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Foreword

Earth has been used as a building material for millennia. Architecture in the ancient cultures of Egypt, the Middle East, China, Central Asia, and Latin America was closely tied to this material. In Central Europe, as well, there is archaeological evidence of the use of earth as a building material for thousands of years. Within the individual regions, practical experiences with the material and the resulting building rules were passed down for generations leading to construction methods which were affordable and optimally developed for the respective climates. The buildings were constructed from locally available materials which were sourced using environmentally friendly methods. Earthen structures blended well into the landscape and shaped the picture of rural regions and urban settlements over the centuries. "Recycling" of the buildings did not pose any problems: earth building materials could be reused indefinitely or could be returned to the natural cycle without harming the environment.

In modern times, all of these aspects can be more or less summed up under the term "sustainable building." For a long time, building materials and architectural design were mainly assessed in terms of structural design, material technology, and economy. Today, however, ecological criteria, particularly a building's energy consumption and its impact on the environment, have become increasingly important in the interest of sustainable development. Clients are requesting nontoxic, healthy building materials which create a comfortable indoor climate. Other popular aspects are the sensual characteristics of building elements, such as unusual textures as well as pleasant tactile surface qualities and a wide range of colors. These add to the desirability of earth as a building material.

In this context, earth can be seen in a new light after years of being marginalized from conventional construction by industrially mass-produced building materials. Today, private as well as public clients are increasingly opting for the building material earth.

This book describes the planning and execution of earth building projects from a modern perspective: it highlights the preservation of traditions for historic conservation and renovation projects while, at the same time, showing current trends in modern earth building. Special emphasis is placed on aspects of sustainability and on how earth can be combined with other "modern" building materials.

The idea of the life cycle of earth as a building material is the recurring theme of this book: it covers all of the processing steps of the soil including the sourcing and extraction of the material, the soil's preparation and processing into building materials and building elements, the useful life of the finished building and its maintenance, and, finally, the demolition and recycling of the building which completes the cycle. Today, the life cycle model of a building material is a generally accepted methodological approach which is used for the quantitative recording and assessment of the production of building materials and building products with regard to sustainability.

This book sums up my years of experience working with earth as a building material. It reflects the knowledge I have gained through my practical work on building sites, as part of my research and teaching at the Bauhaus University in Weimar, Germany, and as a consultant for various national and international organizations and clients. Above all, it has been my 20 years of serving as the President of the German Association for Building with Earth (Dachverband Lehm e.V.), as well as professional exchanges with members of the association while working on numerous projects, which have contributed to the writing of this book.

The first German edition, published in 2010, was soon out of print. The second edition was published in 2013 and incorporated many changes, especially the newly published DIN standards for earth building materials. Many of my international colleagues have expressed an interest in an English translation of this book. Together with my publisher, I have now decided to respond to this wish and hope that the English translation will be met with the same level of interest as the original German version.

The second, revised German edition, which has been reviewed and slightly updated, serves as the basis for the English translation. I hope that earth builders worldwide benefit from this book.

Weimar, Germany
March 2015

Horst Schroeder

Contents

List of Symbols

Symbol	Unit	Parameter	PG[a]
A	m^2	Area	3, 4, 5
A	Bq	Activity	5
A	kN/cm	Compaction work	3
a	mm	Slump	3
a	Bq/kg	Specific activity	5
A_s	cm^2/g	Specific grain surface area	2
b	$Ws/s^{0.5}\ m^2\ K$	Thermal effusivity coefficient	5
C	$W/m^2\ K^4$, $kcal/hm^2\ K^4$	Radiation coefficient for a “non-black” body	5
C_c	–	Curvature coefficient, grading	1
c_N	g/cm^2, N/mm^2	Cohesive strength according to Niemeyer	3
c_p	Ws/kg K, kJ/kg K	Specific heat capacity	5
C_u	–	Uniformity coefficient	1
d	m	Thickness of the building element	5, 7
d	mm	Grain size	1
d	mm	Grain diameter	1
d	mm	Specimen diameter	1, 4
D	Gy, J/kg	Absorbed dose	5
D_f	–	Deformation ratio	4
D_{Pr}	–	Compaction degree	1
d_x	mm	Grain diameter when $x\%$ passes through sieve	1
e	–	Void ratio	1
e	m	Eccentricity of the resultant in the foundation bottom plane	4
E	N/mm^2, MN/m^2	Uniaxial elastic modulus, uniaxial Young’s modulus	4
E_S	N/mm^2, MN/m^2	Constrained modulus	4

