LIME STABILISED MURRAM AS A BUILDING MATERIAL IN KENYA

by

Benedette Nabwile Waswa BSc.

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Philosophy of the University of Glamorgan, U.K.

Department of Civil Engineering and Building
University of Glamorgan, Wales, U.K.

Collaborating Establishment
Building Research Establishment (BRE), U.K.

September 1992

Dedicated to my husband
and children

Abstract

In Kenya soil is the basic house construction material for low-income groups. However, its lack of durability and low strength, are limiting factors to its use. The aim of the current research programme was to establish, for lime-stabilised murram (from Kenya), the optimum lime content, compaction pressures and curing conditions which are necessary to achieve the minimum strength required by the Kenyan standard for stabilised soil building blocks.

A comparative study was also done on murram-cement and murram-lime-gypsum.

Initially mixtures of murram containing different amounts of lime (i.e. 5, 10 and 15wt%) and murram containing different amounts of cement (i.e. 2, 4 and 6wt%) were compacted at 5N/mm^2 and cured at 30°C and 100% relative humidity for periods ranging from 1 to 4 weeks. In the extended work mixtures of murram containing different amounts of lime and lime-gypsum (i.e. 5, 10 and 15wt% lime and 5wt% lime-1.5wt% gypsum, 10wt% lime-3.0wt% gypsum and 15wt% lime-4.5wt% gypsum) were compacted into cylinders at 10N/mm^2 and cured under the same conditions.

The chemical and microstructural changes which occurred during curing were determined using thermal analysis, X-ray powder diffraction and scanning electron-microscopy.

The strength of lime-stabilised murram increases with both increase in curing time and increase in lime content. Addition of up to 6wt% cement and compacting at 5N/mm^2 pressure appears to be less effective with regard to strength development. Increasing the compaction pressure from 5N/mm^2 to 10N/mm^2 increases the compressive strength of the cured murram-lime material by amounts ranging from 50 to 100%, although only the 15wt% lime addition material meets the Kenyan standard requirement for minimum strength (1.5N/mm^2). Addition of small amounts of gypsum produces very significant increases in strength which meet the Kenyan standard requirement, however, this weakens the lime stabilised murram when exposed to wet-dry durability tests. Diluting murram with 30wt% sand enabled higher strengths to be achieved with the same lime content. Stabilising the murram with 10wt% cement and employing 10N/mm^2 pressure also enabled the minimum strength to be achieved, but the material disintegrates when soaked in water. In wet conditions therefore, gypsum addition is not recommended. Also cement stabilisation in the current work fails.

Reaction of lime with murram results in the formation of calcium silicate-aluminate hydrate (C_2ASH_8) and carbonate substituted calcium aluminate hydrate ($C_4AC_{0.5}H_{12}$). When gypsum is present the principal reaction product is ettringite which is a calcium sulpho-aluminate hydrate (C_3A3CSH_{32}).

DECLARATION

I declare that, with the exception of the assistance acknowledged, this thesis is the result of my own studies. This thesis has not been accepted for any other award or degree and is not concurrently being submitted in candidature for any other award or degree.

Signed: Waswa

Date: 28/9/92

Contents

Page

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Acknowledgements

I would like to sincerely thank the Overseas Development Adminstration (ODA) for having selected and sponsored me for this research work.

I am grateful to Dr. S. Wild, my director of studies for his encouragement and enthusiasm throughout the supervision of this work.

I am also grateful to Mr. G. Jones my first supervisor for his comments on soil mechanics and to my external supervisor Dr. D. J. T Webb of the Building Research Establishment for his advice and comments during this work.

I thank Dr. G. Rees for his permission to use the thermal analyser, Dr. J. A. Winter for his assistance on chemical analyses and Miss C.E. Rees for her help on SEM work, in the Department of Science and Chemical Engineering, University of Glamorgan.

I also thank Dr. D. P. Thompson of University of Newcastle Upon Tyne for his help on X-ray analysis.
I am grateful to Dr. M. R. Abdi for his assistance on experimental work and computer graphics.

Many thanks are extended to all the technical staff in the Department of Civil Engineering and Building, University of Glamorgan, for their assistance in the laboratory.

I am grateful to Mr. C. Mwachi of the Ministry of Public Works, Materials branch, Nairobi, for organising the sending of the murram soil to the U.K. for the research work.

I also wish to greatly acknowledge my husband for his understanding, support and encouragement.

Last but not least I would like to acknowledge the support and encouragement of my research colleagues during the research programme.

List of Tables

List of Figures.

List of Plates

Notations

d	Lattice spacing
θ	Angle of diffraction
λ	Wavelength of X-rays
n	Order of diffraction
μm	Micro meter (10^{-3}mm)
ρ_b	Bulk density (Mg/m^3)

Abbreviations

C-S-H	Calcium silicate hydrate
C-A-H	Calcium aluminate hydrate
C-A-S-H	Calcium aluminate silicate hydrate
C-A-S-$\underline{S}$-H	Calcium aluminate silicate sulphate hydrate
TG	Thermogravimetry
DTG	Derivative thermogravimetry
SEM	Scanning electron microscopy
DTA	Differential thermal analysis

CHAPTER 1

A SURVEY OF THE CURRENT METHODS OF FABRICATING AND CONSTRUCTING STABILISED EARTH BUILDINGS IN KENYA

1.1 Introduction

Kenya is located in East Africa and lies between longitudes 34 and 42 degrees east and latitudes 4 degrees north and 4 degrees south. It covers an area of approximately 582,646 square kilometres. The land area is approximately 571,416 square kilometres and the remaining part is covered with water (rivers and lakes) (1). It is bordered by Ethiopia and Sudan to the north, Somalia and the Indian ocean to the east, Uganda to the west and Tanzania to the south. Figure 1.1 (2) shows the eight areas, called provinces, into which Kenya is divided. These are further divided into forty one adminstrative units called districts.

The Kenyan climate varies throughout the country and is determined by topography, altitude and precipitation. The various climatic conditions are classified as:-

a) Semi-arid.

This covers most of the northern and eastern parts of the country and is characterised by:-

i) Very high temperatures (over 30°C);

ii) Low to moderate humidity (20 to 50%);

iii) Little rainfall. Normally rainfall is less than 500mm per annum, but when it occurs is normally very intense falling within a very short period;

iv) High solar radiation, with very little cloud cover, and little vegetation;

v) Local winds, which often create a problem of dust.

b) Savanna grassland.

The savanna grassland covers other parts of the country and consists of scattered shrubs amongst a cover of grasses which grow in large tufts during the rainy season. Within the savanna grassland are the Kenyan Highlands, Mount Kenya being the highest mountain in the country with a height of approximately 5200M (17,058ft) above sea level. The savanna climate is characterised by:-

i) Moderate day time temperatures (27^{o}C), often cold nights (12^{o}C);

ii) Moderate humidity (50%);

iii) Seasonal rainfall with two distinct rainy seasons and the remainder of the year being dry. The long periods of rainfall come in March to June and the short periods of rainfall come in October to December. Total annual rainfall is between 1500mm and 2000mm;

iv) Intense solar radiation.

c) Coastal climate.

This covers the coastal region which is on the far eastern side of the country and is characterised by both high relative humidity (70%) and high temperatures (20 to 30°C). The annual rainfall here is about 900mm (1,2,3,4,). Table 1.1 shows a summary of climatic conditions that prevail in the country.

1.2 The current situation

Kenya is one of those developing countries which is placing great emphasis on rural and urban development. This development involves the provision of water supply for domestic use, houses, roads, education and other basic necessities. Provision of housing in Kenya has presented great difficulties due to lack of basic essential resources such as suitable building materials (e.g. steel, concrete), a shortage of trained manpower and management skills and the absence of an effective communication system. The housing need is becoming increasingly important due to an expanding population, rapid industrial development and the growth of towns. However, limited funds and the increased cost of imported building materials have made it difficult to provide cheap and durable housing for low income groups.

Estimates from the 1979 population census indicated that the population growth rate in Kenya was 3.8% per annum. At this rate the population is expected to increase to 35 million by the year 2000. The population growth rate in urban areas is more than 7% per annum. For example, the population of the capital city, Nairobi increased from 897 000 in 1980 to an estimated 1 429 000 in 1989. This increase can be attributed to rural-urban migration (5). It is estimated that 90% of the population is rural based. Of the population in the urban centres approximately 80% is middle and low income group (6). Although in urban centres there have been housing schemes intended for the low income groups, the current trend due to inflationary factors, is that the middle income groups are displacing the low income groups with the latter being forced into slum accommodation. Hence there is need for some appropriate low cost housing schemes employing low cost building materials and some appropriate simple technologies. It appears however, that those who have funds to invest in housing development are concentrating on the construction of middle or high class residential houses which means that very little is being done for the poorer members of the Kenyan society. The government however is seriously looking for solutions to the problem of providing shelter for the poorer sector of the population. Several steps have already been taken by the Kenyan government including a review of its current by-laws and planning regulations. This is to facilitate the utilisation of cheaper local building materials in its low-cost housing projects. Research by the Housing Research and Development Unit (HRDU), formed in 1967 at the University of Nairobi, into the use of local building materials and the application of appropriate building technology, represents a good base on which to build. The National Housing Corporation (NHC) has been concentrating on the provision of loans for the construction of improved housing in rural areas.

Typical building materials which may be available for building in Kenya, although in short supply, are structural and reinforcing steel, concrete, masonry, timber and soil (6). For residential low-cost housing, steel and concrete blocks tend to be very expensive, requiring skilled labour and expertise, and often involving transport costs, and hence not readily affordable by the low income groups. Timber, though readily available, is becoming expensive and requires transport costs and specialised handling and treatment in order to improve its durability. This leaves soil as a readily available and cheap building material. It requires no handling skills. Householders may dig up the required soil on their land in the vicinity of the intended site, hence cutting down on the costs of transportation and materials. The actual building construction process may be done by the householders on a self-help basis thereby reducing the skilled labour costs. The major disadvantage, however, of soil as a building material is its low compressive strength and poor durability when subjected to moisture variations. The task for researchers, therefore is to look for ways of making the soil into a stronger and more durable building material.

1.3 Earth constructed dwellings in Kenya

1.3.1 Introduction

Soil is considered as a weak and non-durable building material and it is therefore mainly used for low-cost, temporary construction of houses in rural areas and in some parts of urban centres for the poor. These low-cost dwellings are designed by the inhabitants themselves. The construction is simple in form, made out of local building materials and simple technologies.

The use of soil varies according to climate, culture and types of soil available. In Kenya, there are different methods of soil construction which have been adopted from generation to generation. The most common ones are wattle and daub, layering, rammed earth construction and adobe block methods.

1.3.2 Wattle and daub method

In the wattle and daub method, the structural framework of the wall is built by erecting timber poles, driven into the ground to a depth of about 50cm. The vertical timber poles should be of durable material and the end to be driven into the ground is sometimes painted with black tar to prevent attack by the termites. Thin branches, twigs or reeds are then woven horizontally onto the outside and the inside of the vertical framework to form a close knitted surface. The mud (paste made from a mixture of clay soil and water) is usually inserted in between these knitted surfaces. The mud is closely packed and left to dry. More mud is added by plastering both sides of the interwoven framework. This results in a single thick wall which produces good thermal comfort. Decorations can be introduced using different colours of soil after the final layer of mud has been plastered.

The disadvantage with this method is the formation of shrinkage cracks after the mud dries. Also the timber used for the framework will often be prone to attack by termites, and the sections in the ground will be prone to wet rot. In some places where gravel is available, shrinkage cracks may be reduced by slotting stones into the knitted framework after which mud is used to fill the gaps. This also increases the strength of the building (8).

This method is commonly practised in western and central parts of the country. Mud is stabilised with materials such as plant juice, natural oils, cowdung and crushed ant-hills. Without stabilising the mud, the building may only last about 5 to 7 years, whereas with stabilisers the useful lifespan of a building is about 10 to 12 years, but limited due to timber rotting.

1.3.3 Layering method

In the layering method soil is mixed with water to a stiff consistency and placed in position, where it is compacted by hand without use of formwork. The wall is built in layers of approximately 300mm. Each layer is shaped and allowed to dry before the next layer is added. The whole wall is allowed to dry for several weeks to allow shrinkage to occur before plastering and the addition of the roof. During this period of layering, the wall is protected from rain to prevent the soil being washed away. Straw or vegetable matter may also be added to the soil to control shrinkage and cowdung can be added to improve strength and reduce cracking.

1.3.4 Rammed earth construction

In rammed earth construction, a mixture of sandy clay soil and water, of slightly moist consistency is produced to give a cohesive soil mix. This is heaped up in between heavy timber boards, employed as shuttering, and tamped by hand to ensure that the mass of the soil is well compacted to form a dense wall. After a section of a wall has been completed the shuttering is moved to a new position either sideways or vertically so as to repeat the operation. The best result is obtained by the use of soil of varying particle sizes, thus induced stresses developed within the wall are controlled and shrinkage problems are reduced. The strength of a rammed earth wall can be increased by reinforcing the wall with straw, tree branches, plant fibres or hair.

1.3.5 Adobe block method

Adobe is another method where soil is used to form building blocks. Here the soil is brought to a semi-liquid consistency and then cast or formed, in an open mould, into blocks which are allowed to dry in the sun. During the drying process the blocks gain some strength but also develop shrinkage cracks. The blocks are then employed to construct dwellings using mud of similar material to mortar to bind the blocks together. These blocks are known as "adobe". The selection of the soil is very important; the best soil has a clay content high enough to give good dry strength, but not so high as to cause moisture movement problems. Ant-hill soils are known to have suitable properties. In some cases where mud mortar is not used, sisal fibre can be distributed over the horizontal block jointing, hanging down the inside and outside of the wall, and the wall is then given three separate coats of cement rendering. The disadvantage with this method is separation of the cement rendering away from the soil wall because of the soil-wall movement during the drying process.

Once the wall has been completed the roof has to be constructed. Roofing in drier parts of Kenya is made of mud (9). In the northern and southern parts, soil is widely used as a roof covering material. The Masai of the steppe-land covering large areas of southern Kenya, build their houses using mud mixed with cowdung. A traditional flat mud roof, although it needs closely spaced supports, provides a good means of coping with the high daily temperatures. The roof and even the whole structure needs protection against rain which normally comes in storms lasting only a few hours. Roofing with clay tiles is common in urban areas but only for those who can afford it. It is too expensive for the urban poor and for rural areas.

Most of the mud houses have mud floors (10). Hard and durable floors are obtained by beating a damp or sometimes wet soil with a wooden beater. Sometimes gravel is added to make the floor even harder and reduce cracking. The floor is maintained by occasionally smearing it with cowdung. Also soil taken from ant-hills is found to be a good water-proofing material for making floors.

1.3.6 Stabilised earth construction

Considerable research work has been carried out with the object of improving these methods of construction such that the soil will perform in a much more durable manner than was previously expected. A Kenyan/Anglo research project which started in 1980 between the UK Building Research Establishment(BRE) and the Housing Research and Development Unit (HRDU), University of Nairobi, is looking into methods of stabilising soils to increase compressive strength and to reduce linear shrinkage cracking. In addition, block making machines (eg the Cinva ram and Brepak machine) (8) have been developed to improve and standardise compaction in order to increase strength and durability of the blocks. The soil is first mixed with stabilisers such as cement or lime or both depending on the clay fraction present and subjected to pressure ($2N/mm^2$-Cinva ram and $10N/mm^2$-Brepak machine) using the block making machine. After pressure moulding in the machine the blocks are air cured under controlled conditions so that they achieve maximum compressive strength with minimum shrinkage movement. A proto-type building where stabilised soil building blocks have been used is in the Kawangware area, 10 kilometres from Nairobi (9) and is the result of a joint Kenyan/Anglo Research project. A 50 square metre three roomed medical centre was built using murram soils (local name for laterite soils; see chapter 2) stabilised with 4% cement. The murram in this area contained about 15% clay. A Brepak block making machine supplied by the UK through an aid programme was used and the local people were very willing to participate in the construction, thus providing cheap labour. The medical clinic and other buildings formed a community centre. This consisted of the medical clinic which was constructed at a substantial cost saving when compared with traditional concrete block work (i.e about 50% cost saving),and sections including three classrooms (one of which is used by the local ladies group as a handcrafts centre), two small store rooms, and an office.

Other places where similar buildings have been constructed are Ruambwa, Budalangi and Makunda in Western province, Nyamuga and Ogongo in Nyanza province and Mado Gashi in

North Eastern province near the Kenya/Somali border. In these areas schools have been built which have solved accommodation problems both for students and teachers.
The collective participation, i.e. harambee, by local people in the construction of these buildings is not a new practice but is a tradition which has been carried out over many years.

1.4 The Traditional Building Process

Traditional mud construction in the rural areas of Kenya is a highly cooperative venture, although this practice is now dying out as people are beginning to employ more durable building materials such as concrete and steel which have been developed by the more technically advanced nations. In the past, building was a major social occasion in which both men and women of a village co-operated. Among the Kikuyu tribe (the majority of Kenya's population), the men were responsible for the building of the entire structural framework and as they plastered the walls the women did the thatching. Ritual jokes about women for their slowness were made by men as they worked. The women were referred to as "sleepy lizards" on these occasions (11). Conversely the Luhya tribe's women (the author's tribe), were not allowed to climb on top of the roof of a house, therefore they were normally responsible for the walling. The men built the main structural framework after which they thatched and the women plastered the walls and compacted the floors.

With the help of the neighbours, a house could be erected in a day as long as the necessary building materials were available. The site for digging up the soil was chosen by an experienced, responsible person. This was important because unsuitable soil will not mould itself into "balls" especially when being carried from the miximg place to where the house is built. Usually the women carried the soil and would complain if it was not suitable. As mentioned earlier, ant-hill soils are known to provide the best soils for construction.

Although this process is still continuing, especially in rural areas, it is increasingly being replaced, especially in urban areas, by the more modern methods of construction employed by developed countries. These methods also require building materials which are produced by the developed world.

1.5 Health Hazards of Earthen Buildings.

In addition to the rather poor durability of earth constructed dwellings, there are also serious health problems associated with this type of construction. The shrinkage cracks in the earthen walls and floors provide breeding grounds for disease vectors such as triatomine bugs, bed bugs, fleas, soft ticks, mites and cockroaches (12).

Triatomine bugs (especially in South America) hide and breed in crevices in stone walled houses and cracks of adobe and rammed earth walls. These blood-sucking vectors can carry and transmit chagga disease.

Bed bugs hide in cracks in walls and floors and eventually end up in bedding, furniture and clothes. These transmit certain viruses to humans such as viral hepatitis B and their unpleasant bites cause severe irritation.

Cracks in the floor can provide refuges for flea larvae, and can harbour adult fleas which are blood-suckers. They can transmit plague and typhus if they become infected by feeding off a diseased animal (e.g. rats or mice), and subsequently bite a new host.

Soft ticks and house dust mites can inhabit cracks in floors, dust and domestic debris. The argasid ticks are blood feeders and can transmit relapsing fever to humans (9).

House dust mites feed on shed human skin and can cause asthma in sensitive individuals, especially children.

Cockroaches can also be a nuisance in these earth buildings. They feed on food crumbs and transfer their droppings to fresh foodstuffs. The cockroaches hide in cracks and crevices and may carry organisms in their faeces that can cause diseases such as dysentry, typhoid fever and poliomyelitis.

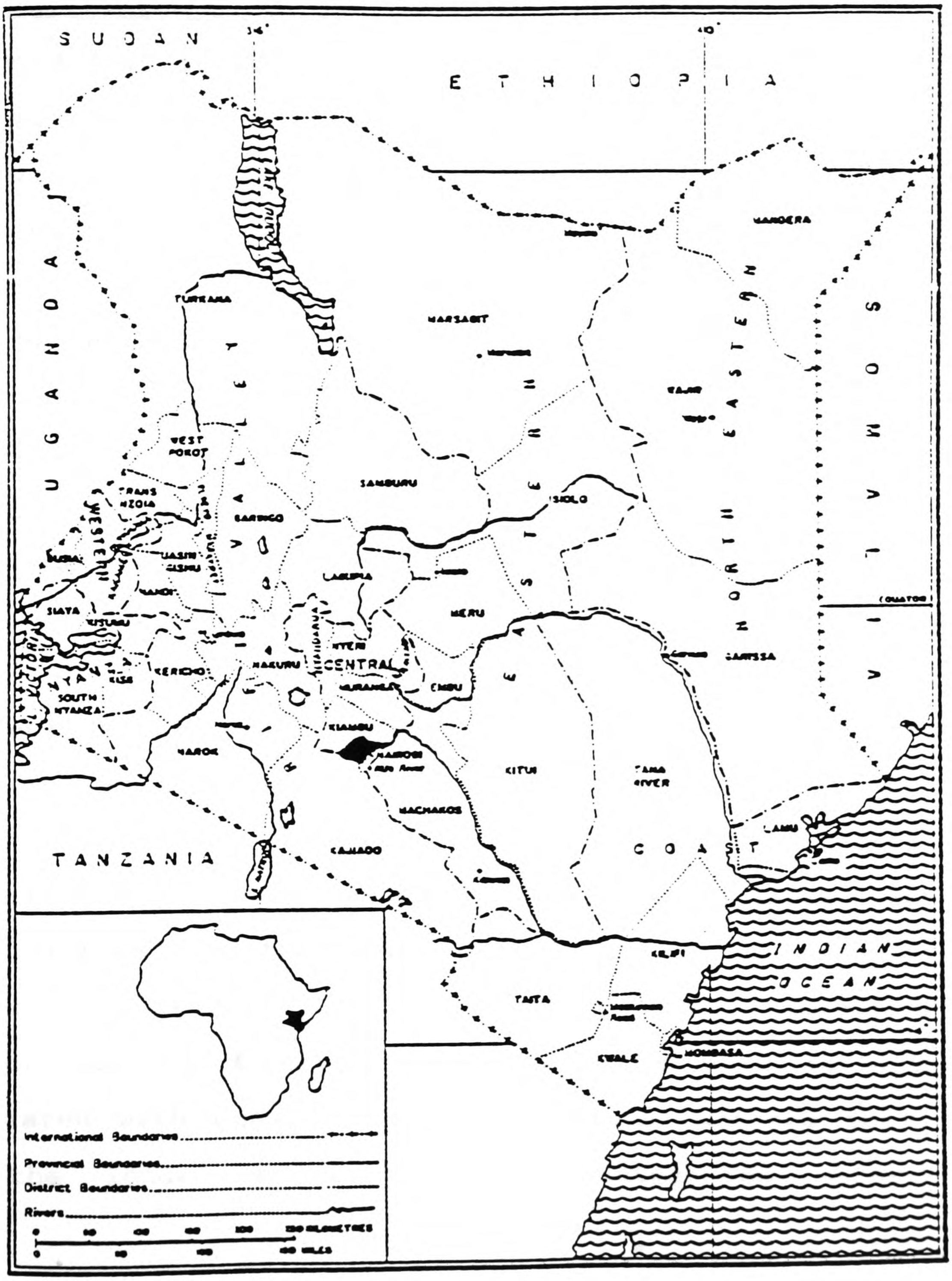
Methods to reduce cracks in the earth buildings, and hence reduce these health hazards and also improve durability would prove a great benefit to the people constructing and inhabiting earthen buildings. It would also encourage people to continue to use soil as an effective locally-available building material for constructing their own dwellings which would alleviate the pressure of demand for accommodation as the population continues to increase. If better quality housing was constructed, the men folk would not have to keep leaving home to seek medical attention for their families. They would then be able to work their farms more efficiently thus ensuring an income within a happy family environment.

