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Guide and Bibliography
to
Service Life and Durability Research for Buildings and Components

PART III – Building Materials and Components:
Characterisation of Degradation

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PART III — BUILDING MATERIALS AND COMPONENTS
CHARACTERISATION OF DEGRADATION

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A. METALS (V. Kucera and P. Jernberg)

A.1 COPPER

A.1.1 Physical properties

Structural copper sheet is available in two main qualities: annealed, soft with a mat surface, and half-hard, rolled to a specular surface. Mechanical data are given in table A.1:1

Table A.1:1 Mechanical data for structural copper

<table>
<thead>
<tr>
<th></th>
<th>General</th>
<th>Annealed</th>
<th>Half-hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>8940</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal exp. coeff. (10⁻⁶ K⁻¹)</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>11.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>≤140</td>
<td>≥180</td>
<td></td>
</tr>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td>220-260</td>
<td>240-300</td>
<td></td>
</tr>
<tr>
<td>Hardness (Hv)</td>
<td>40-65</td>
<td>65-95</td>
<td></td>
</tr>
<tr>
<td>Elongation (A₅₀%)</td>
<td>≥33</td>
<td>≥8</td>
<td></td>
</tr>
</tbody>
</table>

The annealed quality is mainly used for lapping works, where the softness facilitates the shaping. For other purposes the half-hard quality is preferred because of the higher stiffness.

Copper may be alloyed to brass, where zinc is the main alloying element. As brass is not used as a structural material in the normal case, this chapter focuses on “pure” copper.

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A.1.2 Chemical properties

Chemically, the most usual type of “pure” copper sheet is phosphorous oxidised, “oxygen free” copper, with a very low content of oxygen. A typical list of abundance of trace elements in such copper is shown in table A.1:2.

Table A.1:2 Example of trace elements abundance in phosphorous oxidised copper

<table>
<thead>
<tr>
<th>P</th>
<th>As</th>
<th>Ni</th>
<th>Ag</th>
<th>O</th>
<th>Se</th>
<th>Pb</th>
<th>Sn</th>
<th>S</th>
<th>Zn</th>
<th>Sb</th>
<th>Fe</th>
<th>Te</th>
<th>Tot.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ppm</td>
<td>240</td>
<td>85</td>
<td>62</td>
<td>50</td>
<td>38</td>
<td>32</td>
<td>25</td>
<td>17</td>
<td>16</td>
<td>13</td>
<td>9</td>
<td>1</td>
<td>622</td>
</tr>
</tbody>
</table>

The resistance of copper against various chemicals can be summarised as follows:

- **Acids.** Copper is rather resistant against oxygen-free solutions of non-oxidising acids like acetic, sulphuric and phosphoric acid. In oxidising acids, like nitric and chromic acids, or in acid solutions containing oxygen, the corrosion rate becomes appreciable. The rate is greater in concentrated and warm than in diluted and cold acids. Organic acids usually are less aggressive than mineral ones.

- **Alkali compounds.** At room temperature sodium and potassium hydroxides are fairly harmless to copper, while at higher temperatures only diluted solutions can be accepted. Ammonium and cyanic alkali compounds are quite aggressive to copper. An exception is dry ammonium hydrate, which does not react with copper. However, if water is added the reaction will be violent.

- **Salts.** Neutral salts, like nitrates and sulphates and sodium and potassium chlorides, are fairly harmless to copper. Alkali salts, like sodium carbonate, phosphate and silicate, reacts as the corresponding hydroxides, although weaker. Acid and hydrolysing metal salts, especially iron (III) chloride and sulphate, are quite corrosive. Chromates are not aggressive in neutral and alkalic solutions, while in acids solutions are very aggressive. Sulphides should be avoided, as the corrosivity is fairly strong.

- **Organic compounds.** Copper is resistant to esters, glycols, ethers, ketones, alcoholes, aldehydes and most of (other) organic solvents.

A.1.3 Usage aspects

Because of its low corrosion rate and the aesthetic so-called patina formation, copper has long been used for building structures such as roofs, façades and gutters. Many copper roofs on castles and other monumental buildings have retained for several centuries. Thus, large amounts of copper materials are used under atmospheric exposure in different types of climates all over the world.

If conditions are favourable, copper may after some years in outdoor atmospheres develop a characteristic blue-green patina, consisting of basic copper salts and oxides. Sometimes a user is at first disappointed and complains when his newly laid copper roof shows a less attractive, mottled appearance [1]. After 6 to 12 months, however, the surface usually has acquired a
uniform dark-brown colour. In general, the surface does not develop beyond this stage for a number of years. After 4-6 and 7-15 years a green patina usually begins to appear on sloping surfaces under marine and urban conditions, respectively. Vertical surfaces generally stay black much longer, as their time of wetness is shorter. In a marine atmosphere the surfaces facing the sea acquire a green patina sooner than the other surfaces. This is due to the greater supply of chlorides from the sea winds. In rural environment the formation of patina normally is initiated after 20-50 years. If the atmosphere only is slightly polluted, the patina may take an extremely long time to form (hundreds of years) due to the scarce supply of anions for the formation of basic copper salt. It may even fail to form at all if the temperature is low or the exposure conditions very dry. As shown by the potential-pH diagram in fig.A.1:1, green patina will also fail to form under acidic conditions, e.g. near chimneys, where acid smoke strikes the roof. Under such conditions, the corrosion products are soluble. Bitumen may also cause similar but more severe problems (see section A.1.5).

Prepatinated copper sheets are available at the market, to be used where the patina will not or take too a long time to develop. Also, quick patination coating systems for moderate areas are available, to be used at repair or extension of existing constructions.

Rainwater, running at copper-bearing surfaces, generally picks up traces of dissolved copper. The fraction of corrosion products that leave the surface and dissolve in the rainwater depends on the acidity of the micro environment. Accordingly, the dissolution is greatest in urban and industrial atmospheres, highly polluted with SO\(_3\)\[3\]. Such water in contact may cause blue staining on masonry, stonework, etc. It may also cause micro-galvanic corrosion in contact with metals less noble than copper. Consequently, the rainwater from copper surfaces should be properly collected and drawn off through gutters and spouts.

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Fig.A.1:1  Potential-pH diagram, Cu - SO\(_4\)^{2-}, H\(_2\)O; 10\(^{-1}\) M Cu, 10\(^{3}\) M SO\(_4\)^{2-} [2]
As copper in too high concentrations is poisonous, concern regarding copper leakage to the environment due to corrosion of copper roofs has been put forward. The problem should not be neglected, although investigations has shown that copper roofs contribute to a minor part, 1.5-10 % [4,5], of the total copper load in sewage sludge, while, for example, the traffic contributes by 20-25 % [5].

As copper is more noble than most other types of construction metals, measures to avoid ordinary galvanic corrosion have to be taken:

- Avoid electric contact between different metals; apply electric insulating material between them.
- Protect the metals from direct contact of humidity and water; apply a corrosive protective coating at the surfaces, even the copper.
- Otherwise, fasteners, hangers and other details should be made also of copper or of stainless steel, compatible to copper.

Copper in a soil and water environment, mainly found in the case of installations (which is beyond the scope of this book), is just mentioned briefly below.

### A.1.4 Typical micro environments and loads

Agents at outdoor exposures affecting the atmospheric corrosion process of copper are mainly precipitation, time of wetness, temperature (directly by governing the instantaneous corrosion rate and indirectly by the effect on time of wetness), oxygen and air pollution, in the form of gases, molecules dissolved in rainwater and particles. As in all corrosion processes the concentration of oxidative compounds, normally oxygen, in the electrolytic film determines the corrosion rate.

Except from installations, copper in soil or water environments is not very common in the case of constructions and buildings. In the soil, usually the decisive parameters are the concentrations of humidity and oxygen, and the electrical resistivity of the soil. In water the pH value of the water and the concentration of dissolved ionic compounds like chlorides and sulphides are the main parameters governing the corrosion process. In the case of running water, e.g. in pipes, the risk of erosion corrosion has to be considered.

### A.1.5 Typical degradation and failure modes

We may first consider the thermodynamic possibilities for the formation of copper compounds related to the various constituents in outdoor atmospheres [2]. The potential-pH diagram in fig.A.1:1 represents the system Cu - SO₄²⁻ - H₂O at 25°C with a Cu²⁺ concentration of 10⁻¹ mole/litre and an SO₄²⁻ concentration of 10⁻³ mole/litre. As can be seen, copper metal is stable in a substantial part of the stability region of water. This is consistent with copper being a noble metal. The diagram also shows a stability domain for basic copper sulphate, Cu(OH)₁.₅(SO₄)₀.₂₅. The width of this domain depends on the SO₄²⁻ concentration; at decreasing concentration the domain becomes narrower, see fig.A.1:2a. The stability domains for Cu(OH)₁.₅Cl₀.₅, CuOH(CO₃)₀.₅ and Cu(OH)₁.₅(NO₃)₀.₅ versus corresponding anion concentrations can also be seen in fig.A.1:2. The coating of corrosion products forming the patina has a rather complex composition, varying from place to place (table A.1:3) [6]. The main components are generally copper oxide and one or more basic copper salts [6,7].
Fig. A.1:2  
Stability domains of basic copper salts in aerated aqueous solutions with varying anion concentration and pH value; 25°C, $10^{-1} \text{M Cu}$ [2]. (a) sulphate; (b) chloride; (c) carbonate; (d) nitrate

Basic sulphate:  
$$\text{Cu}(\text{OH})_{1.5}(\text{SO}_4)_{0.25}, \text{ Cu}(\text{OH})_{1.33}(\text{SO}_4)_{0.33}$$

Basic chloride:  
$$\text{Cu}((\text{OH})_{1.5}\text{Cl}_{0.5})$$

Basic carbonate:  
$$\text{CuOH}(\text{CO}_3)^{1.5}, \text{ Cu}(\text{OH})_{1.33}(\text{CO}_3)_{0.33}, \text{ Cu}(\text{OH})_{0.67}(\text{CO}_3)_{0.67}$$

Basic nitrate:  
$$\text{Cu}(\text{OH})_{1.5}(\text{NO}_3)_{0.5}$$
Table A.1:3 Basic copper salts in green patina from various atmospheres, defined by anions ranked with respect to concentration [6]

<table>
<thead>
<tr>
<th>Reporter</th>
<th>Object</th>
<th>Time of exposure (years)</th>
<th>Country</th>
<th>Type of atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vernon &amp; Whitby</td>
<td>Copper roofs; copper conductor in marine atmosphere</td>
<td>12-300; 13</td>
<td>UK</td>
<td>Rural: 1. SO$_4^{2-}$, 2. CO$_3^{2-}$, 3. Cl$^-$, Urban or industrial: 1. SO$_4^{2-}$, 2. CO$_3^{2-}$, 3. Cl$^-$, Marine: 1. SO$_4^{2-}$, 2. CO$_3^{2-}$, 3. Cl$^-$, Mixed urban - marine: 1. SO$_4^{2-}$, 2. CO$_3^{2-}$, 3. Cl$^-$</td>
</tr>
<tr>
<td>Vernon</td>
<td>Copper roof on church spire on the isle of Guernsey</td>
<td>33</td>
<td>UK</td>
<td>1. Cl$^-$, 2. CO$_3^{2-}$, 3. SO$_4^{2-}$</td>
</tr>
<tr>
<td>Freeman, Jr.</td>
<td>Copper roofs</td>
<td>16-78</td>
<td>USA</td>
<td>1. SO$_4^{2-}$, 2. CO$_3^{2-}$, Cl$^-$</td>
</tr>
<tr>
<td>Thompson, Tracy &amp;</td>
<td>Copper panels from field test</td>
<td>20</td>
<td>USA</td>
<td>1. SO$_4^{2-}$, 2. CO$_3^{2-}$, 3. NO$_3^-$, 1. Cl$^-$, 2. SO$_4^{2-}$, 3. CO$_3^{2-}$</td>
</tr>
<tr>
<td>Freeman, Jr.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aoyama</td>
<td>Copper conductor for railway</td>
<td>-</td>
<td>Japan</td>
<td>1. NO$_3^-$, 2. CO$_3^{2-}$, 1. SO$_4^{2-}$, 2. CO$_3^{2-}$, 1. Cl$^-$, 2. CO$_3^{2-}$</td>
</tr>
<tr>
<td>Mattsson &amp; Holm</td>
<td>Copper-base materials from field test</td>
<td>7</td>
<td>Sweden</td>
<td>1. SO$_4^{2-}$, 2. NO$_3^-$, 3. CO$_3^{2-}$, 1. SO$_4^{2-}$, 2. NO$_3^-$, 3. CO$_3^{2-}$</td>
</tr>
<tr>
<td>Scholes &amp; Jacob</td>
<td>Copper-base materials from field test</td>
<td>16</td>
<td>UK</td>
<td>1. SO$_4^{2-}$, 2. Cl$^-$, CO$_3^{2-}$, 1. Cl$^-$</td>
</tr>
</tbody>
</table>

In urban and rural atmospheres basic sulphate is predominant, while in marine atmospheres basic chloride usually is the main component. This is in good agreement with the thermodynamics described. Unexpectedly, however, basic carbonate is sometimes found in practice. Fig.A.1:2c indicates that the conditions in the atmosphere would not favour the formation of this type of patina, as the H$_2$CO$_3$ concentration in the water film would only be about $10^{-5}$ mole/litre at equilibrium with the air. The presence of basic copper nitrate, also found in some locations, indicates that the water film on the metal surface may contain an appreciable amount of nitrate (fig.A.1:2d).

Generally the corrosion products first formed are Cu$_2$O and CuO. The copper oxides react rather slowly with airborne molecules and ions, such as SO$_x$, Cl$^-$, CO$_2$ and NO$_x$, with the formation of basic salts, e.g.
4Cu₂O + 2SO₂ + 6H₂O + 3O₂ → 8Cu(OH)₁,₅(SO₄)₀,₂₅
4Cu₂O + 4Cl⁻ + 6H₂O + O₂ → 8Cu(OH)₁,₅Cl₀,₅

provided the pH value of the surface moisture is sufficiently high. The corrosion products give a non-insignificant corrosion protection to the surface.