(continued)

(continued)

Symbol	Unit	Parameter	PG[a]
E_S	W/m^2	Total radiated energy	5
F	kN, N	Force	4
F_s	%	Free swell value	4
G	kN, MN	Dead load	4
G	MN/m^2	Shear modulus	4
H	Sv, J/kg	Dose equivalent	5
h	Sv/a, mSv/a	Dose equivalent rate	5
h	mm	height, specimen ~	1, 4, 7
h_1	mm	Crushed sample height	4
h_o	mm	Initial sample height	1, 4
I	Bq/kg	Activity concentration index	5
I	12-degree scale	Earthquake intensity	4
I_A, AI	–	Activity ratio, ~index	2
I_c, CI	–	Level of consistency	3
I_p, PI	–	Plasticity index	3
I_S	–	Shrinkage index	3
l	mm	Length	7
L_n	dB	Impact sound level	5
$L_{n,w}$	dB	Weighted normalized impact sound pressure level	5
M	Richter scale	Magnitude of an earthquake	4
m_{Ca}	g	Mass percentage of total carbonates, based on m_d	2
m_d	g	Dry mass	1, 3
m_m	g	Moist mass	1, 3
m_s	g	Solid mass	1, 3
m_w	kg/m^2	Mass of water absorbed by capillary action	5
n	–	Porosity	1
Q	J, Ws; 1 J=1 Ws	Heat, quantity of heat	5
q	W/m^2	Heat flow density	5
Q_s	Ws/m^2 K	Heat storage capacity	5
R	m^2 K/W	Heat transfer resistance	5
R	kN	Structural resistance, resultant	4
R	dB	Sound reduction index	5
RH	%	Relative humidity	3, 5
R_{si}, R_{se}	m^2 K/W	Surface heat transfer resistance, interior (i) and exterior (e)	5
R_T	m^2 K/W	Overall heat transfer resistance	5
R_w	dB	Weighted sound reduction index	5
R_w'	dB	Weighted sound reduction index taking adjacent building elements into consideration	5

(continued)

(continued)

Symbol	Unit	Parameter	PG[a]
S	Ws/m³ K	Volumetric heat capacity	5
S	kN	Working load	4
s_d	–	Water vapor diffusion equivalent air layer thickness	5
S_r	–	Degree of saturation	1
t	s, h, a	Time	4, 5
T, Θ	K, °C; 1 K=1 °C	Temperature	5, 6
t_A	h	Cooling behavior	5
U	W/m^2 K	Overall heat transfer coefficient, U-value	5
V	cm^3, m^3	Total volume of a sample	1, 3
v_{Ca}	%	Lime content	2
v_{gl}	%	Loss on ignition	2
V_P	cm^3, m^3	Void volume, pore space	1
V_S	cm^3, m^3	Solid mass volume	1
w	–	Moisture content	1, 2, 3
w	mm	Width	7
w_a	–	Water absorption capacity	5
w_c	–	Practical/continuous moisture content, equilibrium ~	5
w_{hygr}	–	Hygroscopic moisture content	5
w_L, LL	–	Moisture content at liquid limit	3
w_N	–	Moisture content at standard consistency (NIEMEYER)	3
w_P, PL	–	Moisture content at plastic limit	3
w_{Pr}	–	PROCTOR moisture content, optimal ~	3
w_S, SL	–	Moisture content at shrinkage limit	3
α	–	Shape factor	1
β	N/mm^2	Strength parameter	4
β_{AS}, c	N/mm^2	Adhesive shear strength	4
β_{AT}	N/mm^2	Adhesive (tensile) strength	4
β_C	N/mm^2	Compressive strength	4
β_D	N/mm^2	Dry compressive strength	4
β_F	N/mm^2	Flexural strength	4
β_k	N/mm^2	Compressive strength determined in an accelerated test	4
β_S	N/mm^2	Shear strength	4
β_{ST}	N/mm^2	Splitting tensile strength	4
β_T	N/mm^2	Tensile strength	4
β_{TW}	N/mm^2	Tensile strength at standard consistency (Niemeyer)	4
γ	kN/m^3	Unit weight, specific ~	1