One of the principal objectives of this current study is to establish the conditions necessary, in relation to composition and fabrication, for the production of stable and durable soil-based building material. In order to achieve this objective it is first necessary to examine in detail the physical and chemical nature of soils. This aspect is considered in the following chapter.

Table 1.1 Monthly recorded temperature, rainfall and relative humidity ranges at the main stations (1).

Main station	Temperature (°C)	Rainfall (mm)	Relative humidity (%)
Nairobi	12-28	20-300	40-60
Nakuru	9-28	10-250	30-60
Mombasa	20-32	0-200	55-70
Eldoret	9-25	5-300	30-60
Kisumu	15-30	80-250	45-55

Figure 1.1 Map of Kenya



CHAPTER 2

THE NATURE OF SOILS

2.1 Definition of soil

The word soil stems from the latin word "solum". It is used in many professional fields, and, depending on the context in which it is used, it has different meanings. The Oxford Dictionary defines soil as "the upper layer of the earth in which plants grow, consisting of disintegrated rock usually with an admixture of organic remains". This definition is based on agricultural soil science, and may safely be accepted as the one that describes the agriculturalist's concept of soils. A geologist (13, 14) defines soil as that which is produced as a result of disintegration of rock which has or has not been transported from its original position. It is a mixture of granular and clay sized inorganic particles, organic debris and water. A pedologist (15) on the other hand will define soil as a natural body, differentiated in horizons of mineral and organic constituents, usually unconsolidated, of variable depth, which differs from the parent material below in morphology, physical properties, composition and biological characteristics. A civil engineer, whose work is mainly associated with construction on the soil, defines soil as all the loose unconsolidated, disintegrated material, transported or untransported from its original position, lying on top of hard bedrock.

2.2 Soil formation

The formation of soil is a continuous and very slow process taking thousands or millions of years. Most soils are formed by the disintegration of rock as a result of weathering processes which may be classified as physical, chemical or organic. Soils are also formed from the ash products emitted by volcanoes (13, 16).

Physical weathering is caused by repeated physical processes which include wind and water erosion, freezing and thawing, thermal stresses due to changes in temperature, and friction caused by the earth's movement. Thermal stresses, caused by cooling of the rock mass or as a result of daily temperature changes near the surface, lead to cracking. If water percolates into these cracks and subsequently freezes, the resulting expansion opens the cracks further and eventually pieces are broken from the rock mass. In dry climates the sand grains carried by high winds may also cause rapid abrasion and erosion of rock surfaces. Physical weathering leaves the crystal structure of the material unchanged and clearly identifiable with that of the parent rock.

In chemical weathering, the rock minerals are attacked by water or oxygen or acid materials dissolved in the soil water. Carbon dioxide from the air and organic matter in the soil are common sources of such dissolved acids. Clay minerals are examples of soil constituents which are predominantly the products of chemical weathering. Their crystal structures are mainly determined by the environmental conditions under which they have been formed, and do not necessarily reflect the crystal structure of the parent material.

Organic weathering occurs where bacteria and plant life, activated by moisture, causes disintegration of soil particles.

2.3 Lateritic soils

Depending on origin, soils may be classified as transported or residual soils. Transported soils are removed from their place of origin and deposited elsewhere by rivers, glaciation or wind. Residual soils are formed in situ by weathering of the original rocks. They usually consist of particles of various sizes which include stones, sands and clays or, if the finer particles have been leached out,they consist of residual rock debris. During chemical erosion of the weathered rock, the fine silt and clay particles, with carbonates in solution, are frequently removed and carried away by streams and rivers to the sedimentary basins. One residual soil of widespread occurrence in tropical countries such as Kenya, is known as laterite or lateritic soil depending on its composition. Laterites and lateritic soils occupy considerable areas of India, Malaysia, Indonesia, Equatorial Africa and South America (see figure 2.1). The word laterite was derived from the latin "later" meaning brick and the word was first applied by Buchanan in 1807 for describing bricks made of red coloured soils found in the southern parts of India (14, 23). These soils are rich in ferric and aluminium hydroxides. They occur as the weathered mantle of many kinds of rocks, and they tend to be yellow, brown or red in colour. They harden when exposed to air. In India, for example, it was found that when the red soil was exposed to the atmosphere the soil hardened off and an excellent building material was obtained. Similarly, in Kenya, laterite soil blocks cut from the ground, harden off and they have been used to line the external walls of underground sewerage tanks and walls for rural houses. They include not only sedimentary deposits formed in situ but also transported redeposited types which contain admixtures of clays and other transported minerals. The process of formation of these soils is greatly assisted by alternating saturation and desiccation which involves the removal of silica, lime, magnesia, soda and potash leading to concentration of less soluble iron and aluminium oxides and hydroxides in the upper horizons. The iron compounds are responsible for the red, brown and yellow colours of these soils. Concretions occur in the matrix, where there are higher concentrations of oxides in the soil. Extensive accumulations of these oxides give rise to laterite. Ola (17) defined laterites as those soils in which the ratio of silica (SiO_2) to sesquioxides (Fe_2O_3 + Al_2O_3) is less than

1.33. Ratios between 1.33 and 2.0 indicate lateritic soils and those greater than 2.0 indicate non-lateritic types. The major minerals in these soils include Kaolinite [$Al_4Si_4O_{10}(OH)_8$], Gibbsite [$Al(OH)_3$], Haematite (Fe_2O_3) and Quartz (SiO_2). Murram soil which is the principal subject of this study is one of those soils classified as laterites. Table 2.1 shows the composition of some Kenyan soils including murram along with various other soils for comparison (9).

2.4 Soil constituents

Soil is an assemblage of solid particles forming a porous structure and, depending on the circumstances, the pores may contain water or air or both. The solid phase is composed of both organic matter and inorganic or primary rock and clay mineral components i.e. sand, silt and clay particles plus organic matter.

Organic matter is derived from either plant or animal remains which are added to the soil when the organisms die, and which subsequently undergo decomposition at different rates due to chemical and bacterial action. From the engineering point of view, organic matter has undesirable characteristics, the chief of which are the open, spongy structure and the mechanical weakness of the constituents. The acidic nature of the constituents produces acidic pore water which can corrode components and structures contained in the soil.

The inorganic or mineral components usually form the main bulk of a soil and as discussed previously they originate from various types of rocks occurring in the earth's crust. The mineral matter in the soil usually occurs in the form of solid particles of different types, and the physical characteristics of a predominantly inorganic soil are a reflection of the properties of its component particles. The most important of these properties are size, shape and mineralogical constitution. A very hard mineral such as quartz gives rise to particles that are less rounded than those derived from softer minerals under similar weathering conditions. Particle size is a property which influences the physical characteristics of a soil.

In 1908, Atterberg, a Swedish soil scientist, classified soil particles according to their sizes, assuming that all particles were spherical in shape. This classification system is still essentially used today for civil engineering purposes. Determinations are made of the quantities of particles whose sizes lie between sets of arbitrarily defined size limits. These limits are expressed in terms of "equivalent particle diameters", the assumption being made that the particles are spherical. The size range defined by any two limits is referred to as a "fraction" of the soil, and the various fractions are named to correspond with the types of soil which they resemble e.g. gravel, sand, silt or clay (see Table 2.2). The soil is separated

into its respective particle size ranges by either wet or dry sieving or by sedimentation methods (9, 18).
Gravel is defined as that portion of a soil sample which passes a 63mm BS sieve and is retained on a 2mm BS sieve being subdivided as coarse, medium and fine. The sand fraction is that portion which passes a 2mm sieve and is retained on a 0.06mm sieve again being subdivided into three portions ie coarse, medium and fine. Since sand is primarily composed of quartz particles, it is quite inactive chemically and it is its physical characteristics which are of most interest. The individual grains may be classified as angular or rounded depending on the degree of abrasion received prior to final deposition. Residual soils are usually angular, whereas river beach sands are generally rounded. Wind-blown sands are usually very fine and well-rounded, while ice-worn sand particles have been scoured by the ice. Clean sand particles do not exhibit cohesive properties and so are little influenced by changes in moisture content. Because of the general equiaxed nature of the particles and their size range, the pores between the particles are relatively large; thus sandy soils are very permeable and well-drained and consolidation effects are small. The silt fraction is that portion which passes a 0.06mm sieve and is retained on a 0.002mm sieve, silt particles can be considered as transitional between sand and clays. Physically they are similar to sand other than that they possess a limited amount of cohesion due to inter-

particle water films operating on a higher specific surface. Although they are classified as permeable, moisture can only move through the small pores relatively slowly. Where the smaller-sized particles predominate, silt particles exhibit strong clay-like tendencies and in bulk may undergo considerable shrinkage and expansion when exposed to changes in moisture content.

The clay fraction is that portion of a soil which passes the 0.002mm sieve. The clay particles differ from other fractions both in their chemical consistency and physical properties. Physically they are flat and elongated, or lamellar, and thus have a much larger surface area per unit weight than the equiaxed particles of silts and sands. Because of their colloidal size, clay particles exert a major influence on a soil's behaviour. Chemically they consist of hydrated alumino-silicates which are formed during the leaching process to which the coarser particles of primary minerals are subjected. This colloidal material is primarily responsible for the cohesiveness of plastic soils when clay particles are present. The presence of clay in soil can cause volume instability with changes in moisture content, and an ability to solidify into a hard mass upon drying. A colloid, in theory, can be said to be any particle which exhibits Brownian movement when in aqueous suspension. In practice, the term is usually applied to particles smaller than one micron (0.001mm). The importance attached to the colloidal fraction is associated with the electrical charges which the particles carry on their surfaces. O'Flaherty (18) has explained this by considering the manner in which ions, atoms or molecules are combined to form a crystalline solid. The simplest groupings of atoms is called a unit cell and a three-dimensional repetition of unit cells is given the term "crystal". Within the structural arrangement of a crystal (called space lattice) electrostatic bonds or valencies of atoms are completely neutralised, whereas those atoms at the periphery act in a different manner.

The net result is unbalanced negative charges associated with the surfaces of colloidal clay particles. Another contributor to this unsatisfied electrical charge is the substitution of one ion for another within the crystal lattice i.e. isomorphous substitution. This latter effect is the main source of the surface electrical charges associated with montmorillonitic and illitic soil colloids, whereas the main cause of this surface charge in kaolinitic colloids is the unsatisfied valency phenomenon.

The small dimensions of the void spaces that can exist between clay particles in an unflocculated clay can result in the permeability of clay soils being low and hence difficult to drain. The charged surfaces tend to attract polar molecules such as water which causes the clay to swell. Also the introduction of positive cations modifies the electrical properties of the clay particles' surfaces and instead of the particles repelling each other, which produces an even dispersion, they attract each other and aggregate together (flocculate). Flocculation increases the permeability of a soil and makes it less plastic and more friable.

2.5 Clay minerals

2.5.1 Basic structure and types

Clay deposits are principally composed of quartz and clay minerals (19). The clay minerals represent the commonest breakdown products of most of the chief rock forming silicate minerals. Not so many years ago, clays were believed to be amorphous material having no definite recurring patterns of atoms, ions or molecules. Research which started about 1925 has shown that clay particles are composed of minute flakes in which the atoms are arranged in a series of units to form clay minerals.

The atomic structures of most clay minerals consist of two fundamental building blocks i.e tetrahedra of silica and octahedra of alumina shown in Figures 2.2 and 2.3. The $[SiO_4]^{4-}]$ tetrahedron has one silicon atom equidistant from four oxygens or hydroxyls. A silica tetrahedron sheet is formed from a series of tetrahedral units which are arranged in a sheet-like hexagonal structure so that the oxygen atoms at the basal corners of the tetrahedra are in a common plane, with each shared between two tetrahedra. Thus the silica tetrahedron sheet may be viewed as a layer of oxygens in the base and a layer of hydroxyls at the tips of the tetrahedra.

In the octahedral unit the atoms of aluminium, iron or magnesium are equidistant from six oxygens or hydroxyls. These units form sheet-like layers in which each oxygen is common to three octahedral units. The sheet can then be viewed as two layers of densely-packed oxygens/hydroxyls with the aluminium between the layers in octahedral coordination.

Different clay mineral groups are formed as a result of the bonding together of two or more of these molecular sheets.

There are three major clay mineral groups i.e. kaolin, smectite and hydrous mica groups. The most common, as well as important clay mineral in each group are kaolinite, montmorillonite and illite respectively.

Kaolinite is principally formed as an alteration product of feldspars, feldspathoids and muscovite as a result of weathering under acidic conditions. Montmorillonite forms when basic igneous rocks in badly drained areas are weathered. An alkaline environment favours its formation. Illite is a common mineral in most clays and shales, and is present in various amounts in tills and loess. It develops due to the weathering of feldspars, micas and ferromagnesium silicates, or may form from other clay minerals. The process of its formation is also favoured by an alkaline environment. Both kaolinite and illite have non-expansive lattices whilst montmorillonite is expansive. The montmorillonite mineral is characterised by its ability to swell in a moist environment and by its notable cation exchange properties. The basic reason why montmorillonite can readily absorb water into the interlayer spaces in its sheet structure is simply that the bonding between the layers is weak.

The shape, size and specific surface influence the engineering behaviour of clay minerals.

The typical clay mineral found in lateritic soil, like murram, is kaolinite, which is formed as a result of tropical weathering.

2.5.2 Kaolinite

Kaolinite is chiefly found in highly weathered, well-drained soils and is common in the tropics. It is composed of a single silica tetrahedral sheet and a single alumina dioctahedral sheet. The basal spacing in the tetrahedral and octahedral units is almost identical. Therefore a tetrahedral and an octahedral layer will fit together, the unsatisfied bonds in the tetrahedral layer each displacing one hydroxyl group in the octahedral layer. This forms a single sheet of kaolinite (see Figure 2.4), with the general formula $n[Al_2Si_2O_5(OH)]$.

Kaolinites are considered to be the most stable clays from the engineering point of view. The hydrogen bonds between the elemental sheets are sufficiently strong to prevent water molecules and other ions from penetrating, hence the lattice is considered to be non-expanding. Like the other clay minerals, kaolinite platelets carry negative electrical charges on their surfaces which attract thick layers of adsorbed water but because of the non-expanding lattice the effective surface area to which the water molecules can be attracted is restricted to the outer faces. It is for this reason that the plasticity, cohesion and shrinkage and swelling properties of kaolinite are low compared with other silicate clays.

The theoretical composition of kaolinite (in terms of its component oxides) is 46.54wt% SiO_2, 39.50wt% Al_2O_3, and 13.96wt% H_2O (20). Very limited substitutions of iron and/or titanium for aluminium occur, and such substitutions are restricted to poorly crystalline kaolinite. The cation exchange capacity of these minerals is 3-15 milliequivalent per 100grams. The major cation exchange capacity in kaolinite is attributed to the broken bonds around the edges of the silica-alumina units .

Soils also contain a wide range of other non-clay minerals such as calcite ($CaCO_3$), haematite (Fe_2O_3), gypsum ($CaSO_4.2H_2O$), and gibbsite ($Al(OH)_3$) etc.

2.6 Engineering properties of soils

The chief properties of soil that are important in construction are strength, volume stability, permeability, durability and plasticity (21). It is of common experience that the strength of any wet soil is low and even lower if it contains a high percentage of organic matter. For a clay soil, air drying in a low humidity environment (as it occurs in arid and semi-arid areas) produces an extremely hard and strong material. However, when it is wet, it undergoes considerable deformation under applied load. Inadequate strength is a problem in many forms of construction such as buildings, airfields, roads and tunnels and can lead to very serious economic loss, if not human injury.

Many soils swell or shrink with changes in their moisture content. Seasonal and longer term moisture changes in an expansive clay soil if uncontrolled, rapidly disrupt foundations and road and floor surfaces, tilt supports, crack buildings, break underground service pipes and generally cause financial problems. The swelling and shrinking can be reduced by controlling the change in moisture content.

Water movement in the soil is another factor that should be considered in relation to the prevention of engineering problems. This is determined by permeability. The coefficient of permeability is a measure of the ease with which the water movement occurs (22). The coefficient of permeability of a given soil depends on particle diameter, properties of pore fluid, void ratio, the shape and arrangments of the pores and of the soil particles. The permeability of compacted soils varies with the moulding water content. On the dry side of optimum moisture content (see section 3.4) the permeability is high due to the flocculant soil structure and the low density. A marked decrease in permeability accompanies an increase in the moulding water content. The permeability reaches a minimum at or slightly above optimum moisture content, after which a slight increase occurs. The large decrease in permeability with increasing moulding water content on the dry side of optimum is caused by orientation of the clay-size particles. Wet of optimum, the permeability increases slightly because of the effects of a decreasing dry density which counters the effect of particle orientation.

Permeability presents engineering problems, of which the chief are associated with either pore pressure dissipation or seepage flow. Inadequate pore pressure dissipation leads to a risk of slip failures in earthworks, and high seepage flow can cause tunnelling and breaching failures. Open textured soils and cracking clays will cause either seepage losses from water-retaining structures (e.g dams) or differential surface movement in case of expansive clays. For road engineers, low permeability can result in poor adhesion of a bituminous seal.

It is the aim of engineers to design construction materials that resist processes of weathering, erosion and deformation due to applied loads. Durability is a measure of resistance of a material against destructive processes of nature. Poor durability can be a problem for soils. Deep internal erosion in a natural soil or an earthen embankment result in excessive permeability leading to poor durability. High maintenance costs are associated with poor durability.

In the case of soil buildings, low strength, volume instability, high permeability and poor durability will give rise to unhealthy living conditions (see Chapter 1) for the occupants and continual maintenance problems. Also in areas subject to earthquakes, soil buildings can be unsafe. However, soil can be made more durable by subjecting it to pressure and forming it into building blocks. The improved compaction should improve hygiene (i.e reduce surface cracks in which insects and other disease vectors lodge), reduce housing maintenance repair costs and in general extend the lifespan of a building. The basic raw material needed to produce good building blocks is a soil containing fine gravel and sand for the body of the block together with some proportion of silt and clay to produce cohesion. The soil characteristics must be assessed in relation to the climatic conditions of the area. For example, a dry, semi-arid climate requires different soil blocks from those used in temperate, rainy areas. In drier areas permeability and volume instability are not such a problem as they are in rainy, wet areas. The clay fraction of the soil should be determined in order to estimate and assess its swelling and shrinking potential when subject to variations in moisture content. However, even the most suitable soils may not be sufficient to meet the long-term requirements of good quality building blocks without some form of modification. One way in which soils can be modified to improve their performance is by controlled addition of various stabilizers. The process is called "Soil stabilization". The next chapter examines the essential elements of soil stabilisation and discusses the different methods available to stabilise soils.

