D Clay (*H-J. Schwarz*)

D.1 INTRODUCTION

One third of mankind lives in earth buildings. Such dwellings are especially found in the dry and hot tropical countries, where the manpower is cheap and modern building materials, requiring a huge amount of energy to produce, are very expensive. But one might also find such dwellings in central Europe, mainly for the construction of half-timbered homes, and in these instances, clay is used as a building material.

The service life of clay constructions can be much more than 100 years if carefully protected against water erosion. All other environmental attack is insignificant.

Clay as a building material is very easy to use and to repair, and no specialist is necessary for the construction work. Everybody is able to do it and in addition, the costs are very low in most countries. Only in the industrialised countries is clay a bit more expensive than some other building materials.

Clay is an ecological product with a very good eco-balance. It is usually used close to the excavation site and the transport costs are low. Only a little energy is needed to manufacture clay building materials and in most cases no energy demanding additives are necessary.

D.2 CLAY AND ITS COMPOSITION

Clay as a building material is a mixture of gravel, sand and pure clay. The latter is formed by the weathering of consolidated rocks into fine particles. Clay as a primary weathering product at the place of the formation of the original rock should be distinguished from secondary clay deposits, to which the clay is moved after the weathering. Secondary clays often show a finer grading curve.

Clay as a building material is a tenacious mineral rock from which the smallest fraction of clay minerals is responsible for the tenacious character. Depending on the composition and the origin of the clay, many types of clay with different characteristics could be distinguished, for example morainic clay, slope wash, meadow loam, loess clay.

The classification of constituents of the clay by their grain size means that also in the clay fraction minerals could be found, which do not contribute to the tenacious character. Only the fraction of the clay minerals itself has to be considered if the tenacious character is the question.

Clay minerals are mainly water-bearing alumosilicates. They are formed essentially at weathering of silicates. In addition, iron minerals like hematite and goethite, titanium dioxide as anatas, and in the tropics aluminium hydroxides — mainly gibbsite, are frequently found.

Clays also contain weathering residuals and other newly formed minerals. Weathering residuals are mainly resistant minerals as quartz, muscovite and feldspars, sometimes biotite and rarely chlorite.

The accessory minerals of the original rocks, as zircon and rutile and to some extent apatite, are enriched in the sediments. Newly formed minerals frequently found in clays are the silicate glauconite, the carbonates calcite, dolomite, siderite, the iron sulphides pyrite, markasite and chalcopyrite and galenite. The oxidation of the sulphides gives secondary sulphates like gypsum, jarosite and alunite [1].

Responsible for the typical properties of clays — the soapy consistency, the water binding power, the swelling ability, high adsorption capacity for many inorganic and organic materials, the thixotropy, the plasticity — are the siliceous clay minerals.

According to the main mineral constituents, clays are divided in kaolinite rich and smectite rich (bentonites) clays. The common clays mainly contain illite and some chlorite, kaolinite, smectites and mixed layer minerals (smectite/illite and kaolinite/illite). The last ones are the usual clays for building materials, while the other, more pure clays are rather used in the ceramic, paper and food industry.

The different properties of clays with the same amount of clay-sized particles are based on the mineralogy of the clay minerals. Characteristic is the small mean grain size, which for the smectites falls far below 2 µm. Kaolinic clays are much more coarse and contain in many cases nearly no fraction < 0,2 µm. The mineralogical composition of a clay alters with the grain size of the particles, that means a finer clay has a different composition than a coarser clay.

Kaolinite often forms more or less well-shaped six-cornered plates, which are put together book or money roll like. Illites are mostly lath-like. Montmorrillonites form thin crystals that look like pieces of foil with irregular edges, bent, sometimes folded or rolled at the edges.

A characteristic property of the clay minerals is their cation exchange ability; the anion exchange ability is rather low and is found only in acid environments. The kaolinites have exchangeable ions only at the surfaces. The exchange ability of the smectites and vermiculites is determined by the inter layer cations and their cation exchange capacity is much higher compared to the kaolinites. In the micas the potassium ions are strong bonded between the silicate layers and the ion exchange requires very strong reaction conditions.

The crystal structure of the clay minerals is not very complicated. Clay minerals are made up of $[SiO_4]$ tetrahedrons and $[Me(O,OH)_6]$ octahedrons (Me — metal cation). The tetrahedrons and octahedrons are linked together by common atoms.

The so-called two layer clay minerals, like kaolinite, are composed of layers of one tetrahedral and one octahedral layer. They have aluminium in the octahedral layer and the formula is $\{Al_2[Si_2O_5(OH)_4]\}$. In the so-called three layer minerals the octahedral layer lies between two tetrahedral layers. The group has a very great variety in the composition. In the three layer minerals the layers are negatively charged. To compensate this negative charge cations are bonded between the layers. In addition, water molecules can be present between the silicate layers, which leads to complex formulas. For this reason no formula is given here.

D.3 PLASTICITY OF CLAYS

The tenacity is decisively influenced by the exchangeable cations. For example, with calcium ions house-of-cards and ribbon-like structures are formed and kaolinite is able to bond more than 50% water by volume.

In moist conditions the mineral plates could be moved against each other. After moving, the plates always find new positions where they are fixed by the calcium ions. The clay is plastic.

The cavities survive the drying to a great extent, i.e. the mineral plate structure resists the shrinkage to a dense mass.

Clays always contain a certain amount of quartz that can be bond by the clay minerals. The clay mineral plates surround the quartz grains and create large contact surfaces, which are preserved on drying and give the high strength. The fewer cavities the mass has after drying, the stronger is it. The more thin and flexible the plates are, the less clay is necessary for a strong bonding. Therefore the grading curve of the clay is an important parameter. The smectites have very good properties in this respect.

If sodium ions are solved in the water present, the structure of the kaolinite plates brakes down; a ceramic mass could become a slurry, which can be poured and later on formed to a mass with very high density and dry strength. This mass is no longer plastic.

D.4 CLASSIFICATION OF THE CLAY BUILDING MATERIALS (TECHNICAL PARAMETERS)

The clay building materials can be divided according to their clay content and their technical parameters.

In general, building clays are divided in fat clays with a high content of clay minerals, lean clays with a low content of clay minerals and medium fat clays in between.

Some important characteristic parameters are collected in table D.4:1. The technical parameters are explained in more detail below.