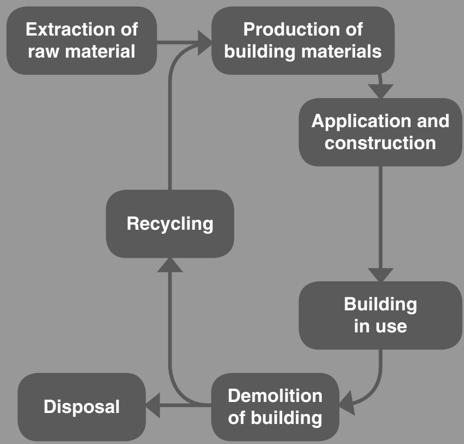
(continued)

(continued)

Symbol	Unit	Parameter	PG[a]
γ_M	–	Partial safety factor	4
γ_{zx}	°	Shear distortion	4
$\Delta\Theta$	K	Temperature amplitude	5
ε'	–	Emissivity	5
ε, ε_x, ε_y, ε_z	%	Strain	4
ε_{bl}	%	Settling	4
ε_c	%	Chemically induced strain	4
ε_{el}	%	Elastic strain +/–	4
ε_f	%	Moisture strain +/–	4
$\varepsilon_{f,l}$	%	Degree of linear shrinkage	4
ε_{fl}	%	Plastic strain, flow	4
ε_T	%	Thermal strain +/–	4
$\varepsilon_{v,el}$	%	Delayed elastic strain	4
Λ	W/m^2 K	Heat transfer coefficient	5
λ (k)	W/m K	Coefficient of thermal conductivity	5
μ	–	Water vapor diffusion resistance factor	5
μ	–	Friction coefficient	4
ν	–	Poisson's ratio	4
ρ	g/cm^3, kg/dm^3	Bulk density, moist bulk density	1
ρ_d	g/cm^3, kg/dm^3	Dry bulk density	1
ρ_{Pr}	g/cm^3, kg/dm^3	PROCTOR density	1
ρ_s	g/cm^3, kg/dm^3	Specific density, solid ~	1
ρ_{sr}	g/cm^3, kg/dm^3	Saturated bulk density	1
τ	N/mm^2	Shear stress	4
Φ	W	Heat flow	5
Φ	–	Creep ratio	4
φ	h	Phase displacement	5
ψ	–	Relaxation	4
σ, σ_x, σ_y, σ_z	N/mm^2	Stress	4
σ_p	N/mm^2	Permissible compressive stress	4
σ_s	N/mm^2	Swelling pressure	3

[a]Parameter group according to Table 1.1

1



The Development of Earth Building

At around 10,000 B.C. a decisive change took place in the history of humankind: the prevalent mode of food procurement, which until that time was hunting and gathering, was gradually replaced by mixed farming. This new lifestyle was accompanied by the need to build permanent shelters for people and, where necessary, for animals, as well as structures for agricultural storage. Among the building materials used for these structures were natural stone, wood and, above all, earth.

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1.1 Historical Roots of Building with Earth

Depending on the prevailing climate and vegetation as well as the geological conditions of a region, different building styles and construction methods developed over the course of the history of humankind: in hot and dry climates without major sources of wood, *massive construction* using load-bearing earthen walls dominates. In addition, these structures function as a "heat buffer" against intense insolation. In transitional climates or mountainous regions with abundant sources of wood, *framed construction* prevails: here a separate wooden skeleton carries the structure's loads. Earth, often in combination with stone, is used as an infill material and has a space-enclosing function. There are also transitional construction types which combine the two systems.

Both building styles can be traced back thousands of years in the different regions of the world.

Based on what is known today, the transition to a sedentary lifestyle started in *Southwest Asia*, in the region of present-day Turkey, Iran, Iraq, Lebanon, Syria, Jordan, and Israel. This is also where archaeological evidence of the first permanent dwellings dating back to 10,000 BC has been found.

Among the oldest permanent earthen houses are those found in the area of present-day's Anatolia in Turkey and in Palestine (Figs. 1.1, 1.2, and 1.3). The approximately 8000-year-old structures of Çatal Höyük, Anatolia, exhibit a surprisingly high standard. The load-bearing exterior walls were constructed of earth blocks with interior wooden supports carrying the roof construction. The roofs were flat, made of poles and grasses or reed and a layer of puddled earth for protection against rainwater. The houses were entered via the roof. The individual structures themselves were grouped together like honeycombs touching each other [1].