Origin of soil / Details	BRS House	JAMAICA			SUDAN			KENYA				EGYPT	TANZANIA		ST VINCENT	YEMEN ARAB REP		BOTSWANA			CAMBIA	BANGLA-DESH
		Red Bauxite	Knolls clay	Denbeigh clay	Fetehab	El Hizam	Derosheb	Kavangware murram	Red coffee	Makundo	Ruambwa	Shale clay	Red	Yellow	Clay	Dhamar	Aluaji	Lobatse A	Lobatse E	Jwaneng	Kotu	
Chemical analysis																						
Al_2O_3	N/A	48.89	18.6	17.2	9.51	9.81	4.49	11.72	28.84	12.30	10.76	18.3	18.40	14.70	17.10	14.76	11.18	14.27	10.58	1.87	13.00	16.9
SiO_2		3.82	57.4	62.5	58.12	61.91	79.96	39.15	39.00	67.93	74.99	51.3	59.30	74.20	48.80	51.10	48.40	69.65	75.77	75.00	73.10	66.70
P_2O_5		Nil	0.05	<0.01	0.16	0.13	0.02	0.07	0.06	0.15	0.07	0.15	0.02	Nil	0.13	0.43	0.31	0.01	0.03	0.07	0.03	0.06
SO_3		Nil	<0.01	<0.01	Nil	Nil	0.32	Nil	Nil	0.02	<0.01	0.83	0.12	0.04	0.04	0.01	0.09	<0.01	<0.01	0.04	<0.01	<0.01
K_2O		0.12	1.27	0.25	0.52	0.78	0.23	1.10	0.52	2.05	2.55	1.17	0.60	1.58	0.45	2.18	1.81	0.84	2.30	0.38	0.14	1.66
CaO		2.41	1.06	0.35	6.67	6.40	6.57	0.89	0.13	2.58	1.12	2.59	0.20	0.54	8.71	5.59	11.32	0.08	0.18	7.42	0.12	0.17
TiO_2		1.38	0.73	0.93	1.53	1.02	0.52	1.06	1.40	0.58	0.56	0.98	0.76	0.24	0.93	0.86	1.05	0.45	0.56	0.14	1.04	0.85
Mn_2O_3		Nil	0.15	0.04	0.30	0.31	0.13	2.35	0.44	0.09	0.15	0.05	0.13	0.06	0.15	0.13	0.15	1.71	0.13	Nil	Nil	0.02
Fe_2O_3		15.73	7.73	8.39	7.94	5.88	2.54	30.71	14.43	3.65	3.14	8.19	9.78	1.86	9.41	7.34	6.17	6.09	4.42	0.94	7.26	6.29
Na_2O		0.78	1.82	1.13	0.08	0.88	0.51	0.86	0.14	1.26	1.55	3.32	0.13	4.37	1.30	1.12	1.90	0.03	0.19	0.08	0.04	0.16
MgO		0.06	1.22	0.55	3.12	1.95	0.89	0.14	0.20	1.06	0.53	1.79	0.29	0.40	5.69	3.40	3.51	0.30	0.37	1.92	0.09	0.51
Loss on ignition		26.45	8.02	9.40	10.52	8.90	5.43	9.10	12.94	6.53	3.70	11.66	9.80	2.64	7.37	12.19	14.37	0.51	1.11	11.30	6.03	7.65
$Al_2O_3 + SiO_2 + Fe_2O_3$		68.44	83.73	88.09	75.57	77.58	86.98	81.58	82.27	84.06	88.89	77.79	87.48	90.76	75.31	73.20	65.75	90.01	90.77	77.81	83.36	89.89
$K_2O + Na_2O$		0.9	3.09	1.38	0.58	1.46	0.74	1.96	0.66	3.31	4.10	4.49	0.73	1.98	1.34	3.30	3.71	0.87	2.49	0.46	0.18	1.82
Sieve Analysis																						
Retained on 6.3mm Fine Gravel	0	0	0	0.5	0.8	9.6	0	38.41	0.76	2.2	1.0	<0.1	Nil	1.1	12.48	0.15	10.93	27.9	1.7	5.04	15.04	0.24
Retained on 0.6mm Coarse sand	2.0	12.0	1.6	2.8	5.4	10.0	14.0	26.91	20.11	18.2	15.60	0.6	0.6	7.6	21.34	0.41	9.69	11.1	10.3	5.24	9.03	1.47
Retained on 0.2mm Medium sand	6.0	26.0	6.6	6.6	13.2	25.4	31.0	11.70	29.81	16.1	19.20	3.6	21.4	23.5	17.99	1.28	9.34	6.8	16.3	17.17	10.41	6.27
Retained on 0.075mm Fine sand	54.0	60.0	10.8	14.0	30.1	42.5	56.4	7.36	26.53	16.8	23.0	11.7	41.9	35.6	11.50	1.96	12.10	8.0	21.7	41.6	20.31	8.75
Passing 0.075mm Silt and clay	38.0	28.0	81.0	76.1	43.1	57.8	31.6	15.62	22.79	47.7	41.2	84.1	36.1	32.2	36.69	96.20	57.94	46.2	51.0	30.95	45.21	83.27
% Linear shrinkage	N/A	N/A	11.0	4.6	12.2	11.3	7.9	3.1	7.4	N/A	N/A	N/A	8.2	7.6	9.1	8.7	N/A	5.1	6.8	4.8	3.0	13.0
Silica–Sesquioxide $\left(\frac{SiO_2}{Al_2O_3+Fe_2O_3}\right)$	N/A	0.06	2.18	2.44	3.33	3.96	11.37	0.92	0.88	4.21	5.39	1.94	2.18	4.48	1.84	2.31	2.79	3.42	5.19	26.7	3.61	2.88
Stabiliser sand/soil	–	soil	1.1	1.1	soil	soil	soil	soil	soil	1.1	1.1	5.1	soil	soil	1.1	1.23	NOT USED	soil	soil	soil	soil	1.0
%lime	–	2.0	–	–	6.00	6.00	6.00	–	7.00	–	–	10.0	–	–	–	–		–	7.00	–	–	–
%cement	5.00	5.00	6.00	8.00	–	–	–	4.00	–	5.00	5.00	3.0	6.00	5.00	7.00	8.00		8.00	–	7.00	6.00	6.00
28 day Wet compressive strength (MN/m^2)	N/A	4.68	2.2	3.4	4.70	6.15	3.30	3.30	2.1	3.6	3.6	1.13	N/A	N/A	4.82	7.20	N/A	5.51	1.06	8.56	6.18	7.58

Table 2.1 Composition of some selected soils (after Webb (9)).

Constituent part	Size range	BS test sieve	Fraction
Coarse gravel Medium gravel Fine gravel	60 to 20mm 20 to 6mm 6 to 2mm	63 to 20mm 20 to 6.3mm 6.3 to 2.0mm	GRAVEL
Coarse sand Medium sand Fine sand	2.0 to 0.6mm 0.6 to 0.2mm 0.2 to 0.06mm	2.0mm to 600um 600um to 212um 212um to 63um	SAND
Coarse silt Medium silt Fine silt	0.06 to 0.02mm 0.02 to 0.006mm 0.006 to 0.002mm		SILT
Colloidal material	<0.002mm		CLAY

Table 2.2 Soil classification

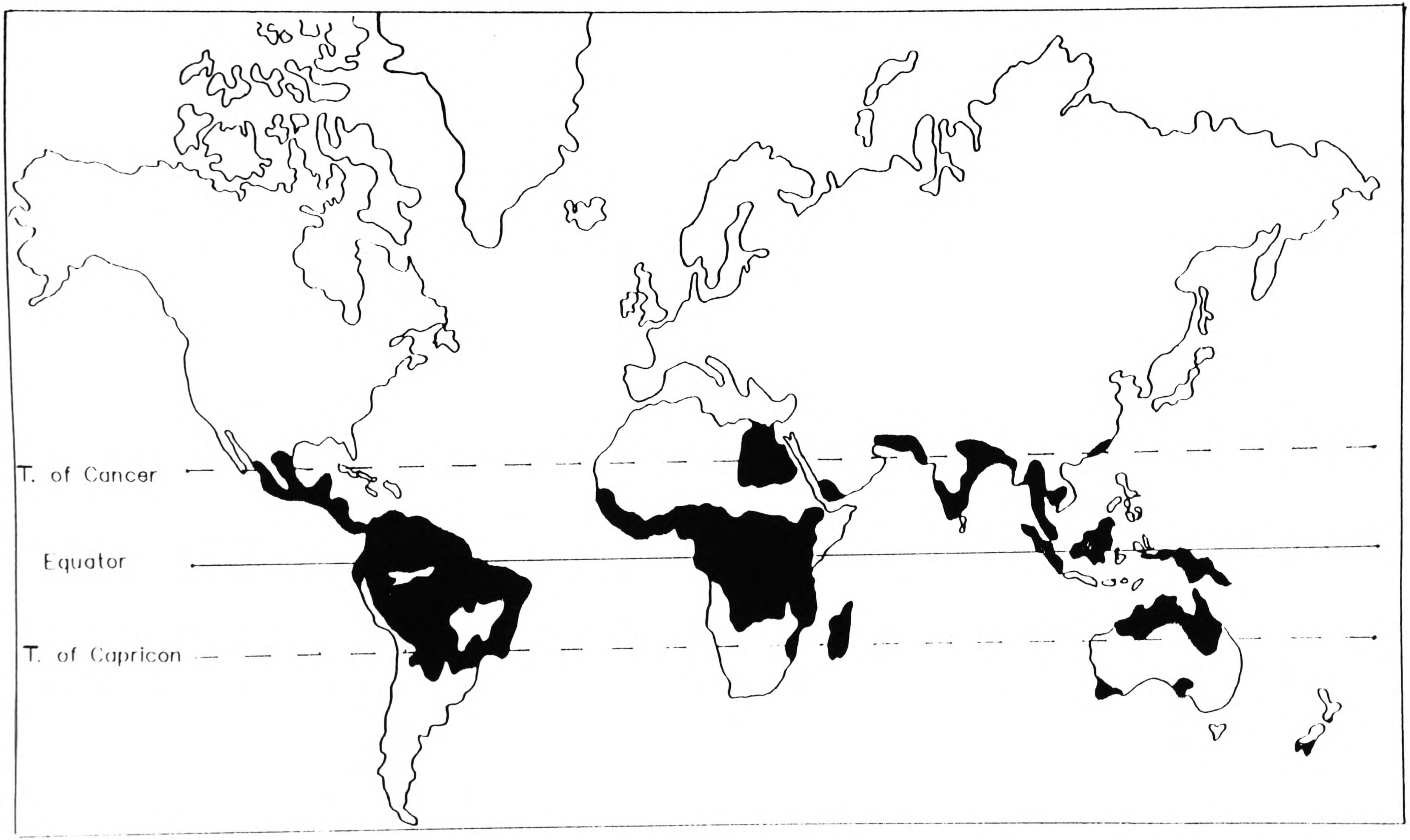


Figure 2.1 World distribution of laterite/lateritic soils (black portions).

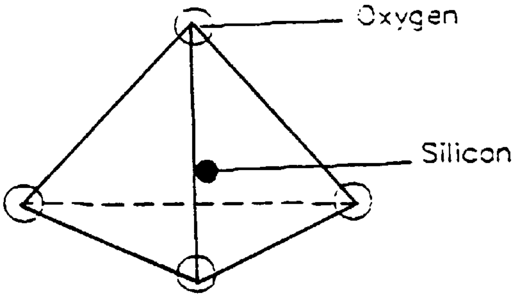


Figure 2.2 Schematic diagram showing single silica tetrahedron.

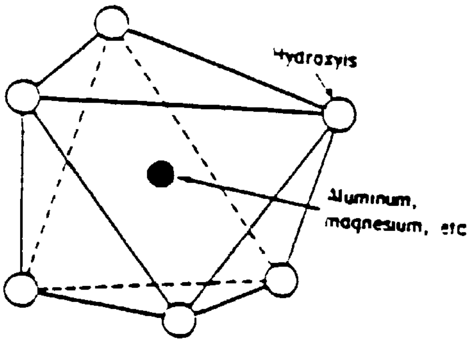


Figure 2.3 Schematic diagram showing single alumina or magnesia octahedral unit.

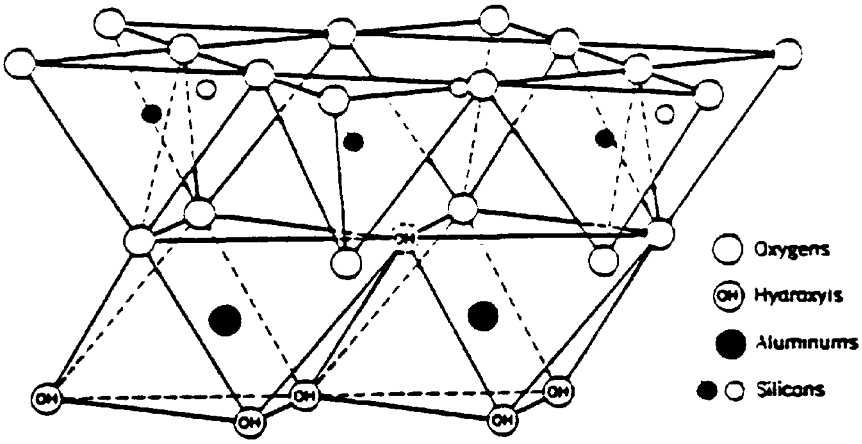


Figure 2.4 Diagramatic sketch of the structure of Kaolinite layer

CHAPTER 3

SOIL STABILISATION

3.1 Introduction

The traditional methods of soil construction such as rammed earth, wattle and daub, adobe etc (see Chapter 1) are still commonly used in many drier regions of the world. Although soils may be strong for building construction in these regions, it is not very durable and has little resistance to moisture. The effects of its poor weathering performance can be seen in many developing countries where rural houses must be frequently maintained or even completely rebuilt at intervals (especially after the rainy seasons).

Methods to improve the natural durability and strength of soil have been practised in numerous countries, and stabilizers such as natural oils, plant juices, animal dung and crushed anthill, have been used for many centuries. In recent years the techniques of soil stabilization using stabilisers such as cement and lime, first developed for use in structures such as road pavements, runways, embankments, dams and foundations, have been used to convert soil into a building material with properties comparable with other building materials such as concrete and fired clay bricks.

Tests have been developed to indicate which soils are most suitable for stabilization and to predict their durability and strength when stabilized (23). Failure to make adequate use of these tests has sometimes resulted in poor performance and this has led to the belief that stabilized soil can never reliably form a satisfactory building material.

3.2 Preliminary soil tests

The composition of a soil and its particle size distribution or grading determines how effectively it can be compacted and stabilized. A well-graded soil should be selected for stabilisation, i.e. one that contains the appropriate proportions of different size particles, such that all the voids between the larger particles are filled with smaller ones. In order to determine the particle size distribution of a soil it is necessary to separate and determine the proportions of different sized particles, fine gravel, coarse sand, fine sand, silt and clay. Silt and clay can only be separated by sedimentation methods while the other fractions can be effectively separated by dry sieving. Field tests have been devised to separate the fines from the rest of the soil. These involve shaking the soil in water and either decanting off the finer material which is in suspension, or allowing the soil to settle into different layers and then measuring the thickness of each layer. The latter method may not give a very accurate clay content especially when a high silt/clay fraction is present. The plasticity of a soil can also be used to predict the amount of clay fraction present.

To be suitable for blockmaking the clay content should be between 5% and 30% of the volume i.e. between 1/20 and 1/3 of the total column height of the sedimented soil (24). The disadvantage with the sedimentation test is that it does not separate the silt and clay, and because silt behaves differently from clay, this could result in wrong conlusions about the soil's suitability for stabilisation.

It is advisable therefore that for all important soil building projects a full laboratory analysis should be carried out on the soil, using the appropriate tests in BS 1377, or equivalent standards issued by other countries. However alternative on site shrinkage tests have been developed to avoid the expense of having to perform laboratory tests (9).

The plasticity of a soil is another property to be considered when selecting a soil for stabilisation. This is particularly so because a highly plastic soil has a high affinity for water, and thus is likely to swell when water is added or shrink when water is lost. The plastic properties of a soil can be conveniently expressed in terms of its plasticity index using standard tests. The plasticity can be determined by observing the changes that take place when water is gradually removed or added to a soil.

If sufficient water is present in the soil, the clay particles will be dispersed and the clay will behave like a liquid. As the water content is reduced, a point will be reached when the system no longer behaves like a liquid and below which it possesses shear resistance. This point is called the liquid limit and is usually defined as the moisture content at which the soil passes from a liquid to a plastic state.

With further drying the clay system will increase in density and then behave like a plastic paste, so that it is continously deformed when a force is applied to it but still retains its new shape when the force is removed. Reducing the moisture further eventually causes the clay to crumble under load and not to deform plasticly. At this point the clay is at its plastic limit which can be defined as the moisture content at which the soil becomes too dry to be plastic. The numerical difference between the liquid limit and plastic limit of a soil is the plasticity index and is a measure of the range of moisture content over which the soil will possess plastic properties. Both the liquid limit and plasticity index are affected by the amount of clay present in a soil and the type of clay mineral present. Fine-grained soils which have a low degree of plasticity have liquid limits less than 35%. The clay content of such soils is generally less than 20%. Soils with high plasticity have liquid limits in excess of 50% and their clay content is normally more than 40%. A high liquid limit and plasticity index indicates that a soil has a great affinity for water and will therefore be more susceptible to moisture movement. Such a soil is likely to be difficult to stabilise with cement and would require a larger amount of stabilizer than one with a low liquid limit and plasticity index. On the other hand, soils with higher values of liquid limit and plasticity index may be more effectively stabilised with lime because of its excellent ability to modify the plastic properties of clay soil. The maximum recommended (21) values for liquid limit and plasticity index of a soil suitable for stabilisation are 50 and 30 respectively and are also probably valid for earth walls rammed in place or made from pressed blocks. Higher values than these would require excessive amounts of lime for effective stabilisation.

The surface layer of soil usually contains organic material in the form of humus which may seriously affect the stabilization process. In most cases removing the top soil and using only the soil beneath will ensure that no organic matter is present. However in some regions (particularly near rivers) organic matter can be found to a considerable depth. In these localities it is desirable to test the soil for the presence of organic matter.

Also in some areas (eg arid and semi-arid regions), the presence of soluble inorganic salts, particularly sulphates, may make the soil unsuitable for stabilization. This is because any increase in moisture content can lead to chemical reactions which result in expansion and disruption of the soil. A sulphate content of up to 1% is acceptable but this depends on the type of sulphate and the amount of clay present in the soil. Particular attention should be given to the effects of immersing stabilised soil specimens in water and to their subsequent wet strength. The Kenyan standard specifications for stabilised soil blocks (25) requires that;

i) the soil must be free from deleterious materials such as organic matter and soluble salts;

ii) the maximum particle size of the soil must be less than 6mm;

iii) the sum of the aluminium oxide, silicon oxide and iron oxide should be greater than 75% of the total oxide components and

iv) the clay and silt content should exceed 10%.

3.3 Choice of stabiliser

After all the preliminary tests have been carried out, the next task is that of choosing a suitable stabiliser. The aim here is to increase the soil's load bearing capacity and its resistance to the destructive properties of weather. This can be achieved by choosing a stabiliser which does one or more of the following:-

- increases the strength and cohesion of the soil
- reduces the moisture movement of the soil and
- makes the soil waterproof.

Also the choice of a stabiliser is dictated by economic criteria (26).

The strength of a soil can be increased and satisfactorily maintained when wet by addition of cementitious materials of which the most widely used are hydrated lime and ordinary Portland cement. The rigid skeleton formed when cement is used in stabilisation resists moisture movement, in addition to improving the strength of the soil. Similarly lime, as well as improving the strength, also alters the physical properties of clayey soils to give improved stability in the presence of water. Ordinary Portland cement has proved to be most effective and hence is the most common stabiliser for both sandy and clayey soils. In clayey soils however a high percentage of cement will be needed for complete stabilisation thus becoming uneconomical. Also many developing countries do not manufacture Portland cement and therefore have to rely on imported material to meet their local needs. Even those countries like Kenya which produce their own cement tend to use it only for infra-structure projects and prestige buildings, or export it to earn foreign currency, rather than use it for low-cost housing. In addition cement becomes too expensive where it has to be transported from the manufacturing plant to the rural areas.

Other types of stabilisers such as bitumen, asphalt and certain resins act as waterproofing agents by providing a physical barrier to the passage of water. These stabilizers are expensive to import, especially in most developing countries where they are not available. Also preparation costs (i.e. for heating, storing and mixing) are too high.

A requirement therefore exists for an effective and easily available stabiliser which can be produced efficiently on a small scale close to its point of use. Lime does fulfil these criteria although it is more restricted in its application than is Portland cement due to the requirement that it must chemically react with the clay minerals in order to be effective. Most countries do have accessible sources of calcium carbonate in the form of chalk, limestone, coral etc., which can be readily decomposed by burning to give quicklime. Hydrated lime is then obtained by addition of water (27). The whole process can be carried out economically on a small scale, for example in rural areas of developing countries. One problem in following this approach is in the selection and control of the raw materials and the burning and hydration process both of which are quite critical. In particular if the limestone contains sulphates in, for example, the form of gypsum, instead of stabilising the soil the addition of "lime" could lead to increased dimensional instability in the presence of moisture. Also if the hydration and subsequent storage of the lime is not carried out correctly a large proportion of the lime may become carbonated. Although carbonation in itself does not have any deleterious effect it does substantially reduce the effectiveness of the lime as a stabiliser. Therefore before using lime as a stabiliser, it needs to be tested for quality and when using it great care should be taken to minimise carbonation as much as possible.

3.4 Compaction

To achieve maximum durability for a stabilised soil the soil must be compacted. Compaction of a soil is a very important process as it increases the contact area between soil particles, promotes closer packing and reduces void space. This improves the soil physical properties by increasing the resistance of the soil to deformation under applied load. To be effective it is important that maximum dry density is achieved when compacting a soil. This is reached when the soil is compacted under specified and controlled conditions of moisture content and pressure. The addition of water to a dry soil sample helps bring the solid particles together. At low moisture content the soil is stiff and it is difficult to pack. As the water content increases, the water starts to act as a lubricant, and increased workability combined with surface tensile forces allow closer contact between particles. Thus for a given amount of compaction the soil-water-air mixture occupies a progressively smaller volume as the moisture content is increased, thus increasing in dry density. As more and more water is added, a stage is reached when the air-content of the soil attains a minimum volume under the given amount of compaction. The moisture content corresponding to the maximum dry density is called the "optimum moisture content". Addition of water beyond this point reduces the maximum dry density because the extra water starts to occupy the space which would have been occupied by the soil.

The maximum dry density and optimum moisture content varies with the type of soil. Atkins (28) has shown that, at optimum moisture content, the maximum dry density of a gravel-sand mixture is significantly higher than that of heavy clay, although the material densities are similar. This is because of the enhanced specific surface of clays and the much greater proportion of adsorbed water. The addition of stabiliser to a soil affects its dry density and optimum moisture content. For example Kezdi (29) has shown that after the addition of Portland cement stabiliser, the maximum dry density increases more for sand than for heavy clay.