Table D.4:1 Characteristic parameters of clays

Parameters	Lean	Medium fat	Fat
Clay content	low	middle	high
Uptake of water	high	middle	low
Swelling up/shrinkage	weak	middle	high
Tenacity	low	middle	high

D.4.1 Sieve and sedimentation analysis

The constituents of clay are classified according to its grain size. The percentage of each fraction is determined by a sieve analyses which gives the grading curve, represented graphically in fig D.4:1.

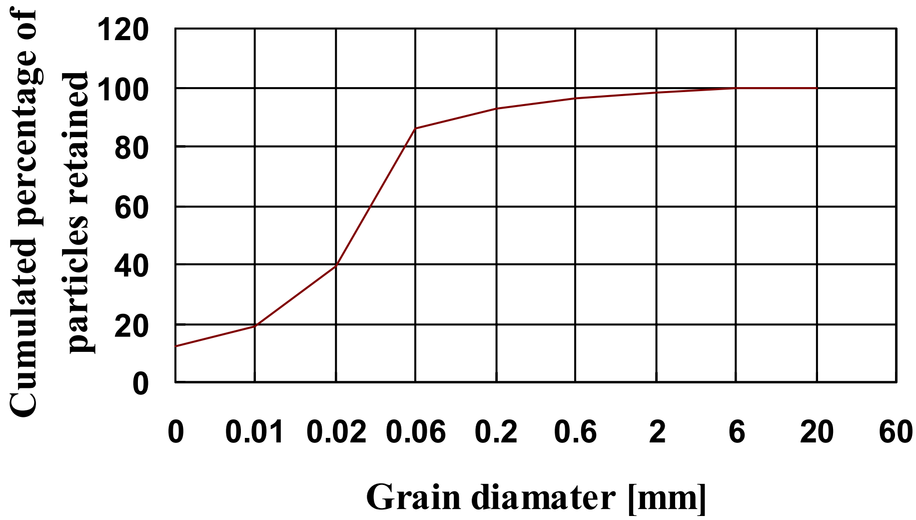

Fig.D.4:1 Grading curve of a silty clay

D.4.2 Atterberg consistency limits

The different states of tenacious soils, referring to the consistency, are divided according to Atterberg [2] in fluid, plastic, semi-solid and solid.

The "liquid limit" w_L is determined by the water content at the transition point from the liquid to the plastic state. In the laboratory the liquid limit is measured by an apparatus for plasticity test after Cassagrande [3].

The "plastic (rolling-out) limit" w_P is determined by the water content at the transition point from plastic to the semi-solid state. It is measured by the rolling-out test [3].

The "plasticity index" I_P is the difference between the liquid limit and the plastic limit, w_L-w_P, and characterises the plastic behaviour of a tenacious soil like a building clay.

D.4.3 Compressive strength

The compressive strength of dry building clay is determined by its cohesion (depending on the clay content) and the grain friction. For the fine building clay materials the compressive strength increases with the clay content. For the coarse building clay material the clay fraction can be lower to get the required compressive strength (due to grain friction).

The compressive strength can be increased by suitable treatment of the building clay (ramming, kneading, suspending, compressing). An increase in compressive strength can also be obtained by additives. It should be kept in mind that additives not only have positive effects on the properties of a building clay but also negative ones.

Usually the compressive strength as estimated by the simple compressive experiment is sufficient reliable. In the simple compressive experiment the "cross" tensile strength of the material is dominant and is measured simultaneously. Therefore it is not necessary to measure separately the tensile strength, the tensile bending strength or the shear strength. Only for the testing of clay plaster and to assess the stability of the edges of clay building stones the tensile bending strength is important. The bonding strength plays a part when testing clay plasters.

The compressive strength of dry clay building units varies generally between 0,5 to 5,0 N/mm^2. Load bearing clay building units should always be tested for their compressive strength. It should be at minimum 2 N/mm^2.

Closely connected to the strength parameters is the modulus of elasticity, in the range 6000 to 7000 N/mm^2.

D.4.4 Proctor density and the best water content

Proctor density and the best water content are the result of the Proctor test [4].

The water content of a building clay mixture is optimised when the maximum dry-density is reached with minimum compression energy. If the water content is too low, the compression energy will be higher. If the water content is too high, the compression energy cannot be absorbed and the dry-density will be reduced.

In the Proctor test a building clay sample is compressed under well-defined boundary conditions. The water content of the sample is varied several times during the experiment. After each run the water content and the dry-density of the sample are measured. At the end the dry-densities could be represented as a function of the water content.

The peak of the Proctor curve gives the maximum dry-density under the defined compressive conditions, the so-called Proctor density ρ_{Pr}. This is estimated for:

- "fat" clay (more than 50% clay) as $\rho_{Pr} \approx 2000$ kg/m^3
- sandy clay (more than 50% sand) as $\rho_{Pr} \approx 2200$ kg/m^3
- gravely clay (more than 50% gravel) as $\rho_{Pr} \approx 2500$ kg/m^3

The corresponding water content is the best water content w_{Pr}. If the water content is lower or higher compared to w_{Pr}, the dry-densities obtained will in both cases be lower than ρ_{Pr}.

The best water content w_{Pr} is important especially for rammed earth constructions. According to the Proctor curves this water content is reached at about 12,5%. Is the clay rammed at a higher water content, in addition to a lower dry-density, more shrinkage cracks and settlement movements occur. At a water content of more than 2% below the best value, the required compressive strength cannot be reached by ramming.

These best values obtained with the compressing experiment are the basis for the compression that should be reached during the realisation of the construction. The Proctor test is suitable to building clays for rammed earth constructions and pressed adobes.

D.4.5 Capillary uptake of water

Basis for the method to determine the uptake of water coefficient is the DIN 52617 [5], which has to be modified in the application to water-sensitive clays.

According to DIN 52617 the uptake-of-water coefficient w of a wet sample is related to the water uptake per unit area and time according to:

$$W = w \cdot \sqrt{t}$$

where:

W [kg/m^2]	uptake of water per unit area
w [kg/m^{2}h^{½}]	uptake-of-water coefficient
t [h]	time

For the determination of the uptake of water, a sample, watertight at the side faces, is initially dried to mass equilibrium, and then dipped in water to wet the suction area. By weighting the sample before and after the wetting in distinct time intervals, the amount of water taken up can be found.

During the examination of several heavyweight clays uptake of water coefficients (w) between 1,1 to 5,5 kg/m^{2}h^{½} have been found [6]. The capillary water capacity (Φ_k) of these clays was between 0,18 to 0,32 m^3/m^3.

Bentonite-sand mixtures and fat clays with a high content of swelling clay minerals have low w-values, see fig D.4:2.

