistency is placed in the bowl of the apparatus and its surface smoothened. The maximum thickness in the centre should be 1 cm.
3. A groove is then made using a special device, which is always held perpendicular to the surface of the bowl.
4. By turning the handle at a speed of 2 cycles per second, the bowl is lifted and