3.5 Summary

The preliminary tests that are carried out to determine the suitability of a soil for stabilisation have been discussed. The stabilised soil is compacted in order to achieve increased strength and durability. Also soil of a particular type will respond differently with addition of different stabilisers and it is therefore of prime importance that the correct stabiliser is chosen in relation to the nature of the soil to be stabilised. In the present work, preliminary tests show that the murram soil being studied has a high clay content which renders it suitable for lime stabilisation. Economically, lime is considered to be cheaper than stabilisers like cement or bitumen, since its production does not need sophisticated equipment.

Lime stabilisation modifies the nature of a soil and imparts particular properties to it. The properties which develop depend on a number of factors including the lime-clay reaction and the conditions in which that reaction occurs. The following chapter discusses clay-lime reactions and the effects of these reactions on the properties of the lime stabilised soil.

CHAPTER 4

LIME STABILISATION OF SOILS

4.1 Introduction

Before the discovery of Portland cement, lime was the main binding agent used for construction, and despite its decline in popularity, its use as a binder is still valid. Both Portland cement and lime tend to set and harden when mixed with water although lime is normally non-hydraulic and hardens by carbonation at a much slower rate than cement. However, when lime is mixed with pozzolanic materials such as clay soils hydration reactions produce cementitious products similar to those formed in hydrated cement, and if carbonation is minimised substantial strength can develop. Lime has thus proved to be adequate for some applications such as mortars, plasters, foundations and building blocks (30). Also, lime possesses additional qualities such as good workability and the ability to accommodate moisture movement without cracking, thus making it more suitable in some applications than Portland cement.

The raw materials for manufacturing lime are, normally, naturally occurring substances such as limestone, dolomite, sea shells or coral. Lime can also be obtained as a residual product in the manufacture of sugar, paper and acetylene. Thus, the variety of sources from which lime can be obtained offers an opportunity to promote the material in several countries and in different parts of a country. In Kenya, there are a large number of limestone deposits, although they are not suitable for high quality lime production (31). The crystalline limestones and marbles in the country are generally dolomitic, located at Sultan Hamud in Machakos District of Eastern Province and Homa Bay, Rangwa, Muhoroni and Koru in Nyanza Province. White hydrated lime is produced by Bamburi Portland cement company at Bamburi near Mombasa on the cement factory site.

Grey air-slaked lime is produced by the Kenya Marble Quarries Company near Nairobi which supplies the Nairobi area, and the Homa Bay Lime Company at Koru supplies the Western Rift Valley area where many end-user industries, i.e. the sugar and paper factories, are located. Some of these limes are of low purity. Pure hydrated lime contains 75.7wt% CaO whereas the white hydrated lime contains approximately 70% CaO while the grey air-slaked lime contains only about 55% CaO (32). Not much use is made of these limes in construction because they have proved to be expensive and a number of precautions must be taken in order to use them i.e. lime is a caustic material and reacts with skin. Also it readily reacts with carbon dioxide in the air to form calcium carbonate thus reducing its reactivity and effectiveness.

If for purposes of soil stabilisation lime has to be produced on a small-scale employing local technology, some basic understanding of the raw material is desirable as the first step in quality control.

The main capital outlay in small-scale lime manufacture is a kiln and a storage shed, both of which can be locally fabricated with hardly any imported inputs. However the fabrication of the kiln is a skilled operation, and so is the firing process. Careless slaking of the fired product, and poor storage and packing can undermine the entire object of quality production. Also the presence of contaminants such as sulphates can render the lime unsuitable for stabilisation purposes. Thus a continual programme of quality control and testing of lime-stabilised soil would have to be undertaken to ensure a consistent and reliable product.

4.2 Soil-lime reactions

Soil-lime reactions, unlike soil-cement reactions depend on lime attack of the clay minerals found in the soil. Addition of lime to a soil initiates several reactions. These include cation exchange, flocculation-agglomeration, and pozzolanic reactions (33, 34, 35, 36, 37, 38). In addition some carbonation of the lime will occur particularly in the surface regions and this should, where possible, be minimised as it contributes little to the strength development (38) and consumes lime which would otherwise be available for pozzolanic activity. The first two reactions take place rapidly in a matter of minutes or hours, whereas the pozzolanic reaction is a long term process which may continue for periods in excess of one year.

Addition of sufficient lime to a soil supplies an excess of calcium ions and cation exchange will occur, with Ca^{2+} ions replacing dissimilar cations from the clay in the soil. The general order of replaceability of the common cations associated with soils is given by the lyotropic series $Na^+ < K^+ < Ca^{2+} < Mg^{2+}$ etc (37, 38) i.e. cations tend to replace those to the left of the series and monovalent cations are usually replaced by multivalent cations.

The cation exchange capacity of the clay (39, 40) is largely related to the degree of substitution of ions in the octahedral sheet. The hydrogen of the exposed hydroxyls may itself be replaced by an exchangeable cation, although this substitution is mainly applicable to clay minerals such as kaolinite and halloysites because of the exposure of the hydroxyl sheet on one side of the layer. In the presence of lime the exchange of calcium ions for other cations and the saturation of the surface of clay particles with Ca^{2+} ions modifies the electrical properties of the clay particles in such a way that they attract each other and stick together. This process is termed flocculation. Diamond and Kinter (36) also suggested that the rapid formation of calcium aluminate silicate hydrates as cementing material is significant in the development of stable flocs and agglomerates. The surface adsorption of lime is a major factor affecting the initial changes. Calcium hydroxide

($Ca(OH)_2$). is rapidly adsorbed onto the clay particle surfaces in the early stages. The amount of calcium hydroxide immediately adsorbed (approximately 3wt%) corresponds to the lime fixation point. Flocculation then results and the soil is said to have been "modified" (see section 4.3) (41). Croft (34) also argues that amorphous cementitious products rapidly bond clay particles at their points of contact. The extent of this reaction largely depends on the quantity of soluble silica and alumina present in the clay. A slight strength development takes place at this stage.

The Ca^{2+} ions which are attracted onto the clay particle surfaces to balance the charge deficiency reduce the undesirable water absorbing or hydrophilic condition of clays which is created when H^+ and Na^+ ions are adsorbed on clay particle surfaces. This reduces undesirable properties such as drying shrinkage and swelling. Modification of a clay by addition of lime therefore, clearly depends on the nature of the dominant cation originally adsorbed, and also upon the clay type (20, 41, 18). For example a sodium-dominated montimorillonite (which has a high cation exchange capacity) will require a relatively high addition of lime to achieve calcium saturation and the full potential flocculation effect. In contrast, a kaolinite clay will require a considerably lower amount of lime to achieve the full potential.

With excess lime present in the system (over and above the lime fixation point), after the initial rapid reaction has occurred, continued slow chemical (pozzolanic) reaction takes place, which is responsible for the stabilisation of the soil. Silica and alumina are involved in this reaction. The major mechanism by which this reaction occurs (20, 42) is a through solution and precipitation mechanism. In the high pH condition of the lime solution the solubilities of silica and alumina are increased and that of calcium decreased (see Figure 4.1). Thus silicate and aluminate ions leave the clay particles and enter the lime saturated solution. At a critical concentration, precipitation of calcium silicate and aluminate hydrate phases takes place which produces cementation. This initial formation of cementitious reaction products, particularly at contact points, rapidly produces stable flocs.

Over long curing periods and high temperatures the development and growth of these reaction products bind the bulk soil particles together hence improving the strength of the soil. For maximum reactivity, the pH value in the voids should remain at 12.4 (37, 20). The solubility of silicate and aluminate ions especially those of clay minerals, is very high at this value.

Pozzolanic reaction gives rise to the formation of a wide range of hydrated calcium silicate and aluminate cementing agents. There are three major categories of compounds which form. These are calcium-silicate-hydrates, calcium-aluminate-hydrates and calcium-silicate-aluminate-hydrates. They are usually accompanied by the formation of some calcium carbonate. In most reports X-ray diffraction methods have been used to identify the reaction products (34, 41, 42). Most of the available silicate is consumed in the formation of an amorphous cementitious calcium silicate gel denoted as C-S-H gel. However, Arabi, Wild and Leng Ward (43) have confirmed that a significant proportion of aluminium, which is made available as a result of the lime-clay reaction, is incorporated into the cementitious gel phase and the gel is therefore more appropriately termed a C-A-S-H gel rather than a C-S-H gel. In addition to the gel phase a number of crystalline calcium aluminate hydrate phases have been observed to form principally C_2AH_8 and C_4AH_{13} (44). At elevated temperatures the lime-clay reactions generally give rise to formation of a third calcium aluminate hydrate termed hydroganet (C_3AH_6). It forms preferably at temperatures above about 30°C and once formed it is stable at room temperatures. C_2AH_8 and C_4AH_{13} are in fact unstable and tend to transform to the stable C_3AH_6 over long periods of time, the transformation being more rapid at high temperatures. The only crystalline calcium silicate aluminate hydrate which has been observed to form is Strätling's compound, C_2ASH_8. It forms in kaolinite-lime systems at normal curing temperatures where lime is not in excess (43, 45). It has been suggested that the long-term strength development of lime-clay material may be attributed to the gradual crystallisation of the gel phase (38) which forms an interlocking structure although the evidence for the crystallisation process is not very convincing and particularly when curing at elevated temperatures continued development of gel (44) is a more likely factor in strength enhancement rather than crystallisation.

The effect of lime on clay soils is the result of reaction between the lime and the clay fraction in the soil. This influences the consistency and plasticity of the soil and it's compactability. It also modifies its swelling and shrinkage characteristics, its permeability and strength and thus affects its durability. These changes are discussed in the following section.

4.3 Effect of lime on soil properties

4.3.1 Consistency limits

Addition of lime to clay soils affects their plastic properties. The effect is normally instantaneous and causes reduction in plasticity of cohesive soils, so that they become more friable and more easily worked. This comes about as a result of cation exchange and flocculation (see section 4.2) (35). Although the bonding between the clay particles within a floc or aggregate is increased, bonding between aggregates is relatively weak. The aggregates behave like particles of silt which have a low plasticity. Very small quantities of lime are required to bring about these changes in plasticity. Generally the amount needed varies from 1 to 4% depending on the amount and type of clay mineral present in the soil.

The plastic limit (P.L.) of cohesive soils increases when treated with lime (34, 36, 37, 46, 47). The amount of increase varies directly with the amount of lime added, up to a point where addition of more lime will make no change. This point is called the "lime fixation point" (36).

Hilt and Davidson (40) observed large increases in P.L. of clay soils when small amounts of lime were added. They noted the largest increases occur in soils containing montmorillonite while the increases for illitic-chloritic and kaolinitic clay soils were affected somewhat less. Mateous (48) showed empirically that the minimum amount of hydrated lime required to be added to montmorillonitic clays for maximum increase in plastic limit (PLmi) was

PLmi =([%age passing 2 μm sieve]/35) + 1.25.

The effect on the liquid limit varies depending on the type of soil being stabilised. For example the liquid limit of kaolinite clays increases when treated with lime. Croft (34) suggested that this increase was due to the action of hydroxyl ions which modified the affinity of the surfaces of the clay particles for water. Further additions of lime gave rise to little change in the liquid limit. Mateous (48) also reported an increase in liquid limit of illitic clays with lime addition. By contrast the value of liquid limit of montmorillonite gradually decreases with increasing lime content. Hence the action of hydroxyl ions referred to previously would appear not to be significant in expansive clays.

The effect of lime on the liquid limit (L.L.) of clay soils also depends on the kind of cation present in the soil and the extent to which these cations are exchangeable. Clare and Cruchely (46) report data showing a drastic increase in L.L. upon addition of lime for a particular clay, which was calcium saturated in its natural state. Diamond and Kinter (36) observed that mixes of lime and calcium-saturated clay, stored so as to prevent evaporation and carbonation, assumed an increasingly dry appearance. This reaction would be reflected by an increase in the L.L. of the soil.

When the L.L increases on the addition of lime, the increase is not usually as great as the accompanying increase in the plastic limit. Therefore the separate effects on liquid limit and plastic limit usually combine to produce a rather sharp decrease in plasticity index.

As curing proceeds, further changes in the Atterberg limits may occur, which result in further decreases in plasticity index. Dumbleton (49) showed increases in L.L. whereas Akoto and Singh (47) observed decreases in L.L. with time. Arabi (20) from his investigation of the effects of curing period and curing temperature on the plastic properties observed increases in the L.L and P.L and decreases in the plasticity index with increase in temperature and curing period.

4.3.2 Shrinkage and swelling

Dry clay has a considerable capacity for moisture uptake which can lead to a substantial volume increase. An immediate benefit obtained by lime treatment of clays is the reduction or complete elimination of swelling potential and swelling pressures. These modified characteristics are usually attributed mainly to substitution of other cations by calcium. The reduction in swelling also results from decreased affinity for water of calcium saturated clay and the formation of a cementitious matrix which resists volumetric expansion. Mitchel et al (50) showed that 4% dolomitic hydrated lime was very effective in stabilising an expansive clay soil and reduced the swelling from 17% to less than 3%, after treatment. The addition of lime to clay soils also increases the shrinkage limit. Shrinkage limit is the moisture content below which shrinkage no longer occurs. It describes the limit between solid and plastic states of a clay, and is usually distinguished by a colour change, the clay becoming much paler at water contents below shrinkage limit. According to Mateous (48), quicklime is more effective in reducing the shrinkage characteristics of a soil than hydrated limes. With small additions, high calcium hydrated lime is more effective than other hydrated limes or cement, but with about 8% addition all limes cause a similar increase in shrinkage limit.

Shrinkage due to moisture loss from the stabilised soil is of importance in relation to the problem of shrinkage cracking in buildings.

4.3.3 Compaction properties

The advantage of lime over cement when used in the stabilisation of soils is its tolerance for delay in compaction after mixing. Delay in compaction of cement stabilised soils will greatly affect the resulting strength since the cementing agents formed from hydration of cement immediately after mixing will be destroyed if the mix is compacted at a later time. The pozzolanic reactions in lime stabilisation, which principally determine the strength development in soil-lime mixtures, are slow. Therefore, delay in compaction will not affect the ultimate strength as long as the soil-lime mix is kept in a sealed environment to avoid carbonation of the lime and as long as the curing temperatures are not too high. At high curing temperatures i.e. > 50°C (41) gel formation is rapid and delay between mixing and compacting results in a reduction of the final strength.

Lime treatment of clay soils broadens the compaction curve (see figure 4.2), thereby ensuring that for a particular mix the required density can be achieved over a much wider range of moisture contents.

Thus wider moisture control specifications are possible enabling soils in quite moist conditions to be compacted satisfactorily. As stated in section 2.6, the addition of lime to clay soils increases the optimum moisture content and reduces the maximum dry density for the same compactive effort. The reduction in dry density is due to flocculation (41) which produces a more open network of soil particles and is also influenced by the immediate formation of cementitious products (38) which reduces compactibility and hence the density of the treated soil. The major part of these changes occurs for relatively small additions of lime (up to about 5wt%) and further additions of lime produce only minor reductions in maximum dry density and minor increases in optimum moisture content. Higher compaction densities are obtained in lime treated kaolinitic clays than in soils in which clay minerals with expandable structures predominate. This is confirmed by Croft (34) who suggests that it is due to the high demand by expandable clay minerals for adsorbed and lubrication water relative to that by non-expandable clays such as kaolinite.

4.3.4 Permeability

The flocculation-agglomeration that occurs immediately lime is added to clay soils produces a more open structure, allowing easier flow of water between particles thus increasing the permeability. After compaction and long periods of curing the development and growth of the reaction products bind the bulk soil particles together, thus reducing the void spaces. This reduces permeability of the soil-lime mixtures. At low curing temperatures, however, where limited amounts of gel are being formed, permeability increases with curing time.

Arabi and Wild (41) have shown that permeability is not related simply to overall or total porosity, because pores below a certain size (approximately 40nm) are unable to transmit water by capillary action. However, if the porosity due to pores of radius less than 40nm is discounted, there is a consistent decrease in permeability with decrease in porosity. As previously stated the very marked increase in permeability on the addition of small amounts of lime to the clay soil is a result of the effect of the lime on the water absorption properties of the clay soil and of flocculation. With increased lime contents permeability gradually falls, even at low temperatures when gel formation is limited. This is mainly because excess lime, over and above that required to complete the ion exchange process, occupies the pore spaces between the soil particles and produces more efficient packing (41, 51).

4.3.5 Compressive strength

The strength development in a soil that can be produced by adding lime depends on the type and proportion of clay minerals present, the amount of lime added, the curing environment, the curing temperature and the curing time. When the desirable pozzolans are available, they react readily with lime to improve the strength of soil-lime mixtures. Clays generally show a significant increase in strength when lime is added. Montmorillonite, an expansive clay, shows a rapid initial increase in strength with small additions of lime, even though after additional curing time the total strength gain is less than that developed in other clay minerals (38).

Strength increases with increasing lime content up to a point called the "optimum lime content" and then decreases with addition of lime in excess of this point (38, 11). This is due to the fact that lime itself is a soft material with a layered structure which when moist tends to exhibit plastic behaviour. Thus any lime in excess of that able to react with the clay, will produce regions of weakness and nullify the cementing action of the lime-clay reaction. The rate of strength development of soil-lime mixtures which is determined by the rate of formation of cementitious products is very sensitive to temperature and relative humidity (52). High temperatures increase the rate of formation of cementitious products and high relative humidity ensures that the water required for the reactions is retained in the soil-lime mixtures. Strength increases at a decreasing rate as lime is consumed in the reaction and the availability of active clay particle surfaces declines. As the cementitious gel builds up around the clay particles it blocks off access of lime to the clay particles and the reaction is curtailed. Thus if excess lime is added, unreacted lime will remain indefinitely. A useful formula for 'Lime optimum modification' (LOM) which estimates the optimum amount of lime for stabilisation has been developed by Webb (9) and Adam (11) where

LOM =([% passing 63um sieve]/42) + 1.25

This equation follows on from the work cited by Davidson (40) and was proved effective which was proven in both Kenya and Sudan when high clay fraction soils were stabilised with hydrated lime.

Ola (17), working on lateritic soils from Nigeria has shown strength increases in the range of 300 to 900% by adding up to 6% hydrated lime to the soil. Coad (26) has reported an improvement in strength between 150% and 185% for lateritic soils from Ghana stabilised with 6% lime compared with unstabilised specimens. Akoto and Singh (47), studying lateritic soil from Kenya have also demonstrated strength improvement of 180%, using 12% hydrated lime.

4.3.6 Deleterious compounds affecting lime stabilisation

The extent to which the soil-lime reactions proceed is affected primarily by natural soil properties. Some of the major properties and characteristics are clay mineral content, types of clay minerals present, presence of salts such as sulphates and chlorides and soil organic matter.

When added to a clay soil, lime chemically attacks the clay mineral fraction. The quantity of lime to be added is related to the clay mineral content of the soil, as the clay minerals are needed for reaction. Ingles and Metcalf (21) suggested that the addition of up to 3% lime would modify silty clays, heavy and very heavy clays, whilst 2 to 4% was required for the stabilisation of silty clays, and 3 to 8% was proposed for stabilisation of heavy and very heavy clays.

All clay minerals are attacked, although those possessing the highest available silica normally react more strongly. Thus, three-layer clay minerals, the lamellae of which expose silica faces on both sides, are more reactive than two layer minerals the lamellae of which expose silica at one face only. However, a silica surface should not be considered "available" if it is bound to a similar surface by ions not readily exchangeable. Thus illite, kaolinite and chlorite, although attacked, are much less reactive than montmorillonite (35).

Organic matter is a deleterious component which affects lime stabilisation. Dumbleton (49) found that soil organic content affected both lime and cement stabilisation. The organic matter retards or inhibits hydration and pozzolanic activity because it preferentially absorbs calcium ions (35). Thompson (53) reported that soils with organic contents greater than 1% generally did not respond well to lime treatment. Hence lime treatment of top soil is not advisable.

The effect of sulphates on lime and cement stabilisation were investigated by Sherwood (54) who found that the presence of sulphates also has a detrimental effect. This is due to the formation of ettringite (calcium sulpho-aluminate hydrate), $[Ca_3Al(OH)_6]_2(SO_4)_3.26H_2O$. Under certain circumstances (i.e. in saturated conditions and within particular pH ranges) the ettringite forming reaction can result in the development of colloidal material which initiates osmosis and excessive water absorption and swelling (55, 56). The expansion disrupts bonding in the stabilised soil and hence leads to volume instability. The amount of expansion during ettringite hydration and growth is a function of the amount and rate of release of alumina into solution, as well as the amount and type of sulphates present. These factors influence the quantity and crystal morphology of the ettringite formed. Mitchel et al (57) claimed that a non-expansive mono sulphate calcium aluminate hydrate first forms in high alumina content lime treated kaolinite-sand mixes. The monosulphate then converts to an expansive trisulphate form (ettringite) after a period of a few months. Conversely, ettringite starts to form at early curing stages (after a few days) in the low alumina lime-treated montmorillonite-sand mixes. Mehta and Klein (58) also established that the formation of monosulphate hydrate is favoured in a relatively high alumina content environment whereas ettringite formation is favoured in a lower alumina content environment. Once ettringite crystals have nucleated they continue to grow unless the temperature of the system drops below 15°C. Below this temperature, and assuming the presence of soluble carbonates in the system, ettringite may change to thaumasite, $[Ca_3Si(OH)_6]_2(SO_4)_2(CO_3).24H_2O$. This change occurs by isostructural substitution of silica for alumina and carbonate for sulphate and may also initiate water absorption and swelling. If however expansion can be prevented or minimised sulphates can have a beneficial effect on lime stabilisation. Abdi (55) has shown that considerable strength enhancement can be achieved by addition of sulphates. Investigating the effect of gypsum ($CaSO_4.2H_2O$) on lime stabilised kaolinite, he found that additions of 2wt% and 4wt% gypsum to kaolinite stabilised with 6wt% lime had minimal effect on the volume stability of the stabilised samples but resulted in a marked increase in compressive strength. The volume increase of the cured and soaked samples was of the order of 0.5% but the strength increased by about 60%. Higher gypsum contents than this produced excessive expansion.