The experimental results concerning the investigations of the influence of the compression on the capillary uptake of water are not clear. Considering fat and silty clays, the w-values for stamped samples with a high raw density are lower than those of hand-made samples.

Sandy clay samples behave in the opposite way. Here the w-value of the stamped samples — with a higher raw density as well — lies clearly higher than the values of the hand made samples.

Obviously several phenomena overlap, such as the mineralogical composition and the pore distribution. Uncompressed very sandy clay has such great pores that the capillary force is substantially diminished.

Compared with other building materials with similar pore structure, the capillary uptake of water is a very slow process. This reduced absorption rate is caused by the swelling characteristic of the clay minerals and the associated sealing effect.

Stabilising building clays by adding about 2% cement alters the pore structure to such an extent that the uptake-of-water coefficient increases up to 22,5 kg/m^{2}h^{½}, some 16 times higher than for non-stabilised clays, and thus in parity with the absorption rate of a weak burned clay brick.

The absorption rates of light-weight and heavy-weight clays are of the same order, see fig D.4:2-3. In the region of low bulk densities < 500 kg/m^3, a marked difference between straw light-weight clays and mineral light-weight clays exists. For straw lightweight clays the capillary absorption capacity of the plant fibres and the higher portion of capillary pores become effective. The expanded clay aggregates, on the other hand, show a very high degree of closed pores. Even more obvious is the difference of the water capacity.

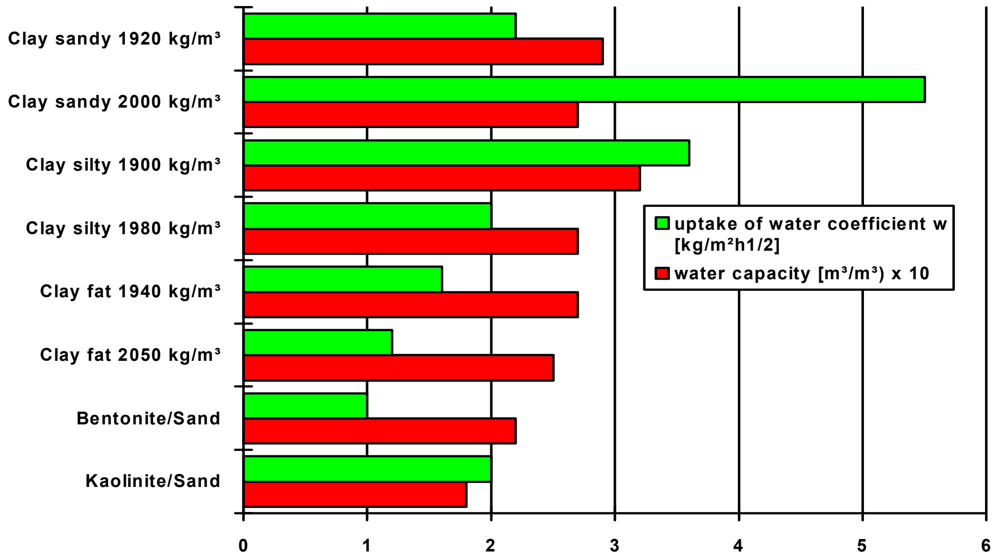

Fig.D.4:2 Uptake-of-water coefficient and capillary water capacity of heavy-weight clays [6]

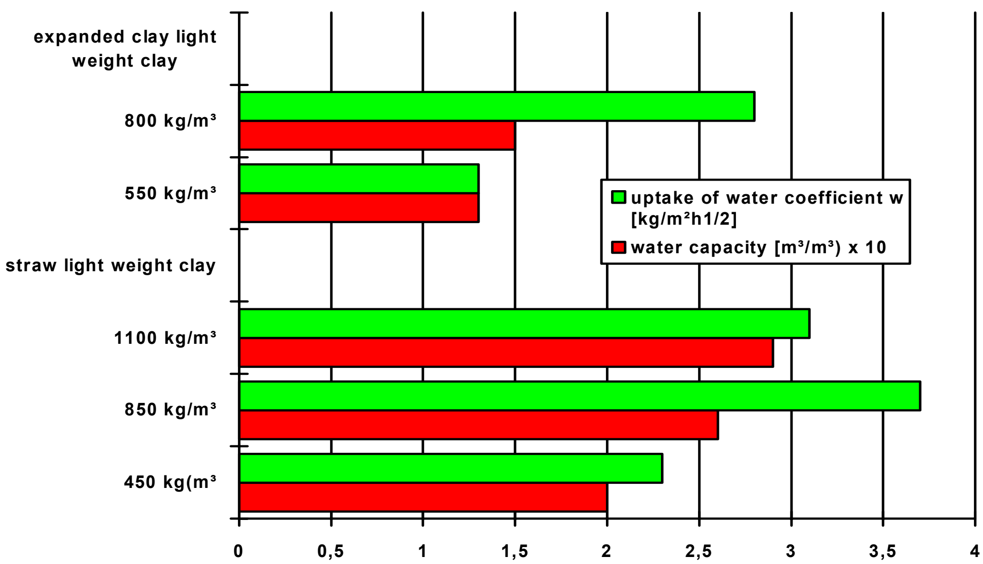

Fig.D.4:3 Uptake-of-water coefficient and capillary water capacity of light-weight clays [6]

D.4.6 Water vapour diffusion

Basis of the method is according to DIN 52615 [7].

The relative water vapour resistivity μ represents the capability of a building material to hinder diffusion of air humidity. The μ-value is the ratio of the thickness of an air layer to the thickness of a layer of the building material considered, both layers yielding the same water vapour resistance. For air, by definition $\mu \equiv 1$, and for solid materials $\mu > 1$, see table D.4:2.

There are two different methods to measure the relative water vapour resistivity: the wet cup and the dry cup method. The results differ between the methods, see table D.4:3. For example, for heavyweight clay with the wet cup method the μ values vary between 6 to 8, whereas with the dry cup method the μ values are higher, varying between 15 to 23.