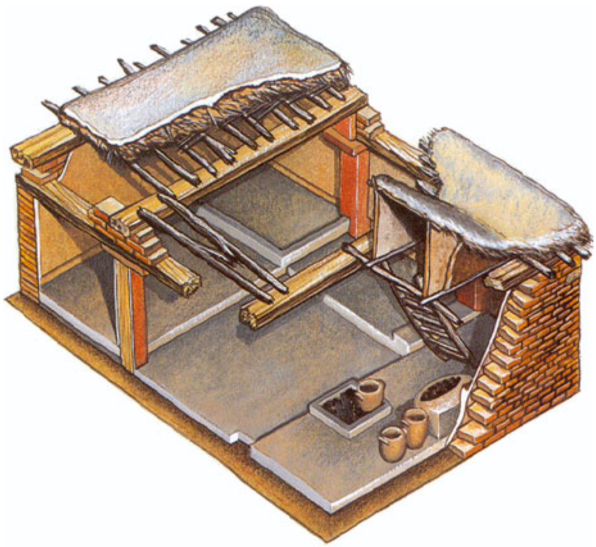

Fig. 1.1 Model drawing of an earth block house, Çatal Höyük, Anatolia/Turkey, around 6000 BC [1]

Fig. 1.2 Archeological excavation site, Anatolia/Turkey, around 6000 BC

Fig. 1.3 Earth block structures, Jericho, Palestine/Israel, around 6000 BC

Fig. 1.4 Rammed earth construction in Ancient China, Shang Dynasty, around 1320 BC [2]

Large areas of *China* are covered with clay-rich soils, particularly loess soil. There is evidence of load-bearing structures made of earth as well as framed construction in combination with earthen materials spanning several thousand years.

Figure 1.4 is a historical depiction of the rammed earth building technique which is tied to the following story: Fu Yueh, a minister under a ruler of the Shang Dynasty (around 1320 BC), is said to have been the inventor of this technology and the first "rammed earth master builder." According to legend, Fu Yueh acquired his position in an unusual way: one day, the Emperor had such a vivid dream of a wise and able man that he woke up and had a picture drawn of the person he had seen in his dream. He sent messengers with the picture of this man all over the country to look for him. The messengers encountered Fu Yueh who resembled the person in the picture and, at the time, was busy building a rammed earth house. This is the scene depicted in the illustration. Fu Yueh was called to the court and appointed to a minister position [2].

The production and use of earth blocks has also been known in China for thousands of years. Figure 1.5 shows the production of earth blocks during the time of the Ming Dynasty [3].

The largest and most famous structure in China is the Great Wall of China. It is also the largest structure ever built by humans. It took around 2000 years to build the approx. 50,000 km of total length known today. Depending on local availability,

Fig. 1.5 Production of earth blocks in Ancient China during the time of the Ming Dynasty [3]

Fig. 1.6 The Great Wall of China, section in Gansu Province, built around 220 BC [4]

the materials used included wood, stone, and earth (also in the form of fired bricks) as well as vegetal material for reinforcement. Figure 1.6 shows a section of the wall dating back to the Quin Dynasty built using the rammed earth technique around 2200 years ago [4].

Egypt is another classic example of an earth building country with a building tradition dating back thousands of years. The annual floods of the Nile River brought fertile mud from the Ethiopian highlands which dried in the sun and became solid. When the mud got wet, it became malleable once again. This fundamental knowledge

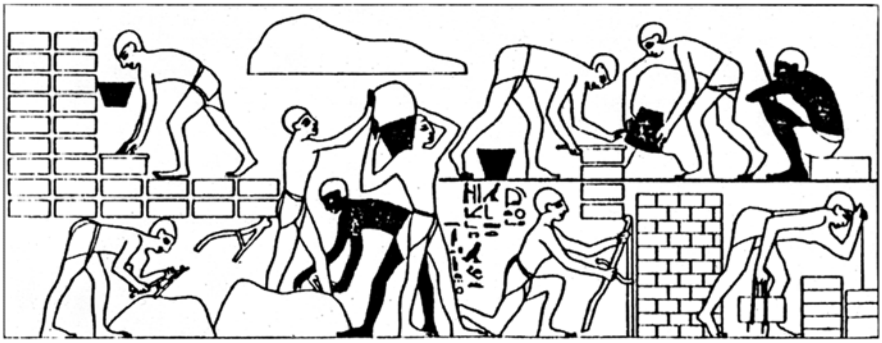

Fig. 1.7 Production of earth blocks in Ancient Egypt, around 1500 BC [5]; depiction in the tomb of Vizier Rekhmire, Theban West

