

Clay Materials—for the Self-Reliant Potter

Henrik Norsker

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Preface

This book is the second in a series of books for potters and ceramists working in developing countries.

The term “self-reliant potter” is the common name for the series and this reflects the condition of potters in many developing countries. Imported materials and equipment are seldom available, and the supply of raw materials within a country is often difficult.

Self-reliance is therefore a practical approach to ensure profitable pottery production under such conditions.

The book is mainly directed to:

- Trainers, field workers involved with promotion and training.
- Technicians doing research in ceramics centres.
- Students of pottery in ceramics training institutes.
- Potters in established cottage and small scale industries.

Acknowledgments

This PDF Document

Typesetting

This document was typeset by Erik Haugsby from the source material provided via the CD3WD:

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This document attempts to replicate the source material and present it in a more accessible structure.

As the source material is freely available online and the cost of a print version of this text is prohibitively high, I believe this document is an important contribution to the collective knowledge of potters.

It improves upon the HTML version of the information by consolidating all sections into a single document, which is both viewable on the computer and can also be printed. Furthermore, it introduces clickable links/references between sections and tables.

Formatting: Changes, Errors, Omissions

I have attempted to preserve the original text and formatting.

Some changes to formatting, especially of tables, was unavoidable due to the LaTeX typesetting.

Some corrections were made to spelling and grammar.

Unfortunately, no images are available in the online version of this document. Inline references to images have been maintained, but will always appear as `??`. Appendices are also missing.

The possibility of minor or unavoidable changes in layout and formatting, as well as unintentional errors in transcribing the original text, cannot be excluded.

Should you find any errors or omissions, I would greatly appreciate you either notifying me by email, or initiating a pull request via Git.

Link to GitHub project: <https://github.com/erikhaugsby/materials/>

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The Author

Henrik Norsker

Henrik Norsker has been making pottery since 1970. He left his pottery workshop in Denmark in 1976 to help with establishing a pottery school in a village in Tanzania. Since then he has continued working with promotion of modern pottery in developing countries. Besides Tanzania, he has worked for ceramics projects in Bangladesh and Burma. He is presently working for a ceramics project in Nepal.

The Deutsches Zentrum für Entwicklungstechnologien

Deutsches Zentrum für Entwicklungstechnologien-GATE

Deutsches Zentrum für Entwicklungstechnologien-GATE stands for German Appropriate Technology Exchange. It was founded in 1978 as a special division of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. GATE is a centre for the dissemination and promotion of appropriate technologies for developing countries. GATE defines "Appropriate technologies" as those which are suitable and acceptable in the light of economic, social and cultural criteria. They should contribute to socio-economic development whilst ensuring optimal utilization of resources and minimal detriment to the environment. Depending on the case at hand a traditional, intermediate or highly-developed can be the "appropriate" one. GATE focusses its work on the key areas:

- Dissemination of Appropriate Technologies:

Collecting, processing and disseminating information on technologies appropriate to the needs of the developing countries: ascertaining the technological requirements of Third World countries: support in the form of personnel, material and equipment to promote the development and adaptation of technologies for developing countries.

- Environmental Protection:

The growing importance of ecology and environmental protection require better coordination and harmonization of projects. In order to tackle these tasks more effectively, a coordination center was set up within GATE in 1985.

GATE has entered into cooperation agreements with a number of technology centres in Third World countries.

GATE offers a free information service on appropriate technologies for all public and private development institutions in developing countries, dealing with the development, adaptation, introduction and application of technologies.

Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH

The government-owned GTZ operates in the field of Technical Cooperation. 2200 German experts are working together with partners from about 100 countries of Africa, Asia and Latin America in projects covering practically every sector of agriculture, forestry, economic development, social services and institutional and material infrastructure. The GTZ is commissioned to do this work both by the Government of the Federal Republic of Germany and by other government or semi-government authorities.

The GTZ activities encompass:

- appraisal, technical planning, control and supervision of technical cooperation projects commissioned by the Government of the Federal Republic or by other authorities
- providing an advisory service to other agencies also working on development projects
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- provision of materials and equipment for projects, planning work, selection, purchasing and shipment to the developing countries
- management of all financial obligations to the partner-country.

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Chapter 1

Origin of Clay

Clay is a product of the continuous weathering of the Earth's surface. Our study of clay begins with how the planet Earth was formed.

The Earth was created some 5,000 million years ago, according to scientific theory. At first it was a gaseous molten mass, which slowly contracted. While the mass was still molten, the heavier materials like iron and nickel sunk to the centre of the Earth. As the hot Earth gradually cooled, a layer of solid materials formed the crust. The crust feels very secure to us, but it is only about 40 km thick, floating on a 3000 km deep layer of molten materials.

Slow currents in this molten sea cause whole continents to move at speeds of up to 2 cm per year. Where continents grind against each other, earthquakes and volcanoes occur. The map shows how all the big continents have changed location during the last 200 million years. Africa was then so far to the South that it was covered by polar ice masses. The Indian plate moved North, and when it collided with the Asian continent the highest mountains on Earth - the Himalayas - were formed. In this way the crust of the Earth has changed continuously since it was formed. Where we see mountains today there may formerly have been wide oceans, and tropical forests may have been covered with arctic ice million of years ago. weathering: Weathering also causes major changes. Solid rocks are broken up by the alternate action of sun, rain and ice. The resulting small rock particles are carried away by water, and even mountains wear away in a few million years. Clay and many other ceramic raw materials are produced by this process.

1.1 Minerals and Rocks

1.1.1 Minerals

A mineral is a substance which has a uniform chemical composition, in the form of one or many crystals. Quartz and feldspar are minerals, and so is salt. Salt crystals (sodium chloride) have a cubic shape which can easily be seen under a magnifying glass. When salt is dissolved in a glass of water and left for a while crystals will form slowly as the water evaporates.

1.1.2 Rocks

Most rocks are made up of several different minerals, though some rocks like gypsum only consist of one mineral. The rock named granite contains the minerals quartz, feldspar and mica, and the individual crystals can be seen clearly with a magnifying glass. Rocks can be arranged in three major groups; igneous rocks, sedimentary rocks and metamorphic rocks.

Igneous Rocks

When the young Earth slowly started to cool, different minerals formed crystals in the mass of molten rocks (also named magma). A variety of crystalline rocks were formed, according to the different conditions of their locality. Thus the igneous rock called basalt was created at a great depth, and contains little feldspar compared to granite, which formed near the surface.

If the rock cooled very slowly, the crystals had time to grow large, whereas rapid cooling produces small crystals. This process is still going on today where movement in the crust of the Earth causes deep layers of molten materials to rise to the surface. An erupting volcano lets out hot magma on the surface, where it cools quickly. The resulting volcanic rocks have microscopic size crystals, since the rapid cooling allows little time for the crystals to grow.

Sedimentary Rocks

Sedimentary rocks are made of materials produced by the crumbling of old rocks. All rocks eventually break up in the course of time when exposed to weather, and the broken up rock particles are carried away by water. These particles of clay and sand are transported to lower lying areas, or to the sea where they settle one layer upon the other. In the span of millions of years, the growing weight of sediments causes the deeper layers to compact and gradually turn into rocks, called sedimentary rocks. Much later, the movement of landmasses sometimes turns the whole area upside down, so that the old sea floor, with its sedimentary rocks, becomes a new range of mountains.

The upper part of new mountains consists of sedimentary rocks resting on deeply set igneous rocks. After some millions of years, the upper sedimentary rocks erodes away by weathering and the deeper igneous rocks are exposed.

Sedimentary rocks like sandstone and shale can often be recognized by their layered structure. Limestone is a sedimentary rock created by the left over skeletons of billions of small animals that lived in the ancient seas. Gypsum is formed by chemical sedimentation, in areas where seawater evaporated on a large scale. This produced a high concentration of gypsum which formed crystals in a fashion similar to the formation of salt crystals in a glass of salty water.

Metamorphic Rocks

Igneous and sedimentary rocks are sometimes changed into new forms by high temperatures and high pressure. Marble is an example of a metamorphic rock that is formed from a sedimentary rock named limestone.

1.1.3 Rock Cycle

Fig. ?? shows how one continental plate moves under another, causing some rocks to be exposed to high temperatures and pressure. Sedimentary or metamorphic rocks melt, and may later return to the surface as igneous rocks. These later will erode to become clay and sedimentary rocks. Fig. ?? shows this rock cycle graphically.

1.2 Formation of Clay

The formation of clay from rock is a most common event, taking place daily everywhere in the world. If a piece of granite is picked up and broken in two, the fresh faces of the stone will show a shiny surface and the crystals of the different minerals can be identified. The black shaded crystals are mica. The yellow, white or red colored crystals with a pearly shine are different types of feldspar. The clear colorless crystals are quartz. The weathered surface of the granite will most probably show a rough surface with many holes, where the soluble feldspar crystals have been washed away by rain, whereas the less soluble crystals of mica and quartz remain. This is the beginning of the process of changing feldspar into clay.

Weathering breaks up the granite rocks and enables the water to wash away the soluble soda, potash or lime parts of the feldspar. These soluble parts are carried away by water and the soda ends up adding to the salt of the oceans. The process is shown in fig. ?. Most of the remaining alumina and silica of the feldspar combines with water and forms a new mineral: clay. Some of the silica from the feldspar does not take part in formation of clay and forms instead another mineral known as quartz.

1.3 Primary Clay

Clays which have not moved from the location of their parent rock are known as primary clays. Kaolin (also called China clay) is a primary clay.

1.3.1 Steam and Acid

In some cases the parent rock was exposed to steam from volcanic activity or to acid seeping down from above. The acid or hot steam slowly changed the rock into clay, quartz and mica in the same location. Such a deposit may only contain 25% clay, and in some cases where the granite rock is only partly changed the clay content may be 10% or less.

1.3.2 Kaolin

Kaolin clays are pure, without impurities like iron oxide and limestone. Therefore, they have a high melting point (about 1780°C) and they fire to a white colour. Kaolin has little plasticity due to its large particle size.

1.4 Secondary Clay

Clays which have been removed from their place of origin and have settled somewhere else are called secondary clays. Fig. ?? illustrates this process; rain washes the clay out from the site of its parent rock and the clay is carried downhill by rivers and streams.

1.4.1 Grading

A rapid river can even carry small stones, but as the flow of the river slows down, the heavy particles will start to settle, then the coarser sand, and finally the fine sand. The clay remains suspended in the water and will only settle where the river flows into a lake or a sea. At the mouth of the river, the silt and coarser clay will settle, whereas the fine clay will only settle further away. In this way, the original materials of the erosion process are graded according to their particle size (fig. ??).