Table D.4:2 Bulk density and relative water vapour resistivity according to [8]

Material	Bulk density [kg/m^3]	μ- mean at 20°C / 60% RH
Heavy-weight clay	2000	10 - 11
Light-weight clay	1200	8 - 10
”	900	6 - 8
”	600	5 - 6
”	300	4 - 5
Brick	1100	4 - 6
Lime sandstone	1600	10 - 25
Gas concrete stones	400	3 - 5
Wood (spruce, fir)	450 - 500	20 - 40
Wood wool building slabs	350 - 500	2 - 5

Table D.4:3 Bulk density and relative water vapour resistivity according to [6]

Material	Bulk density [kg/m^3]	μ- mean at 20°C / 60% RH
		dry cup method
Heavy-weight clay, fat	2050	23,0
”	1960	19,5
Heavy-weight clay, silty	1980	15,5
”	1890	15,1
Heavy-weight clay, sandy	2060	22,5
”	1880	18,2
		wet cup method
Heavy-weight clay, fat	2050	7,0
”	1960	6,8
Heavy-weight clay, silty	1980	6,0
”	1890	5,9
Heavy-weight clay, sandy	2060	7,5
”	1880	7,2
Expanded clay, light-weight clay	650	6,8
”	800	8,1
Straw, light-weight clay	450	2,2
”	950	3,1
”	1250	4,4
Clay plaster, silty		9,8
Clay plaster, fat		8,0

D.4.7 Uptake of water — hygroscopicity

Building clays have very favourable hygroscopic properties. They can exchange great amounts of humidity with the environment and have better humidity regulating properties than all other building materials.

To facilitate good interaction with water vapour, materials with poor hygroscopic or diffusion hindering properties should be avoided, e.g. tight coatings.

Usually climatic conditions are not stationary, and then materials are not in equilibrium with their environment. In this case, the limiting factor for the rate of vapour exchanged between the environment and a hygroscopic component is normally the transport rate at the surface rather than any interior gradient of the material moisture concentration.

To determine the equilibrium humidity, small samples should be put above saturated salt solutions. The difference between the mass of the sample in equilibrium with the saturated salt solution and the dry mass measured afterwards gives the moisture content.

The time dependency of water absorption is determined by measuring the mass increase as a function of time of a sample, put in higher relative humidity after drying at about 50% RH. Comparing unburned bricks with bricks of the same shape, the unburned material takes up about 30 times the amount of water than the burned material in two days [9], rising the relative humidity from 50% to 80 % (see also fig. D.4.4.).

Absorption and desorption take place first at the surface of the building component. Subsequently deeper zones will be affected.

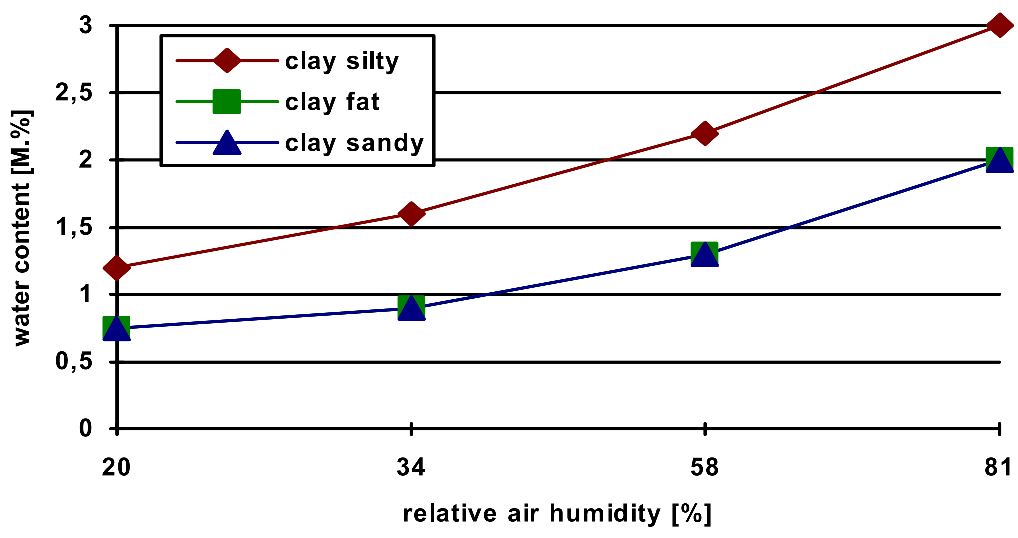

Fig.D.4:4 Equilibrium humidity of heavy-weight clays [6]

Straw light-weight clay shows increasing equilibrium humidity with decreasing bulk density, as can be seen in fig.D.4:5. This can be explained by the increasing straw content. Expanded clay lightweight clay shows decreasing equilibrium humidity with decreasing bulk densities, caused by the closed pores of the mineral aggregates.

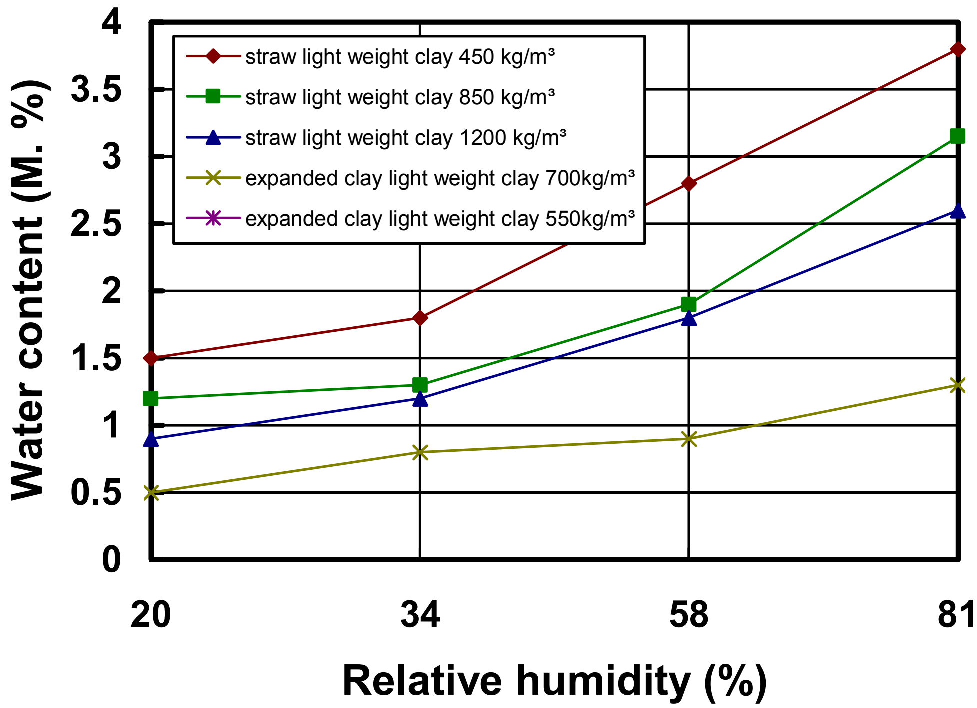

Fig.D.4:5 Equilibrium humidity of light-weight clays [6]

The type of the clay minerals has also a great influence. Thus the equilibrium humidity of a mixture of montmorillonite and illite (60% RH, 14,8 M% water content) lies by the factor 17 higher than the equilibrium humidity of kaolinite (60% RH, 0,8 M% water content) and reaches nearly the same value as loose rye straw (60% RH, 12,8 M% water content) [9].