4.4. Curing of lime stabilised soil blocks

Curing conditions are of major significance in determining the ultimate performance of components such as stabilised soil blocks. These conditions include temperature, time, moisture content and relative humidity.

As stated earlier, higher strengths are obtained at higher curing temperatures for lime-stabilised soils. This is of economic importance in warm weather countries like Kenya.

Also stabilised soil blocks should be moist cured and rapid drying should be avoided as this leads to undesirable shrinkage cracks. For soil-lime systems the pozzolanic reaction (a hydration process) can only take place in the presence of moisture. Drying, if allowed to take place too soon, results in low strength and poor durability. Proper methods of curing are therefore those which ensure that an adequate amount of moisture is retained in the blocks so that the chemical reactions continue until the required strength is obtained and the reaction is completed. Some of the methods employed (29) are ponding, frequent sprinkling of water, wet sack covering, steam curing, use of sealed containers and use of water-proof plastic membranes.

If under moist conditions the required strength is not obtained but lime is in excess then the curing period must be extended or the curing temperature increased. If the required strength is not obtained and lime is fully consumed then insufficient lime is being added. Therefore achieving a specified strength requires a critical combination of curing time, curing temperature, lime content and relative humidity. In addition initial compaction pressure (see section 3.4 of Chapter 3) also strongly influences final strength.

In the field (9) the freshly moulded blocks are laid out in a single layer, on a non-absorbent surface, and covered with a water-proofing membrane to retain moisture within the blocks. These are allowed to stay for a period of about 5 days depending on the local soil and ambient conditions. This is termed the primary curing period. For cement stabilisation this period is as little as 2 days.

After primary curing the blocks are removed from their protective cover and stacked in a pile. Water is sprinkled onto this stack of blocks and a cover placed over the top. This cover could be a plastic sheet, grass or reeds to reduce moisture loss. Periodically another layer of blocks is added to the stack and each time water is sprinkled onto the blocks and the stack covered. The covering helps to reduce moisture loss and maintain a high relative humidity. This period is called the secondary curing period and should be at least 14 days. Lime-stabilised soil blocks will probably take twice as long as cement-stabilised blocks to cure under the same curing conditions.

When curing lime-stabilised soil blocks, care should be taken to minimise carbonation by covering them. Temperature is also vital in accelerating the pozzolanic activity which contributes to strength development. Curing temperatures of up to $50^{o}C$ may be obtained by siting the blocks in a sunny position and covering them with black plastic sheets.

4.5. Durability of lime-stabilised soils

Durability is defined as the ability to age without deteriorating, that is to last in spite of frequent use and hard wear. This definition must however be qualified as no material has an infinite lifetime. Also the same material may have a long lifetime in one environment while deteriorating in another. For example, adobe blocks may last for several years in an arid climate, but may disintegrate rapidly in a wet one. Climatic conditions therefore play an important role in determining how durable a material is. Durability is the ability of the material to withstand extreme environmental conditions over a specified period of time. It is the quality of maintaining a satisfactory appearance whilst still performing its required functions (59).

Durability can be assessed indirectly by subjecting the material in question to weathering tests and monitoring crack formation by visual inspection, determining weight loss and measuring strength. Accelerated weathering tests under laboratory conditions are aimed at reproducing the outdoor weathering behaviour of a material by subjecting the material to extremely severe conditions. This permits assessment of durability within a shorter period than is required under actual conditions of use. In general acceleration is achieved, not by intensification of the environmental factors responsible for breakdown, but by increasing the frequency of occurrence of these factors.

Some of the weathering tests (9) that have been applied to building blocks include:-

i) wet-dry cycling
ii) water absorption
iii) water spraying

iv) brushing test

i) Wet-dry cycling

The 28 day cured samples are completely immersed in water for a period of 12 hours or overnight. These are then removed from the water and left to dry in the sun. The procedure is repeated for 7 days i.e. wetting and drying the samples for 7 cycles. Visual inspection is done and if the sample falls into pieces, cracks or bursts then it is considered unsuitable for durable construction. This test is important especially in areas which have very heavy rainfall followed by very dry and hot conditions. Another technique which could be useful in semi-arid regions of Kenya is that of cycling the test samples through extreme conditions of temperature and then testing the samples for durability employing the tests discussed below. The temperatures in some areas of Kenya may vary from 10°C in the night to about 35°C during the day. The rain comes, after long periods of drought, and usually results in flooding (see Chapter 1).

ii) Water absorption test

In this test the weight of a sample block is taken before and after overnight immersion in water and the percentage moisture absorption is calculated. The Kenya Specification for Stabilised Soil Blocks (25) recommends that the water absorption should not exceed 15% of the original mass of the sample. Burnt Fletton clay bricks have a water absorbance of about 22%.

iii) Water spray test

This involves using a horizontal spray of water from a 100mm diameter spray head under a pressure of 1.5kg/cm^2. This pressure is chosen to give a much greater impact force than that expected from driving tropical rain. The cured sample is placed 200mm from and parallel to the face of the spray head. Water is sprayed continuously for a period of 2 hours onto the sample after which it is examined visually for erosion and pitting. The resulting weight loss is determined. Severe erosion and pitting indicate the sample is not durable. Webb (9) has shown that a lime-stabilsed soil block manufactured under a compacting pressure of 2N/mm^2 is not durable as it shows considerable erosion and pitting after the 2 hour spray test. However, by employing a compacting pressure of 8N/mm^2 the stabilised block withstood the test.

iv) Brushing test

The brushing test is important especially in semi-arid areas where erosion occurs under the abrasive action of wind-borne sand. Several different types of brushing tests are employed. The Kenyan Specifications for Stabilised Soil Blocks (25) recommend the use of a wire scratch brush made of 0.4mm diameter wire bristles assembled in 50 groups of 10 bristles each and mounted to form 5 longitudinal rows and 10 transverse rows on a 200 X 60mm hardwood block.

The test sample is submerged in water at room temperature for 6 hours. It is then removed and oven dried at a temperature of 70^{o}C for 42 hours. All areas of the specimen are then brushed twice with the scratch brush. This should be held with the long axis of the brush parallel to the longitudinal axis of the specimen. The srokes are applied to the full height and width of the specimen with a firm stroke corresponding to approximately 1.5kg force. Eighteen to twenty vertical brush strokes are required to cover the sides of the specimen twice and four strokes are required on each end.

The procedure is repeated for twelve cycles and the specimen then dried to a constant weight at 110 $^{+}$ 5^{o}C and the dry weight determined. The weight loss can be used to determine how durable the block is.

Another suggested (9) test is to employ an "A'court" machine in which eight samples each of 100 X 100 X 25mm are moved horizontally beneath 8 static hoppers all containing fine sand. The sand rubs against the upper face of each sample, (which is in contact with the lower face of each hopper) giving abrasive action. At frequent intervals over a period of 8 hours each sample is weighed to determine the amount of sample abraded away. The weight loss gives an indication of the abrasion resistance of the product.

4.6 Summary and aims

The current chapter has reviewed the literature which relates to the stabilisation of soils with lime. It has shown that four basic reactions occur when lime is mixed with soil and water i.e. cation exchange, flocculation pozzolanic activity and carbonation. Cation exchange, flocculation and agglomeration are principally responsible for the observed changes in plasticity, shrinkage and workability. Although lime carbonation may contribute slightly to strength increase of the soil-lime mixtures, the pozzolanic reaction mechanism is regarded as the prime source of strength development. Lime-stabilised soil appears to have been employed successfully (mainly for road construction) throughout the world with certain soils (clays and silty clays). The amounts of lime used are in the range of 2% to 15% by weight of the dry soil. Encouraging strength and durability results have been obtained when lateritic soils are stabilised with lime, and the soils show greater volume stability and reduced plasticity. The strength and durability of lime-stabilised soil can be improved even further by increasing the pressure at which the soil is compacted. Also small amounts of gypsum added to the clay-lime mixtures have been shown (55) to increase the strength of the compacted material soil. However, the long-term strength and durability of these compositions have not been fully investigated.

The present work is intended to investigate the strength development of murram stabilised with various amounts of lime and lime-gypsum cured for different periods of time under constant temperature and relative humidity. It is also aimed at evaluating the performance and durability of the stabilised soil under various conditions of temperature and relative humidity in relation to the Kenyan climate. The detailed aims are listed below. They are:

i) to establish, for lime-stabilised murram, the optimum lime content and the appropriate curing times and compaction pressures which are necessary to achieve the minimum strength required by the Kenyan standard (25) for stabilised soil blocks

ii) to critically compare the strength development of the lime-stabilised and cement stabilised material

iii) to determine whether the addition of small amounts of gypsum, or the addition of filler such as sand, can provide strength enhancement and therefore more efficient utilisation of lime

iv) to assess the relative durabilities of the murram based materials specified in i) and ii) above

v) to propose, on the basis of performance and economic viability the most appropriate stabilised murram material for use as building blocks.

The durability tests discussed have one deficiency in that they do not adequately take into account the environment of an in-situ block within the wall of a dwelling. The outer surface of such a block experiences a very different environment from that of the inner surface. The inner surface is normally dry and is subject to relatively small variations in temperature. The outer surface is subjected to impact from rain droplets and very wide variations in both temperature and moisture content. The continuously changing moisture and temperature gradients across the blocks result in differential movement within the blocks generating tensile strain and internal stress. This results in cracking and weakening which when combined with the impact of rain on the outer surface, produces breakdown and spalling of the material. One object of the current research is to more closely reproduce this enviromnent in an accelerated form. Durability equipment will therefore be designed for this purpose.

The soil will be first classified using BS 1377:1990. X-ray diffraction analysis and standard analytical methods will be used in order to establish the clay content, the soluble salt content and the mineral components. The murram will be mixed with various percentages of lime and gypsum and compacted (at optimum moisture content) into cylinders. Two different compaction pressures will be employed to evaluate the effect of compaction pressure on ultimate performance. The cylinders will be cured in a typical curing environment for different periods and their compressive strength determined. The cylinders will then be subjected to a range of durability tests. The reaction products when lime and lime-gypsum react with murram will be analysed using X-ray powder diffraction analysis, thermogravimetric analysis and scanning electron microscopy.

The performance of lime-stabilised murram will then be evaluated in relation to compaction pressure, curing period, composition and reaction products.

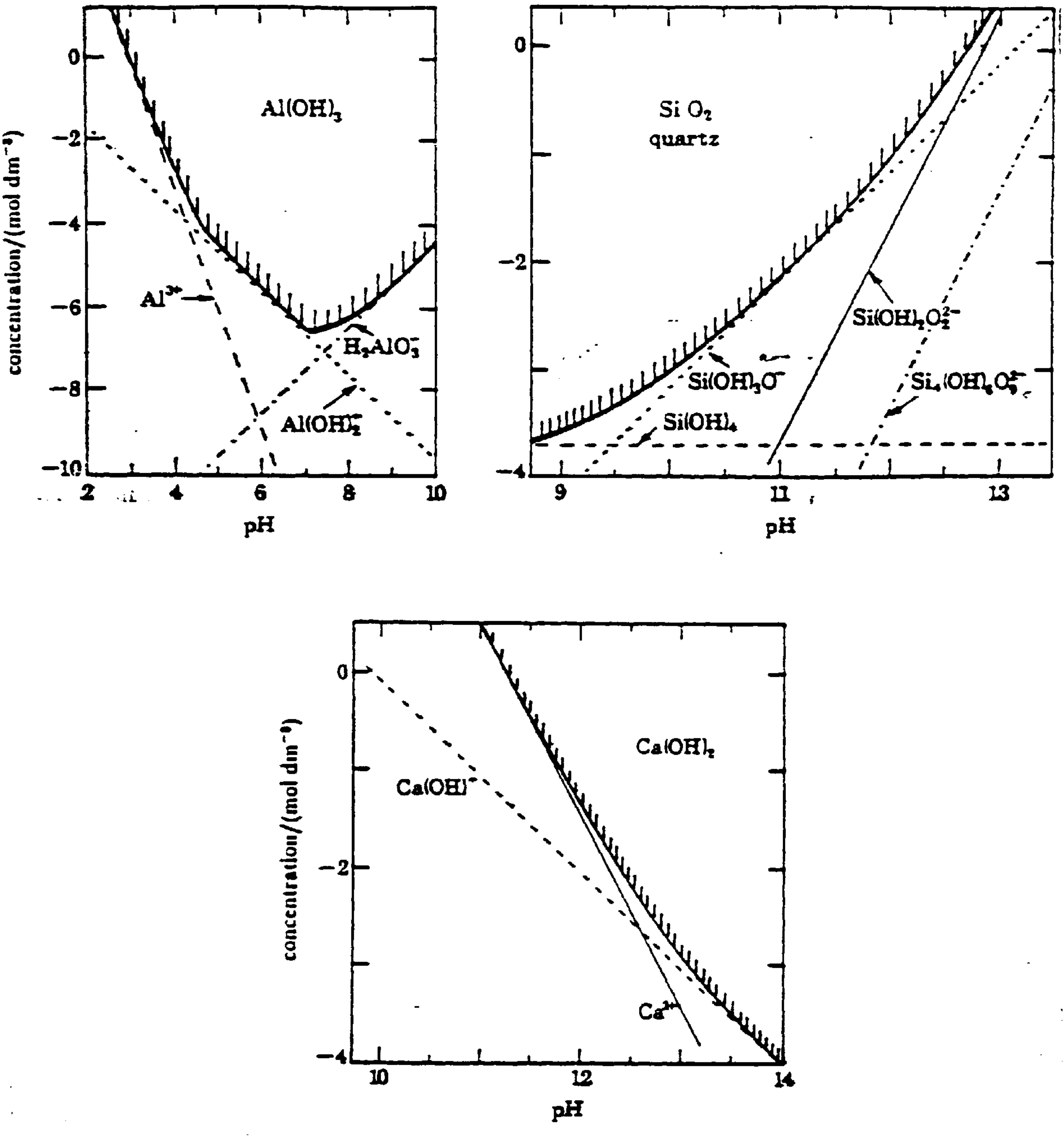


Figure 4.1 Solubility diagram for alumina, quartz and calcium hydroxide (logarithmic ordinate) (after Ottewill (60)).

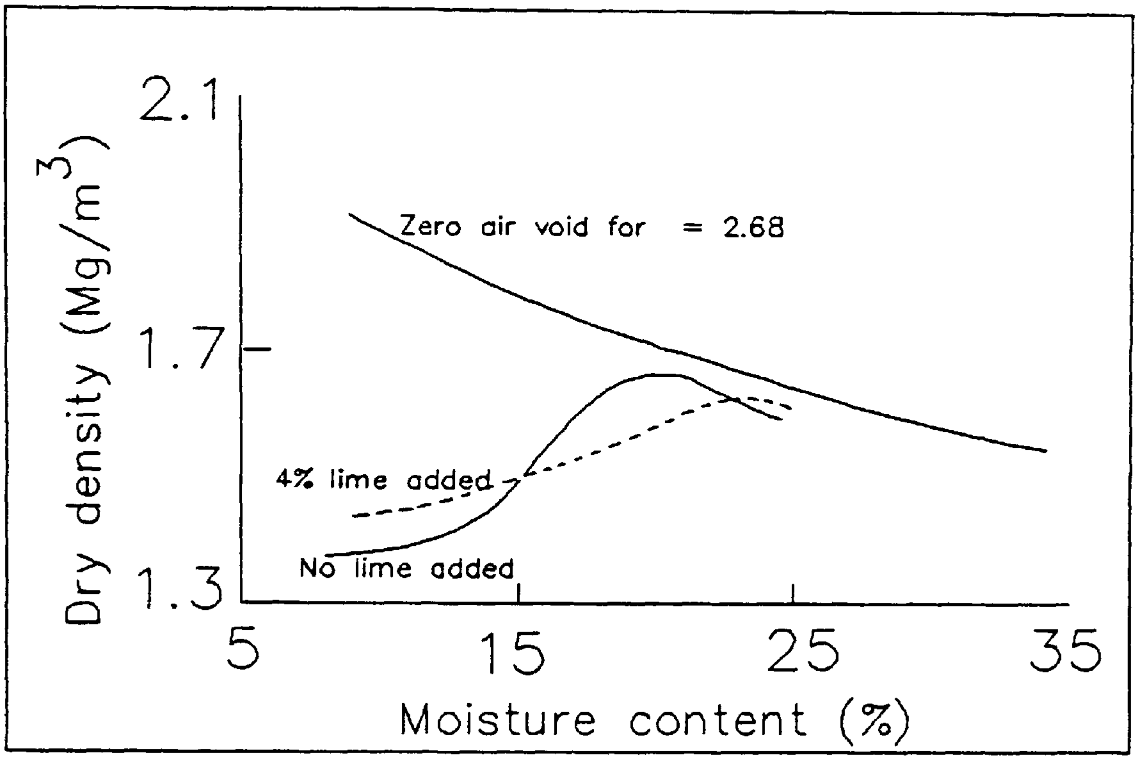


Figure 4.2 Influence of lime addition on the compaction curve of clay soil (after Ingles (65)).

CHAPTER 5

EXPERIMENTAL METHODS

5.1 Soil characterisation

5.1.1 Source

Ten soil samples each weighing about 18kg were supplied by the Ministry of Public Works, Materials Department, Nairobi, Kenya. The samples were collected at different points along a road alignment of the existing Mataara road of Kiambu District of Kenya. The description of the soil samples shown in Table 5.1 was provided by the suppliers. The soil samples were then flown in sealed tins to the United Kingdom (UK) for the intended research work. These samples were selected to represent murram soil, a laterite soil found in Kenya. From the sampling table and from sample inspection there were no clear distinguishable features between the samples. Therefore all ten samples were combined into one single sample. The ten samples were mixed, air-dried and crushed to pass a 6mm BS sieve size. The crushing was done using a mechanical crusher. The Kenyan Standard for stabilised soil blocks recommends that soil for manufacture of stabilised blocks should have particles with a maximum size of 6mm.

Various tests and analyses were carried out on the soil in order to fully characterise the type of soil being studied. These are discussed in the following sections.

5.1.2 Atterberg Limits

The liquid limit of the soil was determined using both the Casagrande apparatus and the cone penetrometer as described in BS 1377:1990.

Using the Casagrande apparatus the liquid limit was taken as the water content at which the two sides of a groove cut in the soil sample contained in the cup, would touch over a length of 13mm after 25 impacts.

With the cone penetrometer the liquid limit was taken as the water content at which the cone, allowed to drop freely, penetrated into the soil sample contained in the metal cup by a depth of 20mm.

The plastic limit was taken as the water content of the soil at which cylinders of 3-4mm diameter started to crumble when rolled between the hand and a flat plate. It is the lowest moisture content at which the soil is plastic.

The plasticity index is then taken as the difference between the liquid and plastic limits.

In this study the Atterberg limits were determined for the murram soil mixed with 0, 5, 10 and 15wt% lime.

5.1.3 Linear shrinkage

The linear shrinkage test was carried out using a semi-cylindrical brass mould in accordance with BS 1377:1990. A soil sample was mixed with water to make a homogeneous paste at the liquid limit. The internal surfaces of the brass mould were oiled and then the mould was filled with the paste. The surface was levelled off using a straight edge. The filled mould was left at room temperature for 24 hours after which it was oven-dried at 105°C for a further 24 hours. The length of the soil in the mould was measured after the 48 hour period. The difference between the original length and the final length expressed as the percentage of the original length was taken as the linear shrinkage of the soil.

In the field a simple open wooden mould can be used to determine how a soil will respond when water is added to or removed from it. Using this mould type (Figure 5.1), Webb (9) has shown (see Table 5.2) that the linear shrinkage can be used as an indicator of the amount and type of soil stabiliser required for stabilised building blocks.

Shrinkage tests were also carried out in this type of mould. The reduction in length of the soil mass was measured daily until there was no further change.

In addition to carrying out shrinkage tests on murram (the clay content of which is principally kaolinite) shrinkage measurements were also carried out on a series of synthetic soils made up from kaolinite-sand mixtures for purposes of comparison.

5.1.4 Specific gravity (SG) and soil pH

The specific gravity of a soil is the ratio of the weight in air of a given volume of soil particles to the weight in air of an equal volume of distilled water at 20°C. It is rarely used as an index for soil classification, but its determination is essential in relation to other soil tests, such as porosity and void ratio, and is particularly important for the determination of particle size using sedimentation methods. The specific gravity of the murram was determined using the density bottle method described in BS 1377:1990.

Both the Electrometric and Calorimetric methods in BS 1377:1990 were used to determine the pH of the murram.

5.1.5 Particle size distribution

Two different procedures were used in order to cover the wide range of particle sizes which were encountered in the soil. These were wet sieving followed by dry sieving and, sedimentation The methods are described in BS 1377:1990.

Particles with sizes greater than 63 µm were separated from the finer ones by washing. A 75g soil sample was placed on the 63um sieve and washed over a sink with a jet of clean water until all the fines were washed off i.e until the water passing through was as clean as the original. The material thus retained on the sieve was allowed to drain and transferred to an evaporating dish. This was then placed in an oven to dry overnight. The dried soil sample was weighed and passed through a range of sieves from 2mm to 63µm sizes. The sieves were shaken by hand and the proportion retained on each sieve was weighed and recorded.