1.4.2 Grinding

The clay may travel thousands of kilometers before it settles. During transport the clay particles are subjected to the grinding action of pebbles in the streams. This works very much like grinding in a ball mill and makes the clay particles still smaller, thereby adding plasticity to the final clay.

1.4.3 Impurities

The river or stream carrying the clay will also pick up all kinds of impurities on its way through the landscape. These impurities will later be deposited together with the clay. It is very rare to find a pure secondary clay, i.e. a white firing plastic clay.

The most common impurity is iron oxide (rust) which gives the fired clay a buff, red or brown colour. Iron oxide exists in slightly different forms which may be yellow, red, grey or brown in the raw clay. However, the different iron oxides all turn into red iron oxide (Fe_2O_3) during an oxidizing firing. The clay may also contain organic matter which was added in the form of leaves and other vegetation from contemporary forests. This organic matter (carbon) gives the raw clay a grey or black colour, but as the carbon normally burns away during firing it does not affect the fired colour of the clay. Black clay is usually not black after firing. Other impurities like feldspar, mica and limestone lower the melting point of clay.

In general, secondary clays are plastic and have a lower melting point compared to primary clays, due to their impurities. The quality of secondary clays varies from one deposit to another, and even within the same deposit the quality of a clay can vary considerably.

Chapter 2

Prospecting and Mining Clay

2.1 Prospecting Clay

Pottery clay can be found in most countries. In areas where pottery or brick-making have a long history suitable clay deposits will already be well known. However, introduction of new techniques like glazing or high temperature firing may call for new types of clay. In some countries the land may still be virgin from a potter's point of view and before any production facilities are established a reliable source of good pottery clay must be found.

2.1.1 Practical People

It is worth talking to people who make water wells, and builders of dams and roads. They should have first-hand information about the soil of the region. Farmers in the area will know about the upper layers of soil on their fields. Sometimes clay is used for other purposes, like whitewashing houses or medicine. In Tanzania iron smelters use a highly refractory clay for their furnaces, and in Nepal the brass makers use a local fireclay for their casting moulds.

2.1.2 Prospecting

When setting out to explore the countryside one should bear in mind how nature created clay. Recent deposits of plastic clay are most likely found in the plains and valleys, or along rivers. They are often close to the surface. Older secondary deposits may be found in the hills where the land was raised and folded, millions of years after the clay was deposited. Such deposits may be covered with a thick layer of other materials.

River Banks

A good potter's clay will often be covered by several meters of overburden. Instead of digging test holes through the overburden at random, a general idea of the deeper soils in the area can be obtained by examining the soils exposed in river banks, escarpments and cut areas where a road or a railway was made

through a hill. Quarries, wells and ditches should be examined as well. Termites bring soil up from below, and the material from termite hills indicates the quality of soil located 1–2 meters down.

Field Testing

In the field a few simple tests can establish whether the clay is worth examining further. First, take a sample from about 30 cm inside the exposed surface, and mix it with water. If it turns into a plastic sticky mass it is clay. Then knead it well and form a rope the thickness of a pencil. If you can bend this rope around two fingers without seeing big cracks, the clay has plasticity (fig ??).

If you bite the plastic clay gently with your front teeth you will get an idea of how finely grained the sand content is.

Then rub a sample of dry clay in the palm of your hand until the fine particles are rubbed away. What remains is the grit content, which may be particles of feldspar, quartz or mica.

Small pieces of limestone will cause trouble in pot-making, so the deposit and its vicinity should be examined for signs of white or grey limestone. Lime powder thoroughly mixed with the clay will lower its melting point and is often used for low-temperature pottery. But a piece of limestone the size of a pinhead will crack the pots or bricks when they are exposed to moisture after firing. Screening the clay through a fine sieve reduces this problem, but if possible, it is better to look for another clay. Lime content can be tested by putting a few drops of dilute hydrochloric acid on a sample. If there is lime, bubbles will form from the reaction.

Sample Collection

If the clay, after field testing, has proven to be of interest samples should be collected for further and more thorough testing. The quality of clay from different places in the same deposit will differ slightly, so in order to get a representative sample, clay from 4 different spots within a few meters' distance are dug out. The clay should not be taken from the exposed surface of the deposit but rather from 30–50 cm inside since the clay at the surface may be contaminated with other soils or washed out by rain.

The 4 samples are mixed well at the location and a sample of about 5 kg is then packed and labeled with its location .

Make a sketch of the location as accurately as possible, indicating features of the landscape like big trees or rocks. If a motor vehicle is used, note the exact distance on the odometer from the nearest town to the clay site. A photograph of the clay site will help in finding the right site again later.

Probe Digging

In areas where initial survey and testing indicates deposits of suitable clay, holes should be dug in a regular grid in order to ascertain the size of the deposit. Initially, holes should be dug with a grid distance of 50 m. and where the best quality clay is discovered, the distance can be reduced to 15 m. It is worthwhile to ensure that the deposit is large enough to supply the planned production for a long time. The holes can be dug with a spade, but if a hole is more than 2 m deep the sides of the hole should be supported by planks.

A bucket auger (fig ??) is a very useful tool for taking samples. One or two people rotate the auger, which drills its way into the soil. The shaft can be extended so that samples can be taken from depth of 5 m or more. The bucket auger can be made at a local machine shop.

Map

A map should be made of the whole grid area, and on the map the probe holes are marked with a number, thickness of overburden and depth of clay layer.

The map is drawn with the help of a few fixed features, like trees and large stones (fig ??). The distance between three fixed points is measured as accurately as possible. The map is made in a scale of 1:100 (1 cm on the map represents 100 cm (1 m) in reality) or 1:200 (1cm=2m). The three fixed features are then marked on the map like on fig ?. The location of the test holes is measured and marked on the map according to its distance from the fixed points. Each test hole is given a number, which is marked by the hole itself, on the test sample label and on the map.

After testing of all the samples has pinpointed the best area, a more detailed plan (e.g. scale 1:50) of that area should be drawn, showing the depth of the various layers of top soil, clays and possibly other materials.

2.1.3 Economy

After having established the quality of the raw clay, the approximate size of the deposit and the thickness of the overburden the final decision of whether or not to start mining the clay remains to be done. Many factors control the economy of mining clay:

- The distance from the deposit to a suitable road, and the cost of transport to the workshop. It may be necessary to construct a small track from the deposit to the nearest road.
- The cost of removing the overburden compared to the amount of clay underneath.
- The cost of renting or buying land.
- The quality of the clay. If the raw clay contains large amounts of sand, it may be necessary to wash the clay at the mine in order to reduce the cost of transport.

The total cost of opening up the mine, and the cost of digging and transporting the clay as listed above should be calculated as cost per kilogram of clay. This cost per kilogram is then compared with the cost of possible alternative sources of clay.

2.2 Clay Mining

2.2.1 Before Mining

The clay you intend to mine may have been deposited in an ancient lake as shown in fig ?. It may have taken hundreds of thousands of years to fill the

lake with sediments, and during that period variations in climate, course of rivers, etc., caused the layers of sediments to vary. Each layer may contain its own type of clay or sand and the thickness of each layer may vary considerably.

Clay Layers

Before you start to dig the clay, expect it to be limited to certain layers. Today these layers will often be positioned horizontally in the same manner as they were laid down (fig ??). But they may also have been turned upside down by later folding of the landmasses and could be positioned as suggested in fig ?? and fig ?. The digging of probe holes as mentioned above should indicate how the clay layers are positioned.

Overburden

First the top soil or overburden has to be removed and piled away from the clay pit where no future clay digging is planned. Care should be taken to avoid mixing top soil with the clay. If the overburden is several meters thick, it may be worthwhile to hire a bulldozer to clear away enough top soil for several years' clay mining.

In some cases, the overburden is too thick to be removed, and underground mining must be considered. This method is especially tempting if the clay is situated on a riverbank, on a slope or on an escarpment so that horizontal shafts can be dug. That will save the tedious task of removing the overburden, but this advantage may be offset by the extra cost of using lumber supports for keeping the walls of the underground shafts from collapsing. Underground mining of clay in vault shaped shafts without supports is often seen but is dangerous.

Digging Tools

Commercial mining of clay on a large scale in industrialized countries uses heavy machinery (fig ??). In most other places manual methods are more economical.

Manual digging is done by spade or hoe. A shovel is no good for breaking up clay, but it is useful when loading the clay into a wheelbarrow or truck. A wheelbarrow is used for bringing clay from the pit to a vehicle.

Supervision of Clay Winning

While digging, the worker should sort out roots, limestone, rocks and other unwanted material. The digging should always be supervised by an experienced person who can judge the quality of the raw clay. As the working of the clay pit progresses it may reach layers of inferior clay. The supervisor should regularly test the quality of the clay using the simple methods described above. Production of first class pottery demands raw materials of consistent and uniform quality. A potter adjusts production methods to the clay, and if it suddenly changes its behavior, it may ruin the production. If, for example, the clay becomes more plastic it may cause pots to crack during drying.

Even within the same layer of clay the composition of the raw clay may differ. Therefore, it is prudent to dig clay from several levels or locations at the same time, and to mix the material before loading it for transport. A worker can dig 4 to 8 tons of raw clay per day, depending on conditions in the clay pit.

If the worker is paid according to quantity (piece work) the quality of the clay may suffer unless the supervision is thorough. In the long run, it may be less costly to pay by the hour (time work) in order to get better quality clay.

Safety

Clay is normally extracted from open pits, which are much safer compared to underground mining. However, safety should also be a concern in open pits. Clay should not be dug from a vertical clay face higher than 2 m because a large portion of the face could break loose and bury the worker. The digging of clay in deep pits should be done in benches as shown in fig ?? . The overburden is removed away from the clay face being worked on, so that no top soil will get mixed with the clay itself. The benches on the clay face are made in steps about 1 m high and 0.5–1 m wide. The material from different levels can be thrown to the bottom of the pit for mixing, in order to even out variations in clay quality.

Record

A record should be kept of where in the pit the different batches of clay are extracted, so that sudden changes in the quality of clay can be traced to specific locations in the pit, and these can be avoided in the future. The movement of the digging area is recorded on the original map and is compared with the location of the original test holes. In this way, the supervisor can decide in which direction and to which depth to direct the digging, and he will be able to avoid clay beds of inferior quality that are shown on the test hole map.