The absorption rate of all clay samples is greatest just after the change in air humidity and decreases continuously. The water amount absorbed is approximately proportional to the square root of the absorption time $\sqrt{t}$.

D.4.8 Shrinkage — drying

Corresponding to the uptake-of-water propensity of clays, during the drying of clay building materials a corresponding shrinkage takes place. Fat clay with the same consistency as a lean clay takes up more water because of its higher clay content.

In case of a very fast and intense drying, the shrinkage leads to tensions in the clay that result in fissures and cracks. This fact has to be considered especially with clay rendering. Fat and very fat clays with a high shrinkage potential are not suitable for rammed earth constructions. To keep the shrinkage within limits, clays with a high portion of clay minerals have to be shortened by aggregates.

Another possibility to prevent the disadvantage of the shrinkage is to work with small prefabricated building units where the shrinkage has taken place before the construction.

The linear dry measure of shrinkage is determined with test samples (prisms) with a length of at least 20 cm, starting with a water content near the rolling out limit.

The dry measure of shrinkage results from the mean value of at least three test samples of the same clay. This measure could also be used to classify building clays, confer table D.4:4.

Table D.4:4 Dry measure of shrinkage of clays [8]

Clay	Dry measure of shrinkage
Lean	< 2%
Medium fat	2 - 4%
Fat	4 - 6%

Beside the dry measure of shrinkage also the time dependent change of drying is of great importance. As can be seen in table D.4:5, usually 50% of the absorbed amount of water is released again in the first five days. Only with bricks and vertical coring bricks this period is exceeded considerably, somewhat with normal concrete. Further drying occurs only with samples of aerated concrete and expanded clay lightweight clay in a comparable short period of time. These samples dry completely in 28 days at the most. Heavyweight clays and straw lightweight clays lose their rest humidity very slowly, so that the time to the complete dryness reaches within 40-80 days. With brick samples, normal concrete and lime-sand stone the drying curve is linear and flat after 2-5 days, and equilibrium humidity is not reached after 110 days. Wetting periods of one and 24 hours are distinguished only by the amount of loss of water and not by the time factor.

Table D.4:5 Drying time at 23°C, 50% RH after one hour wetting [6]

Material	**Bulk density [kg/m^3]**	**Drying time [days]**	
Drying level		*50%*	*100%*
Clay stone	1900	3	60
Clay stone silty	1950	5	80
Straw light-weight clay	1200	4	60
Straw light-weight clay	550	2	40
Straw light-weight clay	450	3	40
Expanded clay, light-weight clay	750	4	28
Expanded clay, light-weight clay	700	3	28
Brick	1850	13	>110
Vertical coring brick	1200	14	90
Lime-sand brick	1800	5	>110
Aerated concrete Hebel	600	2	21
Aerated concrete Ytong	450	4	28
Normal concrete B25	2200	7	>110

D.4.9 Heat conductivity and heat capacity

The heat conductivity λ and the heat capacity c are dependent on the dry-density ρ. Clay without light aggregates shows good heat accumulation properties. The heat conductivity is in this case relatively high. The heat resistance can be improved by adding lightweight aggregates, lowering the λ-value of clay from 0,9 down to 0,1. The heat capacity of massive clay building parts is of the same magnitude as those of bricks and concrete (see table D.4:6).

Table D.4:6 The relation between the bulk density and the heat parameters of clays [9]; comparison to other building materials [8]

Material	ρ [kg/m³]	λ [W/mK]	c [kJ/kgK]
Heavy-weight clay	2000	0,95	1,0
Light-weight clay	1200	0,47	1,0
”	900	0,26	1,1
”	600	0,15	1,2
”	300	0,09	1,3
Brick	1100	0,37	0,9
Insulating brick	1200	0,47	0,9
Lime-sand brick	1600	0,80	0,9
Gas-concrete stone	600	0,18	1,1
Wood (spruce, fir)	450-500	0,14	2,0-2,4
Wood-wool board	350-500	0,09	1,6

ρ — bulk density, λ — heat conductivity, c — specific heat capacity

D.4.10 Thermal expansion

The temperature dependent changes in length are of importance in clay renderings. To avoid damages the coefficients of expansion of the rendering and the support should be the same if possible. For clay building parts and other materials the values in table D.4:7 were found experimentally [9].

Table D.4:7 Thermal expansion coefficient for building materials

Material	Thermal expansion [mm/mK]
Heavy-weight clay	0,0043 - 0,0052
Clay masonry	0,0062
Lean clay mortar	0,007
Lime mortar	0,005
Cement mortar	0,01
Concrete, gas concrete	0,01
Lime-sand stone	0,007
Resin plaster	0,13 - 0,3

D.4.11 Sound insulation

The sound insulation property of clay building materials depends on their dry-density (air-borne sound) and their composition, especially their elastic additives (structure-borne or impact sound), respectively.

Good air-borne sound insulation values have clays with a bulk density between 1000-2000 kg/m^3. The impact sound insulation value of clay without any additions is much better than of other harder building materials of the same bulk density, because of the elasticity of the clay minerals.

D.4.12 Fire resistance

Clay is fire resistant even in the case of minor addition of plant fibres like straw as long as a density of 1700 kg/m^3 is not exceeded.

D.5 FIELD TESTS FOR BUILDING CLAYS

D.5.1 Appearance, smell

In principle building clay has to be free of humus, roots and other organic constituents. The ionic balance of the clay minerals could be influenced negatively by processes of fermentation, which develop from the decay of organic constituents.

The colour gives a hint on the kind of clay minerals. The smell, particularly when freshly dug, helps to recognise organic compounds.

D.5.2 Sedimentation test

By shaking clay in a glass with much water (1:3), the gravel and the coarse sand fraction settle down quickly at the bottom, while the silt- and clay particles need much more time. From the thickness of the sedimentation layers the fine and coarse fraction of the clay can be estimated roughly. Usually several layers are visible. The organic parts float at the water surface.