Estimated ranges of atmospheric corrosion rates at intermediate exposure periods (10-50 years) for copper are given in table A.1:4

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Corrosion rate (µm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Urban and industrial</td>
<td>1 - 3</td>
</tr>
<tr>
<td>Marine</td>
<td>1 - 2</td>
</tr>
</tbody>
</table>

For various types of copper alloys, the atmospheric corrosion rates at three different long-term tests are shown in fig.A.1:3. The weight loss is approximately the same for low-alloyed coppers, brasses, nickel silvers and tin bronzes.

The corrosion rate of copper decreases slowly with time, appearing to follow an exponential decay function as shown in fig.A.1:4 [3]. This behaviour indicates the formation of a partially protective layer of corrosion products. The protective action is probably due mainly to the presence of basic copper salts. In a study in UK [9], six contractors were asked to estimate the average service lives of copper roofs. The answers ranged from 60 to 100 years, and from 60 to 120 years, for harsh and mild environment, respectively. Mean values in the two cases were 83 and 92 years. However, with a sheet thickness of 0,6-0,7 mm and say, a corrosion rate of 1 µm/year that further decreases by time, service lives of hundreds of years could be expected. Functioning copper roofs at historical buildings of more than 300 years may also be found at many sites in Europe.

Typical corrosion rates in soil, fresh water and sea-water are 1, 10 and 50 µm/year, respectively. An exception is soils with extremely low pH values and high salt concentrations, where the corrosion rate can reach as much as 50 µm/year.

True corrosion defects of copper roofs are not very usual. However, bitumen may cause drastic corrosion [10]. Unprotected bitumen oxidises in contact to oxygen, at which acid reaction products are formed, being very aggressive to most types of metals. If bitumen is applied at a construction part above a copper roof, rainwater acidified by the bitumen may run down and put the copper material at risk. Such water — pH values about 1,5 have been detected — will hinder the normal formation of protective corrosion product layers, i.e. patina. In practice, 50 % diminishing of the thickness of a copper sheet after only 15 years has been found.
Fig. A.1:3 General corrosion rates for copper and copper alloys in the atmosphere, sloping surfaces. A = low-alloyed Cu; B = low-Zn brass; C = high-Zn brass; D = Ni silver; E = Sn bronze [3].

Fig. A.1:4 Penetration depth vs. exposure time for copper. Δ = urban, □ = marine, ○ = rural.
The reduction in mechanical properties due to general corrosion is usually small, in most cases less than 5% in ultimate tensile strength and less than 10% in rupture strain [6]. For high-zinc brasses, however, greater changes occur because of dezincification [3]. Zinc is dissolved selectively from the alloy, which results in portions of porous copper with poor mechanical properties. The diagram in fig. A.1:5 shows that \((\alpha+\beta)\)-brasses are somewhat more prone to dezincification than pure \(\alpha\) - and \(\beta\)-brasses, probably because of local cell interaction when \(\alpha\) - and \(\beta\)-phases occur together in the structure. Small additions of As — about 0.02 - 0.04% — inhibit dezincification in \(\alpha\)-brass.

High-zinc brasses, if under tensile stress, are also susceptible to stress corrosion cracking on atmospheric exposure outdoors [6]. The risk of stress corrosion in brasses is greatest in industrial and urban atmospheres characterised by high concentrations of sulphur dioxide and ammonia. The stress corrosion susceptibility is markedly lower in marine atmospheres.

![Diagram](image)

Fig. A.1:5 Maximum dezincification depth vs. proportion of zinc in binary brasses after 16 years of exposure in different atmospheres [1]. △ = urban, □ = marine, ○ = rural.

A.1.6 References

1. Mattsson, E. and Holm, R. (1968), Sheet Met. Ind., Vol. 45, No.270
5. Deutches Kupfer-Institut, Düsseldorf, (to be published)
B Natural Stone (T. Yates and A. Lewry)

B.1 INTRODUCTION TO NATURAL STONE

This chapter is primarily concerned with the characterisation of natural stone used for buildings and associated hard landscaped areas. It does not cover the design or installation of buildings or the use of natural stone as aggregates or as roadstone.

Stone has been used in buildings both as a structural and decorative material for a long time. Traditionally, building stone has been extracted and used within the immediate local region - which resulted in the evolution of building design to take into account the materials available and their qualities. The exceptions were major buildings where stone was imported for architectural or aesthetic reasons or because of the absence of suitable local materials. Changes in transport now allow materials to be moved across great distances and imported from almost any country in the world - leading to their use in regions or countries which are significantly different from their traditional areas. In some cases the initial driving force for the use of a particular stone is the cost, availability or colour - and only then are its qualities questioned. Some balance is needed in which the design takes account of the stone’s properties or that only stones of suitable quality are used if the design is fixed. But this leaves open the question of how can quality be assessed and which qualities are important for a particular stone or design.

Natural building stones are obtained from the three basic types of rock: igneous, metamorphic and sedimentary.

Igneous rocks (e.g. granites) are those which have crystallised from molten rock or “magma”. The grain size of the igneous rocks is determined by the rate at which the molten rock cools - a slow cooling rate producing a coarse-grained rock, and a rapid cooling rate producing fine-grained rocks. Granite is the main igneous rock used for buildings but the name covers a wide range of rocks of various origins and mineral compositions. Granites contain between 50 and 75% feldspars (K, Ma, Ca, or Ba aluminous silicates) [1] that mainly determines the colour and between 10 and 35% quartz (SiO₂). These rocks are usually dense and range in grain size from fine to coarsely granular. The porosity of igneous rocks is usually very low and this, together with their mineral composition, makes them resistant to weathering. In the building industry the term `granite’ is sometimes used to describe a number of igneous rocks that are not technically true granites.

Metamorphic rocks (e.g. slates and marbles) are formed by recrystallisation of the parent rock as a result of being subjected to high temperature and/or pressure. These conditions are usually caused by deep burial or movements of the earth’s crust.

Sedimentary rocks (e.g. limestone and sandstone) are the main source of building stones in many countries. The formation of these rocks is a two stage process. First a sediment is deposited; this can originate from a number of sources such as fragmentation of earlier rock, the accumulation skeletons of aquatic animals, or by chemical deposition in lakes or seas. The second stage is the cementing of the sediment to form a hardrock; this is assisted by compaction and pressures generated from movements of the earth’s surface.
Sandstones are formed by the fragmentation of earlier rocks, such as metamorphic gneisses and igneous rocks. The particles of parent rock were transported mainly by the action of water, leading to deposition in layers on the floors of seas, lakes and estuaries or by wind action, leading to deposition in deserts. During transport the sediments were sorted in size; in general the finer particles would have carried further than coarser ones, and the longer the sediment took to deposit, the greater the degree of sorting. The degree and method of sorting determine the texture of the sandstone.

All sandstones contain quartz (silica) along with a variety of other minerals such as mica and feldspar. Once the sediment has been laid down it can be bound together by a number of different cements:

1. siliceous — containing silica
2. calcareous — containing calcium carbonate
3. dolomitic — containing dolomite (calcium magnesium carbonate)
4. ferruginous — containing iron oxide
5. argillaceous — containing clay

The nature of the cementing material has a profound influence on the durability and the physical properties of sandstones with the siliceous sandstones generally being the most resistant to weathering.

Limestone sediments are usually formed from the skeletons and shells of aquatic animals, from chemically formed grains such as ooliths or a combination of these. Ooliths are formed by the crystallisation of calcium carbonate from solution around a nucleus that could be a fragment of shell or a grain of sand. Oolitic deposits are formed in seas where there is a tidal action that is essential for their formation and grow. Limestones whose sediments originate from aquatic organisms are usually formed under marine conditions but can be produced in freshwater.

Limestones are all cemented with calcium carbonate (calcite) and their durability and physical properties are determined more by the structure of the rock (for example the porosity and pore size) than by its chemical nature. In some cases, limestones are converted to magnesium limestones by a process called ‘dolomitisation’. In this process the calcite is gradually replaced by dolomite, a double carbonate of calcium and magnesium.

The characterisation of natural building stone is important as it allows the suitability of a stone to be assessed. Characterisation tests applicable to building stone can be divided into four groups:

1. Physical properties of the stone (for example compressive or flexural strength)
2. Durability of the stone (for example will it be frost resistant)
3. Safety of the stone in use (for example the slipperiness of paving)
4. Petrographical and microscopical properties (for example mineralogy or porosity)

Characterisation can be based on both direct measurements of some properties, where the stone is subjected to the same conditions that it would encounter in use, and also indirect measurements, where the internal structure of the stone is used to determine a different property. Indirect tests are particularly common in assessments of durability. In addition, the petrographic and microscopic properties are determined by analysis of samples that are independent of the proposed final use.
B.2 PHYSICAL PROPERTIES

The physical properties of natural stone vary widely, not only between the three major group of stones but even within a single stone type. Table B.2:1 provides a summary of published data based on [2] but with additions from others including [3] and the German Standard DIN 52 100 [4]. Table B.2:1 is divided into three groups - aggregation properties, thermal properties and mechanical properties - and these are used as the basis for the outline of each the range of appropriate properties.

B.2.1 Aggregation properties

Porosity, water absorption and permeability are all important physical properties because they characterise the internal structure and the way water can reach the interior of the stone. Water ingress is the key to the weathering of natural stones as it is involved in all the major dissolution and expansive processes that result in the decay of the stone. However, thermal and mechanical properties must also be considered in assessing decay and decay mechanisms.

Building stones are polycrystalline mineral aggregates and therefore intergranular bonding, cementing matrix, pore shape and pore size are often more important than the properties of individual grains. Density, porosity (including pore size distribution) and permeability are all determined by the relationship of the grains and their surrounding cements, but in the denser igneous and metamorphic rocks the pore space may well be in the form of fractures or cleavages along the grain boundaries.

B.2.1.1 Density

The density of a stone can be described in a number of ways. The first is the bulk density ($\rho_b$), also termed the apparent density. This is defined as the mass divided by volume (including the pore volume) and the units are g cm$^{-3}$ or tonnes m$^{-3}$. The second description is the real density, which is the mass divided by the volume excluding the pore volume, for example by measuring the stone after crushing. The third term used is the bulk specific gravity, a dimensionless measure. Traditionally, stone with densities of between 1.7 to 2.2 tonnes m$^{-3}$ have been considered as workable stone but now stones of much greater densities, often associated with better weathering properties, can be worked with modern equipment.

B.2.1.2 Porosity

Porosity ($f$) is the ratio of pore volume to bulk volume. In general the porosities of igneous and metamorphic rocks are low (<5%) compared to that of sedimentary rocks (up to 40%). With respect to stone decay, pores are important in that they are fluid receptacles and sites of weakness for internal stresses. Limestones, which have a predominance of pores of larger diameters, appear to be more durable than those with a very small mean pore size. Microporosity is defined as the percentage volume of pore with a diameter equal to or less than 5 mm and this appears to be a critical value for durability and frost sensitivity.

Porosity is described as ‘open’, i.e., pores that form an open system and are accessible by air and water, or ‘closed’, i.e., pore spaces that are isolated from the environment. The ‘open’ pores can also be divided into two groups: those that will readily absorb water at atmospheric pressure, and those that are only accessible when the sample is subjected to a vacuum or prolonged immersion.
B.2.1.3 Permeability

The ease of fluid flow through a rock is defined empirically by Darcy’s law:

$$Q = \frac{mPA}{vL}$$

where:

- $v$ = fluid viscosity (poise)
- $Q$ = discharge ($\text{cm}^3/\text{s}$)
- $m$ = permeability (darcy)
- $P$ = pressure difference (bars)
- $L$ = flow distance (cm)
- $A$ = cross-sectional area ($\text{cm}^2$)

This is important because the absorption of fluids in rocks depends on the connected, effective (i.e. permeable) porosity (that is the open pores). Rock permeability can be decreased by a factor of 10 by sealing of pores due to dissolution and reprecipitation of soluble minerals. Permeability can be applied to liquids in the vapour phase as well as those present as liquids.

B.2.2 Thermal properties

The term thermal properties can be used to describe a range of parameters that describe both the movement of heat within and through a stone and the resultant effect of this movement on the mechanical properties of the stone.

B.2.2.1 Thermal expansion

Thermal expansion is usually expressed in mm per metre per degree centigrade and table B.2:1 shows that most stones have values of between 4 and 15 which for a 60°C temperature rise would result in an expansion of between 0.24 mm and 0.90 mm per linear metre.

In the most stones expansion (or contraction if the temperature falls) is fully reversible when the stone returns to its original temperature. However, there are some stones, particularly some fine to medium grained marbles that can retain a residual expansion when cooled which leads to a disruption of the crystal structure and a resultant loss of flexural strength.