2.2.2 Stockpiling and Weathering

Planning

Clay mining is impractical or impossible during rainy seasons, and in some areas of the world the ground freezes hard during winter. Therefore, it is necessary to extract sufficient clay during the dry season or during the summer to cover a whole year's production. That means you will have to plan your clay digging and production 0.5–1 year ahead, or you will run out of clay.

Weathering

Storing the clay in the open, and exposing it to the action of rain, sun or frost is called weathering. The alternate wetting and drying, or freezing and thawing, improves the plasticity of the clay by breaking it into smaller particles.

Weathering will reduce the content of possible organic matter in the clay, and this may have a bleaching effect on the raw clay. Weathering also washes out soluble salts. The clay should not be piled higher than 0.5 m. Clay may be weathered from a few months up to one year.

Clay Storing

When clay is received at the pottery it should be piled as shown in fig ?? . Each truck or cart load is spread out in a thin layer covering the whole storage area. This makes horizontal layers.

The raw clay is collected from the clay bin by making vertical cuts in the pile, so that a little clay from each truck load is part of each batch of clay used in production. This procedure will ensure a more uniform clay quality.

Chapter 3

Clay Washing and Clay Body Preparation

3.1 Washing at the Pit

After extracting the clay from its pit, it is normally brought directly to the pottery for further treatment. However, some raw clays contain so much sand that it is more economical to dispose of the sand at the clay pit, thus avoiding the cost of transporting this unwanted material. The true clay content found in primary clay deposits may be only 15% or less. The whiteness or the refractoriness of such clays may still make it profitable to mine them.

3.1.1 Commercial Kaolin Mine

In some commercial kaolin mines, clay is extracted by washing the clay face in an open kaolin pit with a high-pressure water-jet. The fine clay is carried away with the water leaving behind most of the coarse materials. In older mines, the resulting clay slurry is run through troughs, where the non-clay materials settle, after which the clay slurry is pumped into settling tanks. After siphoning off the clear water, the clay slip is de-watered in filter presses and dried in ovens. In more modern works, the trough type settling tanks have been replaced by centrifuges.

Smaller clay works cannot afford such machinery. Instead the raw clay is mixed with water, and stirred either manually in ponds or in a washmill.

3.1.2 Washing Ponds

Next to the clay pit and close to a source of water two or more shallow ponds are dug, measuring about 4 m by 2 m and 0.5 m deep. The sides of the ponds can be lined with bricks or simple wickerwork plastered with clay.

The pond is half filled with water and the raw clay is added until the pond is nearly full. The raw clay is then stirred with a shovel, until all the clay is separated from the sand. With dry sandy clays this may take less than 20 minutes. Finer clays need longer stirring and for very fine ones it may be

necessary to let the clay soak for a day. However, clay that fine is in no need of having its sand removed.

When all the clay is suspended in water and the material at the bottom of the pond is only sand (without a clayey feeling), the clay slurry can be transferred to a settling pond. If possible the settling pond should be located at a slightly lower level so that the clay slurry can run in by itself. Otherwise, the clay slurry is transferred by bucket, which is filled in a small pit connected to the stirring pond with a pipe. In this way the bucket will not disturb the settled sand in the stirring pond.

When a very pure clay is desired, the clay slip is led through several settling pits before filling the final settling pond. During the slow flow through the intermediate pits, the fine sand particles will settle and only the much finer clay particles will flow on.

After the clay has settled in the settling pond, the clear water on top can be transferred by pump or by bucket, back to the stirring pond, which first has been emptied of its sand. The bucket or pump intake should not be dipped into the settling pond since that would stir the settled clay. Instead the surplus water is led to a small pit next to the settling pond, and water is taken from here. For each stirring pond several settling ponds are needed. The clay is then left in the settling pond until it is stiff enough to be removed for further drying.

3.1.3 Washmill

For large quantities of clay an animal powered washmill is useful (fig ??). The circular tank is half filled with water and raw clay, preferably dry and without large lumps, is added while stirring, until the tank is almost full. After stirring for 1–2 hours (depending on the properties of the clay), the clay will be suspended in the water, while stones and coarse sand settle at the bottom. The clay slurry is then run into settling ponds.

The washmill can also be operated continuously; first it is filled as described above and when the clay and sand have been separated, more raw clay is added gradually. The added raw clay will sink to the bottom, where it is worked by the harrows, and an equal amount of clay slurry will run off at the upper outlet. Fresh water is added from a pit with an inlet at the bottom of the tank. After operating the washmill continuously for some days, sand and stones accumulated at the bottom of the tank has to be cleaned out.

Sand Separator

If the fine sand content of the clay is not desired, the slurry is run (on its way to the settling tanks) either through a fine mesh sieve, a grooved tray (fig ??), a series of settling tanks (fig ??) or a sand separator (fig ?? and fig ??).

Washmill Construction

The washmill is built of bricks laid with cement mortar. The centre section supports the beam that turns the harrows. The beam turns in simple bearings, that can be made of hardwood which is kept well greased. A sluice system with adjustable outlet levels can be fitted with a grate to catch roots and other organic material. The harrows should be made of iron or of wood reinforced

with iron. Fig ?? shows how an extra set of harrows hinged onto the main harrows improves the disintegrating action. The tank should not be more than 1 m deep, and increased capacity is achieved by widening the diameter of the circular tank. A tank with a diameter of 4.5 m can wash at least 6 ton of raw clay at a time.

The washmill can be powered by one or two persons or by a draught animal. A motor could also power the washmill, but since a rather high gear ratio is needed, the washmill becomes much more costly. Alternatively, the raw clay can be washed in a high speed blunger.

3.2 Clay Body Preparation

Two different methods are used for preparing the clay for production: dry and slop. Each method has many variations, and the right choice of techniques and machinery depends very much on the nature of the clay and on the type of ware to be produced. Therefore, before deciding on any method, the clay should first be tried out thoroughly—from preparation of clay to forming, glazing and firing.

3.2.1 Dry Method

After weathering, the clay is dried completely. If the clay can be used as it is, without having sand or stones removed, the dried clay is wetted directly and left until it has a plastic consistency. Then it is kneaded manually or in a pugmill. fig ?? shows such a system with dry clay stored in the back, a slaking pit in front, plastic clay covered under wet cloth ready to be pugged.

In most cases, however, sand and other impurities have to be removed. The dried clay is then first pulverized either manually by a lever hammer, or with the help of a hammer mill or pin mill.

Lever hammer

The lever hammer is operated by two persons. One steps on the short lever, thereby lifting the long lever onto which a heavy iron or wooden hammer is fixed. This falls on the clay, which is fed to the hammer by the second person, who may also screen the powdered clay.

In many countries, the same traditional machine is used for rice hulling.

Hammer mill

A hammer mill or plate mill of the type used for grinding grain may be cheaper to operate compared to the lever hammer. It can be powered either by an electric motor or small diesel engine. In the hammer mill, a number of small exchangeable hammers are mounted on a rotating disk. The hammers disintegrate the material by impact until the particles are small enough to pass through a curved screen. The screens can be changed, so that coarse material like grog can be produced as well.

The rotation of the hammers produces suction at the centre and pressure at the perimeter. Therefore, the inlet of material should be at the centre the point of suction. The pressure helps to blow the ground material through the screen. The outlet should lead into a big cotton bag that retains the clay but

lets the air through. Some hammer mills have the inlet at the perimeter, and that produces a lot of dust, which is a health hazard to the operator. The dust nuisance can be reduced by fixing an outlet with a long tube on top of the mill casing to release air pressure.

Pin mill

This mill has a rotor fitted with beaters which rotate between stationary pins. The material is fed through a hopper to the centre of the mill. The rotating beaters hit the material and fling it outward where it hits stationary pins. When it is fine enough, it passes the sieve surrounding the rotor.

The pin mill is suitable for slightly moist clay materials, which otherwise tend to clog the hammer mill screen.

Screening

After the clay has been pulverized, it can be mixed with other dry materials like sand, limestone, feldspar, kaolin, talc or grog (see p. 47). The mixture should be screened again, or put through the hammer mill an extra time in order to ensure proper mixing of the different materials.

For larger potteries a vibrating screen as shown in fig ?? will be useful. The screen can be replaced so it can be used for different particle sizes.

Wetting

Water is then added to the clay, either by pouring water into a pit in the centre of the clay and leaving it to be absorbed, or by sprinkling an even amount of water onto about 5 cm thick layers of clay, which are then covered by subsequent layers. After soaking, the clay is kneaded either by foot or hand. The clay should then be left in a moist place for at least a week. This could be a clay cellar, or a clay pit covered with wet cloth and plastic sheets.

Prolonged storage will improve the plasticity of the clay and give it a stiffer consistency.

Kneading

After storage, the clay should be kneaded again, either manually or in a pugmill. A vertical pugmill can be constructed locally. An animal powered pugmill of a type often used in brickworks is shown at fig ??. The barrel is made from metal or wood and a vertical shaft is fitted with blades set at a slight angle, which forces the clay downward.

Conclusion

The advantage of the dry method is that little equipment is needed. Its drawbacks are that the workers are exposed to unhealthy clay dust, and that the clay only develops its full potential plasticity after prolonged storage. In some cases, troublesome impurities can only be removed by the slop method.

3.2.2 Slop method

The clay is made into a slip, other materials are added, and after screening the slip is dewatered until the clay has the right consistency. There are numerous variations of the slop method and a few examples are described below.

3.2.3 Industrial slip house

In industrial production of white ware, clay bodies are made up of several different clays, with additions of feldspar, quartz and other materials. Feldspar and rock quartz are first crushed to the size of gravel (2–4 mm) before further grinding in a ball mill. For that, one of the following machines is used.

Jaw crusher

This machine is used for the initial crushing of rocks (fig ??). Large lumps of rock are reduced to 15-25 mm pebbles. This initial reduction can also be done manually with a hammer. A jaw crusher is often used for producing grog.

Roller crusher

Crushing rollers are used for breaking down lumpy clay or shale. The rollers may be smooth or with grooves, and they rotate in opposite directions to each other. The space between the rollers can be adjusted.

Pan grinder

One or two heavy wheels made of granite or steel rotate on a pan of similar material and crush the pebble size material to sand (fig ??). In some cases, the pan is perforated. The pan grinder can also be used for crushing grog and for preparing clay bodies, especially granulated bodies for dust pressing of tiles.