formed the basis of the production of sun-dried mud blocks which could be made stronger and more durable by adding sand or plant fibers and could be improved even further through firing. The Old Testament describes the use of chopped straw in the production of earth blocks [Exodus 5:7f.; 16:18f].

Figure 1.7, an illustration from around 1500 BC, shows the individual technological steps used in the production of earth blocks from soil preparation to using the blocks for building [5]. The symbolic depiction of Hatshepsut, the reigning pharaoh of that time, as a master builder during the production of earth blocks emphasizes the importance of this activity in Fig. 1.8 [6]. The origin of vault construction using sun-dried earth blocks can also be traced back to Egypt. Figure 1.9 shows an earth block vault used as a storage room in the tomb of Ramses II from around 1300 BC.

There is archaeological evidence of an earth building tradition dating back thousands of years in the relatively woodless but clay-rich regions of *Mesopotamia,* located between the *Euphrates* and *Tigris*, in *Afghanistan* and *Iran*. Figure 1.10 shows sun-dried earth blocks from different parts of this region [7]. They exemplify the already highly developed technique of prefabricating building elements.

Earth blocks were also used to construct large religious buildings in this region. Built in the shape of pyramids, these buildings can easily be compared to the ones in Egypt in terms of their size. Figure 1.11 shows the condition of the pyramid (Ziggurat) of Chogha Zanbil after its restoration. It was built around 1500 BC by Elamite rulers in the area of present-day Iran [8]. This category of buildings also includes the Tower of Babel [Old Testament, Genesis 11:3] which was built using sun-dried earth blocks with an exterior cladding of fired bricks.

Furthermore, this region is home to the oldest known written rules for building with earth. Documented on fired clay tablets, they date back to the time of the Babylonian ruler Hammurabi who lived around 1800 BC [9].

To the north are the Central Asian steppes and deserts of *Turkmenistan*, *Uzbekistan*, and *Kazakhstan* whose cultures go back thousands of years and where earth has been used as a building material for more than 5 millennia [10]. Figure 1.12 shows the ruins of the ancient city of Afrasiab, the predecessor to present-day

Fig. 1.8 Pharaoh Hatshepsut during the production of earth blocks made of mud from the Nile River, around 1500 BC [6]

Fig. 1.9 Earth block vault near Luxor/Egypt, around 1300 BC

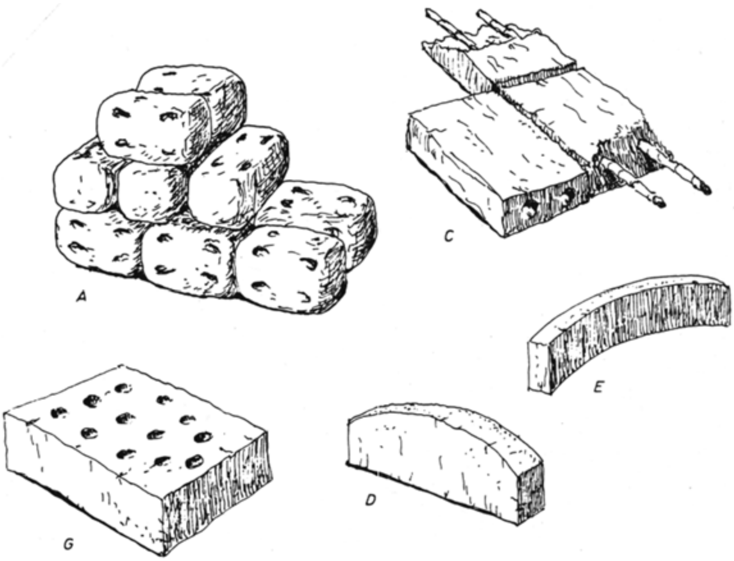

Fig. 1.10 Sun-dried earth blocks and prefabricated building elements in Mesopotamia and Afghanistan, fourth millennium to sixth century BC [7]

Fig. 1.11 Ziggurat Chogha Zanbil, Iran, around 1250 BC [8]

Samarkand in Uzbekistan which was completely destroyed by Genghis Khan during the Mongol invasion in the thirteenth century. Present-day Samarkand, Bukhara, and Chiwa are cities with a 2500-year-old history and earth building tradition.