D.5.3 Nibble test

This is an easy way of assessing the presence of sand, silt or clay: take a pitch of earth and chew it lightly between the teeth:

- Sandy soil: Hard sand particles feel disagreeably gritty between the teeth, even if the sand is very fine.
- Silty soil: The silt particles are much smaller than those of sand and although they still feel gritty, the sensation is not disagreeable. Silt is a lot less gritty than sand.
- Clay soil: the clay particles are not at all gritty. On the contrary, clay feels smooth and floury between the teeth. A small lump of dry earth containing a lot of clay will stick to the tongue and be difficult to work free.

D.5.4 Sticking test — rubbing and wash test

The clay sample is wetted with water and kneaded. Then the wetted clay is placed in the palm of one's hand and left to dry, after which the clay is scraped off. Depending on the behaviour of the clay during this process, sandy, fat, or silty building clay may be distinguished.

If the clay only sticks somewhat to the hand (easy to get rid of the dried clay by slight rubbing and the rest with a small amount of water), the clay has a high content of silt. If the clay remains firmly attached to the hand (impossible to get rid of by rubbing and with water a lot of time is needed), this clay has a high content of clay minerals.

D.5.5 Shaking test

Like the sticking test this test is used to distinguish between building clays that are sandy, silty and fat in texture. The sample should be earth moist. The clay sample is shaken to and from in the palm of the hand and pressed between the balls of the thumb. Depending on the composition the surface of the clay thereafter looks more or less shiny. A dull surface is characteristic of fat clay.

D.5.6 Kneading test / consistency test

This method is used to distinguish between fat, medium fat and lean building clays. The sample, which should be earth moist, is kneaded and rolled on a porous support to a small spindle of about 3 cm in diameter. By kneading and rolling over and over again, more and more water is extracted from the sample. Eventually the clay spindle crumbles. At this state the stiffness of the sample is proved by pressing together the sample between the fingers. The greater the stiffness, the greater is the content of the clay fraction.

D.5.7 Ball test

This is another method to distinguish between fat, medium fat and lean building clays. The sample should be plastic. A ball, about 5 cm in diameter, is formed and dried. The dry ball is brought to fall down on a hard base from a height of about one meter. If the building clay is fat the ball stays complete.

D.5.8 Cutting test

A clay ball made of wet building clay is cut with a knife in two parts. If the cross section surface looks dull to moderate shiny the building clay is silty, while a very shiny surface indicates a clay with a high content of clay minerals.

D.5.9 Hydrochloric acid test

Lime containing clays usually have a whitish appearance, have a low tenacity and are for this reasons unsuitable for clay constructions.

To determine the lime content, a droplet of 20% hydrochloric acid is placed on the sample. The development of carbon dioxide leads to foaming and bubbling. If no foaming is visible the lime content is lower than 1%. If weak and quickly decaying foaming is evident the lime content is about 1-2%; whereas the lime content is 3-4%, if clear and lasting foaming is present, and 5% with evidence of an intense and lengthy foaming action. Also, dark lime-free clays rich in humus can show a carbon dioxide development.

D.6 REQUIREMENTS ON CLAY BUILDING TYPES

D.6.1 Construction with sun dried earth blocks, adobes

An adobe construction is a solid wall made by sun dried bricks or blocks of clay. The material used is a medium fat to fat building clay with at most a small portion of light-weight aggregates, by which high compressive strength and heat capacity are reached. The shape of adobes is in principle free of choice. The form of the adobes has to be 3-5% greater than the intended final size because of the great dry shrinkage.

There are three methods to produce sun dried earth blocks:

Adobes extruded:
This material stems usually from brickworks as the preliminary stage to the burned brick. Here the plastic clay passes an extrusion press and is cut in blocks on leaving it.

The composition of the material and the manufacturing method are usually those chosen for making a burned product and not an unburned adobe. However, when using such adobes for an exterior wall caution is advised. To produce adobes by extrusion, manufacturing methods that are specially designed for producing unburned adobes is instead recommended, e.g. no compression in vacuum (a greater amount of pores which gives a stronger frost resistance and a better heat insulation).

Adobes pressed:
This kind of clay building material is formed in small hand or motor operated presses using earth moist clay as raw material. Gravels greater than 10 mm are sorted out. The building stone produced in this way are nearly non-plastic and can immediately be stacked to dry out.

Adobes filled in forms:
The plastic building clay is put in a form manually and smoothened, and then immediately taken out. The formed clay has to start drying before it is stacked to dry out completely.

The fat or medium fat building clay for the adobes is shortened with sand. Often organic additions are added in small amounts (chopped straw, chaff, saw dust, etc.). An addition of a greater amount of mineral or organic lightweight building materials leads to a lightweight adobe that cannot be used for supporting constructions.

Additives like cement or bitumen can be mixed in if an increased strength or reduced water sensitivity is required. These measures alter as mentioned also other physical properties related to construction, like heat and humidity transport, and therefore are not always advisable.

For hand made adobes the following specific requirements should be fulfilled [8]:

- Clays medium fat to fat
- No particles greater than 5 mm
- Test bricks of the desired size, prepared with the suitable mixture, should not warp after drying or show shrinkage cracks greater than 50 mm and/or 3 mm width
- Compressive strength not less than 2 N/mm^2.

During manufacturing the produced adobes have to be controlled regularly.

D.6.2 Rammed earth construction

"Rammed earth" constructions are made by ramming clay into shuttering. The building clay used for this work is normally rather lean and earth moist. With this construction type, large building units could be build up which form a monolithic structure after drying, with a high heat capacity and a sufficient compressive strength for supporting walls.

The natural occurring lean clay needs no shortening for rammed earth constructions. Mineral additions are merely added to fat building clays or if the coarse grain fraction is missing. Then the dry shrinkage rate is diminished to a tolerable amount and the stability of the building unit is increased. Non-mineral additions are not tested in praxis of the rammed earth constructions and are not recommended.

For rammed earth constructions the following specific requirements should be fulfilled [8]:

- Clays lean to medium fat
- Grading curve with a good mixture of different grain sizes until 1/8 of the wall thickness or 50 mm
- Prepared clay mixture earth moisturised
- Preparation of cubes of $20 \times 20 \times 20$ cm^3 of the specific mixture for testing (see below)
- Minimum compressive strength 2 N/mm^2; testing of the samples has to be in the direction of ramming
- Shrinkage at drying not greater than 2%.

The clay building material has to be controlled regularly during the construction.

D.6.3 Lightweight building clay as fillings

In this technique the lightweight clay is used as a non-supporting filling material. The loads have to be born by an independent bearing structure.