Hammer mill

The hammer mill is widely used because it is so versatile. It is mainly used for softer materials like clay, limestone, talc and gypsum, but can also be used in an emergency for grinding feldspar and quartz, provided these have first been shattered by calcining above 600°C. The hard materials will quickly wear out the hammers and the sieve of the mill. ball mill: the final grinding takes place in a ball mill, which can grind materials up to coarse sand size. A ball mill is a hollow mild steel cylinder, lined with special bricks made of hard rock (like granite), or porcelain, or a thick rubber sheet. The ball mill is filled about 50% with pebbles of flint or porcelain, 25% material for grinding and 20% water (measured by volume). The ball mill is rotated slowly, so that the pebbles constantly roll down the inner slope of the cylinder, and the material is ground by the rubbing action between the pebbles. (See appendix ??).

In large factories, each raw material is ground separately and then mixed in a blunger according to its slop weight. In smaller factories kaolin, feldspar and quartz are measured by dry weight and milled together. In that way the total ball milling time can be reduced by adding kaolin after the harder materials (quartz and feldspar) have been milled for some time.

A coarse screen fitted to the ball mill holds back the pebbles while the clay slip is poured out and led to a blunger through wooden troughs.

Blunger

In the blunger (mixing ark) plastic sedimentary clay (often ball clay) is added to the milled materials. The blunger shown at fig ?? stirs the clay slip by rotating two sets of blades at 17 rpm (rotations per minute), and blunging time for ball clay is more than 10 hours. A high speed blunger with a single shaft propeller (fig ??) cuts blunging time to 1–2 hours and is now replacing the slower type.

Screening and de-magnetizing

After blunging, the clay slip is screened through a fine mesh screen (80–150 mesh per sq. inch). The screen is vibrated to prevent it from getting clogged. By fitting a coarser sieve mesh above the fine mesh screen the clogging problem can be reduced. 2- and 3-deck screens are commonly used.

In production of white ware, the clay slip is passed through magnets that catch iron compounds, which would otherwise produce brown specks in the fired product. The magnets are either permanent magnets or electromagnets. Old loudspeaker magnets suspended in the blunger are adequate.

Filter press

The clay slip contains about 50% water when being screened, and half of that must be removed before the clay has the right consistency for forming. In modern industries, dewatering is done in a filterpress. This consists of a series of frames which form chambers when fitted together. Each chamber is lined with a filter cloth, and the slip enters the chambers through holes in the frames. The filter cloth is hung over both sides of the frame and the two halves of the cloth are sewn together around the inlet hole. The frames are fitted together in one long row, and sealed by tightening a heavy screw.

The clay slip is then pumped into the filterpress under pressure ($7-10\text{ kg/cm}^2$) and the water is forced out through the filter cloth. The water drains away through grooves in the frames.

Filtering time varies according to the particle size of the clay and the pumping pressure. Filtering of a coarse grained kaolin clay may take only two hours, whereas a highly plastic clay may take 8 hours. After the water has stopped dripping from the frames, the tightening screw is opened and stiff clay cakes are removed from between the frames and transferred to the clay storage.

Compressed air pump

A durable and simple filterpress pumping system can be made with the help of an air-compressor and a tank capable of handling pressures up to 10 kg/cm^2 . At the bottom of the tank a pipe connects to the filterpress inlet. After filling the tank with clay slip, compressed air is pumped into the tank. An adjustable pressure valve maintains the desired pumping pressure. When the clay in the filterpress is dewatered, the compressed air is shot off, the pressure in the tank is released and another batch of clay slip is loaded.

This system has several advantages over a conventional piston pump system:

- The clay slip is forced through the filterpress under a constant pressure, thus reducing filtering time and lamination problems.
- Maintenance cost is very low, since no moving parts come in contact with the abrasive clay slip.
- The pump system is much cheaper and it can be made from locally available parts.
- It uses very little energy.

The pressure tank is the most expensive part, but this cost can be reduced by using a smaller tank, which is then charged twice during one filterpress operation.

Pugging

The clay is then left to mature in the storage area for at least two weeks in order to improve its plasticity. However, the clay still requires hand or machine kneading to remove entrapped air and make the clay uniform.

Kneading table

A kneading table works the clay with horizontal and vertical rollers (fig ??). The upper horizontal rollers press the clay down, and afterwards the vertical rollers press the clay up. This alternate movement up and down squeezes entrapped air out of the clay and gives it a uniform consistency. The clay is laid in a circular wad on top of the kneading table, and each operation takes about 50 minutes.

The kneading table is mainly for bodies with low plasticity, like porcelain bodies, but is little used today.

Pugmill

The pugmill has replaced the kneading table in modern ceramics plants. It is a more costly machine, but it produces a better quality clay, especially if the clay is de-aired during pugging. The pug mill consists of a large cylinder with an axle running through its centre.

Sets of iron blades are attached to the axle and these both cut the clay and move it forward. Clay is fed from one end and pressed out through a mouth piece at the other end in a continuous column, that is cut up in convenient pieces ready for forming.

The flow of clay through the cylinder is not even. The clay at the centre moves at a different speed compared to the clay next to the cylinder wall, and this produces different densities in the clay body. That causes stress in the finished ware, which may warp during drying or crack during firing (these special cracks are called lamination cracks). Hand kneading after pugging is often required.

A de-airing pug mill takes the clay through a chamber where a strong vacuum is maintained by a vacuum pump. In this vacuum all entrapped air is sucked out of the clay, which greatly improves its plasticity. At the same time, de-airing reduces the problems of lamination stresses in the finished products.

Chapter 4

Nature of Clay

A look into the chemical and physical properties of clay will help in understanding its behavior, and how to correct problems like cracking and warping which occur during drying or firing.

4.1 Simple Clay Chemistry

Chemistry is the science which describes what substances are made of and how they combine with each other. This science makes use of special names and symbols. Once learned, they are quite simple to understand.

4.1.1 Elements

An element cannot be broken down into more simple substances, and it consists of only one kind of atom. Oxygen (O) is the most common element on earth.

4.1.2 Compounds

A compound is composed of different elements bound together chemically.

Water (H_2O) is a compound made up of two parts, or atoms, of hydrogen (H) and one part, or atom, of oxygen (O). Silica (SiO_2) is another compound and consists of one silicon atom (Si) and two oxygen atoms (O). This is the most abundant material in the earth's crust.

Ceramic minerals are usually in the form of oxides: this means oxygen (O) is a part of the compound. Minerals are compounds.

4.1.3 Mixture

A mixture is a physical, not chemical, combination of compounds (and sometimes elements), and each compound remains chemically unchanged in the mixture. For example, a glaze made of feldspar, quartz and limestone is initially a mixture, but during firing a chemical combination takes place and the fired glaze changes into a compound.

4.1.4 Chemical Symbols

There are about 100 elements and each of these has a name and a chemical symbol, which is used as a shorthand name.

Oxygen is written as capital O and hydrogen as H, whereas other symbols have two letters: silicon = Si and aluminum = Al.

Compounds are written in a similar way, with capital letters marking the individual elements:

- *Water* = H_2O
- *Salt* = NaCl

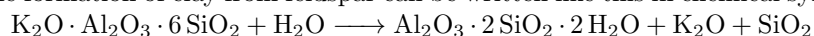
The small number 2 in H_2O indicates that there are two atoms of hydrogen for each atom of oxygen in water.

Formulas of complex ceramic materials are written as combinations of oxides with a high period (·) between them to show they are chemically combined.

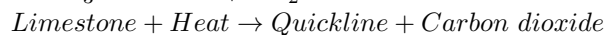
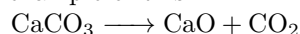
For example, potash feldspar is written $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$

4.1.5 Chemical Reactions

The formation of clay from feldspar can be written like this in chemical symbols:

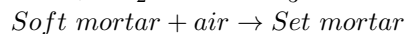
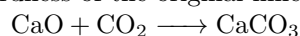


All materials are made of elements which are chemically bonded together. However, under certain conditions, a material may be changed into another by changes in the elements making up the material. Heat often provokes such chemical changes, and the production of quicklime by heating limestone to 900°C is an example of this:



Carbon dioxide (CO_2) mixes with air, and the remaining quicklime (CaO) is slaked with water and can then be mixed with sand to form a mortar for house construction.

The trick is, that the mortar sets (becomes hard) when the calcium oxide (CaO) takes back carbon dioxide (CO_2) from the air and thereby regains the hardness of the original limestone (CaCO_3):



4.2 Chemical Changes in Clay Crystals

4.2.1 Kaolinite

There are several types of clay minerals, so in individual clays the clay particles or crystals may differ. The clay mineral found in kaolin clay is called kaolinite and its formula is $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

This shows that for each part of alumina there are two parts of silica and two parts of water. The water (H_2O) of the clay mineral is not the physical water added to the clay to make it plastic, but chemical water existing within the kaolinite crystal itself.

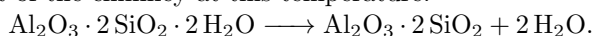
When kaolin clay is fired, several changes occur within the clay crystal, as shown below. (It is, however, not necessary to remember these chemical reactions in detail. They serve here as illustrations of chemical changes taking place in the fired clay.)

100–200°C

Physical water evaporates.

450–600°C

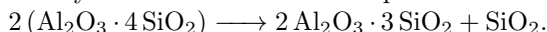
The chemical water in kaolinite is released and steam can often be seen coming out of the chimney at this temperature.



The release of the chemical water causes a weight loss of 13.95% and the kaolinite crystals are permanently changed. This is called the ceramic change, in which the clay loses its plasticity forever.

950°C

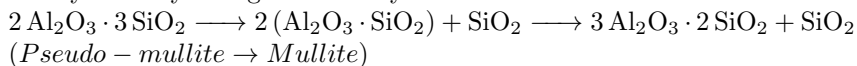
A new crystal is formed at this temperature and the process is:



One part of silica is released and adds to the free silica in the clay body. Free silica may already be present in the form of sand.

1100–1400°C

Gradually the clay changes into a crystal called mullite:



More silica is released during mullite formation and the alumina content increases. Mullite crystals are long and needle shaped, and form a lattice structure which reinforces the clay body in much the same way as iron bars reinforce concrete structures. The silica is released in the form of cristobalite crystals which may cause dunting on fast cooling.

4.2.2 Montmorillonite

There are several other types of clay minerals, but we shall only discuss montmorillonite, which is often present in native clay along with kaolinite.