Along the Indus River, in present-day Pakistan, lies Mohenjo Daro, a city built of earth blocks around the beginning of the third millennium BC [11].

Fig. 1.12 Earth block walls in the city of Afrasiab, present-day Samarkand, Uzbekistan

In the so-called New World as well, in Pre-Columbian *Peru*, people were familiar with different earth building techniques. It is estimated that 130 million sun-dried adobes were used to build the Huaca del Sol pyramid of Moche (around 200–500 AD) whose dimensions are 120×120 m^2. Chan Chan, the largest city in Pre-Columbian America, had approximately 60,000 inhabitants in the fourteenth and fifteenth centuries. Today, the city still covers 25 km^2 and is blanketed by large mounds of adobe block debris. The different city quarters were laid out at right angles and surrounded by high adobe walls. The rammed earth building technique was also known.

Figure 1.13 shows a rammed earth palace wall in Chan Chan decorated with friezes (thirteenth century AD) [8].

There is also a long history of building traditions in North America. Figure 1.14a shows the concept of a Pueblo Indian pit house (Arizona, New Mexico) incorporating a support structure of wooden beams for the flat roof and a layer of puddled adobe as a cover. The houses were entered via a ladder through an opening in the roof (around the second century AD) [12]. This type of house construction is surprisingly similar to the Neolithic earth block homes of Çatal Höyük, Anatolia (Fig. 1.1), which were also entered via the roof.

The small town of Taos along the Rio Grande Valley north of Santa Fe, New Mexico (USA), has preserved a Pueblo Indian settlement with its main core dating back to the thirteenth and fourteenth centuries. The settlement's building style has its roots in the pit house. The buildings as well as their entrances are at ground level and rise up to four floors (Fig. 1.14b). The walls, which are made of adobes, are refinished with earth plaster once a year.

The "Pueblo de Taos" is a UNESCO World Heritage Site.

Fig. 1.13 Ruins of a palace constructed in rammed earth technique, built in Chan Chan in present-day Peru in the thirteenth century AD [8]

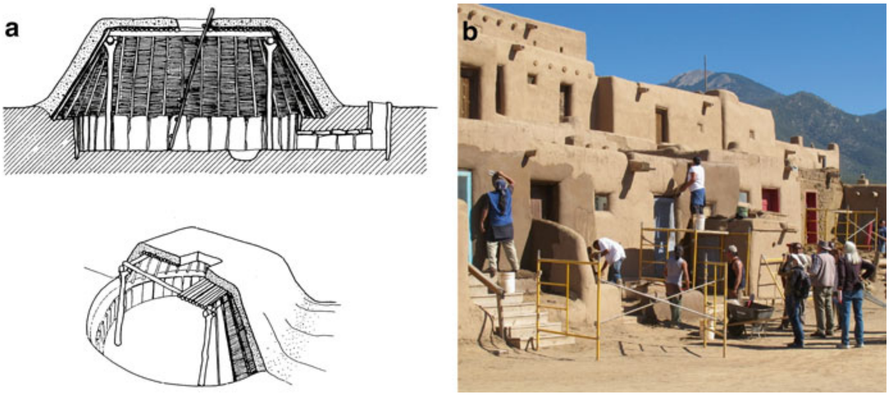

Fig. 1.14 Adobe homes of the Pueblo Indians in the Southwestern USA. (**a**) Pueblo Indian pit house in North America about second century AD [12]. (**b**) Pueblo de Taos, New Mexico, USA, adobe buildings with flat roofs and earth plaster

1.2 Earth Building as Cultural Heritage

In the course of the centuries, the knowledge of traditional earth building techniques became lost in many parts of the world. Even in the poorest developing countries, “modern” building materials such as concrete and cement have begun to replace or have already replaced earth as a building material. Here, earth or mud often equals poverty. As soon as they can afford it, people use concrete or fired brick for building, particularly in urban areas. In the rural regions of developing countries, however, earth as a building material has survived in the everyday building practice.