Lightweight building clay is a mixture of clay and lightweight additions that lower the density of the clay, improve the heat insulation properties and reduce the measure of shrinkage. For this reason exterior walls made of lightweight clays could be erected without any additional heat insulation. The rough surface of the dried clay mixture is a non-slipping support, suitable for rendering.

As organic additions are suitable, e.g. straw, reed, wood chaff, wood-wool and cork-meal. As mineral additions expanded clay, perlite and similar materials are possible. If straw is used as addition, attention should be paid to the length of the straw that should correspond to the width of the building unit. The straw should be stable and tear-resistant. The best choice is rye and wheat straw.

For lightweight clay constructions the following requirements [8] should be fulfilled:

- The get a sufficient tenacity to bind all additives the clay has to be medium fat to fat
- Tenacity proved by hand tests
- Stability, drying behaviour, compressive strength and bulk density tested on suitable specimens, corresponding to the intended construction unit
- Bulk density below 400 kg/m^3 is not recommended for construction technique reasons
- Compressive strength, not less than 0,5 N/mm^2, proved by test samples
- Gravel and sand with grain sizes greater than 2 mm sorted out to get a low bulk density.

The clay portion of a lightweight clay mixture is governed by the tenacity and the bulk density required, in its turn depending on the target value of the heat conductivity of the construction.

D.6.4 Clay mortar and clay plaster

To get a mortar or a plaster the building clay is shortened with sand or other aggregates. Clay plasters can be reinforced by suitable additions. For clay mortars and clay plasters the following specific requirements should be fulfilled [8]:

- Fat or medium fat building clay
- Balanced grading curve, i.e. all grain sizes should be present; no grains greater than 5 mm.
- Not too fat mortar to get good working properties and to avoid shrinkage cracks; very lean mixtures have low tenacity
- To examine the clay mortar or plaster, test mixtures should be applied to wall elements
- Clay mortars shall have a strong connection to the adobes
- Clay plasters have to be abrasive resistant, crack formation is not tolerable.

In addition a great number of possibilities exist to work with clay as a building material, not presented in this paper. Please refer to the specialised literature [9, 10].

D.7 IMPROVEMENT OF MATERIAL PROPERTIES

The improvements of the material properties of building clays are necessary only in special cases. In many cases some clay properties can be improved by suitable additions and additives, but possible, negative side effects has to be checked always.

D.7.1 Reduction of crack formation on drying

The formation of cracks during the drying of a clay plaster should not be accepted. The most important factors in this respect are the water content, the grading curve, the clay content and the type of clay used. Reducing the water content is the easiest way to reduce the tendency to crack. Because there is a lower limit in the water content — the minimum processing water content — other possibilities have to be considered.

A further possibility is the increase of the non-clay part, the shortening of the building clay. The higher this content, the less is the shrinkage. Especially the addition of fibrous materials leads to a reduction of the linear dry measure of shrinkage. The reason for this is the lower clay content as well as the fibre property to fix a certain amount of the mixing water.

The addition of very small fibres increases the tensile strength of the clay in the plastic state. The crack formation is reduced in general. The formation of large cracks is blocked at the expense of the formation of more small cracks at the same place.

Constructive measures could be used all the time by choosing the right drying conditions for the clay, e.g. to allow the raw adobes a slow and constant contraction. Raw adobes shall not be put in the sun and have just very little contact to the support.

D.7.2 Improving the water resistance

Only clay building parts and clay plasters that are exposed immediately to weathering have to be protected against the influence of water. In many cases a waterproof coating is enough. But if the surface is damaged, especially with clay plasters, the water input leads to severe damage by swelling and frost action. Waterproof clay building parts allow construction works in humid environmental conditions.

A rule is that cement and bitumen are suitable for rather sandy building clays while lime is suitable for a building clay rich in clay minerals. Furthermore, it is to consider that kaolinite rich clays do not behave exactly as montmorillonite rich clays do.

According to [9], the additives for stabilisation enclose the constituents of a clay, thus hindering the water to penetrate and consequently also the swelling and softening of the clay.

In addition to that, and for many centuries, animal products as blood, urine, excrement, casein, bone glue and other stabilising additives have been used to increase the weather resistance of a clay surface. If applied in the right manner, this effect is confirmed [9].

D.7.3 Improving the tenacity

The higher the tenacity of a building clay, the greater is the compressive and abrasive strength in the dry state. No special requirements concerning the tenacity are made on building clays. If the tenacity is insufficient it can be raised by the addition of fat clay or pure clay minerals but also by a better processing, e.g. by kneading and souring. Just a prolonged stirring and kneading of a clay, say ten instead of one minute, leads to an improved tenacity by 50%.

Also the mineral, animal and plant additions, which were added to increase the weather resistance, change the tenacity — in most cases positively, but in some cases negatively. The suitability and necessity of such additions and additives have to be proved for every single case.

D.7.4 Improving the dry-compressive strength

The compressive strength of clay depends on the grading curve, the water content and the static or dynamic compression during the processing of the clay building part, as well as on the type of the clay minerals. If the sand has a grading curve corresponding to a highly dense packing with a minimum of pore space, that is the clay and silt content is just enough to fill the pore space between the sand grains, then the greatest density is reached which in most cases coincides with the greatest compressive strength.

A higher compressive strength for adobes is needed only to increase the edge strength, which is important looking to the transport, stacking and the walling up. Damages of the edges of the adobes occur not so easy.

The optimum grading curve corresponds nearly the so called "Fuller-parabolic curves", as used in the determination of the additions to concrete. They should be applied to clay only for the grain fraction greater than 0,002 mm.

During the processing of building clay the hand-made adobes often have the same strength as the ones compressed with mechanical presses, because the latter not always end up with the best orientation of the clay particles.

When compressing clay, ramming by beating or vibrating is more effective than a static pressure.

As for clay constructions in general, not the maximum dry-density and thus the optimum water content according to the "Procter curve" but the processibility and the tenacity are decisive. Therefore in most cases a higher amount of water should be used. For the manufacturing of greater adobe blocks a value of the "best value" after the Procter test plus 10% has approved.

The kind of clay minerals has the effect that, e.g. for kaolinitic adobes, a higher compressive pressure leads to a 50% higher compressive strength, while at the same conditions a montmorillonitic clay result in a 100% increase. An addition of montmorillonite to lean clay made its compressive strength higher. Also the mineral addition like lime and cement mentioned above, which contribute to an increase in the water resistance, make the compressive strength higher.