The montmorillonite mineral has this formula: $\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$

This mineral contains 4 silica (SiO_2) for each alumina (Al_2O_3) which is twice as much compared to the amount of silica in kaolinite. Its crystal structure is also different from kaolinite, and it easily breaks into smaller particles. That makes the clay extremely plastic and gives it a soapy feeling.

An addition of 1% pure montmorillonite to a clay body may improve its plasticity as much as an addition of 10% of ball clay.

Bentonite is a primary montmorillonite clay mined in the U.S.A., but the term bentonite is often used for other commercial montmorillonite clays as well.

The release of free silica, takes place in montmorillonite above 950°C, but almost double the silica is released, compared to kaolin. Therefore, clay bodies

with high amounts of montmorillonite contain a high percentage of free silica after firing, which may cause the ware to crack during cooling.

4.3 Physical Nature of Clay

4.3.1 Shape and Size of Clay Minerals

The clay crystals of kaolinite are shaped as flat hexagonal flakes (fig ??). They are extremely small and can only be seen with the help of an electron microscope. Each crystal contains thousands of layered sheets stacked on top of one another as in a pack of playing cards. The sheets are only loosely bonded together and they easily break into thinner flakes, which retain their hexagonal shape.

4.3.2 Water of Plasticity

Plasticity can be defined as the property of clay that enable it to be shaped without cracking and keep its new shape. This property is only found in clay.

Clay owes its plasticity to its thin plate like particles. When the clay is in a stiff plastic state, a thin film of water surrounds each clay particle. This film of water acts as a lubricant and enables the particles to slide past one another when the clay is formed, but the particles stick to one another and retain the shape once forming stops.

When more water is added to the plastic clay the clay particles start to move more freely and cannot hold onto one another as before. The clay becomes very soft and cannot retain its shape. After adding more water the clay becomes liquid, and in this state it is called a slip.

4.3.3 Particle Size

Plasticity, or the ability of the clay particles to hold onto one another, is directly related to the size of the clay particles. The smaller they are, the greater the total surface area and the more there is to hold onto.

A clay with large particles cannot pass our rope test, whereas a fine plastic clay can be bent without breaking. Each of its fine particles needs only to move a little to accommodate the bending, whereas the particles of the coarser clay have to move so far that they break apart.

4.3.4 Electrical Charge

Clay particles behave like small magnets, which attract each other when they have opposite polarity (North-South or plus-minus) but repel each other when they have the same polarity. The polarity of the particles depends on the non-clay materials. When the clay particles repel each other, the plasticity of the clay is low; whereas when they attract each other, the plasticity is high and more water is needed to make the clay soft.

4.3.5 Souring

Many sedimentary clays contain carbon (decayed vegetable matter), which make the clay sour (acid) during storage. The acid polarizes the clay particles so they

attract each other, thereby increasing the plasticity of the clay. Adding calcium to a clay has a similar effect.

Additionally, aging clay allows bacteria to produce colloidal gel, a sticky slippery substance that adds to plasticity.

4.3.6 Casting Slips

A typical clay needs a 100% addition of water to make it into a slip. For slip casting it is desirable to have as little water as possible, in order to reduce problems of shrinkage and wet plaster molds. Addition of washing-soda and water-glass (sodium silicate) changes the electrical polarity of the clay particles so that they repel each other and as little as 50% addition of water will make the clay into a slip.

4.3.7 Strength

A clay containing very fine particles will collapse under its own weight during forming, because the particles slide too easily. Addition of coarser particles will give “bone” to the plastic clay by preventing the fine particles from sliding excessively. The additive can be sand, grog or a coarse clay like kaolin.

4.3.8 Effect of Clay Preparation

Clay crystals tend to cling together in lumps, that behave like large particles. By blunging the clay, especially in a high-speed blunger, these lumps can be broken down. Prolonged storage (also called aging) of the plastic clay under moist conditions gives the water time to penetrate the lumps of clay crystals and surround the individual crystals with its lubricating film. Water helps to break down the individual crystals, and so furthers the plasticity of the clay. Kneading and pugging brings the clay particles into closer contact, and helps to remove air pockets. This improves the strength and plasticity of the clay, and prevents forming or firing problems due to trapped air.

4.4 Drying

After forming, the next step in pottery production is drying. All potters have experienced warping or cracking during drying, so let us look at the causes of these problems.

4.4.1 Surrounding Air

In the drying process, all the lubricating water (also termed water of plasticity) has to get out of the clay and into the surrounding air. When the water content of the clay is equal to the surrounding air the process of drying stops.

4.4.2 Drying Shrinkage

Fig ?? shows 4 stages of a clay from forming condition to bone dry. “A” shows the clay in its plastic state; all particles are surrounded by water (shown as small dots) and they easily slide when the clay is formed. When the clay is left

to dry, the water moves from within the clay to its surface through the pores between the clay particles.

As the water leaves the spaces between the particles, they move closer together and will finally touch one another as shown in “B”. The clay shrinks as the water disappears, so clearly the more water a clay requires to become workable, the more it will shrink on drying. That also means that the more plastic a clay is, the more it shrinks. At this stage, termed leather hard, there is still plenty of water left between the clay particles, but since these are already in contact no more shrinkage will take place.

4.4.3 Pore Water

The water between the clay particles will continue to move out of the clay until the moisture content is the same inside and outside the clay. The remaining water is called pore water, and the finer the clay particles, the higher the amount of pore water. Only when the clay is heated to above 100°C will the last pore water escape.

The pore water may be as much as 5% of the clay weight, and it is therefore important that the initial heating of the kiln is done very slowly, so that this pore water can escape before it turns to steam at 100°C. Steam will crack the pot or cause pieces of it to explode.

4.4.4 Rate of Drying

All potters know that clay dries faster in dry, warm and windy weather, and that the rate of drying can be slowed down by covering the clay with plastic sheets or wet cloth. Clay ware must dry evenly so that it shrinks evenly. A handle on a cup tends to dry faster than the cup itself, and the different rate of shrinkage will produce a crack in the handle unless care is taken to let the whole cup dry slowly.

Water from the core of the clay travels through the thickness of the clay to the surface, through all the small gaps between the clay particles. Therefore, clay with very fine particles dries slowly, and coarse clay dries faster. Fig ?? shows how the water in a very fine clay cannot pass through the outer layer of the clay, which has already dried and closed the gaps. This can be corrected by “opening up” the clay: i.e. adding grog, sand or another coarse grained clay (fig ??).

Ware with thin walls dries quickly and evenly. Thick-walled designs are more likely to warp or crack. They should be dried very slowly, and additions of sand or grog up to 20% are very helpful.

4.5 Particle Orientation

4.5.1 Unstable Particles

Playing cards standing on their edge are very unstable arrangements and clay minerals, having a rather similar shape, behave in the same way. When pressure is applied, clay particles position themselves with their flat sides facing the pressure.

4.5.2 Particle Orientation

An example of this is shown in fig ?? . A clay with its particles randomly positioned is left to mature for a long time. Gradually the force of gravity causes the particles to orientate themselves with their flat side facing the pull of gravity.

4.5.3 Differential Shrinkage

Such alignment of particles produces higher drying shrinkage in one direction, since more particles (and more water) are stacked in that direction. The additional water causes greater shrinkage during drying, and the shrinkage in one direction may be several times greater than in the other direction (fig ??). This difference may cause problems in drying and firing.

4.5.4 Throwing

When throwing a pot on the wheel, pressure is applied to the wall of the pot from both sides and the clay particles will position themselves parallel to the wall (fig ??). In forming the bottom of the pot, pressure should be applied towards the wheelhead, while moving the fingers from outside to the centre. Otherwise, the particles will not be aligned, and the bottom will crack (fig ??).

4.5.5 Extrusion

When forming clay by extrusion, particle orientation takes place when the clay is forced through the die (fig. 43-5). A screw extruder produces another problem, called lamination, by the pressure from its screw blades. In the extruded column of clay a spiral lamination is formed. This may cause products to warp or crack during drying or firing.

4.5.6 Slip Casting

In a slip casting mould, the suspended clay particles are sucked towards the inner wall of the plaster mould, and they align themselves with their flat sides towards the mould face (fig. 44-1). If the design of the cast has sharp corners, the particle orientation (and thereby the direction of shrinkage) will be at right angles to each other and the pot may crack here during drying.

4.5.7 Kneading

During prolonged storage the clay particles position themselves according to the pull of gravity and one purpose of kneading (wedging) the clay before forming is to break up this particle orientation.

4.5.8 Firing

During firing, shrinkage also takes place, and particle orientation may create problems of warping similar to those mentioned for drying.

4.6 Firing

The clay body goes through a number of stages during firing.

> 120°C: Water Smoking

The water of plasticity evaporates first and then the pore water. Rapid increase of temperature will build up steam pressure, and may crack the clay.

220°C: Cristobalite expansion

Cristobalite is created from silica at temperatures above 900°C. When the clay is fired a second time it will expand nearly 3% at 220°C. On cooling, cristobalite shrinks again. Rapid cooling at this temperature may crack ware.

350–600°C: Ceramic Change

As described above, the chemically bound water of the clay crystal is released. The clay is very fragile and porous at this point. The clay particles are held together by a sort of “spot welding” at the points of contact. This process is called sintering (fig ??).

573°C: Quartz Expansion

The quartz crystal (SiO_2) expands suddenly and will shrink again at this point during cooling (about 1%). The clay structure during heating is still open enough to accommodate this change, but if cooling is too rapid, the ware may crack.

500–900°C: Oxidation

Organic matter in the clay is burned out. If the clay has a black core after firing, then this stage of firing was done too fast. When the rise of temperature is very rapid, the surface may vitrify before the carbon dioxide inside the clay has escaped, and the entrapped gas will bloat the clay at a later stage of firing. “Bloating” is seen as bubbles or voids, which occur inside the clay and on the surface.

Limestone (CaCO_3) gives off its carbon dioxide (CO_2) at 825°C.

> 900°C: Vitrification

At this temperature the soda and potash in the clay will start to form a glass by combining with the free silica. As the temperature rises, more and more glass will be formed, involving materials like limestone, talc and iron oxide. The melted glass will gradually fill the pores between the clay particles as shown in fig ?? . This vitrification process also causes the clay to shrink.

4.6.1 Firing Shrinkage

Firing shrinkage is a simple indication of how much a clay is vitrified. Another indication is how much water the fired clay can absorb. Vitrified clay has more glass filling its pores, so it absorbs less water.