It is in large part due to the international activities of the organizations ICOMOS and CRATerre in the field of the preservation of traditional earthen architecture that building with earth has once again become part of peoples' cultural identity in many third-world countries. Within ICOMOS a number of specialized work groups focus on the preservation of historical structures, among them the International Committee for Earthen Architectural Heritage (ISCEAH) which works in the field of earth building (http://isceah.icomos.org).

The inclusion of historical earthen buildings in the UNESCO World Heritage list of architectural monuments [13] has triggered a change in thinking in the countries concerned: presumed poverty is slowly changing to pride in the countries' own historic building traditions and accomplishments. Out of the 759 cultural monuments added to the World Heritage list in 2013, 143 or 19 % are partially or completely built out of earth. Among them are the Great Wall of China; the earth block "tower houses" of Shibam, Yemen; the famous Alhambra in Granada, Spain; or the Potala Palace in Lhasa, Tibet [52].

The status of an architectural monument brings with it the commitment to adhere to the principles of conservation and restoration of historic structures according to the Venice Charter which was agreed upon by the participants of the Second International Congress of Architects and Specialists of Historic Buildings in 1964.

In developing countries, "sustainable" tourism is beginning to develop around these restored earthen architectural monuments leading to desperately needed foreign revenue. The rammed earth houses in Ait Benhaddou in Southern Morocco, shown in Fig. 1.15a, have been designated a UNESCO World Heritage Site and serve as an example of this development. These houses give impressive testament to the engineering skills and accomplishments of their builders. Although this building technique is still known in rural areas today, especially by the older generation, it is at risk of being forgotten. The reason for this can be traced to profound changes within the building practice itself: whereas building used to be an activity mainly conducted by the village community or the extended family, it is now carried out by small businesses for money.

Efforts to preserve special earth building techniques will lead to the creation of new museums similar to the open-air museums found in Germany. In this context, it is essential to document endangered earth building structures and traditional earth building techniques as part of our cultural identity.

In 2011, a "Map of Earthen Heritage in the European Union" was published as part of an EU-funded project. The map was created in cooperation with 50 authors from 27 European countries [14]. It can be found at www.culture-terra-incognita.org. This map shows the geographic areas for the different earth building techniques of half-timber construction with various types of earthen infill, earth block masonry, rammed earth, and cob. The representation of the respective areas in Germany is based on an incomplete data base. Therefore, a map based on geographic information systems (GIS) is currently under development (dev.lehmbau-atlas.de) [15].