Thermal stress due to differential mineral expansion and thermal gradients within a piece of stone can lead to micro-cracking between and in the mineral grains. Damage from this process is probably minimal when compared to frost damage though this can also be considered a form of thermal stress. A number of mechanical or physical properties can be used to reveal the extent of change due to thermal and frost action, these include changes in elasticity or flexural strength. Non-destructive methods can also be used, for example, ultrasonic or acoustic methods could measure the decrease in elasticity and continuity of the structure and as a result the extent of weathering on building stones.
Table B.2:1  Physical properties for different stone types

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Aggregation properties</th>
<th>Thermal properties</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bulk density (tonnes m³)</td>
<td>Porosity (%)</td>
<td>Permeability (m (-logd))</td>
</tr>
<tr>
<td>Granite</td>
<td>2.5 - 2.7</td>
<td>0.1 - 4.0</td>
<td>9 - 6</td>
</tr>
<tr>
<td>Gabbro</td>
<td>2.8 - 3.1</td>
<td>0.3 - 3.0</td>
<td>7 - 5</td>
</tr>
<tr>
<td>Rhyolite-</td>
<td>2.2 - 2.5</td>
<td>0.3 - 5.0</td>
<td>8 - 2</td>
</tr>
<tr>
<td>Andesite</td>
<td>Basalt</td>
<td>2.7 - 3.1</td>
<td>0.1 - 5.0</td>
</tr>
<tr>
<td>Quartzite</td>
<td>2.5 - 2.7</td>
<td>0.3 - 3.0</td>
<td>7 - 4</td>
</tr>
<tr>
<td>Marble</td>
<td>2.4 - 2.8</td>
<td>0.4 - 5.0</td>
<td>6 - 3</td>
</tr>
<tr>
<td>Slate</td>
<td>2.6 - 2.9</td>
<td>0.1 - 5.0</td>
<td>11 - 8</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.0 - 2.6</td>
<td>1.0 - 30.0</td>
<td>3 - 0</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.8 - 2.7</td>
<td>0.3 - 30.0</td>
<td>9 - 2</td>
</tr>
<tr>
<td>Shale</td>
<td>2.0 - 2.5</td>
<td>2.0 - 30.0</td>
<td>9 - 5</td>
</tr>
<tr>
<td>Soapstone</td>
<td>2.5 - 2.8</td>
<td>0.5 - 5.0</td>
<td>6 - 4</td>
</tr>
<tr>
<td>Travertine</td>
<td>2.0 - 2.7</td>
<td>0.5 - 5.0</td>
<td>5 - 2</td>
</tr>
<tr>
<td>Serpentinite</td>
<td>2.2 - 2.7</td>
<td>1.0 - 15.0</td>
<td>7 - 2</td>
</tr>
</tbody>
</table>
B.2.2.2 Thermal conductivity
This is a measure of the insulating capacity of a stone and it is a property that is becoming of greater importance in constructions where thermal efficiency is important. Thermal conductivity can be calculated using the formula:

\[ K = \frac{qL}{A(t_1 - t_2)} \]

where:

- \( K \) = thermal conductivity
- \( q \) = rate of heat flow
- \( L \) = thickness of material
- \( A \) = area of isothermal surface
- \( t_1 \) = temperature of hot surface
- \( t_2 \) = temperature of the cold surface

In general, dense rocks have a higher thermal conductivity than porous stones.

B.2.2.3 Diffusivity
This is a measure of the rate of heat transfer across the body of a stone. From this the extent of temperature changes (how deep) and the magnitude across a stone body can be calculated.

B.2.3 Mechanical properties
This section describes a number of important mechanical and physical properties of stone that can be used as a basis for its characterisation [5-7].

B.2.3.1 Hardness
Engineering hardness tests measure the resistance of the surface of a material to indentation or scratching by a hard object; the object varies from a steel sphere to a diamond pyramid depending on the test.

Mineralogists generally determine the hardness of a mineral by reference to an empirical scale of standard minerals. Mineral hardness is a crude scratch test and Mohs devised the most common scale.

B.2.3.2 Tensile properties
The tensile test measures the resistance of a material to a static or slowly applied force. From this test a stress-strain plot can be obtained where:

engineering stress: \[ \sigma = \frac{F}{A_0} \] (\( A_0 \) = original cross-sectional area)
engineering strain: \[ \epsilon = \frac{(l - l_0)}{l_0} \] (\( l_0 \) = original distance between the gage marks)

For most materials the stress-strain curve is linear until a yield point beyond which the
material does not undergo further plastic deformation until breaking point is reached. The stress at the yield point is defined as the yield strength and the maximum stress as the tensile strength. The modulus of elasticity (Young’s modulus, E) is the slope of the stress-strain curve in the elastic region. This relationship is Hooke’s law:

\[ E = \frac{\sigma}{\varepsilon} \]

B.2.3.3 Compressive strength
Brittle materials are generally tested in compression since this is the mode of stressing in which they are most often used and is also the easiest mode to test. The advantage of this test is that, unlike the tensile test where necking will occur, the true stress-strain curve can be estimated for larger strains. As a rule of thumb compressive strength is a magnitude greater than bending strength, which in turn is an order of magnitude greater than tensile strength.

B.2.3.4 Modulus of rupture
This a material dependant quantity calculated from the bending strength measured by three or four-point loading. The specimen fails in tension and the failure load is dependant on the critical crack size on the specimen’s surface. This can mean that the result is very dependant on the presence of fractures or flaws on the material’s surface. Introducing a critical flaw, such as in a single notch bend specimen, and measuring the fracture toughness of the material can alleviate this problem.

B.3 CHEMICAL PROPERTIES

B.3.1 Igneous rock
These rocks contain mainly silicate minerals that consist of crystal lattices in which metal cations, such as Ca, Na, K, Mg, etc., are incorporated. Cations exposed at the surface may become hydrated due to unsaturated valencies in the structure. Hydrogen ions will penetrate the mineral surface and subsequently break down the silicate structure by a process of ion exchange. This will “free” ions, which can be transported away, leaving gaps in the crystal lattice and a ‘weathered structure’.

B.3.2 Metamorphic rocks
Quartzites are sandstones that have recrystallised as a result of being subjected to pressure and high temperatures. Chemically they are largely silica with the result is that their chemical properties are similar to those of igneous rocks.

Slates, whose parent rock is clay-based (e.g. siltstone or mudstone), are susceptible to the same forms of ion leaching as igneous rocks. However, if impurities such as calcium carbonate and iron pyrite are present they are also susceptible to attack by acidic gases or rainwater. These reactions are expansive and the reactivity of these mineral impurities is dependent not only on the amount present but the location of the mineral within the slate’s microstructure.

Marbles are derived from limestone and dolomite limestone. Their main chemical
constituent is calcium carbonate or calcium/magnesium carbonate. These minerals are readily attacked by acids and acidic gases resulting in dissolution and the possible formation of expansive products particularly gypsum.

B.3.3 Sedimentary rocks

Sandstones are bound together by a number of different cements (see section B.1). In general the nature of this cement will determine the chemical properties of the stone. However, the presence of other minerals, for example clays, can lead to rapid deterioration if the stone is subjected to wetting and drying cycles.

Limestones are similar to marbles but they tend to have an increased reactivity if they are porous with a more open structure.

B.4 WHAT IS STONE USED FOR?

Traditionally, the main use of stone, such as limestone, sandstone and granite, has been in structural masonry units, however, in recent times many stone types have been used for cladding applications. Stones are also be used for flooring if they are sufficiently resistant to abrasion.

Traditional uses include roofing where slate, due to its good cleavage and weathering properties, has been exploited.

B.5 FORMS OF DEGRADATION AND FAILURE MODES OF NATURAL STONE

B.5.1 Physical weathering

B.5.1.2 Effect of moisture/temperature

The degree of moisture absorption of a stone will depend on its porosity and permeability. Due to the heterogeneous nature of stone, a temperature gradient will lead to internal stresses that may eventually result in degradation of the stone.

Freezing and thawing cycles will occur if the temperature change is around 0°C and includes significant periods below 0°C. The resulting decay may be caused by:

1. volume increase of water below 0°C
2. volume increase of water to ice
3. displacement of water from frost front
4. conversion of ‘pore water’ to ordered water’

Water can be considered a corrosive element with the main damage caused during the ‘drying’ phase; this could be due to the swelling and contraction of certain minerals or drying gradients within the stone inducing mechanical stresses.
B.5.1.3 Salt crystallisation
The crystallisation of water-soluble salts, derived from the atmosphere or the soil, can cause stresses which may lead to the degradation of stone. Deposition near the stone’s surface can be a major form of decay and results in surface spalling and the generation of a new fresh surface for further physical and chemical decay.

B.5.1.4 Erosion
This is normally due to wind-borne dust or sand. It can cause damage to the surface by impact and abrasion but except in arid areas is only a minor contributor to decay.

B.5.2 Chemical weathering
Carbon dioxide (CO₂) is the only naturally abundant acidic gas, producing a pH of around 5.6 in rainfalls in urban areas this may increase to 5.1 due to increased CO₂ concentrations. Industrialisation has lead to the more acidic sulphur oxides, nitrogen oxides and their derived compounds being a major contributor to acid attack.

Calcereous stones can be attacked by acidic precipitation that causes dissolution of the calcite. In polluted atmospheres calcium sulphate and calcium nitrate may form and, if exposed to rainfall, also dissolve. If calcium sulphate recrystallises gypsum will be formed which can cause subsequent salt damage as a result of the formation of expansive hydrate salts. Problems can occur if sandstone is in contact with a limestone and the gypsum is ‘washed’ into the sandstone where it subsequently re-crystallises.

Silicate rocks weather by ion exchange that results in discolouring and softening of the surface followed by pitting and crumbling.

Slates, which contain calcium carbonate and iron pyrite, are attacked by sulphuric acid produced by the reaction between the two impurities. Calcium sulphate is produced as a by-product and this expansive reaction results in splitting of the slate along the mica layers.

B.5.3 Biological attack
The action of higher species, such as lichens, is to degrade the stone by mechanical as well as chemical microns. Micro organisms may deteriorate stone due to the formation of by-products such as acid (inorganic and organic), sulphates and nitrates.
B.6 CHARACTERISATION OF NATURAL STONE

B.6.1 Microscopic structure

B.6.1.1 Petrography
This would involve visual examination of the rock from the quarry, either of the block or a hand specimen. The petrographic observations could include the homogeneity of the rock, e.g. mineral veins, flaws and bedding that could affect the performance in use. Sections of the rock are then normally taken and these can be polished or prepared so that there are optically transparent (“thin”). These specimens can then be examined by optical microscopy for the gross mineral composition and microstructure of the rock.

B.6.1.2 Scanning Electron Microscopy (SEM)
The utilisation of an electron beam focused on a small cross-sectional area of a sample allows spatial probing of composition and the imaging of topography. The introduction of primary electrons with a sample produces signals, for example X-ray, cathodo-luminescence, back-scattered electrons, Auger electrons, and transmitted or absorbed electrons, the energies of which are related to elemental composition. There are also signals related to the topography of the surface, such as secondary electrons and, to a lesser extent, back-scattered electrons. SEM is best used to analyse rough fracture surfaces and can be coupled with semi-quantitative or qualitative elemental analysis by the use of an X-ray detector.

B.6.1.3 Porosimetry
Examination of specimens by optical or electron microscopy coupled to an image analyser can give information about the pore structure of a rock. However, due to the nature of these techniques the sample area examined is very small.

Larger specimens can be examined by mercury intrusion porosimetry. Here mercury is pumped into the sample under pressure, the volume of mercury pumped in at different pressures can be measured and a pore size versus pore volume curve produced. These techniques are quantitative however it can result in misleading data if the mercury intrusion process damages the sample or the ‘porosity’ is in the form of microfractures.

B.6.2 Chemical and mineralogical properties

B.6.2.1 Petrography
Examination of polished sections by reflective and thin section by polarised/non polarised transmitted light gives information on the mineralogical composition of the rock specimen.

B.6.2.2 Electron microprobe
This works on the same principle as SEM (section B.6.1.2) except to achieve quantitative elemental analysis polished samples and a high resolution X-ray detector are used.
B.6.2.3 X-Ray Diffraction (XRD)
The interaction of a monochromatised x-ray beam with a crystalline powder will produce a characteristic pattern. Such patterns are used for qualitative analysis, leading to the identification of the phase or compound. A mixture of crystalline solids can be analysed using this technique, however, there are problems with superimposition and background noise which normally leads to a detection limit of between 1-5 weight percent.

B.6.2.4 Fourier Transform Infra-red (FTIR) Spectroscopy
Chemical bonds absorb infrared radiation by stretching or bending of the bond. Every type of chemical bond has a distinct frequency range to its bending and stretching modes. The position of the absorption peak within the frequency range is dependent on the chemical environment. Normal IR spectroscopy is carried out in the transmittance mode on ground samples suspended in gel between potassium bromide/iodide disks. However, FTIR coupled with optical microscopy allows examination of the rock specimens’ surface in the reflective mode.

B.6.2.5 X-Ray Fluorescence (XRF)
Bombardment of a target with X-rays will expel an electron from an atom by the photoelectric process if the energy of the X-ray photon exceeds the binding energy of the electron. This produces a vacancy that can then be filled by outer-shell electrons resulting the emission of a characteristic X-ray. Detection of these characteristic X-rays leads to quantitative elemental analysis of the specimen. This process is the basis of the electron microprobe except electrons are the bombarding media. The probe is a surface technique whilst XRF is associated with bulk analysis. Not every ionisation will result in the emission of a characteristic X-ray. This process competes with another process in which the atom returns to its ground state by the emission of an electron known as the Auger electron. The probability of this type of event increases markedly as the atomic number decreases.

Auger electrons also have characteristic energies and give chemical as well as elemental information (B.6.2.6); the maximum energy is equal to the difference between the energy of the exciting X-rays and the binding energy.

B.6.2.6 Electron spectroscopy
This is the study of the energy distribution among the electrons ejected from a target material being irradiated by X-rays, ultraviolet radiation or electrons. The convention for distinguishing between electron spectroscopy methods is the mode of excitation. The two principal forms are X-ray Photoelectron Spectroscopy (XPS) and Ultra-violet Photoelectron Spectroscopy (UPS). A common notation is Electron Spectroscopy for Chemical Analysis (ESCA). ESCA is probably the most used technique for chemical studies due to its sensitivity to surface chemistry.

B.6.2.7 Neutron-gamma techniques
Neutron-gamma techniques involve the measurement of gamma rays that result from the interactions of neutrons with the material under analysis. Neutrons can interact by inelastic scattering from a nucleus, producing a nucleus in an excited state. Subsequent de-excitation results in the emission of characteristic gamma rays. The constraints of the method are that it only provides elemental data on a bulk sample but will provide information on low atomic number elements down to and including hydrogen.
B.6.3 Physical properties

B.6.3.1 Strength measurements
Strength measurements are important engineering properties and the mode of testing will depend on the final usage of stone. If the block is to be in compression the compressive strength is measured normally by crushing of a block and a failure load plus the stress-strain curve are measured. Flexural or bending strength is normally measured by three point loading. From the failure load a material dependent quantity, the Modules of Rupture (MOR) can be calculated by the use of the following equation:

\[
\text{MOR} = \frac{2Fl}{3bd^2}
\]

where:

\( F \) = failure load
\( l \) = length of specimen under the two top loading points
\( b \) = breadth of the specimen
\( d \) = depth of the specimen

Care should be taken to test sufficient samples (typically 20 or more) so that the sample is statistically representative.