4.6.2 Glass Melt

The melted glass formed in clay bodies is normally stiff, and will not cause the clay to collapse suddenly. Feldspar produces a stiff glass that allows for a long firing range. Limestone, on the other hand, only becomes a strong liquid flux when fired to above 1100°C. This will cause the ware to collapse suddenly

Glass of vitrification produces a strong finished body. But if the body is fired too high it will lose strength and become brittle.

Chapter 5

Clay Bodies

5.1 Raw Materials

Only a few clays can be used as they are found in nature for pottery production. Most often, addition of other clays or materials like sand, limestone or feldspar is needed to produce a mixture suitable for specific forming and firing techniques. A mixture made up from different clays and materials is called a clay body.

Different methods of shaping demand different types of bodies. For the potter's wheel a good plastic clay is desirable, whereas much less plasticity is needed for pressing of tiles.

The ingredients of a clay body can be divided into four groups according to their function: plasticizer, filler, opener and vitrifier. The plasticizer is used for increasing the plasticity, the filler is the cheap bulk material, the opener promotes drying and reduces plasticity, and the vitrifier or flux makes the body more fusible.

All the non plastic materials like feldspar, whiting etc. also work as openers of the body.

5.1.1 Kaolin

This is a primary clay and therefore rather coarse, with little plasticity. Kaolin opens up a plastic clay, so that it dries more easily. It is a refractory clay, increasing the melting point of the body, and it makes the body more white. The clay mineral in kaolin is kaolinite, which benefits bodies. Kaolin is a more costly material for clay bodies. Raw kaolin, i.e. unwashed kaolin containing high amounts of silica sand, is cheaper and beneficial if the clay body can tolerate the extra sand.

5.1.2 Ball Clay

This is a secondary clay with fine clay particles, which make it very plastic. Ball clay normally fires white, but the term is sometimes used for any highly plastic clay used to increase plasticity of a body. The white firing types increase maturing temperature of fusible clays and add whiteness.

Many ball clays are grey or black when dug, indicating a high content of vegetable matter (carbon). 10%–20% addition of ball clay greatly improves the

plasticity and green strength of a clay body. A white firing ball clay is normally expensive.

5.1.3 Native Clay

This simply means a secondary clay, firing to a red or buff colour. It makes up the bulk of the body for buff or dark firing earthenware and stoneware. Preferably, it should be dug close to the site of the workshop to keep its cost down. In the best of cases, it can be used without any additions. Adjusting the properties of a native clay can be done by adding kaolin for opening up the clay to reduce drying cracks, or by adding ball clay to improve its plasticity, as listed in fig ?? . However, it is better and cheaper to try to find another native clay that can do the same job.

5.1.4 Bentonite

This is the commercial name for an extremely plastic clay also known as montmorillonite clay. It exists in smaller quantities in many natural clays, but in pure form it is used as a drilling fluid, in paint and chemical industries and for binding molding sand for iron casting.

In ceramics it is used to increase plasticity and green strength of clay bodies, and an addition of 1–2% to a glaze helps to keep the glaze materials suspended. An addition of 1% bentonite may increase plasticity of a clay body as much as 10% ball clay.

When montmorillonite is present in larger amounts it may cause drying trouble, because of its high shrinkage and reluctance to dry at all.

5.1.5 Feldspar

Feldspar is a very common mineral found in most primary rocks in amounts up to 60%. It is used as a flux in clay and glazes. Many different types of feldspars exist, the main groups are: potash spar, soda spar and lime spar.

Melting point: 1100° to 1260°C. A mixture of 65% potash spar and 35% soda spar has the lowest melting point.

Feldspar is mainly used in porcelain bodies and white firing stoneware but the cost of grinding the feldspar limits its use for other type of ceramics. As a substitute, most rocks (both granitic and volcanic) can be used. A cheap source of ground rock is the dust produced where stones are crushed for road or building construction.

Feldspar can be recognized by its pearly lustre and opaque appearance. The crystal has two main cleavages, that are nearly at right angles to each other. The colour is whitish, grey or different shades of red. Once a feldspar has been shown to you, you will easily recognize feldspars on your own.

5.1.6 Nepheline Syenite

Nepheline syenite resembles feldspar but contains less quartz; so its melting point is lower, and it can be used as a body flux at temperatures above 1060°C. Rocks containing nepheline occur widely. Nepheline rocks contain about 2%

iron oxide, which will color white bodies. Commercial nepheline syenite has had its iron oxide removed by magnetic separation.

5.1.7 Glass Powder

Ground glass is a cheap source of flux for both clay bodies and glazes. Broken glass can be collected from breweries or window glass shops. The low melting point of glass makes it a good body flux for production of vitrified earthenware, but it has to be ground to a fine powder and mixed very well with the other materials.

5.1.8 Limestone

Calcium carbonate is the chemical name for whiting, limestone, chalk, marble and coral. All these materials can substitute for one another in clay bodies. They are cheap and easy to grind, and can be used in both clay bodies and glazes as flux. Carbon dioxide is given off before 900°C ., and what is left is calcium oxide. The weight loss amounts to 44%. The carbon dioxide gas may produce pinholes in once fired raw glazed ware. Wollastonite ($\text{CaO} \cdot \text{SiO}_2$) does not give off carbon dioxide during firing and can substitute for limestone in fast firing bodies.

Calcium oxide should be kept under 2% in stoneware bodies. It is mainly used in earthenware. Its fluxing action is strong, and gives the clay a narrow firing range. Above 1100°C . fluxing action increases rapidly, causing high limestone ware to collapse suddenly. Calcium oxide in the body decreases the tendency of glaze crazing, and it decreases the red coloring effect of iron oxide.

5.1.9 Talc

Talc is usually cheap, and it occurs in many locations throughout the World. Solid forms of talc are known as steatite or soapstone. Talc deposits may contain impurities like limestone, quartz, clay and iron. Its colour varies from white, greenish, or grey to brown, but it fires to a cream or white colour or grey if its iron content is high. Talc from different deposits varies, therefore testing is needed before using talc from a new source.

Talc improves resistance to thermal shock and acid. It reduces the tendency of glaze crazing, by preventing expansion of the clay after firing due to moisture absorption. During firing the water in the talc mineral is released, causing a weight loss (loss on ignition) of about 6%. Talc starts to work as a flux around 1030°C , and it produces a stiff glass compared to other fluxes. That gives it a long vitrification range, and the ware will not suddenly collapse when overfired as is the case of limestone. Talc is able to produce a vitrified body and at the same time reduce the tendency of warping and firing shrinkage. Small additions of talc reduce the melting point of the clay body; large additions make it more refractory.

Talc powder has a small amount of plasticity. In plastic forming and slip casting talc causes no problems, but in semi-dry press molding, some types of very fine grained talc may produce lamination problems. This can be overcome by ensuring proper wetting of the talc particles, followed by granulation of the body allowing air to escape during pressing.

Talc is especially valuable for fast firing bodies and for production of wall tiles and electrical insulators.

5.1.10 Dolomite

Dolomite behaves in a body as a more or less equal mixture of limestone and talc would do, except that no silica is introduced. Loss on ignition is around 45%.

5.1.11 Quartz

Quartz is a crystal form of silica or silicon dioxide. Silica is found as part of rocks and clays and it is so common that it makes up 60% of all materials in the crust of the Earth. As a free mineral, not combined in clay and other materials, it occurs as quartz, silica sand, sandstone, and flint pebbles. The cheapest source of silica is sand. All sands contain silica in the form of small quartz crystals, but a particular sand may contain small crystals of other minerals e.g. mica. That should not cause problems in a clay body, unless the potter attempts to produce white flawless porcelain.

Additions of silica make the clay more refractory and open up the body, thereby reducing shrinkage and drying problems. As is the rule with all other ceramic materials, the finer the particles, the more actively the silica will combine with other minerals and form a glassy substance with the fluxes in the clay during firing. When the silica in the body remains free (uncombined chemically), it expands and shrinks suddenly at certain temperatures, as shown on the graph in fig ???. These sudden changes may cause the fired body to crack, but they also assist in prevention of crazing as explained below.

5.1.12 Grog

Grog is crushed, already fired clay. The quality and behavior of the grog depends on the original clay. It is extensively used in production of firebricks, saggars and other refractory products, for reducing firing shrinkage and increasing thermal shock resistance. In clay bodies for crockery and tiles it is mainly used to improve the forming and drying characteristics, without changing the final composition of the body. Grog gives "bone" to the body during plastic forming, eases its shaping and prevents it from collapsing during throwing on the wheel. It reduces the problems of warping and cracking during drying (as sand also does), but without adding the problems of cooling cracks that quartz sand may cause.

Grog is normally produced by crushing unglazed waste products in a hammer mill or in a pan grinder. The grog particles should be sharp edged.

5.1.13 Coloring Oxides

Oxides used for coloring clay bodies have to be fairly cheap. That excludes most oxides, leaving us with iron oxide, manganese dioxide and ilmenite. Coloring of engobes for decoration will not be dealt with here.

Iron oxide exists in two main forms. Red iron oxide (Fe_2O_3) is the same as rust, and has a dark red color. Black iron oxide (Fe_3O_4) has a coarser particle

size than red iron oxide. Black iron oxide can be produced by roasting iron metal to 400° to 700°C in the flue channel or chimney of the kiln. The black crust of oxide is knocked off the metal and ball milled. Ochre is a yellowish material often used for painting houses. It contains iron oxide in a mixture of clay, sand and sometimes limestone. When the ochre contains manganese, it is called umber. Both materials can be used as coloring agents in clay and glazes. Ilmenite ($\text{FeO} \cdot \text{TiO}_2$) is a black crystal, often occurring as black stripes in beach sand together with zircon sand.

The coloring effect of iron oxide depends very much on the atmosphere and temperature in the kiln:

- Iron oxide in an oxidizing firing below 1020°C will produce a brick red colour.
- Oxidizing firing to 1100°C turns the red colour darker and brownish.
- In a reducing firing the colour will be grey or black.

Above 1000°C iron oxide acts as a strong flux in reducing atmosphere, but when the condition is oxidizing, its fluxing action only starts above 1200°C. Whiting present in the clay has a bleaching effect on the red colour of iron oxide. In red firing surface clays iron oxide content is often 10%.

Manganese dioxide (MnO_2) is dark brown to black. As a colorant in clay it produces yellow, brown, purple or black colors. It acts as a strong flux. Only half a percent of manganese will give red clay a brown colour, and with increasing amounts the clay will become black. Black colors are obtained by adding a mixture of iron oxide and manganese dioxide.