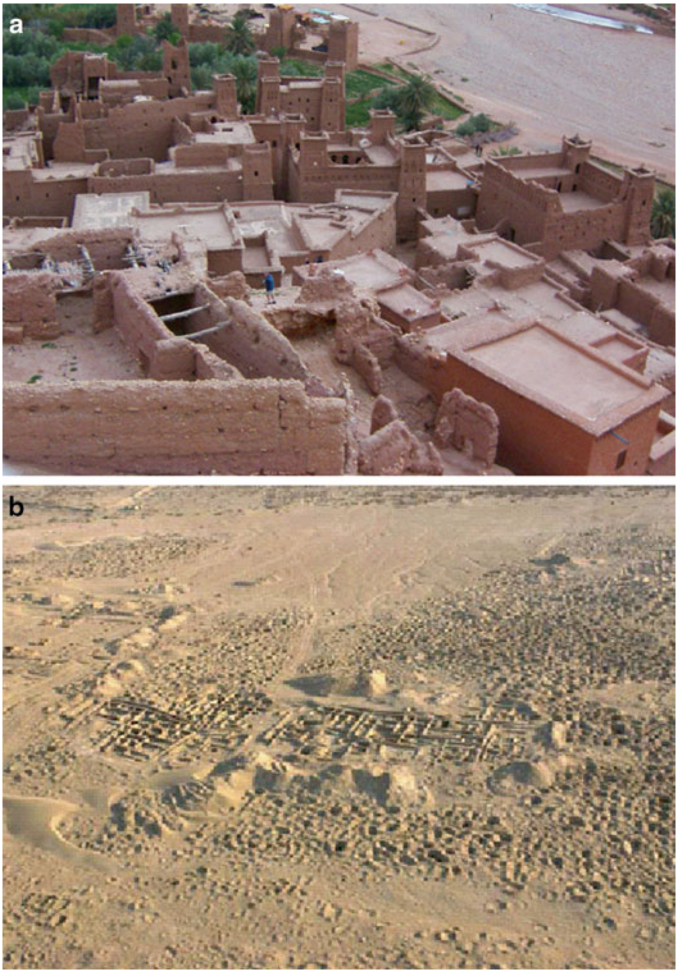

Fig. 1.15 Cultural heritage of earth building materials. (**a**) UNESCO World Heritage Site: traditional rammed earth houses in Ait Benhaddou, Southern Morocco. (**b**) "World Monuments in Danger 2008 (WMF)": urban settlements using earth building materials dating back to the Sumerian time period (around 3500 BC) located in the former Iraqi war zone (www.wmf.org)

Such "inventories" have already been taken in many different European countries and regions, such as France [16], Portugal [17, 18], the Czech Republic [19] (http://hlina.info/cs.html), and Italy [20].

For more than 40 years, the activities of the private organization World Monuments Fund (WMF) (www.wmf.org) have been dedicated to keeping at-risk architectural monuments from further deterioration or destruction. Monuments in isolated and difficult-to-access places and war zones are particularly threatened. Every 2 years the WMF publishes a list of the 100 most threatened architectural monuments with the goal of drawing attention to the precarious situation of these monuments and of finding worldwide sponsors for urgently needed stabilization work.

On the WMF 2008 Watch List, the situation of the archaeological excavation sites of the Uruk and Sumerian period (around 3500 BC) in Iraq, which are located in the middle of the Iraqi war zone, is defined as particularly critical. The walls of these urban settlements are made of earthen materials (Fig. 1.15b).

1.3 Historical Development of Earth Building in Germany

Around 8000 years ago, mixed farming slowly made its way to Central Europe and present-day Germany via trade routes from the Southeast. Wood and earth were available almost everywhere as building materials for house construction, but in this region houses had to be planned differently: whereas in the Eastern Mediterranean region the houses needed to protect their occupants, livestock, and supplies from the summer heat, they now had to protect them from precipitation and the cold of winter.

The building designs of that time can be reconstructed today with the help of post holes which stand out from the surrounding building area as dark circular discolorations. The design principle of these houses was based on post constructions with woven branches as the support frame for a coat of straw clay (Fig. 1.16) [1]. Reconstructions of these early wooden post buildings can be seen in a number of open-air museums, such as in Oberdorla or at the State Office for Preservation of Monuments and Archaeology (Thüringischen Landesamt f. Archäologie u. Denkmalpflege) in Weimar in the German State of Thuringia (Fig. 1.17) [21].

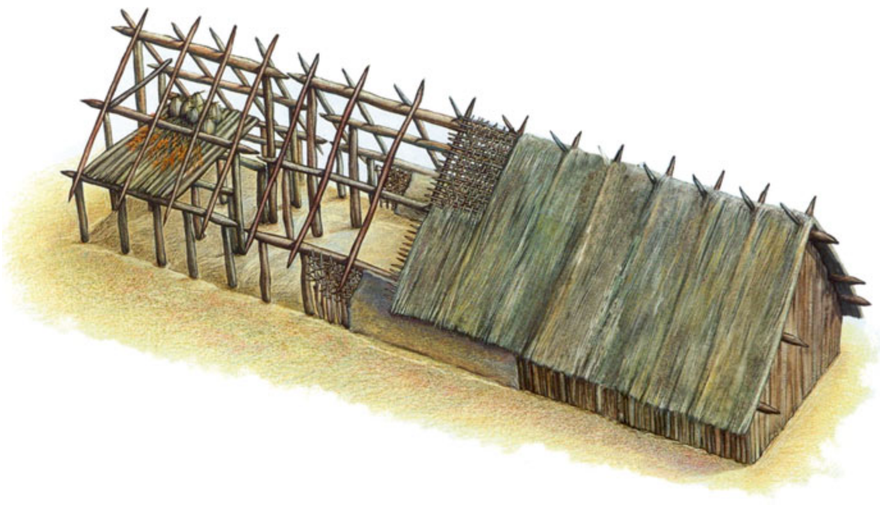

Fig. 1.16 Longhouse of Central European woodland farmers around 4000 BC [1]