B.6.3.2 Abrasion resistance
When stone is used as flooring or exposed to an environment with high wind speeds and particulate matter (e.g. deserts) abrasion of the surface will occur. Typical tests to quantify this effect look at the degree of material removed when the sample is subjected to abrasion with a metal disc or blasted with sand carried by a high-speed air jet.

B.6.3.3 Co-efficient of friction
An important safety aspect of flooring is that it should have sufficient grip or friction when it is being walked on. Various tests have been devised to quantify this property. The two most commonly used types are static tests, where a weight is moved across the surface (e.g. the tortoise test), and the dynamic test, where a rubber tipped pendulum swings across the surface of the stone.
B.7 ASSESSMENT OF DURABILITY

When considering how to test for durability, an approach must be selected. Currently, durability tests can be divided into four approaches:

1. benchmark tests
2. reference materials/comparative tests
3. environmental/stress testing
4. site testing

These approaches are not mutually exclusive in that tests have been or can be designed to incorporate one or more of these approaches.

B.7.1 ‘Benchmark’ tests

These are usually accelerated tests designed with a pass/fail criterion defined using historical data on a material’s performance within a certain environment. An example of this is the British Standard for roofing slate; a slate is subjected to three accelerated tests: water absorption, wetting/drying and acid immersion. If the slate passes all three, it is deemed to be durable in the United Kingdom environment. The American Society for Testing and Materials (ASTM) test method for slate carries this approach a step further by setting a series of levels for two accelerated test (see table B.7:1); these levels are then used for service-like prediction on the basis of historical knowledge of the material in use. Benchmark tests are relatively inexpensive and quick but are limited to a single material and climate.

Table B.7:1 Service-life prediction for slate using ASTM C 406

<table>
<thead>
<tr>
<th>Classification</th>
<th>Modulus of rupture across grain (MPa)</th>
<th>Water absorption (max, %)</th>
<th>Depth of softening (max, mm)</th>
<th>Service life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade S₁</td>
<td>62</td>
<td>0,25</td>
<td>0,05</td>
<td>&gt;75</td>
</tr>
<tr>
<td>Grade S₂</td>
<td>62</td>
<td>0,36</td>
<td>0,20</td>
<td>40-75</td>
</tr>
<tr>
<td>Grade S₃</td>
<td>62</td>
<td>0,45</td>
<td>0,36</td>
<td>20-40</td>
</tr>
</tbody>
</table>

B.7.2 Reference materials/comparative tests

The Building Research Establishment salt crystallisation test simulates the effects of salt change on limestone; reference materials are included in the test against which the unknown is assessed. The limestone are then placed into durability classes A to F (see table B.7:2); by experience the result is taken a stage further by defining the exposure zones of a building in which the stone can be safely used (see fig B.7:1).
Table B.7:2  Effect of environment on the suitability of limestone for the four exposure zones of a building

<table>
<thead>
<tr>
<th>Limestone durability class</th>
<th>Crystallisation loss (%)</th>
<th>Suitability zones for various limestone in a range of climatic conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inland</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low pollution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No Frost</td>
</tr>
<tr>
<td>A  &lt;1</td>
<td></td>
<td>1-4</td>
</tr>
<tr>
<td>B  1 to 5</td>
<td></td>
<td>2-4</td>
</tr>
<tr>
<td>C  &gt;5 to 10</td>
<td></td>
<td>3-4</td>
</tr>
<tr>
<td>D  &gt;15 to 35</td>
<td></td>
<td>3-4</td>
</tr>
<tr>
<td>E  &gt;35</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>F  Shatters early in test</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

\( a = \) The exposure zones are illustrated in fig B.7:1
\( b = \) Probably limited to 50 years' life

Comparative tests are likewise inexpensive and quick, with knowledge of the material, climate and in-service performance needed. Precision will be limited by the consistency of any equipment used and the reference standards.

Fig. B.7:1  Exposure zones of a building in which a stone can be used
B.7.3 Environmental and stress testing

These tests try to simulate/accelerate the service environment or stress the materials by intensifying the environmental factors it is susceptible to.

Climatic chambers such as VENUS attempt to accelerate all environmental conditions; rainfall, sunlight, pollutants, temperature etc. Simpler chambers can be used to look at the effects of wet/dry surfaces, pollutants and temperature on stone degradation.

These tests do not need reference materials but are slower and more expensive, requiring confirmation of the results with on-site measurements.

B.7.4 Site testing

The building’s can be monitored ‘in-situ’ or materials can be exposed to a range of environments. An example of large site testing project is the International Materials Exposure Programme (IMEP) which was set up to investigate the long-term impact of acid deposition on building and building materials (including stone). This programme provided a range of pollutant and meteorological climates.

Site testing is site specific with a high level of confidence but a meaningful range of environments should be selected.

B.8 REFERENCES

4. German Standard DIN 52100 (1986) Prüfung van Naturstein, Richtlinen zur Prüfung und Auswahl van Naturstein (Testing of natural stone; Guidelines to the testing and selection of natural stone), Deutsches Institut für Normung e.V. (DIN), Berlin
C  Masonry *(T. Yates and A. Lewry)*

C.1  INTRODUCTION TO MASONRY

Masonry is a composite material made from units and mortar joints; the units can be made from a variety of materials. The European Standards Committee CEN/TC125, which is responsible for masonry, has considered seven materials for units:

- clay
- AAC
- concrete
- gypsum
- natural stone
- artificial stone

This chapter will deal mainly with clay bricks and mortar; the majority of the other materials are covered in other chapters.

C.2  CLAY BRICK MANUFACTURE AND COMPOSITION

C.2.1  Brick manufacture

Bricks are ceramic components that are generally manufactured from claystones, shales or siltstone, moulded and then fired. Bricks are formed by three distinct methods [1]:

1. Soft mud method - soft mud are poured into moulds and dried before firing. This is not a commonly used practice in modern brickmaking.
2. Stiff mud method - plastic clay is extruded through a die and then the bricks are cut to size.
3. Semi-dry or dry press method - clay is pressed into a mould.

During the above ‘forming’ processes additives are commonly used to colour the brick or inhibit efflorescence.

Apart from the composition of the starting materials, the firing temperature, the kiln type and the time kept at the temperature are probably the most important factors in determining the nature and quality of the brick produced [2].

Three principal types of kiln are used:

1. Scone kiln — constructed of unfired bricks that are plastered on the exterior. The bricks are stacked so that a channel allows heat to travel by convection. This kiln type is not commonly used;
2. Periodic kiln — the shape may be beehive, rectangular or square. These kilns are dome-roofed with fire bases around the outside of the wall base;
3. Tunnel kiln - commonly used because they are efficient and fire uniformly resulting in a chapter, reproducible product.
The firing process generally controls the physical properties of bricks; differences of 50-100°C can radically alter properties. Firing is carried out by slowly raising the temperature and allowing volatiles to escape and oxidation to occur before raising the temperature further. Generally, water is removed by heating from 100-400°C that results in a material with a porosity of 30-40 vol. % [3]. This is followed by the removal of clay hydroxyl water and oxidation in the range 400°C to 800°C. Above 800°C to 1400°C sintering or densification occurs via chemical reactions, grain growth and development of a liquid phase. The porosity decreases as a result of sintering and leads to an increase in strength of the final product.

Generally, the ideal point to stop firing results in a brick that is ‘steel hard’ with a low-water absorption. Overfiring wastes energy and underfiring generally results in poor quality bricks.

C.2.2 Brick composition

Bricks are normally produced from raw materials consisting of at least 50% kaolins and clays that together with water give the necessary plasticity to the material when forming it to components.

The liquid phase, produced during firing, transforms to glass without crystallisation on cooling. The result in a brick is usually composed of a crystalline silicate phase, Mullite (3Al₂O₃.2SiO₂), the remaining quartz from the raw materials and some minor phases, which are all bonded together by a glassy matrix. The porosity of the brick could still be as high as 20% and the glassy phase could constitute 60% of the brick. This means that the brick is really a composite with the crystalline phases embedded in the glassy matrix whose typical composition is given in Table C.2:1.

Table C.2:1 The approximate composition of the glass in a ceramic such as brick [4]

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>71-77</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1-4</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>7-16</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1-5</td>
</tr>
<tr>
<td>MgO</td>
<td>0-2</td>
</tr>
<tr>
<td>CaO</td>
<td>0-1</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0-3</td>
</tr>
<tr>
<td>K₂O</td>
<td>4-8</td>
</tr>
</tbody>
</table>
C.3 MORTAR COMPOSITION AND MANUFACTURE

Mortar is a cementitious material made of a binding agent, such as Portland cement and/or hydrated lime, mixed with water and sand as filler. The sand is usually screened in order to avoid too coarse or fine particles.

Cement manufacturing processes can be wet (ground wet and fed to the kiln in a slurry), semi-dry (ground dry and moistened before feeding to the kiln) or dry (ground dry and added as a dry powder). The dry processes are more recent developments that consume less energy. Cement is highly alkaline, having a pH of 12-13. Cement powder is stored and distributed in either bulk or bag form.

Cement is derived from mixing limestone/chalk and clay or shale, together with other minor materials that impart different properties to the resulting product. There are four stages in the manufacture of cement:
1. Crushing and grinding the raw materials;
2. Blending the materials in the correct proportions;
3. Burning the prepared mix in a kiln to produce cement clinker, in the past, bottle or chamber, later continuous shaft kilns were used; modern works use rotary kilns, fired by coal, oil or gas;
4. Grinding the cement clinker together with about 5% gypsum/anhydrite in a ball mill to produce a fine powder; the gypsum can be used to control the setting time of the cement.

The constituents of different cements are as follows:

C.3.1 Portland cement

Ordinary Portland Cement (OPC) comprises approximately 60-67% lime, 19-25% silica and 3-8% alumina, with varying small amounts of iron oxide, sulphur trioxide, magnesia, titanium oxide and manganese oxide.

OPC in its unhydrated form consists mainly of four minerals:
1. Tricalcium silicate, 3CaO.SiO₂ (abbreviated to C₃S);
2. Dicalcium silicate, 2CaO.SiO₂ (C₂S);
3. Tricalcium aluminate, 3CaO.Al₂O₃ (C₃A);
4. Tetracalcium aluminate-ferrite, 4CaO.Al₂O₃.FeO₂.

Modified Portland cements include:
- Sulphate resistant  These contain less than 3% tricalcium aluminate
- Ultra-high early strength  Extra gypsum is added to the mix
- White  Obtained by careful selection of raw materials
- Coloured  5-10% pigment is added to the mix
- Air entrained  A plasticiser is added to improve frost resistance and workability
- Waterproofing  Small amounts of calcium and aluminium compounds are added to the mix in the final grinding stage
- Rapid Hardening  The OPC is finer
When mixed with water, cement undergoes a sequence of hydration reactions that slowly transform the cement paste to a hardened matrix of hydrated products. The most important hydration reactions are those involving C\textsubscript{3}S and C\textsubscript{2}S that leads to the formation of calcium silicate hydrate (C-S-H) gel and calcium hydroxide (Portlandite).

C.3.2 **High alumina cement**

A mixture of bauxite and lime containing the following:

- 35-40% lime
- 40-50% alumina
- up to 25% iron oxide
- no more than 5% silica.

C.3.3 **Slag cements**

- Portland blast-furnace slag cement A mixture of Portland cement and 50-90% blast-furnace slag
- Supersulphated blast-furnace slag A mixture of blast-furnace slag, calcium sulphate and a small amount of Portland cement
- Portland pulverised fuel ash cement A mixture of Portland cement and pulverised fuel ash (PFA).

C.3.4 **Lime mortar**

Lime is produced by burning crushed, high purity limestone/chalk (96-98% calcium carbonate) in kilns, at temperatures of between 800°C and 1500°C. At these temperatures carbon dioxide gas is liberated and the oxide is produced. The lime is cooled, stored and used as the burnt lime (quick lime), or mixed with water and used as the hydrated lime (slaked lime).

Although the native of mortar has changed considerably over time, modern masonry mortar is usually a mixture of ordinary Portland cement (OPC), sand, lime and additives (for example plasticizers or air-entrapment agents).

C.4 **PHYSICAL PROPERTIES**

The physical properties of brick and mortar vary widely, however, they can still be described by those laid out in the stone chapter (B.2) — aggregation, thermal and mechanical.

Brick properties will depend on the firing temperature composition of the raw materials, forming methods and the firing conditions. Firing of a brick does not alter the pore size distribution but will lower total porosity, thus increasing final strength. However, insufficient
firing will result in a differential pore structure i.e. the surface has a much lower porosity than the interior. The raw materials control the pore size distribution of the final product; clay have small pores but the addition of sand and crushed brick shifts the distribution towards larger pore sizes. Forming processes such as hand moulded and pressing led to bricks with large pore sizes whilst extrusion produces a product with small pore sizes. Although porosity is important other factors such as water permeability and mechanical strength must be taken in account.

Mortars have two distinct, important sets of properties, which are those of fresh mortars and of hardened mortars. Mortar serves to cushion the units of masonry, giving them full mutually bearing, in spite of their surface irregularities. Furthermore, the mortar seals the space between the units and/or the wall surface, preventing water, damp and wind from penetrating. Therefore not only the properties of hardened mortar, but also those of fresh mortar relate to the properties of masonry. The physical properties of a hardened mortar, determining the structural performance, will be dependent on the composition of the mix and the setting conditions. These properties include bond strength, compressive strength, elasticity, permeability and durability. Types of masonry mortars, classified according to compressive strength, are given in table C.4:1 [5].