D.7.5 Improving the abrasion resistance

The abrasive resistance of clay surfaces can be improved by many additives like sodium water glass, bone glue, cottage cheese, lime, paraffin, floor polishing and linseed oil varnish. Furthermore, after traditional recipes a clay floor can get a very durable, abrasive resistant surface by painting it with bull's blood, strew Fe_2O_3 over it and hammer this cover in the clay. In the past also other materials as tar and bull's gall were used [9].

D.7.6 Increasing the heat insulation

The heat insulation properties of building clay are improved by addition of porous materials. In use are plant parts as straw or coarse cork and natural and artificial expanded mineral products as pumice, expanded clay, expanded glass, etc. The greater the amount of pores, the lighter the mixture and the higher is the heat insulation effect.

It is much more difficult to build up a wall with a high insulation factor using straw light-weight clay than with mineral products, because the plant parts have higher equilibrium humidity content, and furthermore, they tend to mould. Good heat insulation and a high material strength can only be reached by mineral products.

D.8 WEATHER PROTECTION OF CLAY SURFACES

D.8.1 Constructive measures

As being the most durable and difficult to subsequently modify, first of all and from the very beginning constructive solutions should be sought before taking further measures against the weather. To the constructive measures all constructional actions are counted which prevent (rain)-water from reaching the external surface of a building, i.e. roof overhang.

D.8.2 Compacting the surface

By compacting and smoothing the surface it will be enriched by clay particles, leading to a surface which is much more resistant to rain than otherwise.

D.8.3 Coatings

External coatings should be water repellent (see table D.8:1) and have an open porous structure at the same time, i.e. the water vapour diffusion should scarcely be influenced. This is required to facilitate moisture, soaked by the wall during driving rain, to escape outwards. Appropriate products can be used but not in half-timbered houses, because compartment fillings made of clay usually have a lime plaster.

For internal walls any kind of coating could be used. Since building clay surfaces are very absorptive, water-soluble colours stick especially good.

Many historic coatings are made at a lime base. This type can be used as pure lime coating or together with casein, borax and other organic additives and shows good properties.

The common glue-water colours and limewater colours are suitable only for interior surfaces.

Table D.8:1 Uptake of water coefficients w of clay plasters with surface treatment [9]

Coating	Amount used [g/m^2]	w-value [kg/m^{2}h^{½}]
None	0	9,5
Boiled linseed oil	400	0,0
Lime-casein 1:1	420/350	0,6/1,5
Lime-casein 1:8	300/300	0,7
Silin-paint (van Baerle)	700/250/310	0,3
Hydrophobic (Herbol)	390/390	0,0
Baysoline LD (Bayer)	400/290	0,2
Syltrit (Metropark)	350/320	0,0
BS 15 (Wacker)	450/430	0,1
Steinfestiger H (Wacker)	290/290	0,0

D.8.4 Hydrophobing

Hydrophobing agents are colourless, in organic solvents or water dissolved products, which penetrate a building material in the sense of an impregnation medium to give water-repellent properties. The hydrophobing agents reduce strongly the capillary absorbency while the water vapour diffusion is only slightly diminished. In most cases they are silanes, siloxanes and siliconates. Hydrophobing agents in common organic solvents usually yield a good result with a sufficient penetration depth. The penetration depth could be a problem with very fat clays.

The application of this product can be recommended only in very special cases, because they do not allow capillary water transport. Like coatings they should not be used with half-timbered houses. In addition hydrophobing agents are very expensive.

D.8.5 Plasters

For external plastering on unshielded windward sides no clay plaster but a lime plaster should be used. It should be applied on a key reinforced with fibres (straw, etc.) [11]. Cement plasters show usually a too high strength and are not suitable. Plasters should have a low relative water vapour resistivity μ (see table D.8:3) to allow the possible entering moisture to dry out. According to [12] plasters should be up to the standards as given in table D.8:2.

Table D.8:2 Requirements of plasters on clay masonry [9]

Parameter	Limit value
Consistency/slump	17 ± 0,5 cm
Water binding ability	> 90%
Bonding strength β_{HZ}	≥ 0,05 N/mm^2
Relative water vapour resistivity μ	≤ 12
Uptake of water coefficient w	≤ 0,5 kg/m^{2}h^{½}
Compressive strength β_D	3 - 5 N/mm^2
Tensile bending strength β_{BZ}	1 - 1,5 N/mm^2
Tensile strength β_Z	≥ 0,5 N/mm^2 resp. according to the E-modulus
Modulus of elasticity E_{dyn}	≤ 8000 N/mm^2
Shrinkage ε_s	≤ 0,3 mm/m
Density	≤ 2,0 g/cm^3

Table D.8:3 Relative water vapour resistivity μ of lime plasters with additives [9] (plaster composition in parts by volume)

Lime powder	Trass	Screed sand	Skimmed cottage cheese	Boiled linseed oil	Fat clay	Cow dung	µ-value
1		3					11,2
	1	3					10,8
1		6	0,5				6.2
1		15	0,5		3		9,7
1		3		0,05			15,2
1		3	0,25	0,05			28,5
1,5		10			2	6	8,0

D.8.6 Facing, cladding

In addition to coatings and plasters as weather protection for clay wall constructions, linings and covers made of boards, shingles and faced masonry made of burned bricks are used. These solutions are obvious when additional heat insulation is required.

D.9 DURABILITY AND SERVICE LIFE

Clay and clay products for construction work are very sensitive to water, particularly running water. For this reason all the measures which prevent direct contact of a clay construction to water, as described in the previous chapters, are very important to prolong the service life and to enlarge the durability of a clay construction. The service life of clay constructions can be hundreds of years if carefully protected against the attack of water. All other environmental attack is insignificant.

If clay constructions are maintained in the best way, the service life is of the same order magnitude as for other inorganic building materials. In contrary to these building materials like concrete, the strength and the durability against erosion and wetting increases with the age of the clay building parts. Although no scientific investigations concerning this topic are available at the moment, this statement is based on the observations of old clay building parts and the reuse and use of earth stones tens of years old [13]. The assumption can be made that a considerable after-strengthening occurs. Old clay stones show hardness and properties like a fine conglomerate that could hardly be separated by tools.

The consolidation of clay parts under pressure (clay petrification) could explain the existence of buildings like the clay pyramids, the Great wall if China and the Ziggurat of Babylon, should not exist at all on the basis of strength calculations of single clay stones.

More research is needed in these fields to better understand the strength of clay building materials and the development with time, to use this knowledge for construction purposes.

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