Sedimentation using the Hydrometer method was employed for determination of particle sizes less than 63 µm.

The theory of sedimentation is based on the fact that large particles in suspension in a liquid settle more quickly than small particles assuming that all particles have similar densities and shapes. The velocity which a falling particle eventually reaches is known as its terminal velocity. If the particles are approximately spherical the relationship between terminal velocity V, and particle diameter D, is given by Stoke's law i.e.

$$V = \frac{D^2 g(\rho_s - \rho_l)}{18\eta}$$

Though clay particles are far from spherical, the application of Stoke's law based on diameters of equivalent spheres provides a basis for comparison of the particle size distribution in fine soils.

In the sedimentation test a suspension of a known mass of fine soil particles of various sizes is made up in a known volume of water. The particles are allowed to settle under gravity, and from measurements made at fixed intervals of time, the distribution of particle sizes can be assessed. By applying Stoke's law, the maximum diameter of particles remaining above a particular depth after a certain interval of time can be calculated. The mass of the solid particles present can be determined either by sampling from a specified depth or by measuring the density of the suspension with a hydrometer (61). In the present work, the hydrometer method was used.

A 100 ml solution of dispersant (made from 75mls of distilled water and 25mls of sodium hexametaphosphate) was added to about 75g of pretreated soil (as described in BS 1377:1990:part 2) and stirred for 15 minutes using a high speed mechanical stirrer. The suspension was then transferred to a 63μm test sieve placed on a receiver, and washed using a jet of water. The water used did not exceed 500mls. The suspension passing was transferred from the receiver into a 1000 ml sedimentation cylinder without losing any material.

This was made up to the 1000ml mark with distilled water. The sedimentation cylinder was placed in a constant temperature water bath, set at 25^{o}C. The cylinder was allowed to stand in the bath for about 1 hour. The suspension was then stirred vigorously to make it uniform. On completion of stirring the stop-watch was started and the hydrometer was carefully inserted into the suspension and allowed to float freely. Readings of the hydrometer were taken at the top of the meniscus level at the following time intervals; 0.5, 1, 2, 4, 8, 15, 30 minutes, 1, 2, 4 and 24 hours.

Using these hydrometer readings the percentage of particles passing and hence their respective diameters were determined. The percentage passing, K, is given by the formula;

$$K = \frac{100Gs}{m(Gs-1)}(Rh + Mt-x)$$

where Gs = specific gravity

m = mass of oven dry soil after pretreatment
x = dispersing agent correction
Mt = temperature correction
Rh = hydrometer reading

The respective diameters were determined from the use of a nomographic chart for the application of Stoke's law (see appendix 5.1).

5.1.6 Chemical analysis

Many of the properties of clays are dependent on the nature and amounts of various minerals in them, hence the identification, determination and estimation of these components are of great importance. Chemical analysis in the current work was used to determine the water soluble salts present in the soil and to determine the silica, alumina and iron oxide content of the soil.

To determine water soluble salts in the murram soil, about 5g of soil was mixed with 100mls of distilled water and stirred for 24 hours. The suspension was filtered and the clear solution (water extract) obtained was used for analysis. Also another sample filtrate was dried and weighed and the percentage by weight of total water soluble salts was determined.

To determine the oxides content of the soil the following procedure was adopted. About 114mg of soil in powder form was digested using 1ml of 60% perchloric acid and 7ml of 40% hydrofluoric acid. A clear solution was obtained and this was made up to 100mls using deionized water. This solution was then used for the analysis.

Various analytical methods have been devised for chemical analysis of clays and other materials (62). The analytical methods that were used in the present work are

a) Flame Photometry

b) Atomic Absorption

c) Calorimetric methods

d) Titration

e) Absorption Spectrophotometry

a) Flame Photometry

It is well known that when sodium compounds are introduced into a flame, a yellow colour is produced, and potassium and calcium compounds produce respectively violet and brick-red colourations. These characteristic emissions are the result of electron transfer in the atoms of the elements.

The essential features of the flame photometer are a suitable flame and a means of ejecting a solution of the sample into it at a predetermined rate. A filter designed to transmit only the characteristic emission of a particular element, is placed between the source and the photocell so that the intensity may be measured and compared with standard samples tested under the same conditions. This method was used to determine the levels of water soluble sodium and potassium in the soil.

b) Atomic Absorption

If a compound dissociates into its constituent elements, the electron orbits will absorb radiation normally emitted by those elements when in excited states. This effect can be utilised in making accurate determinations of the type and amounts of elements present in a solution of a compound. The elements to be analysed must first be obtained in solution form.

The aqueous phase must then be injected into a flame at a sufficiently high temperature to dissociate all compounds of the element being analysed and to volatilise them without exciting the atomic form. Emission of a characteristic wavelength of the element from a standard lamp is passed through the flame so that a portion of it, corresponding to the amount of element present, is absorbed by the element. In practice only one element is analysed at a time because it is preferable to use a single-element lamp.

The method was employed in the determination of the amounts of water soluble magnesium and calcium present in the soil.

c) Calorimetric method

When dealing with low concentrations, calorimetric methods are particularly appropriate. To be of quantitative use a calorimetric method must be based on the formation of a completely soluble product with a stable colour. The coloured solution must conform with the following relationships

i) Beer's Law:

Light absorption increases exponentially with concentration of the absorbing solution.

ii) Lambert's Law:

Light absorption increases exponentially with the length of the light path.

These laws apply to all homogeneous solutions and can be combined as

$$OD = \log \frac{Io}{I} = abc$$

where OD = Optical density
Io = Intensity of light entering sample
I = Intensity of light leaving sample
a = constant characteristic of particular solution
b = length of light path in solution
c = concentration of absorbing substance

The colour produced may be measured by a variety of methods. In the present work a direct reading spectrophotometer (DR/2000) was used.

It comprises a glass sample cell through which a beam of light from a low-voltage lamp is passed. Light emerging from the sample is detected by a photo-electric cell whose output is displayed on a meter. A prism is employed to give monochromatic light of the required wavelength. Two glass sample cells are filled, one with deionized water (blank) and the other with the prepared sample. The instrument is loaded with the blank to set the zero optical density. The blank is removed and replaced by the sample. The instrument gives the concentrations of species by direct reading from a meter. This technique was used to determine the amount of water soluble sulphate and chloride in the soil.

d) Titration method

This is a well established technique which depends on the measurement of volumes of liquid reagents of known strength.

This method was used to determine the carbonate content in the water extract. A 50ml sample was titrated with standard 0.1M hydrochloric acid using methyl orange indicator. Because the colour did not change, phenolphthalein indicator was added and titration continued until there was a colour change. The total volume of acid used was noted.

e) Absorption spectrophotometry

The principle here is similar to that in atomic absorption spectroscopy and here also the sample must be obtained in solution. Light is passed through the sample solution and a measurement of radiation absorbed (the absorbance) is made. The absorbance is produced by an interaction between the incident radiation and the molecules of the substance being determined. This method is particularly applicable to some components commonly found in clays, such as silica, alumina, iron oxide and titania.

This method was employed for determination of silica, alumina and iron oxide in the murram soil.

Thermogravimetric analysis (section 5.5.2), X-ray analysis (section 5.5.3) and scanning electron microscopy (section

5.3.4) were used to analyse the mineral components in the soil.

5.1.7 Compaction testing.

The Proctor compaction test, described in BS 1377:1990, was used to investigate the compaction properties of murram, and murram containing lime, in order to obtain the optimum moisture content required to give the maximum dry density. Both the standard and heavy Proctor compaction methods were used. This was done to investigate the effect of compactive effort on maximum dry density and optimum moisture content, and also on the strength of the compacted soil.

The Proctor compaction test involves determining the mass of dry soil per cubic metre when it is compacted over a specified range of moisture contents, including that giving the maximum mass of dry soil per cubic metre. The test employs a 2.5kg rammer falling through a height of 300mm (standard compaction) or a 4.5kg rammer falling through a height of 450mm (heavy compaction). The mix is compacted in a cylindrical metal mould having a volume of 1000cm^3 (105mm in internal diameter and 115.5mm in height). The mould is filled in three approximately equal layers, with each layer being subjected to 25 blows (for standard compaction). For heavy compaction the mould is filled in five approximately equal layers, with each layer being subjected to 27 blows. The blows are subjected uniformly over the surface of each layer.

The mixtures investigated consisted of murram containing 0, 5, 10 and 15wt% of lime expressed as a percentage of the dry weight of the soil. The optimum moisture content and the maximum dry density obtained were used to evaluate the weight of the material required to produce cylindrical specimens of maximum dry density, given the volume of the cylindrical mould.

5.2 Specimen preparation

5.2.1 Mixing

From the Proctor compaction results, the total weight of material to make a cylinder of about 100mm in height and 50mm in diameter was determined. Sufficient soil, lime and water to make two cylinders for each mix were weighed into a bowl which was then fitted to a mechanical food mixer. To ensure a homogeneous mix, the following steps were adopted when mixing;

i) 2 minutes dry mixing soil and lime with gear 2
ii) 3 minutes wet mixing soil, lime and water with gear 2
iii) 1 minute kneading with a spatula
iv) 15 seconds mixing with gear 5
v) as in step (iii)
vi) as in step (iv)

Soil-lime-gypsum mixes were also made and in this case the mixing time was increased by 2 minutes i.e one extra minute for dry mixing and another for wet mixing.

5.2.2 Compaction of test cylinders

Cylinders of soil plus lime, or soil plus lime plus gypsum, were compacted in cylindrical moulds (100mm height and 50mm diameter), in accordance with Test 10, BS 1924:1975, at the optimum moisture content to give maximum dry density. The amounts of soil, lime and water for each cylinder were obtained from the general relationships given below:

Let M' = total weight of cylinder

Ms = weight of dry soil

Ml = weight of lime

Mw = weight of water

then

$$M' = Ms + Ml + Mw$$

$$= Ms(1 + Ml/Ms + Mw/Ms)$$

fractional moisture content $W' = Mw/(Ms + Ml)$

fractional lime content $L' = Ml/Ms$

Therefore $M' = Ms + L'Ms + W'(Ms + Ml)$

$$= Ms + L'Ms + W'Ms + W'L'Ms$$

$$= Ms(1 + L' + W' + W'L'$$

and $Mw = W'(Ms + Ml)$

$Ml = L'Ms$

The bulk density ρb is given by $\rho b = M'/V$ where V is the total volume of the compressed cylinder.

The weights required and the cylinder bulk densities obtained using standard compaction and heavy compaction are shown below:-

	L' (g)	Ms (g)	Ml (g)	Mw (g)	M' (g)	ρ_b (g/cm^3)
Standard compaction	0.05	268	14	96	368	1.749
	0.10	245	25	97	367	1.744
	0.15	237	37	103	377	1.792
Heavy compaction	0.05	295	15	93	408	1.915
	0.10	280	28	98	406	1.920
	0.15	263	39	97	399	1.896

Where gypsum was used in addition to lime the proportions of gypsum added in relation to lime were;

L'	Wt% Gypsum
0.05	1.5
0.10	3.0
0.15	4.5

The amount of gypsum was calculated as a percentage of the weight of dry soil. These small percentages were chosen in order to enhance the strength of the cured material and but to minimise the expansion caused by sulphate additions.

Plate 5.1 shows the mould employed in the current work. A plug was located at the lower end of the split mould which was tightly bolted and then lubricated with oil for easier extrusion of the compacted sample. The prepared mixture, enough to give the required density, was weighed and added to the mould in two layers. The first layer was lightly compacted with a metal rod and its surface scarified before the second layer was added. A second plug was located in the top of the mould which was placed centrally on a hydraulic jack in a steel frame (see Plate 5.2). Pressure was applied until the stops on the plugs contacted the two ends of the mould. The pressure was then released and the compacted cylinder extruded using a perspex plunger. The weight and dimensions of the cylinders were noted. Compaction was carried out within 25 minutes of mixing.

The pressure at which the material was compacted was determined separately using a proving ring (No. 2092, max. load 36KN) fixed in a steel frame. The mould was filled with material as described above. The load was then applied until the stops on the end plugs contacted the body of the mould. The force was recorded and using the known cross-sectional area of the cylindrical sample, the corresponding pressure was calculated. Materials compacted using standard compaction required a pressure of $5N/mm^2$ and using heavy compaction a pressure of $10N/mm^2$ was required. For purposes of comparison the pressure achieved in a Cinva-ram is $2N/mm^2$ and that achieved in a Brepak block making machine is $10N/mm^2$.

5.2.3 Curing

The compacted cylinders were placed in sealed polythene boxes. Inside the boxes the samples were placed on a stand with water underneath. The boxes were placed in an environmental curing chamber which was maintained at 30°C and 100% relative humidity. A temperature of 30°C was chosen to match the average daily temperatures that can be expected during the hottest months in Kenya. Results obtained here approximate to what is to be expected in the field especially when the soil building blocks are cured in the sun during the hottest months. Very high relative humidity must be maintained in order to keep the reactions going. In the field this is achieved (see section 4.4) by frequent spraying with water and covering the blocks with polythene sheets.

5.3 Testing

5.3.1 Compressive strength

The cured samples were tested for both dry and wet compressive strengths. The wet strength gives an indication of the perfomance of the sample in its weakest state (see Chapter 2, section 2.6). The 'Kenyan Standard for Stabilised Soil Blocks' (25) recommends a wet compressive strength of at least $1.5 N/mm^2$ after the samples are immersed in water for 24 hours. The dry strength compared with the wet compressive strength should be at least 50% higher i.e. $F(dry) \geq 2F(wet)$.

To determine wet compressive strength, in the present work, samples were soaked in water whilst still in the chamber 24 hours prior to the end of the curing period. Their weights and dimensions were then taken prior to testing. Samples for dry compressive strength testing were removed from the curing chamber at the end of the curing period, weighed and left in the open at room temperature (≈20°C) for about 10days, weighed and then tested for strength. The unconfined compressive strengths of the cylinders were determined using a J.J Lloyd 30KN tensile/compression testing machine employing a cross-head movement of 1mm/min. The specimen was placed centrally on the lower platten of the machine. A self-level cap (see figure 5.2) was placed on top of the sample and the upper platten of the machine lowered until it just touched the top of the cap. This was to ensure that the load was applied uniaxially and was evenly distributed.

The maximum load exerted at failure was recorded and the compressive strength calculated. The equivalent cube compressive strength was estimated by multiplying the corrected cylinder strength by the factor 1.25 given in BS 1881:Part4:1970.

After testing for compressive strength, a small quantity of soil at the core of the cylinder was taken and kept in a sealed polythene bag for thermogravimetric, X-ray and scanning electron microscopy analyses.

5.3.2 Thermogravimetric analysis

This is an analytical technique which is capable of continuously recording the weight of a sample as it is heated or cooled. The thermogravimetric curve thus obtained, expresses the dependence of weight change of the sample on temperature. This in turn gives information on the sample components, their thermal stability, and their thermal decomposition. In thermogravimetric tests, the specimens are heated at a constant rate and the weight changes can be recorded in two ways:

i) % weight loss against temperature

ii) rate of weight loss against temperature

The relationship between the % weight loss and temperature is expressed by the thermogravimetric (TG) curve while that between rate of weight loss against temperature is expressed by the derivative thermogravimetric (DTG) curve (63, 64).

To characterise the individual phases from the DTG curve, previous knowledge of the chemical compositions of the individual phases present, and the transformations which they undergo on heating, is required. For example, when dealing with clay, there are a number of changes which may be reflected in the thermogravimetric curves. The peaks in DTG curves represent weight changes associated with specific reactions. These are:

a) Dehydration

i) Pore water is usually lost by evaporation at temperatures up to about 120-130^oC.

ii) Adsorbed water on the surfaces and absorbed water between the layered structures of the clay minerals resulting from hydrogen bonding is usually lost at temperatures of about 200-300^{o}C.

b) Dehydroxylation

Break-down of hydrates and hydroxides, mainly dehydroxylation of OH^- ions in the lattice structure of the clay minerals occurs at temperatures in the range 250-800^{o}C

c) Decomposition

Decomposition of carbonates such as calcite owing to loss of CO_2 occurs in the temperature range 650-800^{o}C.

d) Changes of state

These are associated with changes in weight due to evaporation of salts such as sodium chloride which occurs at high temperatures (i.e >800^{o}C)

The temperature of the peak weight loss recorded in the DTG is influenced by

i) the initial weight of sample
ii) the rate of temperature rise
iii) the size of the particles in the sample
iv) the furnace atmosphere

Thus to ensure consistency of the results every attempt should be made to keep these factors constant.

In the current work thermogravimetric analysis was used principally to follow the consumption of lime (and gypsum) during curing of the murram and hence to asses the extent of their reaction with the murram. It was also used as an aid to the identification of reaction products formed during curing of the murram-lime and murram-lime-gypsum cylinders. A Perkin-Elmer thermal analyser (model TGS-2) was employed. The instrument comprises three main parts: furnace, balance and chart recorder. About 8-10mg of finely powdered sample was heated in the furnace under a dry CO_2 free nitrogen atmosphere which was achieved by passing the nitrogen over a drying agent (silica gel) and carbosorb respectively before it entered the furnace. The balance is capable of weighing to 0.0001mg. The sensitivity used for the TG was a full scale deflection equivalent to 20% weight loss of the sample, and the sensitivity used for the DTG was 0.1mg/min. The samples were heated from a temperature of 30 to 850°C at a controlled rate of 20°C/minute.

Analysis was carried out on the murram, kaolinite and lime, and also on the murram-lime and murram-lime-gypsum mixes which had been cured for periods from 0 to 4 weeks.

5.3.3 X-ray analysis

X-rays are electromagnetic waves of very low wavelength from 0.001 to 10nm, which are produced when high speed electrons strike a target. Their diffraction patterns are widely used for identifying clay minerals. Interpretation of the diffraction lines is based on the fact that every mineral is structurally different from every other mineral and therefore produces a pattern of diffracted intensities which is unique. Usually, powder samples of soils are used for X-ray analysis because the soil particles are small and suitable single crystals are normally not available. All crystals consist of symmetrical ordered arrangements of atoms which can be imagined as lying on different sets of parallel atomic planes. Since the wavelength of the radiation and the distance between the atomic planes in a crystal are comparable, diffraction occurs when X-rays strike the atomic planes at a certain angle. This diffraction corresponds to a normal optical reflection in which the angle of incidence is equal to the angle of reflection.

When a parallel beam of X-rays of wavelength λ strikes a crystal with parallel atomic planes of spacing $\underline{d}$ it may penetrate to a considerable depth before being absorbed. Constructive interference will take place when the path difference between the waves scattered from adjacent atomic planes is equal to an integral number of wavelengths. The angle at which this occurs is known as the Bragg angle θ. The effect is shown schematically in Figure 5.3. The path difference between the wave scattered at A and that at C in the direction θ is given by $BC + CD = 2\underline{d}\sin\theta$. When the distance is equal to an integral number of wavelengths $(n\lambda)$ constructive interference occurs and a diffraction peak is produced. Thus the condition for diffraction is given by $n\lambda = 2\underline{d}\sin\theta$. This is known as Bragg's law where n is the order of diffraction. This equation can be applied to all atomic planes in crystals and forms the basis for the characterisation of crystals using the X-ray diffraction method. The diffraction patterns are used to determine the d-spacings and as each compound has its own unique diffraction pattern the *d*-spacings can be used to identify and characterise the phases present in a material.

In the present work, X-ray diffraction was used to identify the mineralogical composition of the murram, and the crystalline phases formed during curing of the murram-lime and murram-lime-gypsum cylinders. Use was made of the X-ray diffractometer in the Department of Mechanical, Materials & Manufacturing at the University of Newcastle Upon Tyne. The instrument used was a Philips X-ray diffractometer (verticle type) fitted with a graphite monochromator PW1965 and generator PW1730 operating at 50kV and 25mA. Radiation used was CuK of 1.54179Å wavelength with a Nickel filter and a detector.

The powdered sample was placed in an aluminium holder and scanned at a rate of 1.5 degrees 2θ per minute. The diffraction peaks were recorded on a chart and the *d*-spacing calculated by reading the 2θ angles from the chart and using Bragg's law. It was found essential to use monochromatic radiation because of the heavy fluorescence of the samples.

5.3.4 Scanning electron microscopy

A scanning electron microscope (SEM) is a complex electron optical instrument capable of producing images of surfaces of magnification up to a million times. The electron beam has a similar function to that of visible light in an ordinary microscope. Visible light in an ordinary microscope has a wavelength of 400-600nm, whereas the electron beam employed in the electron microscope has a very short wavelength of the order of 0.005nm. This leads to a great increase in potential resolving power.

In SEM, a reflection geometry is employed. The electron beam is focused to a fine point of the order of 10nm and scanned over the surface of the sample stimulating emission of secondary electrons which are collected and amplified. The output is fed to a cathode ray tube, the spot of which is deflected in synchronism with the scan of the initial electron beam on the specimen surface.

In practice, two cathode ray tubes are employed: one for direct viewing and another for photographing the image. The image formed has a magnification which depends upon the ratio of lengths of the final and initial scanning movement. Specimen preparation is critical and if not performed correctly can seriously impair the observed image. A thin layer of conducting material such as carbon or evaporated gold must be deposited on the surface of a non-conducting material such as clay to prevent an electric charge building up on the surface as this causes a serious loss of resolution and may cause decomposition of the specimen. The coating provides a uniform covering of conducting material, which is almost an exact replica of the surface of the underlying material. The material is deposited on the surface by vacuum deposition. The key consideration in obtaining uniformity of the coating is the type of coating material used. Noble metals such as silver and gold have good electron emission properties.