Table C.4:1 Types of mortar

<table>
<thead>
<tr>
<th>Mortar type</th>
<th>Construction stability</th>
<th>Typical average compressive strength (MN/m²) at 28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-strength mortar</td>
<td>Masonry subjected to high lateral or compressive loads, or severe frost action; masonry below ground</td>
<td>17,3</td>
</tr>
<tr>
<td>Medium high-strength mortar</td>
<td>Masonry requiring high flexural bond strength, but subjected only to normal compressive loads</td>
<td>12,4</td>
</tr>
<tr>
<td>Medium strength mortar</td>
<td>General use above ground</td>
<td>5,2</td>
</tr>
<tr>
<td>Medium low-strength mortar</td>
<td>Non-loadbearing interior walls and partitions</td>
<td>2,4</td>
</tr>
</tbody>
</table>

The physical properties of a masonry wall depend on both the mortar and the masonry units, as well as on the compatibility between the two. The relatively small part of mortar in masonry significantly influences the total performance. Compressive strength of mortar increases with increasing cement content and decreases with increasing lime, sand, water and air content. It is useless, however, to use a very strong mortar the masonry units themselves are weak. Although compressive strength is a prime consideration in concrete, it is only one of several important factors in mortar. Since strong mortars often leads to shrinkage cracking, suitable selection of the type of mortar needs to be done for satisfying a variety of diverse requirements.

Adding epoxies or latexes to the mix can create mortars with exceptionally high strengths and adhesive qualities.
C.5 CHEMICAL PROPERTIES

C.5.1 Brick

The brick’s glassy matrix is similar to acidic silicate glasses and as a result is probably the most susceptible component to dissolution by neutral, acid or alkaline solutions. Water will leach alkali ions from the surface resulting in an alkali-ion depleted layer, which can subsequently be removed by dissolution. Bricks can contain N2SO4 if the fuels during firing are sulphur rich or the temperature is insufficient to decompose the salt.

C.5.2 Mortar

Non-hydraulic lime mortar depends on exposure to air to harden:

\[
\text{Ca(OH)}_2 \text{(s)} + \text{CO}_2 \text{(g)} \rightarrow \text{CaCO}_3 \text{(s)} + \text{H}_2\text{O (l)}
\]

On hardening, carbonation and drying occur simultaneously resulting in a volume contraction. In the case of dolomitic mortars magnesium phases are also present.

Hydraulic mortars contain Portland cement whose main constituents are Portlandite (Ca(OH)2) and calcium silicate hydrate (C-S-H). Naturally acidic rainfall will leach CaCO3 from the surface, however, while being detrimental to any steel reinforcement due, carbonation has been observed to double the strength of OPC mortars and only usually changes the appearance, i.e. staining and efflorescence.

Accelerated carbonation tests were carried out on mortars [6]. OPC was mixed with river sand whose fineness modulus was 3,01. Two types of mortars were produced, whose sets of water-cement ratio and sand cement ratio were 0,6 and 3,22, and 0,7 and 3,75, respectively. Flow of both mortars was about 205 mm. Fig C.5:1 shows results of the accelerated carbonation test, which was performed in the following condition: temperature 30°C; relative humidity 50 %; and CO2 gas concentration 10 %.
Fig. C.5:1 Accelerated carbonation test results

Solid lines in fig C.5:1 were drawn for different specimens using

\[ d = a \sqrt{t} \]

where \( d \) is the depth of carbonation, \( a \) is a constant and \( t \) is the exposure time (days). Fig C.5:2 shows that the carbonation depth after exposure in the test environment for about 50 days is influenced mostly by coarse pores larger than 75 nm.

Fig C.5:2 Relation between total pore volume larger than 75 nm and the depth of carbonation after 50 days exposure [6]

When considering brick masonry as a whole it has been shown that the relative porosity of the brick to the mortar is important, with the most porous material being the site of salt-induced attack.
Mortars contain Portlandite that can react with sulphur dioxide to form gypsum. The resulting result could further degrade the mortar by reacting with calcium aluminate (C₃A) to produce ettringite (3CaO.Al₂O₃.3CaSO₄.31H₂O). Gypsum and ettringite formation are both expansive reactions and can result in cracking.

C.5.3 Incompatibility

The porosity of the brick is also important when considering the setting of the mortar. If the brick contains large pore sizes, the suction effect is fairly low and has been shown to produce a stronger mortar/brick bond. However, this also produces a mortar with a lower strength that is less frost resistant. This situation will also depend on other factors, for example the water saturation level of the brick, the possibility of water retaining additives in the mortar, etc.

C.6 TYPICAL MICRO ENVIRONMENT AND LOADS

The micro environment and loads affecting mortar are movement of water, including moisture, and tensile stress due to shrinkage. Rain penetration is likely to occur mainly through shrinkage cracks rather than directly through masonry units or the mortar itself. Rain and melting snow penetrate the surface, and the mortar is subjected to freeze/thaw cycles during winter in cold regions. Some shrinkage of mortar is inevitable; the amount depends to some extent on the width of mortar joints and the mixture of mortar.

Mechanical loads are of compression under the weight of subsequent courses of masonry, and of shear and tension under wind and seismic actions. Differential settlements of foundations also cause shear stress in the mortar.

Porosity and permeability are the most important properties when considering the accessibility of water to the interior of the brick. It has been shown that the pore size distribution has a critical pore size, in the range of 1-3 µm. In general large pores and low porosity result in a durable product.

C.7 FORMS OF DEGRADATION AND FAILURE MODES OF BRICK MASONRY

C.7.1 Physical failure

The most typical degradation and failure mode of mortar is cracking. Drying shrinkage and moisture movement are the main sources of cracking, besides mechanical loads.

In larger elements, such as load bearing walls, which are restrained from movement, the type of failure is usually attributed to cracking of the mortar. Because of tensile induced stress due to shrinkage, cracking tends to be in the vertical direction. In walls built with small masonry units, the cracking may take place along vertical and horizontal joints, thus forming a step pattern.

Degradation of mortar due to frost action is mainly associated with fine cracks. However,
these cracks normally are of less significance in comparison to cracks that may result from
thermal and moisture movement. The use of finely graded sands in the mortar mix has been
shown to increase strength and frost resistance. Differential pore structures, between the
surface and interior, can cause spalling in brick due to prevention of water migration by the
lower porosity surface.

C.7.2 Chemical weathering

Water-soluble salts, derived from the atmosphere or the materials themselves (e.g. Na$_2$SO$_4$ from
brick), will degrade brickwork; the result is spalling of the surface.

Acids will attack the glassy matrix of brick and it has been estimated that weathering due to
pollutants in industrial area will increase the dissolution of brick 10-fold. However, the
maximum dissolution of brick is approximately 1%.

C.8 CHARACTERISATION OF BRICK MASONRY

In general bricks can be characterised, after production, using the techniques used in the stone
chapter (B.6). However, mortar is an in-situ material and therefore mixes with known properties
have to be prepared or in-situ testing has to be done on the setting material before application.

The most typical degradation monitoring method for mortar may be to observe the cracking
properties, i.e. pattern, density and width distribution. From the cracking pattern the reason
for the degradation can be judged. Information on crack density and width distribution may
help to estimate the service life and suggest repair methods.

While the traditionally method to observe cracking by eye and sketching is still used,
advanced systems have been developed in which crack properties recorded with camera are
assessed using an image analyser.

C.9 REFERENCES

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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 aluminosilicates. 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. Montmorillonites 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 [SiO₄] 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 \( \text{Al}_2[\text{Si}_2\text{O}_5(\text{OH})_4] \). 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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lean</th>
<th>Medium fat</th>
<th>Fat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay content</td>
<td>low</td>
<td>middle</td>
<td>high</td>
</tr>
<tr>
<td>Uptake of water</td>
<td>high</td>
<td>middle</td>
<td>low</td>
</tr>
<tr>
<td>Swelling up/shrinkage</td>
<td>weak</td>
<td>middle</td>
<td>high</td>
</tr>
<tr>
<td>Tenacity</td>
<td>low</td>
<td>middle</td>
<td>high</td>
</tr>
</tbody>
</table>

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.
The different states of tenacious soils, referring to the consistency, are divided according to

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
Part III - Building Materials and Components: characterisation of degradation

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/mm². Load bearing clay building units should always be tested for their compressive strength. It should be at minimum 2 N/mm².

Closely connected to the strength parameters is the modulus of elasticity, in the range 6000 to 7000 N/mm².

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 $\rho_{Pr}$. This is estimated for:

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

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 $\rho_{Pr}$.

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\(^{\frac{1}{2}}\)] 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\(^{\frac{1}{2}}\) have been found [6]. The capillary water capacity \( \Phi_k \) 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\(^{\frac{1}{2}}\), 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.
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#### D.4.6 Water vapour diffusion

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

The relative water vapour resistivity $\mu$ represents the capability of a building material to hinder diffusion of air humidity. The $\mu$-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

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**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]
example, for heavyweight clay with the wet cup method the $\mu$ values vary between 6 to 8, whereas with the dry cup method the $\mu$ values are higher, varying between 15 to 23.

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk density [kg/m³]</th>
<th>$\mu$- mean at 20°C / 60% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-weight clay</td>
<td>2000</td>
<td>10 - 11</td>
</tr>
<tr>
<td>Light-weight clay</td>
<td>1200</td>
<td>8 - 10</td>
</tr>
<tr>
<td>&quot;</td>
<td>900</td>
<td>6 - 8</td>
</tr>
<tr>
<td>&quot;</td>
<td>600</td>
<td>5 - 6</td>
</tr>
<tr>
<td>&quot;</td>
<td>300</td>
<td>4 - 5</td>
</tr>
<tr>
<td>Brick</td>
<td>1100</td>
<td>4 - 6</td>
</tr>
<tr>
<td>Lime sandstone</td>
<td>1600</td>
<td>10 - 25</td>
</tr>
<tr>
<td>Gas concrete stones</td>
<td>400</td>
<td>3 - 5</td>
</tr>
<tr>
<td>Wood (spruce, fir)</td>
<td>450 - 500</td>
<td>20 - 40</td>
</tr>
<tr>
<td>Wood wool building slabs</td>
<td>350 - 500</td>
<td>2 - 5</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk density [kg/m³]</th>
<th>$\mu$- mean at 20°C / 60% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-weight clay, fat</td>
<td>2050</td>
<td>23,0</td>
</tr>
<tr>
<td>&quot;</td>
<td>1960</td>
<td>19,5</td>
</tr>
<tr>
<td>Heavy-weight clay, silty</td>
<td>1980</td>
<td>15,5</td>
</tr>
<tr>
<td>&quot;</td>
<td>1890</td>
<td>15,1</td>
</tr>
<tr>
<td>Heavy-weight clay, sandy</td>
<td>2060</td>
<td>22,5</td>
</tr>
<tr>
<td>&quot;</td>
<td>1880</td>
<td>18,2</td>
</tr>
<tr>
<td>Expanded clay, light-weight clay</td>
<td>650</td>
<td>6,8</td>
</tr>
<tr>
<td>&quot;</td>
<td>800</td>
<td>8,1</td>
</tr>
<tr>
<td>Straw, light-weight clay</td>
<td>450</td>
<td>2,2</td>
</tr>
<tr>
<td>&quot;</td>
<td>950</td>
<td>3,1</td>
</tr>
<tr>
<td>&quot;</td>
<td>1250</td>
<td>4,4</td>
</tr>
<tr>
<td>Clay plaster, silty</td>
<td>9,8</td>
<td></td>
</tr>
<tr>
<td>Clay plaster, fat</td>
<td>8,0</td>
<td></td>
</tr>
</tbody>
</table>

dry cup method

wet cup method

CIB W080 / RILEM 175-SLM

3-41
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.

![Equilibrium humidity of heavy-weight clays](image)

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.
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]

<table>
<thead>
<tr>
<th>Clay</th>
<th>Dry measure of shrinkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lean</td>
<td>&lt; 2%</td>
</tr>
<tr>
<td>Medium fat</td>
<td>2 - 4%</td>
</tr>
<tr>
<td>Fat</td>
<td>4 - 6%</td>
</tr>
</tbody>
</table>

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]

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk density [kg/m³]</th>
<th>Drying time [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50%</td>
</tr>
<tr>
<td>Clay stone</td>
<td>1900</td>
<td>3</td>
</tr>
<tr>
<td>Clay stone silty</td>
<td>1950</td>
<td>5</td>
</tr>
<tr>
<td>Straw light-weight clay</td>
<td>1200</td>
<td>4</td>
</tr>
<tr>
<td>Straw light-weight clay</td>
<td>550</td>
<td>2</td>
</tr>
<tr>
<td>Straw light-weight clay</td>
<td>450</td>
<td>3</td>
</tr>
<tr>
<td>Expanded clay, light-weight clay</td>
<td>750</td>
<td>4</td>
</tr>
<tr>
<td>Expanded clay, light-weight clay</td>
<td>700</td>
<td>3</td>
</tr>
<tr>
<td>Brick</td>
<td>1850</td>
<td>13</td>
</tr>
<tr>
<td>Vertical coring brick</td>
<td>1200</td>
<td>14</td>
</tr>
<tr>
<td>Lime-sand brick</td>
<td>1800</td>
<td>5</td>
</tr>
<tr>
<td>Aerated concrete Hebel</td>
<td>600</td>
<td>2</td>
</tr>
<tr>
<td>Aerated concrete Ytong</td>
<td>450</td>
<td>4</td>
</tr>
<tr>
<td>Normal concrete B25</td>
<td>2200</td>
<td>7</td>
</tr>
</tbody>
</table>
D.4.9 Heat conductivity and heat capacity

The heat conductivity $\lambda$ and the heat capacity $c$ are dependent on the dry-density $\rho$. 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 $\lambda$-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]

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ [kg/m$^3$]</th>
<th>$\lambda$ [W/mK]</th>
<th>$c$ [kJ/kgK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-weight clay</td>
<td>2000</td>
<td>0.95</td>
<td>1.0</td>
</tr>
<tr>
<td>Light-weight clay</td>
<td>1200</td>
<td>0.47</td>
<td>1.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>900</td>
<td>0.26</td>
<td>1.1</td>
</tr>
<tr>
<td>&quot;</td>
<td>600</td>
<td>0.15</td>
<td>1.2</td>
</tr>
<tr>
<td>&quot;</td>
<td>300</td>
<td>0.09</td>
<td>1.3</td>
</tr>
<tr>
<td>Brick</td>
<td>1100</td>
<td>0.37</td>
<td>0.9</td>
</tr>
<tr>
<td>Insulating brick</td>
<td>1200</td>
<td>0.47</td>
<td>0.9</td>
</tr>
<tr>
<td>Lime-sand brick</td>
<td>1600</td>
<td>0.80</td>
<td>0.9</td>
</tr>
<tr>
<td>Gas-concrete stone</td>
<td>600</td>
<td>0.18</td>
<td>1.1</td>
</tr>
<tr>
<td>Wood (spruce, fir)</td>
<td>450-500</td>
<td>0.14</td>
<td>2.0-2.4</td>
</tr>
<tr>
<td>Wood-wool board</td>
<td>350-500</td>
<td>0.09</td>
<td>1.6</td>
</tr>
</tbody>
</table>

$\rho$ — bulk density, $\lambda$ — 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

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal expansion [mm/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-weight clay</td>
<td>0.0043 - 0.0052</td>
</tr>
<tr>
<td>Clay masonry</td>
<td>0.0062</td>
</tr>
<tr>
<td>Lean clay mortar</td>
<td>0.007</td>
</tr>
<tr>
<td>Lime mortar</td>
<td>0.005</td>
</tr>
<tr>
<td>Cement mortar</td>
<td>0.01</td>
</tr>
<tr>
<td>Concrete, gas concrete</td>
<td>0.01</td>
</tr>
<tr>
<td>Lime-sand stone</td>
<td>0.007</td>
</tr>
<tr>
<td>Resin plaster</td>
<td>0.13 - 0.3</td>
</tr>
</tbody>
</table>
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/m³. 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/m³ 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 \( \text{N/mm}^2 \).