5.2 Classification of Ceramics

The traditional classification of ceramic ware is in three groups—earthenware, stoneware and porcelain—is mainly based on the firing temperature. In common usage, the terms often overlap e.g. a term like “low fired stoneware” is sometimes used to describe ware that resembles real stoneware, but is made from clay bodies vitrifying at earthenware temperatures (additions of fluxes). Here we shall only deal with earthenware and stoneware.

5.2.1 Earthenware

Earthenware means pottery that is porous when fired. The firing range normally is 900–1100°C. A wide field of different products fits in this group. Traditional pottery made from local, red firing clay ware (whether glazed or unglazed) is the most common type of earthenware. Unglazed red pottery is often called terracotta. Other types, glazed with white opaque glazes, are known as Faience or Majolica. Glazed wall tiles are normally made from a porous earthen-ware body.

Fuel saving

Earthenware can be as durable as stoneware, and the lower firing temperature saves fuel. The cost of additional fluxes needed for maturing the glaze at earth-

enware temperature compared to that of stoneware is easily paid by the lower firing cost.

Dark bodies

Yellow, red, brown or black bodies are made from local plastic clay containing iron oxide. The starting point is a fairly plastic clay from a nearby source.

First test the clay, and then modify it as necessary:

- if it is too plastic, add sand, grog or a less plastic clay.
- if it has little plasticity, add a plastic clay or remove some of its sand content by washing and screening.
- if it warps during firing, add a more refractory clay or sand.
- if it has little firing strength, add a vitrifier like limestone, talc or a more fusible clay.

When looking for clay materials, keep costs in mind. Instead of adding feldspar as a vitrifier it is cheaper to add a more fusible clay. Instead of adding sand or grog, a less plastic clay could be added.

White earthenware

A body with the appearance of porcelain or stoneware can be produced for earthenware temperatures. Such a body is made with kaolin, a white firing ball clay, and large amounts of talc. Additional flux can be feldspar (preferably nepheline syenite), limestone, dolomite, frit or glass powder.

These recipes can be used as a starting point for experiments. For temperatures in the 1100° to 1200°C. firing range the flux content should be reduced.

High lime content (up to 20%) reduces the coloring effect of iron oxide.

Thermal crazing

Crazing of the glaze is a major problem with earthenware. Another problem is that glazed rims of pots easily chip off. Both problems are caused by different rates of thermal expansion of the glaze and the body. When a pot is taken out of the kiln after firing it is exposed to a sudden temperature drop. The glaze layer and the body will contract, but most often at different rates.

Shown in fig ?? is what happens when glaze contracts more than body, and body contracts more than glaze.

- Glaze contracts more

Fig ?? shows a body (white) with a glaze on top (black). The glaze and the body has contracted at the same rate and there is no tension between the two.

In this case, the glaze contracted more than the body (leaving it shorter than the body), which puts the glaze with a tensile stress (it is pulled apart). If the body is very thin it will bend as shown.

More likely, the tensile stress will be relieved by cracks in the glaze, as shown in fig ???. This is called crazing. The stress, caused by high expansion (and contraction) of the glaze, may be relieved by crazing as soon as the pot is taken out of the kiln or it may take days, months or years. If it takes a long time for crazing to appear, this means that the expansion of clay and glaze is almost equal.

When the body has been exposed to humidity for a long period, water enters the body, which expands slightly (moisture swelling). This expansion may cause a glaze to become too short and it will craze. This kind of crazing is called delayed crazing or moisture crazing.

- Body contracts more

This example shows a body with higher expansion rate than the glaze. The body contracted more than the glaze when it cooled. The glaze is under compression, and if the clay is thin it may bend as shown to relieve the pressure. If body contraction is only slightly higher than glaze contraction, nothing will happen except the glaze will not craze. If a glaze contracts much less than the body, the compression on the glaze becomes too high and the glaze will start to chip off like this. This will not happen by itself, but only if something bangs against the pot. Typically, the rim of a cup will chip off. [here insert 57-6] In extreme cases, high compression of the glaze may cause the body to crack.

Crazing cure

Crazing is cured by adjusting the expansion rate of body and glaze. If the glaze is too big for the body, it is under a constant squeeze and will be less likely to craze. This squeeze is obtained if cristobalite is present in the body.

Cristobalite

Cristobalite is a crystal form of silica (SiO_2) which is formed above 870°C , when some of the free silica in the body changes its crystal form.

The graph in fig ?? shows the contraction of glaze and body during cooling. Both contract gradually until 573°C ., when quartz crystals in the body suddenly contract about 1%. The glaze is still soft enough to accommodate this contraction. The glaze hardens around 500°C , and from then on it contracts at its own rate. In this case, the glaze contracts more than the body and it will craze.

The graph in fig ?? shows contraction of a glazed body containing cristobalite. Initially the graph is similar to the upper one, but at 226°C . When the glaze is hard, the cristobalite in the body contracts 3%, leaving the glaze in compression. In earthenware, the effect is usually only present if the body is close to vitrification.

The conversion of quartz into cristobalite is helped by fine grinding of quartz, by a higher firing temperature, and by presence of talc or limestone. Flint, a form of quartz, converts more easily into cristobalite in earthenware bodies. If the glaze is under too much of a squeeze it may crack the pot or cause shivering and peeling of the glaze.

Moisture crazing

After firing, the porous earthenware body will absorb moisture and this causes the body to expand. If the glaze is not under sufficient compression it will craze. Such delayed crazing may occur a long time after firing. The moisture expansion of the body is reduced by making the body more vitreous. Additions of talc or limestone to the body reduce moisture crazing.

Crazing cure

For both types of crazing the cure is:

- add quartz (or silica), talc, limestone to the body.
- biscuit fire to a higher temperature.
- glaze fire to a higher temperature.
- add silica to the glaze.
- replace alkaline fluxes (soda and potash) in the glaze with boron oxide.

Chipping cure

When the glaze is peeling or chipping off:

- reduce quartz content of the body.
- reduce silica content of the glaze.
- increase alkaline fluxes in the glaze.
- add feldspar to the body (above 1100°C)

5.2.2 Stoneware

If fuel cost is not important and good refractories for kiln furniture are available, the firing range from 1180° to 1300°C offers several advantages over earthenware. At this temperature less fluxes are needed, and it is often possible to find a natural clay that fires to a strong dense body with little addition of other materials. Crazing of the glaze is less of a problem, since at this temperature there is a better body to glaze bond. Even if crazing occurs, the vitrified body will remain waterproof. Another advantage is that the higher firing temperature makes it possible to rely on non-fritted fluxes, like feldspar and limestone, for the glaze.

Examples of stoneware are hotel crockery, floor tiles, sanitary wares, salt-glazed sewage pipes and utensils, electrical insulators and corrosion free vessels for the chemical industry.

Vitrification

Stoneware is hard, strong and dense. Its color varies from buff or grey to brown or black. Due to the high firing temperature, the fluxes in the body gradually melt and fill the space between the clay particles with a glassy mass. This strongly binds the clay particles together, but if the body is overfired it

becomes brittle like glass and loses its strength. Feldspar is the preferred flux for stoneware, because it has a long vitrification range and it produces a viscous glass, that does not cause the ware to collapse suddenly. To vitrify means to become glass-like.

Native clays

Many native clays can be used for stoneware, as dug or in combination with other clays. Stoneware bodies soften during firing, and large items tend to warp or sag unless grog or sand is added to the clay. Earthenware clays low in iron oxide can often be used with additions of fireclay or kaolin.

The optimum recipe for a stoneware body is found by making tests of clay bodies with varying additions of fluxes and/or refractory clay and openers like sand and grog (as listed for earthenware).

Crazing

Crazing is seldom a problem for stoneware since the body itself is waterproof. Furthermore, the body and glaze materials partly melt together and form a strong bond. At stoneware temperature, quartz readily changes into cristobalite, which further reduces the tendency to craze. When crazing does occur the corrections listed under earthenware apply.

Cracking

A more common problem with stoneware is cracking during firing, or more often during cooling.

The main cause is the change in silica crystals at 226°C and 573°C. Free silica in the form of cristobalite expands nearly 3% when heated to 226°C and contracts again when cooled to the same temperature. Free silica in the form of quartz goes through a 1% expansion and contraction at 573°C (see fig ??).

These changes take place suddenly, and because large items do not cool evenly, one part of a pot may reach contraction temperature before another. When one area contracts suddenly, the stress within the pot may cause it to crack. If pots only crack occasionally, the cure is to cool the kiln more slowly, particularly from 700°–150°C. Otherwise changes have to be made in the body.

Cracking remedies

Since the problem is caused by free silica, the cure is to reduce the amount in the body. Free silica comes from quartz or flint added to the body or present in the raw clay, or the release of silica from other clay minerals during firing. One or more of the following changes can be made:

- Grog can replace quartz sand.
- Clay containing high amounts of sand could be washed or replaced by a less sandy clay.
- The release of free silica from the clay minerals cannot be avoided, but since montmorillonite clays (bentonite) release twice as much free silica as kaolin, it may help to reduce the amount of montmorillonite clay in

the body. A well equipped ceramics laboratory can determine the content of montmorillonite clay minerals in a clay, but potters without access to such services will have to rely on practical testing of the different clays available. A clay which is difficult to dry, has high plasticity and a greasy feeling to it, should be suspected of containing montmorillonite.

- Free silica in the body is also reduced by adding a flux that will combine with the silica and form a glass. When silica is part of a glass it will not cause cracking, because glass is non-crystalline.

Chapter 6

Testing of Clay

The tests which are described in this chapter will not all be appropriate for small pottery industries. Cottage industries will be content with making, at most, shrinkage and moisture content tests. However, industries or ceramics training centres involved with development and research work should find most of the tests useful and relatively simple to undertake.

Caution: Testing should only be done for good reasons. Most private cottage and small industries do not have time or resources to carry out regular testing. However, many production losses can be prevented by testing materials when they seem to behave differently than usual. When clay arrives it is inspected, and by making a simple rope test its plasticity can be judged. An experienced thrower will immediately feel differences in the clay body, and should suggest testing to the manager.

In carrying out these tests the most important thing to keep in mind is; consistency. That means, the tests should be made in the same manner each time, so that the results can be compared.

6.1 Testing

The individual tester builds up his own set of standards by which he evaluates his test results.

6.1.1 Equipment

For most of the tests a scale, a ruler and a ceramic kiln are sufficient. A small drying oven is useful for moisture tests and thermal crazing tests. A transverse strength tester is needed for testing the strength of the green or fired clay bodies. These two pieces of equipment can be made locally.