Excellent high magnification images of soil fabric may be obtained by use of SEM. It has the advantage of a large depth of focus, and a wide magnification range. However the high vacuum environment of the specimen can lead to severe distortion of fabric and microstructure and this must be taken into consideration when interpreting images. For example clays will lose much of their moisture in this environment and may therefore undergo severe shrinkage

The SEM used in the current work was a Cambridge Instruments Stereoscan Microscope (Model S240), which was mainly employed for microstructural examination of the 4-week cured Murram-lime-gypsum mixtures. The specimens were fixed onto aluminium sample holders. They were then vacuum dried and given a coating of evaporated gold approximately 10-20nm thick. An operating voltage of 30kV was used.

5.3.5 Durability Testing

5.3.5.1 Introduction

Durability testing was approached in two different directions. Actual testing of the specimens was carried out using currently accepted methods (see section 4.5) (25). In addition a prototype durability testing system was designed and built and its performance assessed. The design was based on the fact that when blocks or bricks are used in wall construction, the arrangement is such that one face of the block is exposed to a changing outside environment while the opposite face is exposed to relatively constant room conditions.

5.3.5.2 Standard methods

The methods described in Chapter 4 were adopted to test the durability of the stabilised soil. The 28-day cured samples were left to dry to a constant weight. The weight and dimensions were recorded before and after drying. The samples were then totally immersed in water for 24 hours. They were removed after this period and their weights and dimensions again recorded. The samples were then dried at a temperature close to 35°C for 24 hours. Again their weights and dimensions were taken. The procedure was repeated for 14 days (i.e Wetting and drying through 7 cycles). After the 7 cycles, the samples were tested for compressive strength.

To investigate the durability of the samples for longer periods of time, another set of samples was cycled 14 times and another 28 times. Again at the end of these cycles, the samples were tested for compressive strength. From the first immersion in water, the weights and dimensions taken can be used to determine the water absorption and the linear expansion of the samples.

In addition the above procedure was repeated but in this case the samples were only immersed in water to a quarter of their full height. One set of these samples was tested for compressive strength and the other was subjected to a spray test (as described in Chapter 4), whereby the ends that were immersed in water were sprayed continuously for 2 hours. They were then inspected for any deteroriation. The samples were again sprayed for four more hours and inspected again for deteroriation.
The brushing test (25) was also carried out on 28-day cured samples of each composition.

5.3.5.3 Design of Durability Test Equipment

The system consists of two parts - the Controller Unit (Plate 5.4) and the Transfer Unit Plate 5.5). It works in conjunction with an Environmental Chamber.
The Controller is housed in a 4U instrument case and contains power supplies and instrumentation which control heat transfer rate and time together with water level and temperature control.
The Transfer Unit consists of the actual heat transfer

devices together with sensors which feed the controller necessary information for it to function. These items are fitted to an aluminium plate which forms the cover to a pyrex glass dish containing water. The bottom quarters of the cylindrical test specimens pass through holes in the aluminium plate and are immersed in the water. Figure 5.4 shows the general layout of the front panel of the system. This has the following controllers fitted:

7 Day Timer - this controls the length of time over which the heating or cooling takes place.

Multi-function Timer - this controls the length of time, during any timed period, that the transfer devices are energised. This is described as the "Duty Cycle".

Temperature controllers - these units (one for heating and another for cooling) set the maximum and minimum temperatures, respectively, that the devices may achieve.

LED - the LED indicates that a heating or cooling cycle is active. It glows RED for the heating cycle and GREEN for the cooling cycle. When the LED is extinguished, the transfer devices are de-energised.

Level Control - this unit adjusts the level of water in the trough between an upper and lower limit.

Digital Panel Meter - displays the displacement transducer output and thus indicates relative movement in the sample.

Rotary Switch - selects the transducer currently being read by the Digital Panel Meter (DPM).

Figure 5.5 shows the general layout of the rear panel.

This consists of sockets which provide for the connection of all necessary sensors/devices/etc. Sockets are also provided for the output of analogue signals relative to the displacement display. Also on this panel are the fuses and mains switch, together with the voltage regulation devices and their associated heat sinks. Figure 5.6 shows the general layout of the aluminium plate. This supports the Peltier Heat Transfer Devices together with their heat sinks. Also mounted on this plate are sensors for level control and for temperature control. Their block diagrams are shown in Figures 5.7 and 5.8 respectively. A solenoid valve allows the water from the head tank to enter the trough.

Plug-in terminal strips allow the plate to be disconnected from the leads so that the unit can be removed from the chamber.

The system is designed around two 19 Watt "Peltier effect heat pumps" (RS ref: 635-088) (see appendix 5.2).

The Peltier devices transfer heat from surface to surface when an electric current is applied to them. The direction of transfer is dependent on the polarity of the supply. Heat sinks are attached to the devices to achieve adequate dissipation of the transferred energy.

The heating controller must be set to a temperature higher than that of the water before the output will energise. Conversely, the cooling controller must be set to a temperature lower than that of the water for the output to be energised.

The rate at which the heat is transferred may be controlled by the use of the multi-function timer. This works in conjunction with both the seven-day timer and the temperature controllers. The mode of operation is to set up a "duty cycle" which turns the device off and on at a specified rate during the normal cycle. This has the effect of slowing down the rate of transfer.

The level control circuit (Figure 5.7) monitors the level of liquid in the trough. There are upper and lower level sensors. The system is designed to energise a solenoid valve which allows water to flow into the trough from a header tank. The valve is energised when both sensors become covered. The level, therefore, drops to a point just below the low sensor, when the valve operates and the trough is filled until the upper sensor is just covered.

The rear panel (Figure 5.5) houses a number of different connections, most of which are non-exchangeable. The Peltier devices are connected via XLR sockets and are supplied with a regulated 3.5 volts DC at a current of about 6 amperes. There are four DIN type (5 pin) sockets below the regulator heat sinks. These are for the connection of the displacement measuring transducers. Supply is $^{+}$ 12 volts DC. The temperature controllers are connected to a pair of DIN sockets to the right of the heat sinks. The stirring paddle connects to the phono type sockets and is supplied at 5 volts DC. Four BNC sockets provide analogue signals from the LVDT inputs. Another BNC supplies the 24 volts DC to operate the solenoid valve and the DIN soccket to its left is the connection to the level sensors.

The durability equipment was designed and built and tested but further developments and modifications were found to be required for its effective operation. The time constraints demanded by the project thus made it impossible for the system to be used to carry out durability tests on the cured samples.

The system functioned very satisfactorily but the particular Peltier heat transfer device tested was found to be of too low power. The temperature difference achieved between the water and the external environment was only a few degrees Celcius even when the upper part of the aluminium plate and the pyrex dish were heavily insulated. Higher power devices are available (e.g 75 watts) but the time required to modify the design to incorporate these high power devices made further development impracticable. However the tests demonstrated that the system does in principle work.

Chainage (Km)	Depth of hole (m)	Description	Sampling Depth (m)	Sample No.
3 + 300	0.20 1.20	Laterite soil from borrow pit Red coffee soil subgrade	0.20 to 1.20	1
4 + 500	0.10 1.10	as above	0.10 to 1.10	2
11 + 000	0.10 1.20	Dark brown gravel soil Loose red coffee soil-subgrade	0.10 to 1.20	3
17 + 000	0.20 1.30	Brownish lateritic gravel soil Loose dark red soi	0.20 to 1.30	4
17 + 500	0.10 1.10	as above	0.10 to 1.10	5
18 + 000	0.10 1.00	as above	0.10 to 1.00	6
19 + 000	0.10 1.10	as above	0.10 to 1.10	7
21 + 000	0.05 1.00	as above	0.05 to 1.00	8
22 + 500	0.05 1.00	as above	0.05 to 1.00	9
24 + 500	0.30 1.10	Light grey laterite soil Light brown loose soil	0.30 to 1.10	10

Table 5.1 Alignment soil samples from Gatukuyu-Mataara road D395.

Linear shrinkage (%)	Type and proportion of stabiliser
less than 2.5	Probably insufficient clay
2.5 to 5.0	1 part of cement to 20 parts of soil
5.0 to 7.5	1 part of cement to 15 parts of soil, or 1 part of lime to 7 parts of soil
7.5 to 10	1 part of cement to 12 parts of soil, or 1 part of lime to 6 parts of soil
more than 10	Insufficient sand - soil is not recommended for blockmaking unless more sand is added.

Table 5.2 Relationship between linear shrinkage of soil and proportion of stabiliser needed. (after Webb) (9).

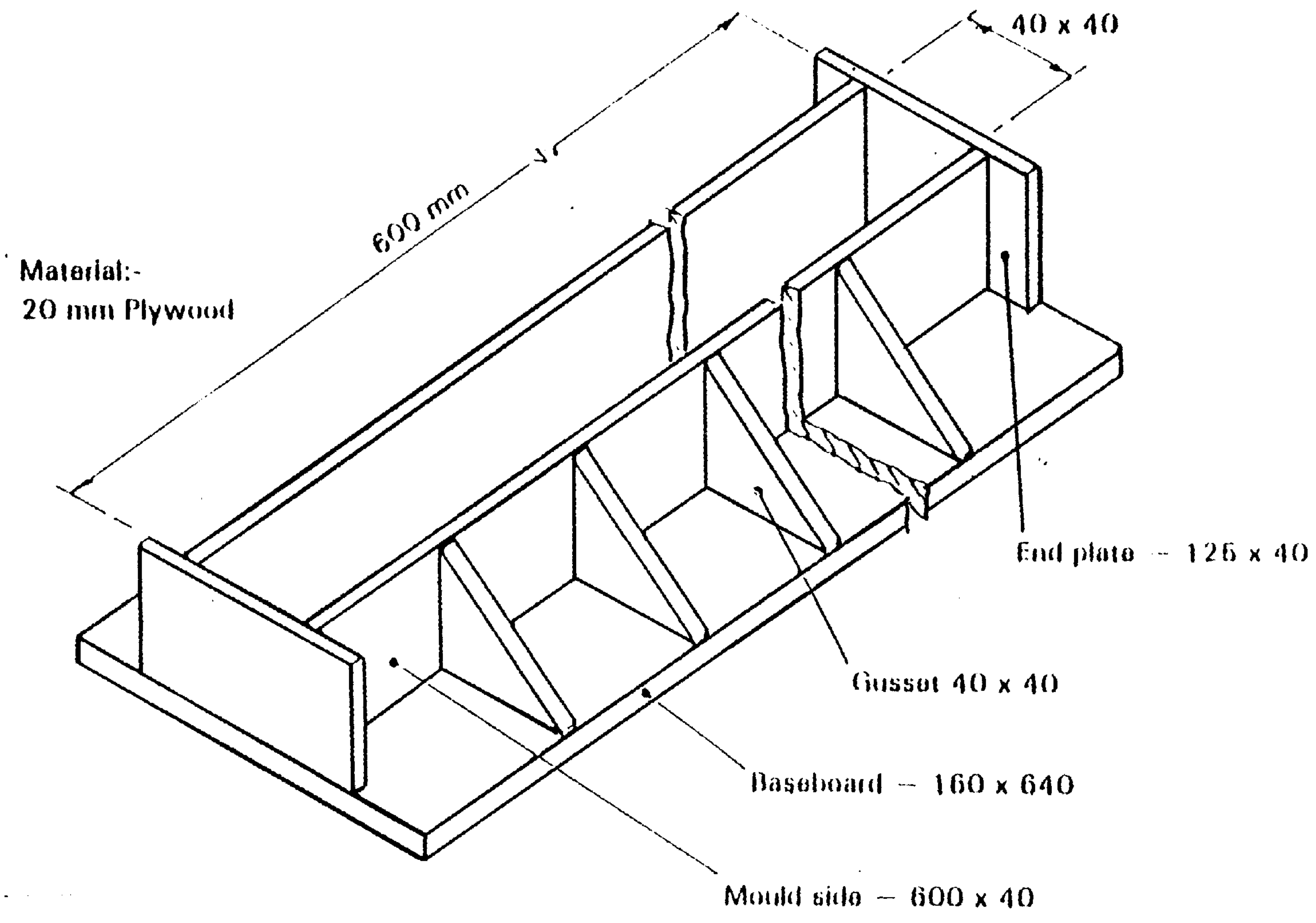


Figure 5.1 Linear shrinkage mould.

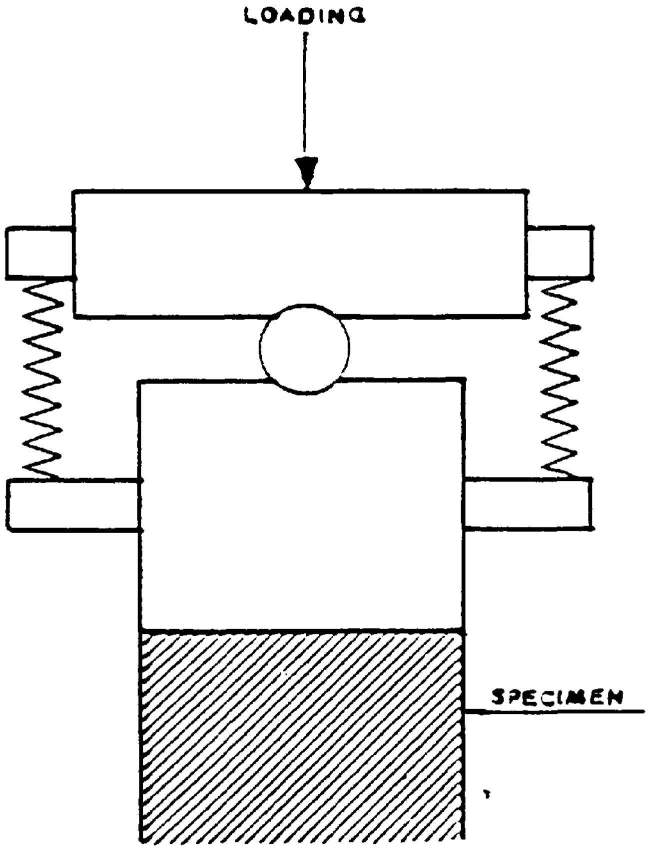


Figure 5.2 Schematic representation of self-level cap (after Arabi) (20)

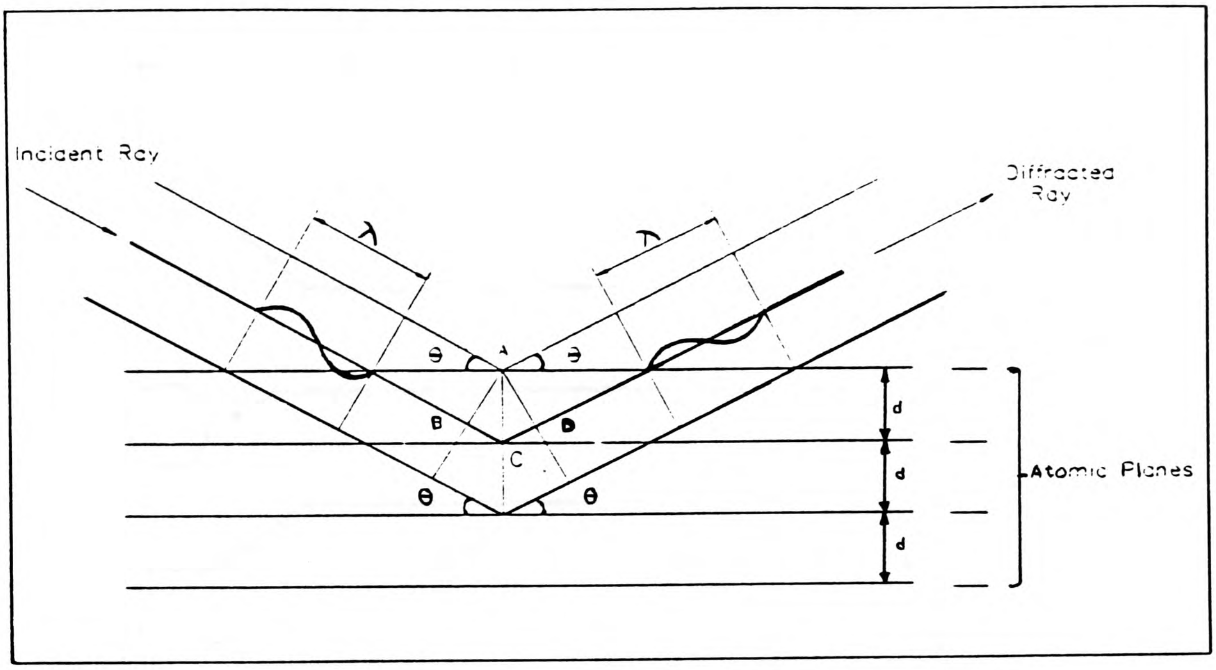


Figure 5.3 Geometrical condition for X-ray diffraction according to Bragg's law.

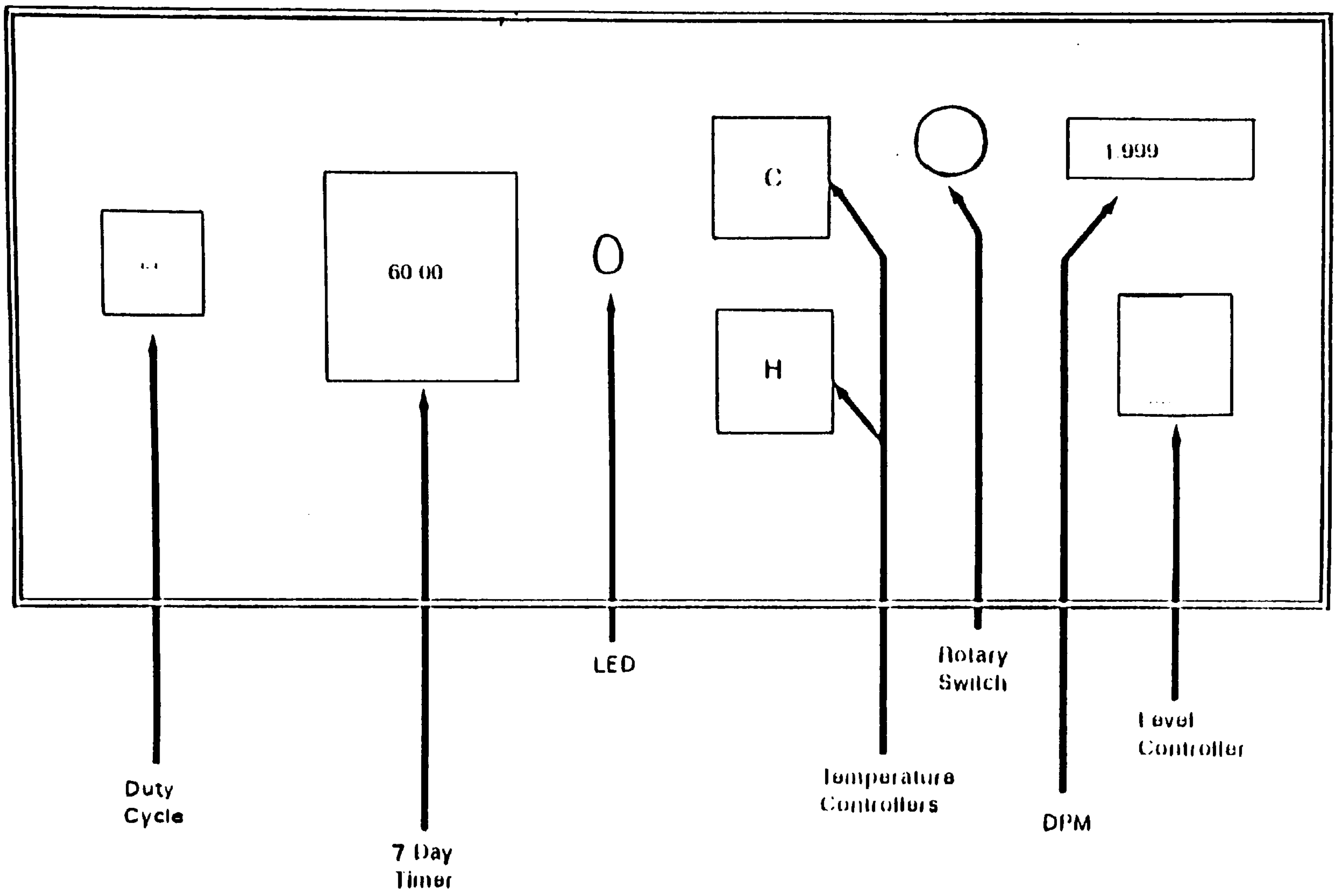


Figure 5.4 Front panel layout of the durability equipment

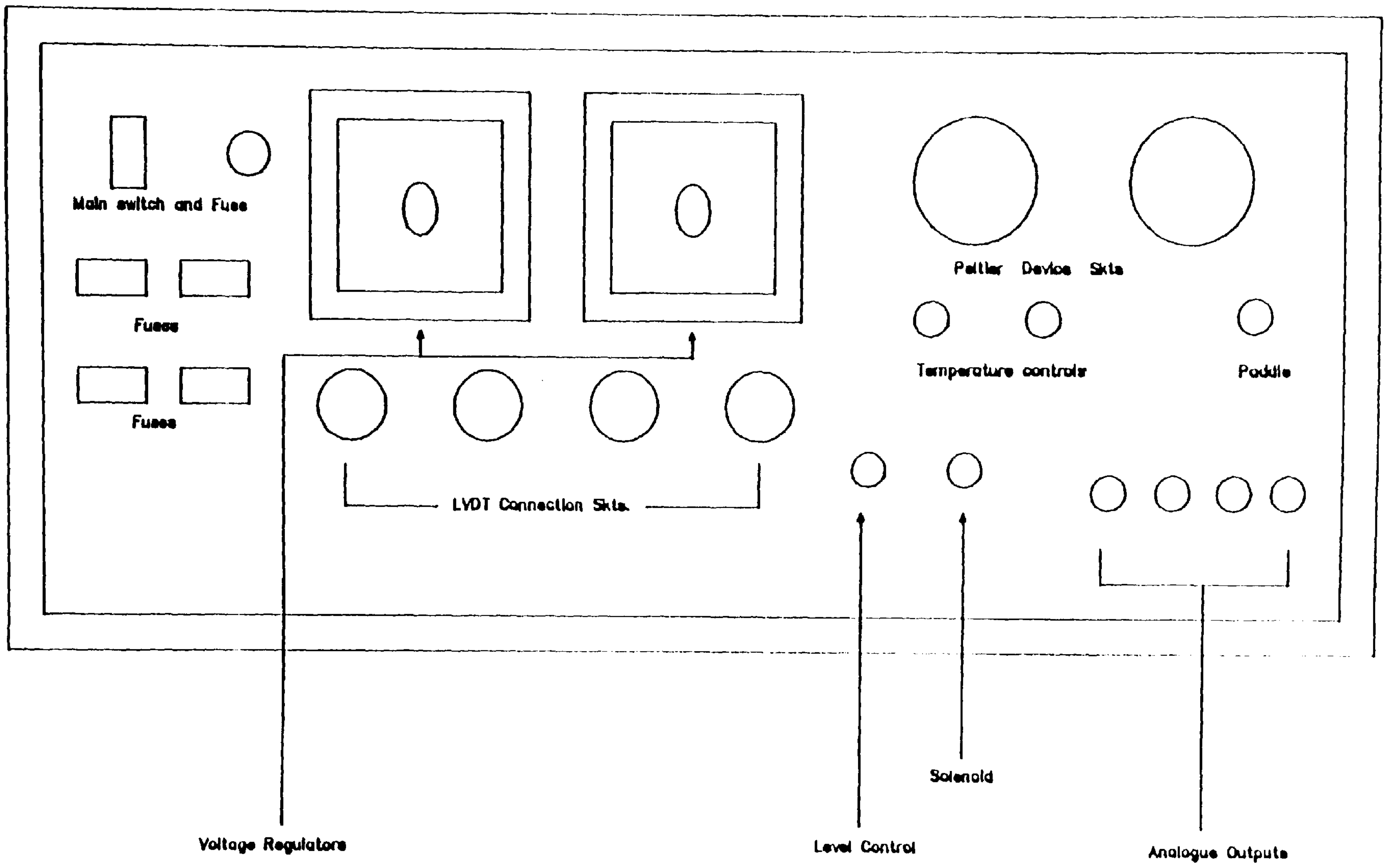


Figure 5.5 Rear panel layout of the controller unit.