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 moisturerised
- Preparation of cubes of 20×20×20 cm\(^3\) of the specific mixture for testing (see below)
- Minimum compressive strength 2 \( \text{N/mm}^2 \); 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-slippping
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/m³ is not recommended for construction technique reasons
- Compressive strength, not less than 0,5 N/mm², 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 Fe₂O₃ 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 lightweight 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]

<table>
<thead>
<tr>
<th>Coating</th>
<th>Amount used [g/m²]</th>
<th>$w$-value [kg/m²h$^{1/2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0</td>
<td>9,5</td>
</tr>
<tr>
<td>Boiled linseed oil</td>
<td>400</td>
<td>0,0</td>
</tr>
<tr>
<td>Lime-casein 1:1</td>
<td>420/350</td>
<td>0,6/1,5</td>
</tr>
<tr>
<td>Lime-casein 1:8</td>
<td>300/300</td>
<td>0,7</td>
</tr>
<tr>
<td>Silin-paint (van Baerle)</td>
<td>700/250/310</td>
<td>0,3</td>
</tr>
<tr>
<td>Hydrophobic (Herbol)</td>
<td>390/390</td>
<td>0,0</td>
</tr>
<tr>
<td>Baysoline LD (Bayer)</td>
<td>400/290</td>
<td>0,2</td>
</tr>
<tr>
<td>Syltrit (Metropark)</td>
<td>350/320</td>
<td>0,0</td>
</tr>
<tr>
<td>BS 15 (Wacker)</td>
<td>450/430</td>
<td>0,1</td>
</tr>
<tr>
<td>Steinfestiger H (Wacker)</td>
<td>290/290</td>
<td>0,0</td>
</tr>
</tbody>
</table>

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 $\mu$ (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]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency/slump</td>
<td>$17 \pm 0,5 \text{ cm}$</td>
</tr>
<tr>
<td>Water binding ability</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>Bonding strength $\beta_{HZ}$</td>
<td>$\geq 0,05 \text{ N/mm}^2$</td>
</tr>
<tr>
<td>Relative water vapour resistivity $\mu$</td>
<td>$\leq 12$</td>
</tr>
<tr>
<td>Uptake of water coefficient $w$</td>
<td>$\leq 0,5 \text{ kg/m}^2\text{h}^{1/2}$</td>
</tr>
<tr>
<td>Compressive strength $\beta_D$</td>
<td>3 - 5 N/mm$^2$</td>
</tr>
<tr>
<td>Tensile bending strength $\beta_{BZ}$</td>
<td>1 - 1,5 N/mm$^2$</td>
</tr>
<tr>
<td>Tensile strength $\beta_Z$</td>
<td>$\geq 0,5 \text{ N/mm}^2$ resp. according to the E-modulus</td>
</tr>
<tr>
<td>Modulus of elasticity $E_{dyn}$</td>
<td>$\leq 8000 \text{ N/mm}^2$</td>
</tr>
<tr>
<td>Shrinkage $\varepsilon_s$</td>
<td>$\leq 0,3 \text{ mm/m}$</td>
</tr>
<tr>
<td>Density</td>
<td>$\leq 2,0 \text{ g/cm}^3$</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Lime powder</th>
<th>Trass</th>
<th>Screed sand</th>
<th>Skimmed cottage cheese</th>
<th>Boiled linseed oil</th>
<th>Fat clay</th>
<th>Cow dung</th>
<th>$\mu$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>0,5</td>
<td>3</td>
<td>11,2</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>0,5</td>
<td>15</td>
<td>10,8</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>3</td>
<td>0,5</td>
<td>0,5</td>
<td>3</td>
<td>15,2</td>
<td>6.2</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0,25</td>
<td>0,05</td>
<td>2</td>
<td>6</td>
<td>28,5</td>
<td>9,7</td>
</tr>
<tr>
<td>1,5</td>
<td>10</td>
<td>3</td>
<td>0,05</td>
<td>2</td>
<td>6</td>
<td>8,0</td>
<td></td>
</tr>
</tbody>
</table>

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.

D.10 REFERENCES

7. DIN 52615 (1987), Bestimmung der Wasserdampfdurchlässigkeit von Bau- und Dämmstoffen


**Other literature not referred to explicitly**

  Blatt 4: Gewellerte Lehmwände, pp. 1.
  Blatt 5: Leichtelehmwände in Gerippebauten, pp. 1-2.
E. Wood (K. Ödeen)

E.1 PHYSICAL PROPERTIES

E.1.1 Main parts of the wood log

In a cut of a wood log a number of main areas can be identified as shown in fig E.1:1. Inside the bark is the cambium layer where the main growth takes place. The rest of the cross section contains the sapwood and the central heartwood. In the very centre is the pith and sometimes the so called juvenile wood.

Fig E.1:1 Cross section and main parts of a log

The border between sapwood and heartwood can be clearly seen in some species, e.g. Scotch pine, whereas it can hardly be visually identified in others, e.g. Norwegian spruce. The sapwood contains both living and dead cells, and serves as nutrient store and for fluid transport. The heartwood contains only dead cells and a lot of extractives and resins that decrease the moisture absorption. This in turn influences many important properties, e.g. moisture deformations and durability. In the figure can also be seen the pith radius through which nutrient is transported in the radial direction.
E.1.2 Sawn timber

After felling, the tree is cut into logs of suitable lengths and transported to a saw mill where it is further fragmented. This process can be made according to different principles. A typical cutting pattern is shown in fig E.1:2.

![Cutting pattern](image)

E.1.3 Drying

The sawn timber has high moisture content and must be dried before further use. The drying is a very crucial process and there is a high risk of damages of various types, such as cracks and deformations. Mostly timber is dried in industrial processes under controlled conditions. A typical drying program for conifer wood (pine or spruce) takes 3 to 6 days depending on dimensions. Drying of hardwood takes longer time. After drying, the wood is conditioned under rain cover outdoor or in special chambers, allowing the moisture content to be equalised and the stresses relaxed. This part of the process takes 2 to 3 days.

E.1.4 The wood structure

The wood structure varies significantly between wood species. In particular there are large differences between softwood and hardwood.

E.1.4.1 Cell types

The following description refers to conifer wood. Softwood has a slightly different cell structure.

E.1.4.1.1 Tracheids

Tracheids are dead cells and they form about 95% of the wood volume. They are shaped as long tubes with closed ends. The length is 3-5 mm and the thickness 25-45 mm. The strength of the wood is basically constituted by the tracheids, which also are responsible for the water transport in the tree.
E.1.4.1.2 Parenchyma cells

The living cells in the wood are called parenchyma cells. They contain nutrient agents and form 1-2% of the total volume. They are shorter and have thinner walls than the tracheids.

E.1.4.1.3 Resin ducts

The resin ducts are inter-cellular spaces surrounded by specialised parenchyma cells (epithelial cells) producing resin.

E.1.4.1.4 Rays

The radial transport of water and nutritious substances goes from the periphery into the pith via the rays. They are formed by both tracheids and parenchyma cells and may also contain resin ducts. The cavities in the different cells are called lumen. An overview of the cell types is given in fig E.1:3.

Fig E.1:3 Cell types in softwood: a) pine, earlywood; b) pine, latewood; c) Norwegian spruce, earlywood; d) and e) ray tracheids, spruce and pine, respectively; and f) and g) parenchyma cells, spruce and pine, respectively [2]

E.1.4.2 Pit system

The wood contains pits of different types. The two main types are simple pits and bordered pits. Simple pits basically exist between parenchyma cells. They are covered by a partly permeable membrane, formed by the middle lamella between the cells.

The bordered pits connect the tracheids and are a lot more complicated, both structural and regarding their function. They are covered by a membrane containing a central, non-permeable part (torus) attached to the surrounding cell wall with an open, fibrous structure (margo). There are also combinations of the two basic pit types (half-bordered pits).

An overview of the pit types is given in fig E.1:4. In the status shown in the figure, the
bordered pits are permeable (via margo) and water can be transported between the pits without obstruction. When the wood is drying the capillary water meniscus will draw the torus towards the pit wall and the pit is closed. In this position the torus is fixed by chemical bonds, which makes the process irreversible. The mechanism is called aspiration. One effect is that dried wood has other permeability properties than green wood. However, all bordered pits do not aspire and there are large variations between species. For example, in sapwood of *pinus sylvestris* a large amount of the bordered pits are not aspired, whereas in *picea abies* they are. A practical effect of this is that it is a lot more difficult to impregnate the latter wood specie.

![Profile of various types of pit pairs](image)

**Fig E.1.4** Pit types

**E.1.5 Wood properties**

**E.1.5.1 Density and porosity**

The gross density of the wood can be expressed in different ways. As both mass and volume depends on the moisture content, this must be mentioned together with the density. A common method is to give the density at a moisture content of 12% by dry weight. The gross density of Scandinavian species of softwood varies within a wide range both between trees and within a single tree. Approximate values are 400-500 kg/m³ for *pinus sylvestris* and 370-440 kg/m³ for *picea abies*.

The compact density for all wood species is approximately 1500 kg/m³. The density and its variation has large impact on most properties relevant to, for example, the end-use. These are:
- strength
- modulus of elasticity
- moisture deformations
- cracking
- surface treatability
- impregnatability
E.1.5.2  Moisture properties

Wood is a highly hygroscopic material and most essential properties vary strongly with the moisture content. Water may be bound in the cell walls, or appears as free water in the cell cavities or as water vapour.

The moisture content is usually expressed relative the dry weight of the wood – the moisture ratio. It can be determined directly by weighing and drying at 103-105°C or by some indirect method. A well established method of this type is to measure the moisture dependent electrical resistance between two nails driven into the wood.

The properties of wood are mainly influenced by the water bound in the cell walls up to the so called fibre saturation point. For Scandinavian softwood this is in the region of 25-30%.

E.1.5.2.1  Moisture fixation

The relation between surrounding climate and moisture ratio at equilibrium is given by sorption isotherms. A typical example is shown in fig E.1:5. The curves have been determined at 20°C. The influence of the temperature may be significant.

![Sorption curves for wood](image)

Fig E.1:5  Sorption curves for wood [3]

E.1.5.2.2  Moisture transport

The moisture is transported in wood both as liquid and as vapour (diffusion). The capillary transport in liquid phase takes place in the cell cavities (lumen) and through the pits, whereas the diffusion also penetrates the cell walls. The diffusion is a much slower process than the capillary transport. It takes about one week for a 25 mm thick panel to reach equilibrium with
the surrounding climate. The dependence on thickness is approximately quadratic so the corresponding time for a 50 mm thick panel is one month.

The rate of capillary transport in the longitudinal direction is 10-20 times higher than in the transverse direction. Therefore, it is very important that the ends of wood panels or other components are protected from contact with liquid water by constructive measures or by suitable treatment.

The moisture transport by diffusion can be characterised by the moisture diffusivity. It is strongly dependent on the moisture content.

E.1.5.2.3 Moisture induced deformations

Above fibre saturation, hardly no deformations occur when the moisture content is changed. However, below fibre saturation the wood swells and shrinks when the moisture content is varied. The deformations are highly different in different directions. For Scandinavian softwood the following deformations values for fibre saturated wood relative completely dried wood are typical:

<table>
<thead>
<tr>
<th>Direction</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangential</td>
<td>8,0</td>
</tr>
<tr>
<td>Radial</td>
<td>4,0</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>0,3</td>
</tr>
<tr>
<td>Volume</td>
<td>12,0</td>
</tr>
</tbody>
</table>

The difference between the tangential and radial deformations causes a panel to deform according to fig E.1:6 when its moisture ratio is changed.

Fig E.1:6 Deformation of a panel during drying [1]
E.1.5.3 **Strength and elasticity**

As wood is a highly anisotropic material, its strength and deformation properties vary significantly in different directions. They are also influenced by test conditions, e.g. temperature, moisture and rate of load application.

E.1.5.3.1 **Stress – deformation curves**

Typical stress – deformation curves for wood loaded parallel to the grains are shown in fig E.1:7. It can be seen that the tension strength is roughly twice the strength at compression. At tension the curve is nearly linear up to failure. At compression the curve shows a horizontal part, where the deformation increases at constant stress. The reason is that the shear strength is reached and there are formed two distinct parts and an inclined "slip surface" will develop, see fig E.1:8.