6.1.2 Goal

The object of testing natural clays and clay bodies is:

- to find out the properties of clay from new deposits and to assess their usefulness in production. (research)

- to be sure that new supplies of familiar clays are similar to former supplies of the same clay. (quality control)
- to test the quality of new clay body mixtures (research)
- to control the quality of clay bodies used in production (quality control).

The tests required for the various situations differ. The table below suggests what test to make.

The quality of clay taken from locations only a few feet apart in the clay deposit may differ. Each lorry load of clay delivered may also differ in quality.

Therefore, the clay samples for testing should be collected from at least 4 different locations within the clay deposit or from where the clay has been dumped.

6.1.3 Quartering

Quartering ensures that the remaining portion is “average quality”. It is then used for carrying out the clay tests.

1. Mix the four samples well .
2. Divide the mixture by a cross cut in the pile.
3. Two portions facing each other are removed and the remaining two portions are mixed well.
4. This is again divided by a cross cut and steps 1-4 are repeated another 3 times.

6.2 Moisture Content

Even if the clay looks and feels dry, it will contain some water. When clay is purchased it may contain any amount of water, and if the clay is bought by weight the water is also paid for. So knowing the water content helps your profits.

Ideally, each batch of clay delivered to the pottery is tested. This test is also done for checking moisture content of plastic bodies, and semi-dry clay bodies for press molding.

1. Sample clay by quartering.
2. Weigh out 200 g (W_{moist}) of the moist clay.
3. Place the clay in a clean cup and heat it to 150°C for 2 hours.
4. Find the weight (W_{dry}) in g of the dry clay.

6.3 Particle Size

A quick test to check clay and sand content of new clay supplies is done by screening procedure.

1. About 500 g clay is dried at 150°C for 2 hours.
2. Weigh the clay.
3. The clay is made into a thin slurry
4. The slurry is screened through one or more fine sieves.
5. The residue left on each screen is dried and put on a set of scales.

This figure indicates the amount of sand in the clay. A 200 mesh sieve holds back particles bigger than 0.0076 mm and some fine sand will pass this screen, but for comparing the quality of new batches of clay with former supplies it is accurate enough.

6.4 Plasticity

6.4.1 Atterberg Number

The more plastic a clay, the more water it will absorb without becoming fluid. So the range of water content over which a clay is plastic is a measure of its plasticity.

The water range, $Lw - Pw$ is called the Atterberg number. The water contents of Lw and Pw are expressed as a percentage of the weight of the wet clay.

The higher the number, the more plastic the clay. Kaolin has an Atterberg number of 10–15, and ball clay has an Atterberg number of 10–15.

1. A portion of clay, about 300 g, is stirred with water to form a liquid slip of creamy consistency. The slip is poured into a clean plaster mould.
2. After a minute or so a knife is dipped into the slip at intervals, noting whether the incision disappears again. When the incision just remains, a sample of the clay around the incision is removed and its weight, W_{wet} is found.
3. The remaining clay in the plaster mould is turned around in the mold until it can be formed in the palm of a hand. Knead the clay between the palms of your hand until it starts to crumble.
4. At that point the plastic limit of the clay is reached and the sample is weighed to find $W_{plastic}$.
5. Dry the clay in the drying oven at 150 C for two hours and find its weight, W_{dry} .

6.4.2 Plastic Limit

The plastic limit, Pw , is the minimum amount of water required to make the clay plastic so that it can be formed.

6.4.3 Liquid Limit

The liquid limit Lw , is the minimum amount of water required to make a clay slip flow under its own weight.

6.5 Loss on Ignition

Pore water is lost around 100°C . Chemically bonded water is released at 350° – 600°C from inside the crystal structure of the clay minerals. Loss of chemically bonded water corresponds directly to the amount of clay minerals present in the clay. Chemical water is not released from sand or feldspar.

Kaolinite: $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O} \longrightarrow \text{Al}_2\text{O}_3 + 2\text{SiO}_2 + 2\text{H}_2\text{O}$ has a loss in form of water of 14%.

Montmorillonite: $\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O} \longrightarrow \text{Al}_2\text{O}_3 + 4\text{SiO}_2 + \text{H}_2\text{O}$ has a loss in form of water of 5%.

A sandy clay with kaolinite clay crystals and showing a loss of 7% would, therefore, contain only 50% clay minerals the rest being non plastic materials like sand, mica or feldspar.

Limestone: $\text{CaCO}_3 \longrightarrow \text{CaO} + \text{CO}_2$ has a loss in form of CO_2 of 44%.

If the limestone test sample shows less than 44% loss on ignition we can estimate the amount of sand or other impurities. Lime decomposes at 825° – 900°C .

The loss on ignition test is mainly used to check raw materials supplies and their quality from batch to batch. If the loss is lower than the standard, it shows that the material of that batch contains more sand or other impurities than normal.

1. Dry a sample, about 200g, in the oven at 150°C for 2 hrs in a clean bowl.
2. Find its weight, W_{dry} .
3. Fire the test sample to 1000°C or higher in an unglazed bowl.
4. After cooling but when it is still warm from the kiln, find the weight, W_{loss} .
5. Compare with results of former tests.

6.6 Shrinkage

Drying shrinkage depends on the fineness and plasticity of the raw clay. Firing shrinkage indicates the degree of vitrification of the clay or clay body at the temperature at which it has been fired (the higher the temperature, the more shrinkage).

1. Mix the clay with water to plastic consistency and knead it well.
2. Form 10 test bars of each clay to be tested. The test bars are molded in a standard mould.
3. Mark the test bars with two incised lines exactly 100 mm apart.

4. Turn the test bars several times while they dry to prevent warping.
5. After the test bars are completely dry (open air) measure the distance between the two cuts in mm.
Drying shrinkage in percent = $100 - \text{dry length (mm)}$
For the most accuracy, take the average of 10 test bars.
6. Firing shrinkage is found by firing 5 of the test bars to the intended firing temperature.
7. Measure the distance between the lines on the test bars in mm.

Here it is recommended to make many test bars in order to ensure more reliable results.

6.7 Softening Point

Clay becomes soft at high temperatures, because various impurities like feldspar, lime and iron oxide start to form a liquid mass between the clay particles. This will cause the ceramic ware to warp during firing and if the clay is used for refractories (like saggars), these may bend under load.

This test is used to compare the refractoriness of different clays.

1. Two test bars, formed as described in the shrinkage test (could be two out of the five used for shrinkage test), are suspended on two points placed 100 mm apart. This leaves the test bar between the two marks unsupported.
2. During firing, the test bar will bend and the degree of its bend is a crude measure for the clay's tendency to sag under load.

The degree of its bend (see fig ??) is measured in mm.

6.8 Porosity

A piece of clay fired to about 600°C will be very porous. As the temperature increases, the feldspar, lime and other impurities will begin to melt together with the silica in the clay, forming a glass. This will gradually fill the pores of the clay, making it less porous. This process is called vitrification, and the more a clay vitrifies the less porous it becomes.

Porosity can be tested by measuring the fired clay's ability to absorb water procedure:

1. Heat a sample of a fired body without glaze to 150°C for 1 hour, or take it directly from a warm kiln after firing.
After drying, find its weight, W_{dry} .
2. Immerse the sample completely in water, and leave it for 24 hrs.
3. After 24 hours, take the test piece out of the water, and dry its surfaces with a piece of cloth.
4. Find the weight, W_{soak} , of the soaked test piece.

Material	Absorption
Red brick	20–40%
Earthenware	5–20%
Stoneware	1–5%
Wall tiles	15–20%
Floor tiles	3–5%

Table 6.1: Levels of water absorption for various materials.

Examples of water absorption are shown in ref 6.1

A body with water absorption of 1% or less, and with low lime content, is termed acid proof. However, floor tiles for dairies and most other uses, where acid proof materials are required, can safely have a water absorption up to 3

Bodies for kiln furniture should have water absorption of 18% or more, otherwise they are likely to break due to thermal shock.

6.9 Transverse Strength

A transverse strength tester is used for testing the strength of dry green test bars of clay bodies or raw clays, and fired bodies.

6.9.1 Green Strength

The strength of green bodies is also an indirect measure of the plasticity of the body. The more fine clay particles a clay contains, the greater its strength. Clay from new deposits can be compared with known clays. By comparing the strength of new clay supplies with old ones from the same source, we can control the quality of our supplies.

Kaolin has a green transverse strength of 7–15 kg/cm², and ball clay has a green transverse strength of 20–90 kg/cm²

6.9.2 Fired Strength

By testing the fired clay body, we can check its strength. The strength of fired bodies (either glazed or unglazed) depends to a high degree on the firing temperature. Around 900°C feldspar, lime and other impurities in the clay start to melt, forming a glassy mixture which "glues" the clay particles together. This process is called vitrification.

The graphs in fig ?? show the relationship between fired strength, firing temperature, and vitrification. As the temperature rises, more and more glass will form until all spaces between the clay particles are filled with it (total vitrification). At that point the clay becomes similar to glass, and it is brittle with little strength.

6.9.3 Transverse Strength Tester

Test bars similar to the ones used for shrink- age tests are used for testing of transverse strength. The test bar is supported at two points (adjustable) and a load is applied to a point half-way between the supports (fig ??). The load is a bucket which is gradually filled with water (or dry sand). When the test bar breaks, the filling of water is stopped and the weight of the water is found.

Testing of fired bodies should be done close to the pivot (*short L2*) whereas testing green bodies can be done farther from the pivot (*long L2*). The test bar is placed evenly on the supports and the load W_2 is placed exactly half-way between the supports. An empty bucket is placed on the hook, and is counterbalanced with the counter weight. The load is made to just touch the test bar by adjusting the balance with a screw-weight.

After reading L_1 and L_2 on the ruler and measuring width (b) and thickness (t) of the test bar, the transverse strength can be calculated (all measures in cm and kg).

The same test bar can be tested 3 times by first testing it with (a) at maximum and then test the two resulting pieces again. Normally at least 3 test bars should be tested and the final result is recorded as an average of all 9 results.

The transverse strength is also called modulus of rupture.

6.9.4 Moisture

The moisture content of the test bar greatly influences the transverse strength. Therefore, the test bars should be dried to the same degree of moisture. With changing weather, that may be difficult to ensure. A safe way of establishing consistent results is, as a standard, to dry all test bars at 100°C for 2 hours.