![Stress - deformation curves for wood](image1)

![Detail of compression failure in wood](image2)

The strength varies strongly with the angle between the grain direction and load, the strength perpendicular to the grains being only about 10% of the strength parallel to the grains. In fig E.1:9 is shown typical curves for the strength of *pinus sylvestris* at different loading modes as well as the influence of moisture ratio. It can be seen from the figure that the strength decreases with increasing moisture ratio up to fibre saturation and then remains constant.
Fig E.1: Influence of the moisture ratio and load direction on the strength of wood [4]

- a = compression // grains
- b = compression ⊥ grains
- c = tension // grains
- d = bending ⊥ grains
- e = shear // grains
E.1.5.3.2  Modulus of elasticity (Young’s modulus)

The slope of the linear parts of the stress – deformation curves is approximately the same for tension and compression that means that the modulii of elasticity are the same. For Scandinavian softwood it is in the region 11-12 GPa parallel to the grains and 4.5-5.5 GPa at perpendicular loading. It should be underlined that characteristic values of strength and elasticity taking the statistical variations into account may be significantly lower than indicated above.

E.1.5.4  Rheology (creep)

The creep deformations of wood must generally be taken into account. The visco-elastic behaviour is important both for load-bearing structures and for the development of deformations and cracks when the moisture content is changed. The creep number (creep deformation vs. short time elastic deformation) after one year is of the order of magnitude of 1 -1.5 parallel to the grains and at constant moisture content. The creep deformations increase with increasing moisture content. In special the increase is dramatic when the moisture content is changed during the loading. One example of this is shown in fig E.1:10. The lower curve is determined on test specimens at constant moisture conditions, whereas the upper curves holds for test specimens where the moisture has been changed cyclically. It can be seen that the deformations in the latter cases are much higher than when the moisture is constant. The phenomenon is explained by so-called mechano-sorption.

Fig E.1:10  Creep deformations of wood at different moisture ratios [5]
E.1.6 Internal factors of inherent solid wood properties

Wood is generally considered to be more resistant to deterioration by micro-organisms than most other plant tissue. The natural resistance of wood to the biological agents is due to the presence of toxic substances in the wood. Other reasons include that the woody cell wall consists of highly complex, insoluble polymers of high molecular weight. These substances must be depolymerised by enzymes, produced by the attacking organisms, into simpler products that can be assimilated by them. The action of depolymerising enzymes is restricted mainly to the non-crystalline region of the cellulose. As the cellulose in wood is more crystalline than that of most other plant tissues, it provides greater resistance to fungal and bacterial degradation. Higher moisture ratio is required to initiate deterioration in wood than in other plant tissues. For instance, in cotton fibres, 10 percent is adequate to initiate degradation by micro-organisms, while nearly no decay can be initiated in wood below the fibre saturation point, i.e. 26 to 30 percent [6].

Besides the above mentioned characteristics with wood, many other inherent wood properties have a close correlation with the durability of the material. Some of the important properties are density, uniformity of growth rings, fibre length, percent of clear bole, straightness of grain, proportion of heartwood, percentage of vessels (in hardwoods), extractives, chemical composition, and presence of juvenile and reaction woods, etc.

E.1.7 Factors associated with wood growth characteristics

E.1.7.1 Density

Many heavy woods are highly durable. This fact may suggest that the wood density is often used as a criterion of decay resistance. That this does not necessarily prevail all the time is indicated by the fact that a number of light woods are among the most durable woods. On the other hand, the heartwood of the relatively heavy woods, such as beech, oak, and maple, is among the least decay-resistant woods. This is because there is no significant difference in the decay resistance of the extractive-free wood substance, irrespective of the species. The superior durability of some woods, including those of light density, is traceable directly to the presence of toxic ingredients in sufficient quantities to inhibit deterioration. Unless the higher durability is correlated with the greater accumulation of toxic substances, there is no convincing and conclusive evidence that variations in density within species or a given tree have much effect on wood durability.

Although wood density has no direct relationship with wood durability, in practice density of wood is still used as one of prime determinants of wood quality (or durability). This is understandably dependent upon the fact that the more dense a timber is, the more substance there is present to be decayed, and for this reason it may endure longer than a more porous one.

Forest growth rate can significantly affect density. This is particularly true for ring- and semi-ring porous hardwoods that tend to show increased density and hardness with increased growth rate. It is commonly believed that softwoods decrease in density with an increase in growth rate despite some studies published reject this notion [7,8]. For hardwoods, regardless of growth rate, the width of the earlywood portion of the ring tends to remain relatively constant.
E.1.7.2  Sapwood and heartwood
The sapwood of nearly all wood species is readily decayed by fungi, and it is only the heartwood of the durable species that is resistant to decay. The susceptibility of sapwood to deterioration by biological agents, besides the fact that it lacks extractives in sufficient quantity or toxicity to inhibit the growth of micro-organisms, is also dependent on that the presence of reserve foods in the parenchyma cells of sapwood may increase its susceptibility to decay, and particularly to bacteria and staining fungi.

The greater durability of heartwood, in comparison with sapwood of the same species, is attributable largely to the presence in the former of a wide variety of toxic extractives such as essential oils, tannins, and phenolic substances. When these are present in sufficient amounts, they prevent or at least considerably minimise the severity of the attack by destructive organisms. This resistance ability of heartwood attributed to the presence of extractives toxic to decay fungi, is often referred as the natural durability of wood. The effect of natural durability on prolonging the service life of wood materials has been demonstrated unequivocally.

Other factors that may explain the greater durability of heartwood includes its lower moisture content, its lower diffusivity, and the blocking of cell cavities by gums, resins and tyloses in the vessels, and tylosoids in the resin canals. Any of these might conceivably and adversely affect the balance between air and water necessary for the growth of fungi.

It is very clear that as the heartwood is more durable, the proportion of heartwood being important where wood materials are exposed outdoors. The lack of well-developed heartwood, for example, in species such as walnut and cherry, would negatively affect the durability. It is also fairly obvious that, even in a wood specie with relatively durable heartwood, the service life of an untreated wood component is determined to relatively large extent by the amount of sapwood present. The disintegration of the less-durable sapwood, especially if it completely surrounds the heartwood, as in poles, may result in functional failures, even though the heartwood remains unaffected. On the basis of many research studies conducted in Sweden and other European countries, the commercially important Swedish timber species for buildings, e.g. pine and spruce, belong to the classes of moderately resistant and slightly or non-resistant species.

E.1.7.3  Lignification
Lignification was the important development in higher plant evolution that provided stiffness to stem tissues, facilitating wood stem aerial growth and protection against destruction by micro-organisms. Lignin type and amount have significant influence on the rate and types of decay found in wood. Lignin contents often vary widely between wood species and within individual portions of the same tree, rendering some portions of the wood, such as the primary cell wall and middle lamella, more resistant to microbial attack. Hardwood lignin is composed of both syringyl and guaiacyl lignin, whereas coniferous lignin only contains guaiacyl residues. Hardwood lignin also differs from coniferous lignin in the types of linkages between the phenyl-propane units.

Wood lignification creates a physical barrier to enzymatic attack on the polysaccharides. Therefore only those organisms which possess enzymes capable of destroying the lignin, or at least of altering its protective association with the polysaccharides, are capable of decaying wood.
Many studies have noted that the resistance of softwoods to soft-rot attack is decreased by partial delignification [9]. Lignin type, content, and pattern of deposition appear to play critical roles in the inception of soft-rot attack. Minor changes in lignin content can produce large decreases in decay resistance. These effects suggest that the pattern of lignin deposition in wood cell wall may be as critical as lignin type in determining natural decay resistance to certain fungi.

### E.1.7.4 Uniformity of growth rings

Uniformity of growth rate has an effect upon wood structure and density variation both within and between growth rings. It is indicated that lack of uniformity represents one of the greatest wood quality problems facing wood-using industries[10-12]. Wood characterised by significant within-ring density variation (i.e. by bands of very dense latewood and alternate zones of low-density earlywood) can present a problem when painted and exposed to the elements. The paint film tends to flake off after a period of weathering. The very dense wood shrinks and swells more than the low density wood, thus causing a relative movement between the film and wood surface. Such wood is also difficult to machine to a smooth condition because of the different hardness between early- and latewood bands. The uniformity of wood structure both within and between growth rings is determined to a great extent by growth rate and conditions under which growth occurs. Silvicultural treatments can affect the uniformity as well as density of wood.

### E.1.7.5 Straightness of grain

Grain orientation that is not parallel to the long axis of a stem often results in slope of grain in manufactured products. This can drastically reduce strength. This kind of grain orientation also adversely affects machining properties and the nature of moisture-induced dimensional changes. Spiral grain and other kinds of non-normal grain orientation are thus to be avoided if possible. A number of investigators have noted an apparent connection between development of spiral grain and growth conditions. It appears that intensive culture practices, and irrigation in particular, tend to reduce the occurrence of spiral grain [13].

### E.1.7.6 Knots

From the standpoint of saw-timber and veneer production, size and frequency of knots is perhaps the single most important aspect of wood quality. Knots greatly affect both appearance and strength, and because of this their presence is a primary factor in determination of log and lumber grades. A number of silvicultural practices can influence knot development, including spacing at time of planting, timing of thinning, treatments to accelerate rate of growth, and pruning.

### E.1.7.7 Occurrence of juvenile and reaction woods

Juvenile wood tends to be low in cellulose and high in lignin compared to mature wood. Acceleration of growth early in a rotation increases the proportion of juvenile wood and tends to cause a reduction in cellulose. Numerous investigations about the effect of growth rate on mature wood have yielded conflicting results.

Acceleration of growth can affect the properties of juvenile wood in a stem. Proportion of juvenile wood that develops in a stem is related to the growth rate at a young age. Stem grown rapidly during the juvenile period will have a relatively high proportion of juvenile
wood, as compared to those grown more slowly, early in the rotation period. Reaction wood formation is also apparently affected by growth conditions.

**E.1.7.8 Fibre length**

Fibre length, like grain orientation, has an effect on wood strength properties. Numerous experiments [14,15] have shown reduced fibre length in softwoods as a result of intensive culture. In contrast, studies involving hardwoods almost invariably show longer fibre lengths after growth stimulation [16,17]. While more information is needed, it is nevertheless clear that fibre length is affected by forestry practices.

In both hardwoods and softwoods, rotation age and growth-accelerating treatments such as fertilisation and irrigation have an effect upon average fibre length in a stem. Rotation age affects fibre length for two reasons. First, juvenile wood near the core is made of shorter fibres than those characterising subsequently formed wood.

**E.1.7.9 Forest decline**

Ecological problems, such as the genetic decline of the forest resources and the negative impact of air pollution on soil and ground water, have damaged forestry and caused forest decline. This tends to negatively influence the wood quality, and in the end the durability of wood building materials. In an investigation comparing wood properties of healthy and diseased trees from a same stand in Sweden, it was concluded that the sapwood percentage in diseased trees was clearly smaller than in healthy ones, diseased trees had higher moisture deficit in the inner sapwood, and discoloration on wood from the diseased trees started earlier and more intensively [18]. It was also found that phenol compounds in outer heartwood of diseased trees was higher than that in healthy trees. The phenol extractives are important. They strongly influence the natural durability of wood materials.

One factor related to natural durability that has become very important is the decay resistant of second-growth timber. Until recently, naturally durable species were primarily cut from old-growth forests. However, these stocks are nearly depleted, and we now harvest many trees from second-growth stands. Preliminary results suggest that the wood from these second-growth trees lacks the natural durability found in the old-growth trees [19,20]. As timber today is produced largely from managed, second-growth forest, it is necessary to change our reliance on natural durable woods, or develop methods for encouraging the growth of these woods at earlier stages within a rotation age. Increased attention should be paid to decay resistance as an important property to be selected for and enhanced in tree-breeding process.
E.2 CHEMICAL PROPERTIES

E.2.1 Chemical composition

Wood consists basically of carbon, oxygen and hydrogen. There are also small inorganic content. These basic elements are combined into a number of organic polymers viz.:

- Cellulose
- Hemicellulose
- Lignin

These agents are formed in the photo-synthesis.

E.2.1.1 Cellulose
Cellulose is built up by glucose units \((C_6H_{12}O_6)^n\), where \(n\) (the degree of polymerisation) is of the order of magnitude of 30 000. The length of the longest cellulose molecules is about 10 mm. The diameter is less than 1 nm \((10^{-9}m)\).

E.2.1.2 Hemicellulose
Also the hemicellulose is a polymer, however with a much lower degree of polymerisation than cellulose. The number of units in the molecule is some hundreds. The polymer is ramified in contrary to the molecules of the cellulose that are of the chain type.

E.2.1.3 Lignin
The lignin molecule is rather complicated and has a high molecule weight. The basic element is of a phenol-propane type. The composition varies highly between species. In the wood structure the lignin appears between the single cells as well as in the cell walls. It acts – together with pectin – as adhesive between the cells and it is therefore of major importance for the mechanical properties of the material.

E.2.1.4 Structure of the cells
The shape of the wood cells is complicated and rather fascinating. The cellulose molecules are bundled into tube-shaped structures – microfibrils – where the single molecules are bound together with hydrogen bonds. The cellulose molecules in the fibrils appear both as parallel, almost crystalline and as unorganised amorphic parts. The structure is shown in fig E.2:1.
In the cell walls a number of parts can be seen, and a cross section of a mature wood cell is shown in fig E.2:2. The primary wall is lignin-rich and reinforced by a net of randomly oriented microfibrils. In the secondary wall the microfibrils are oriented in a direction that varies during the formation of the cell. First the angle between the fibrils and the length axis is 50-70° (layer S₁). Later the direction is changed to 10-30° (layer S₂) and finally almost perpendicular to the axis (layer S₃). Therefore, the secondary cell wall has a very pronounced spiral structure.
Wood has a low nitrogen content, ranging from 0.03 to 0.1 percent by weight, in contrast to the herbaceous tissues that normally contain 1 to 5 percent. The low nitrogen content in wood reduces its susceptibility to decay.

Acceleration of growth can affect chemical composition of a stem. Some studies suggest that fertilisation using high-nitrogen-content fertilisers can adversely influence durability. In theory, fertilisation should increase tree growth, producing a wider band of decay-susceptible sapwood. Furthermore, higher nitrogen levels are often correlated with increased susceptibility to fungal attack [22].

E.3 TYPICAL USAGE

Wood and wood based materials are used in a wide variety of applications in modern buildings. It is found in load-bearing structures, lightweight partitions and facades with or without surface treatment. It is highly appreciated by architects as a valuable material when creating an attractive external and internal environment. It is also a dominant material for doors, window frames, cabinets and kitchen furniture. Critical properties that sometimes restrict their use are related to fire protection, biological attack and moisture-induced deformation checking and cracking.

E.4 TYPICAL MICRO ENVIRONMENT AND LOADS

E.4.1 Durability

Wood forms part of the natural cycling and is influenced by biological and other processes, deteriorating the material. This causes obvious problems and requires special measures in buildings that normally are expected to have a significant service life.

E.4.2 Deterioration mechanisms

The dominating deterioration mechanisms for wood in buildings are biological, mainly rot fungi of various types but also insects and sea organisms. Some observations of attack from bacteria are also reported. Also UV-radiation affects the wood structure.

E.4.2.1 Fungi

There are a large number of fungi that attack wood. They can be separated into two main groups, staining fungi and decay fungi. They all need high moisture content (fibre saturation) or higher and a suitable temperature. One consequence of this relationship is that if the moisture content can be kept sufficiently low, no deterioration of this type will occur and, accordingly, dry wood structures have demonstrated very high durability. Well known examples are some Norwegian wooden churches which are about 1000 years old. On the
other hand, if moisture and temperature conditions are favourable for the fungi, the deterioration can be very fast (a few years).

E.4.2.1.1 Staining fungi

Staining fungi as such are rather harmless. They do not attack the wood substance but is living from nutrition agents solved in the cell lumen. However, the existence of stain is an indication of high moisture content and that the conditions for development of the far more dangerous decay fungi may be present. Important discoloration is caused by staining fungi of *Ascomycotina* and *Deuteromycotina* that invade mainly parenchymatous cells in the sapwood, and the discoloration result from the masses of pigmented hyphae in wood cells.

E.4.2.1.2 Decay fungi

The main types of decay fungi are *brown rot*, *white rot* and *soft rot*. In buildings, brown rot is the far most common. The most important decay fungi causing brown rot are:

- *Serpula lacrymans*
- *Coniophora puteana*
- *Paxillus panuoides*
- *Antroidea sinuosa*
- *Lentinus lepideus*
- *Gloeophyllum sepiarium*

E.4.2.2 Insects and sea organisms

The most important insects attacking wood components in buildings are:

- *Hylotrupes bajulus* (Long-horned beetle)
- *Anobium punctatum* (Common furniture beetle)
- *Callidium violaceum*
- *Camponotus spp* (Carpenter ant)
- Termites

Termites exist approximately between the 50th latitudes (north and south) and can cause very rapid and extensive damage to wood structures. In Europe their presence is to be regarded in the Mediterranean area but generally not north of the Alps.

The wood destroying sea organisms require high salt content (above about 3%) and is therefore not a problem e.g. in the Baltic Sea. The most well known organisms of this type is *Teredo navalis*. 
E.5 TYPICAL DEGRADATION AND FAILURE MODES

E.5.1 Variations in durability within and between trees

Wood is a highly anisotropic material. There are many variations in the natural durability within and between wood species.

E.5.1.1 Variations within individual trees

The decay resistance of heartwood generally tends to be at maximum in the outer heartwood and decreases inward to the pith [23,24]. This pattern is particularly marked in the butt log of the tree in natural durable softwoods and in hardwoods of both temperate and tropical regions, with heartwood that is resistant to deterioration. The variation in durability of heartwood in the radial direction is due to the kind and concentration of toxic chemical constituents of heartwood [25]. That any appreciable difference in durability of heartwood exists in the same growth increment of the tree, as determined at different height of the stem, is fragmentary and inconclusive. Reduction in durability of heartwood within the same increment with increased distance from the base of the tree has been reported [24,25].

E.5.1.2 Variations between trees

The natural durability of the wood of individual trees of the same species may vary within wide limits. Such variability is thought to be largely genetically controlled, although tree vigour and the fertility of the soil on which the trees are grown are known to influence fungal resistance of the heartwood. In addition, size and age of trees also have some effect.

E.5.2 External factors associated with environment in service

The external factors, in contrast to the internal factors that are associated with various wood properties, are related to the environmental conditions in service, which the wood materials are subjected to. When wood is exposed outdoors, it undergoes two kinds of deteriorating processes: (1) natural weathering or ageing process, which is caused by a complex combination of chemical, mechanical, and photo energy factors; and (2) decay and discoloration process, which results from decaying and discoloring micro-organisms acting in the presence of excess moisture for a relatively extended period of time.

As wood exposed outdoors mainly experiences the two degradation processes, the external factors can, accordingly, be further divided into two kinds of degrading agents, e.g. factors associated with the natural ageing process and micro-organisms, respectively.

Besides internal factors (the natural durability of wood derived from distribution and quantity of extractives, and wood properties such as moisture content, density, texture, resin content, width and orientation of growth ring, etc. as discussed previously) and the external factors (the natural ageing process and biological decay attack), the service life of wood building components exposed outdoors is also dependent on many other contributing factors. These factors include the property of finishes used, application techniques, building design, pretreatments, and maintenance. The influencing factors and degrading effects are summarised
in fig E.5:1. As the attention here is focused on the durability evaluation of wood materials, other influence factors on wood materials used in outdoors buildings associated with architectural design, maintenance, and protective coatings are excluded in this discussion.

**E.5.2.1 Ageing process and its effect**

Like all other building materials, when wood is unprotected by finishes and exposed outdoors, a slow chemical and physical disintegration occurs near the surface. The colour of the wood turns to grey and silver, the cells at the surface are roughening and slowly broken down, and the wood surface is gradually eroded. This degradation is commonly termed as natural ageing or weathering process of wood. The ageing process and its effect on wood is schematically shown in fig E.5:2.
The major deterioration mechanism associated with the natural ageing process is photochemical degradation (UV-light) to wood cell-wall constituents, photo-oxidation of the breakdown substances, leaching of the soluble decomposition products, and related mechanical damage of surface elements from the constant swelling and shrinking of the wood associated with surface wetting and drying.

Wood ageing is a complicated natural process and its mechanism is not fully understood. Wood ageing results from a series of combined factors. The initial colour change is the result of lignin and extractive photochemical decomposition, forming free radicals, which lead to further decomposition of the structural carbohydrates and oxidation of phenolic compounds. Light usually does not penetrate wood more than 200 µm in depth. The natural degradation reactions, therefore, are surface phenomena. Xylans are decomposed and leached more readily than cellulose or glucan-rich hemicelluloses. Continual wetting and drying of wood surface with its concomitant swelling and shrinking, lead to surface checking and erosion. These ageing losses are negligible over the service life of most wood assemblies. However, they may become significant for long-term uses of wood materials in outdoor applications [26].

E.5.2.2 Decaying and discolouring organisms and their effects
Many changes in other physical and chemical properties are caused by decaying organisms. These changes range from drastic effects on wood to subtle modifications in properties such as density, and hygroscopicity, electrical conductivity, acoustics, calorific values and dimensions. These changes and their rates of development in wood building materials vary with wood species, the environmental conditions and the organisms involved. It is important to remember that changes in one property are invariably associated with changes in other properties. For example, a loss in wood weight decrease its strength properties. Some subtle changes in
properties such as moisture permeability may increased decay susceptibility and set the stage for further colonisation of other more destructive agents of decay.

Strength and volume reduction are the principal losses associated with decay. Drastic strength losses occur in the incipient decay. At high-stress utilisation of wood, such as in outdoor applications, failure to detect early decay can lead to serious losses. Drastic alternation in dimensions and chemical and physical changes of wood adversely affect many properties, including decreased volume and mass resulting in dimensional collapse of supporting timbers or reductions in many strength properties, increased permeability to liquids, aesthetic losses due to abnormal colours, rough textures or pulled fibres.

E.5.3.3 Protection of wood by chemicals
When the conditions do not ensure that the moisture content can be kept below critical values – by design or surface protection – a chemical treatment with fungicides can be applied. This treatment can be performed in different ways depending on the situation and the required level of protection. The most efficient method is to get the fungicide agent into the wood structure by an industrial vacuum/overpressure technique. There are a large variety of agents and processes for this purpose. Environmental concerns have led to restrictions on certain agents and there are on going and extensive R&D activities to develop new agents, tailor-made to specific applications and with an acceptable impact on the environment.

It is common to distinguish between pressure and vacuum impregnation depending on the type of industrial process. At pressure impregnation water based agents based on salts of chromium, copper and/or arsenic are used which give the wood a characteristic green colour. Vacuum impregnation is normally made with uncoloured agents solved in white spirit. It is solely used for joineries such us windows, doors and outdoor furniture.

E.6 DEGRADATION MONITORING METHODS

E.6.1 Evaluating weathering resistance
When discussing the durability evaluation in the present chapter, both deteriorating factors associated with ageing process and micro-organisms should be considered in accordance with the author's definition of durability of wood building material. There is no apparent standard method for evaluating the ageing resistance of wood building material. For the evaluation of natural resistance ability to micro-organisms, many standard laboratory test methods have been developed, for instance, ASTM D 2017-81(1986).

E.6.2 Evaluating natural durability
For wood building materials exposed outdoors and above-ground, the most important property which largely determines its performance is its resistance to microbial attack. This resistance ability for untreated wood materials is principally dependant on the natural durability of wood material itself.
In general, natural durability has been evaluated by exposing wood samples to the decay agents for various periods and rating the resultant degree of degradation. These tests are sometimes supplemented by extracting the wood and evaluating the toxicity of various fractions against specific organisms. Field trials of natural durability were prevalent beginning in the 1920s, as scientists began to evaluate the properties of many wood species [27,28]. These tests reflected a desire to identify wood with properties similar to existing natural durable species. In USA the toxic nature of heartwood extractives was first established and posed as the reason for decay resistance [29].

Laboratory assay to evaluate natural durability began in the 1940s in an attempt to further explain the durability and identify the toxic compounds [30-35]. In most cases, water, ethanol, or other solvents were used to remove extractives from the wood. These extractives were then tested for activity against a variety of decay and non-decay fungi. In addition, these extracts were often tested for activity against common wood-destroying insects [36]. Most tests were performed in petri dishes or decay chambers using nutrient agar. Although such tests provide a relative guide to chemical toxicity they cannot evaluate more subtle effects such as variation in deposition of extractives in the wood or interactions between different extractives that must also play roles in natural wood durability.

Much of the laboratory research was performed to identify chemicals that could be synthesised as natural preservatives under the premise that such chemicals would be inherently safer and more effective than other biocides. In fact, many of the chemicals responsible for natural durability are as toxic or more toxic than existing wood preservatives. The major advantages of employing naturally durable woods over artificial wood preservatives is the elimination of the need for treating facilities to deliver chemical into the wood. Natural durability, however, can never completely replace the need for wood pressure-treated with chemicals, since some hazards, such as outdoor exposure, are too severe for adequate performance of even the best naturally durable wood species [37].

Improved chemical assay methods, using such techniques as radioisotope labelling, \(^{13}\)C nuclear magnetic resonance (NMR) spectroscopy and ion magnetic spectroscopy, have enhanced the study of natural durability, but methods for studying in situ deposition of toxic extractives are still lacking. The use of tissue-culture techniques may improve our knowledge of synthesis of heartwood extractives, but it will be difficult to study subsequent deposition processes using these methods. Developing an improved understanding of the nature and distribution of extractives related to durability could be especially useful for identifying new approaches to depositing chemicals in wood and protecting it. This approach is particularly interesting because of evidence that the decay-resisting extractives in some very durable woods are distributed in the wood in a manner more resistant to leaching than fungicides that are applied artificially.

However, as concerns about the use of artificial wood preservatives increase, we may come to depend increasingly on natural durability for wood used in some locations, such as outdoor exposure, even under higher decay hazards. This increased demand comes at a time when supplies of durable species are declining and when concerns are being raised about decreased durability of second-growth timber. These trends suggest that renewed efforts must be made to identify methods for improving the genetic capabilities to produce durable heartwood and develop silvicultural practices that favour maximum production of this wood in the shortest period.
E.6.2.1 The British standard BS 1982
One of most widely accepted and used standards for evaluating natural durability of wood is the BSI standard (1980:1990, part 0, part 1, part 2, and part 3) "Fungal resistance of panel products made of or containing materials of organic origin", which specifies a common soil or agar/block test. This test is often not suitable for some types of wood panel products, e.g. wood-based board. The method in part 2 involves small stakes partially buried vertically in non-sterile soil. The moisture gradient that occurs in these stakes allows the test fungi to attack in the area of most suitable moisture content. It is well known that some chemical constituents provide temporary protection against wood decay fungi. This protection is eventually lost in service. The ageing effects on wood durability and the relation between ageing of wood and fungal susceptibility of wood material is not considered in the standard. It is essential that ageing effects on durability should be included in the durability evaluation.

The test samples are usually small blocks. Comparison of test results from small block with that from larger full-size products in practice can be difficult to be used as indication of relative performance of the wood materials in service.

E.6.2.2 The American standard ASTM D 2017-81(1986)
The American standard for evaluation natural decay resistance is ASTM D 2017-81(1986): "Method of accelerated laboratory test of natural decay resistance of wood". This method is similar to the BSI standard and has almost the same limitations. None of the methods is specially designed for testing of wood materials exposed outdoors and above-ground. It is not suitable to use this method to assess the combined effects of ageing in service conditions and the decay fungi on the durability. The methods are also too simple to evaluate the multiple actors and their inter-reactions on the durability. They are mainly designed to clarify effects of one or two detrimental factors.

E.7 REFERENCES