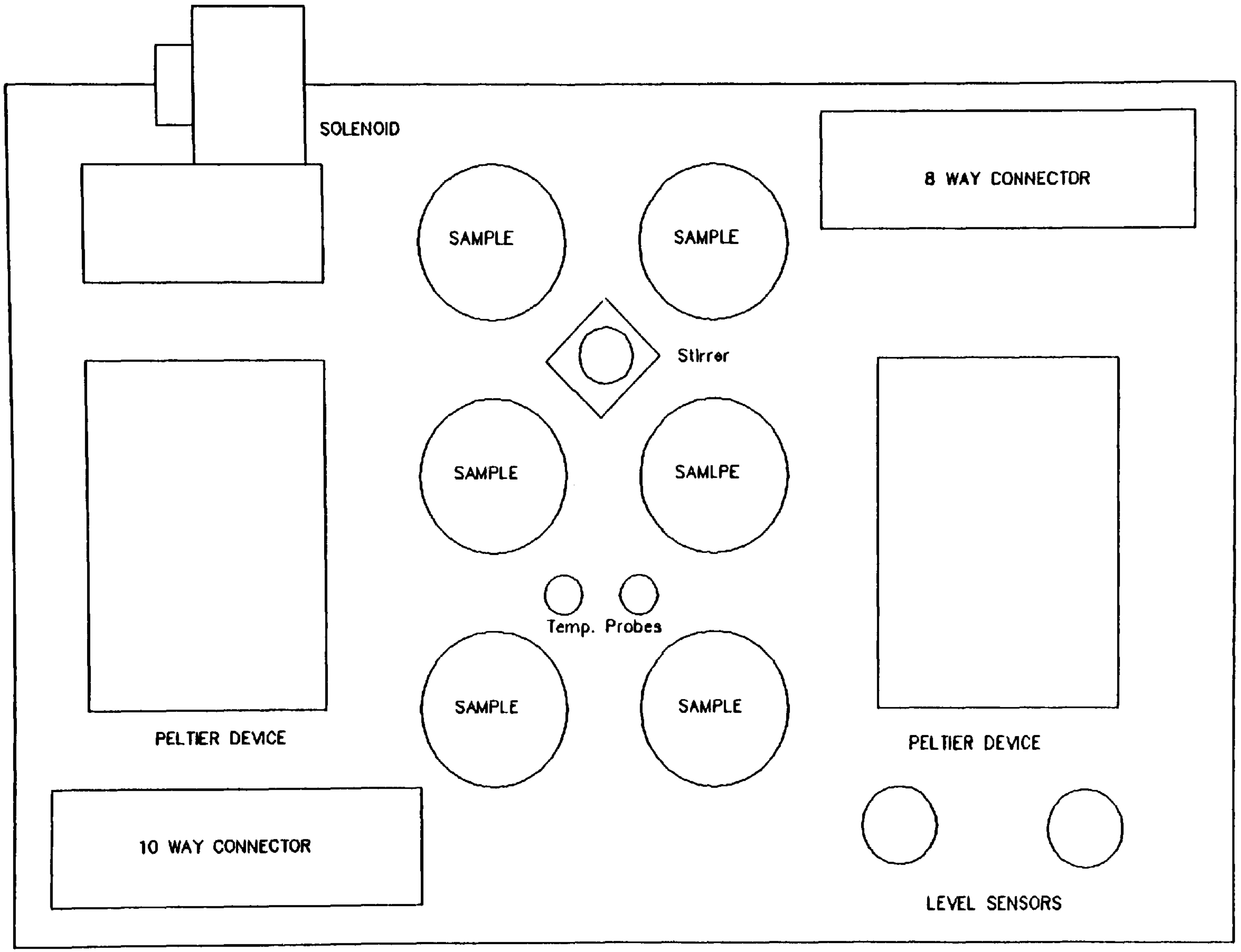


Figure 5.6 Transfer plate arrangement.

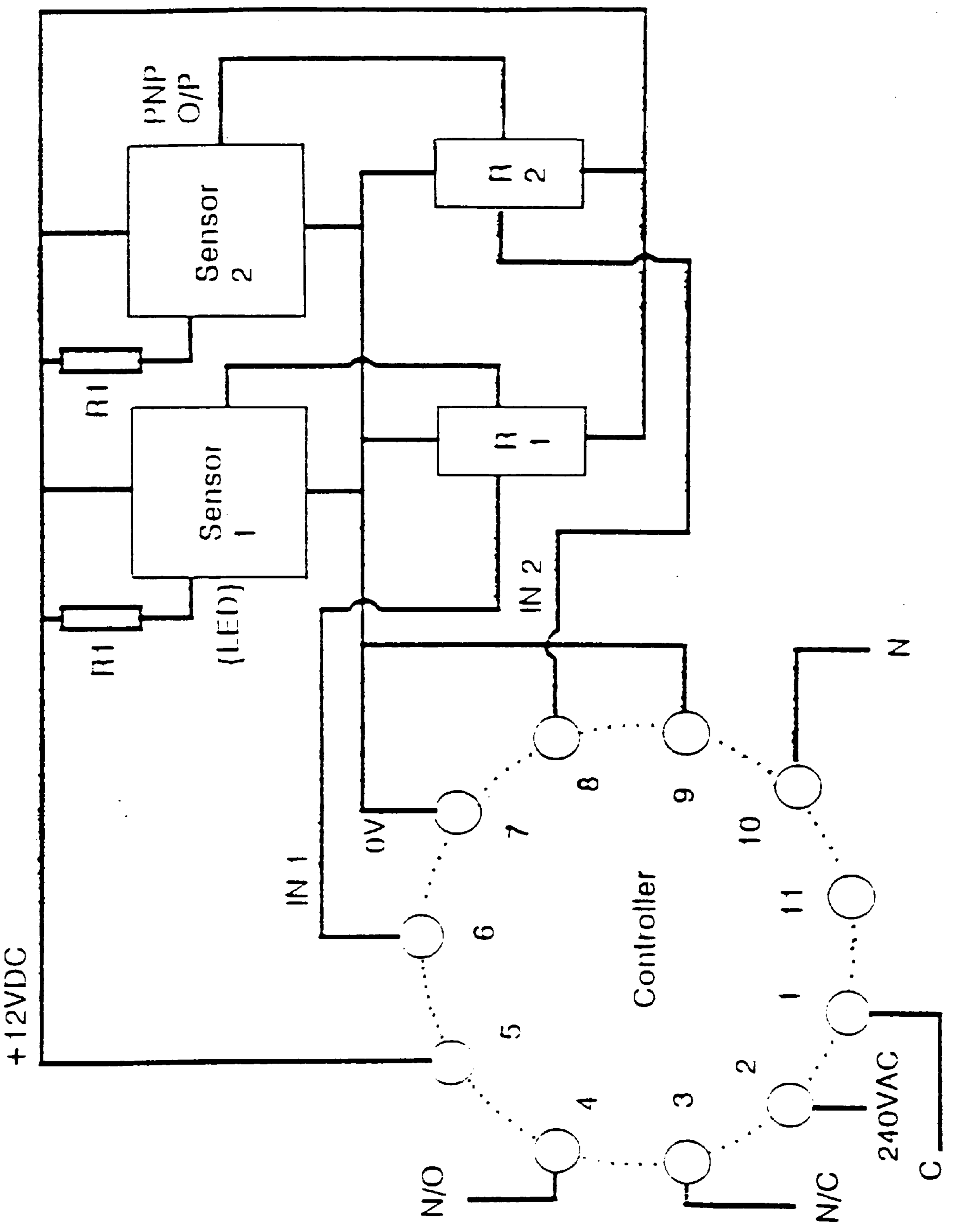


Figure 5.7 Level control block diagram.

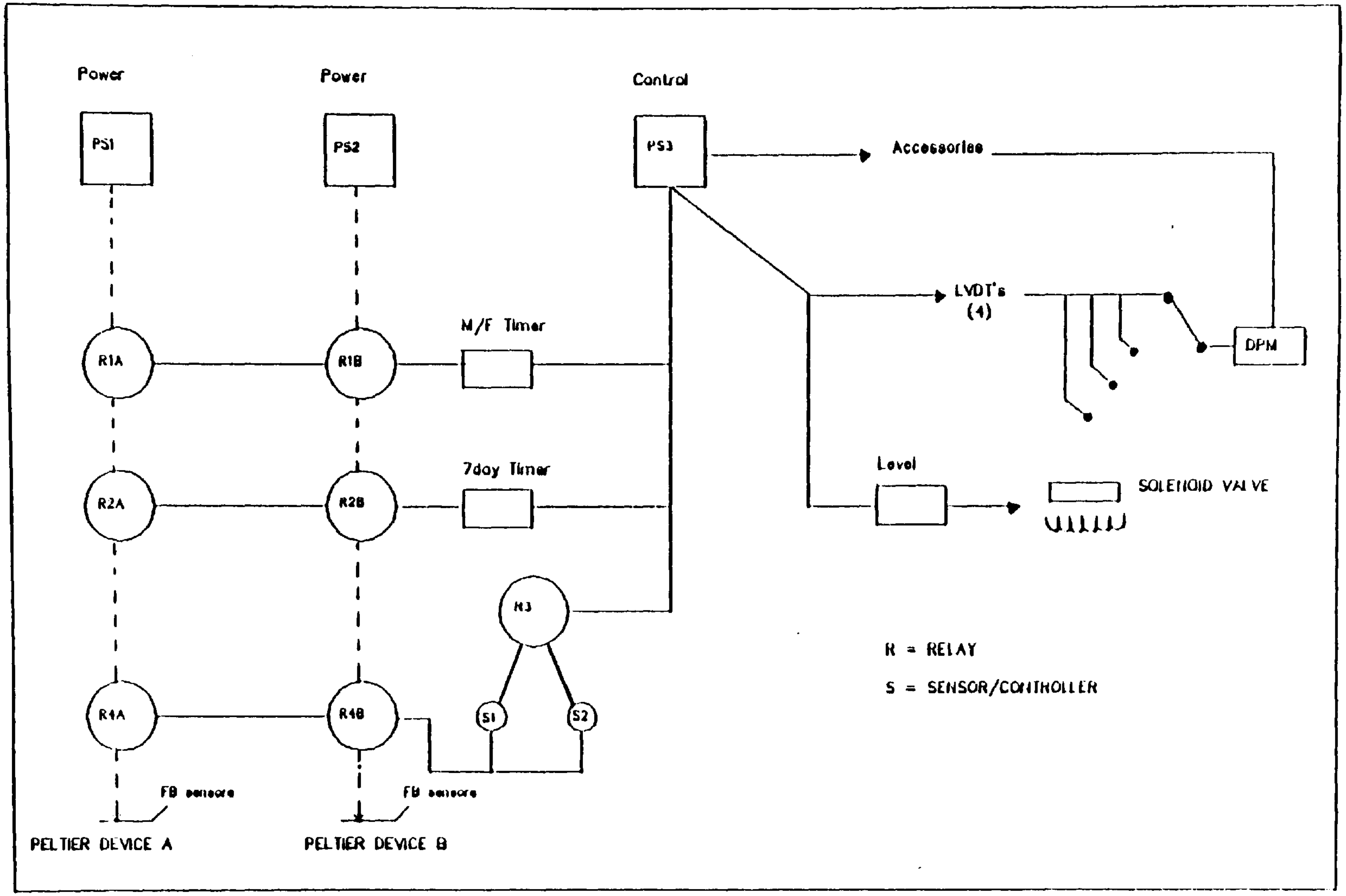


Figure 5.8 Temperature control general diagram.

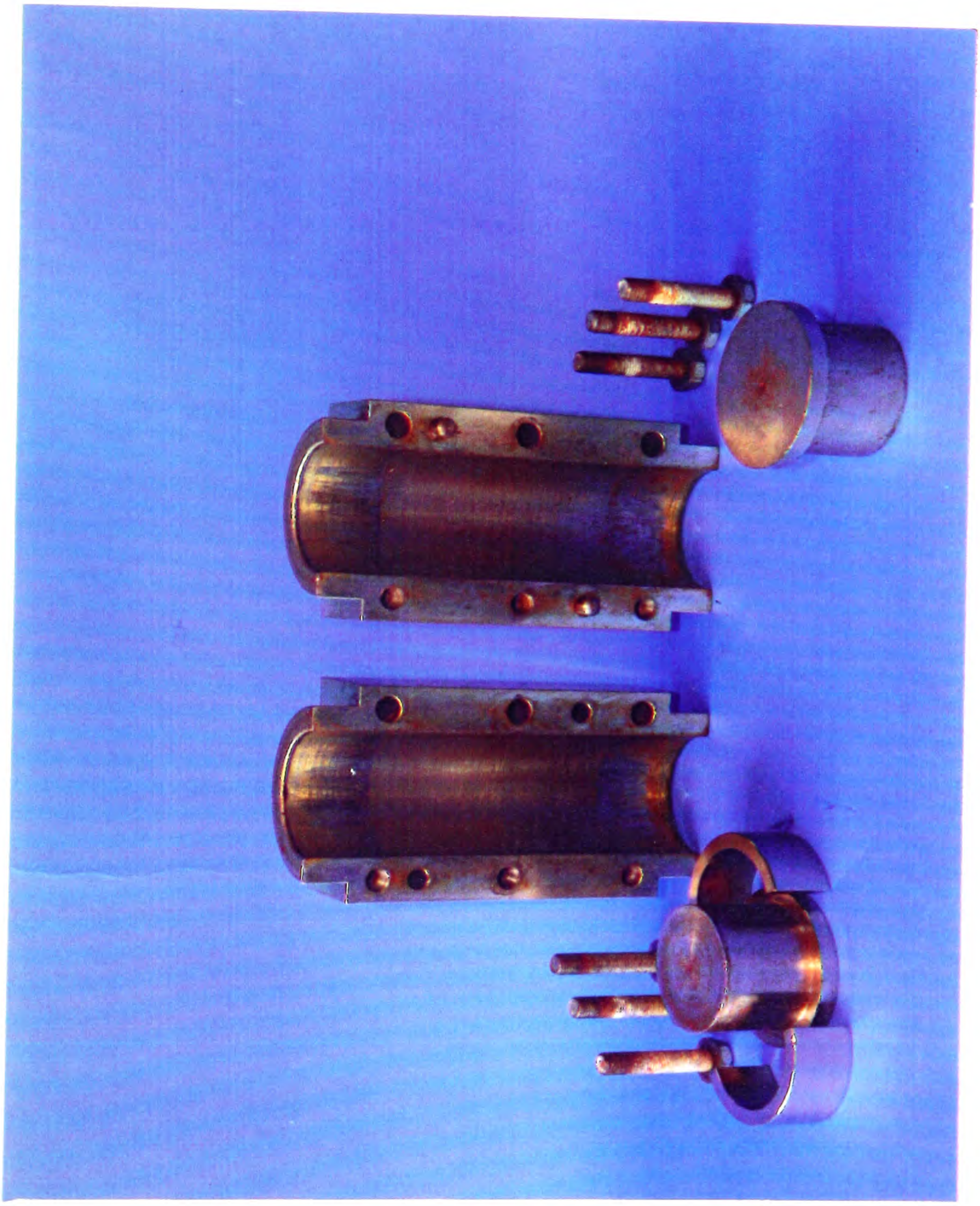


Plate 5.1 Cylindrical split mould components.

Plate 5.2 Arrangement of the moulding equipment.

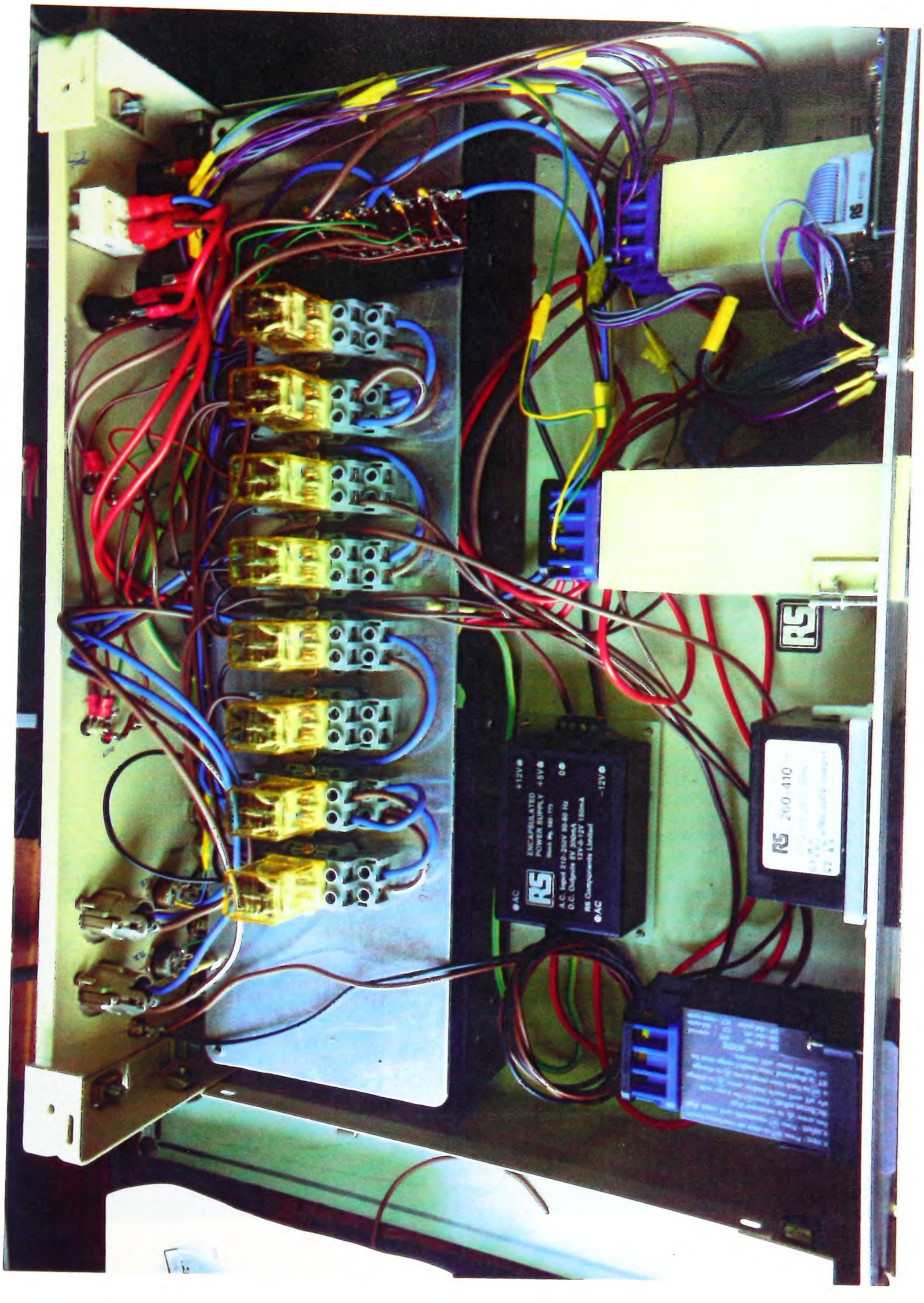


Plate 5.3 Internal connections of the controller unit.

Plate 5.4 Controller Unit.

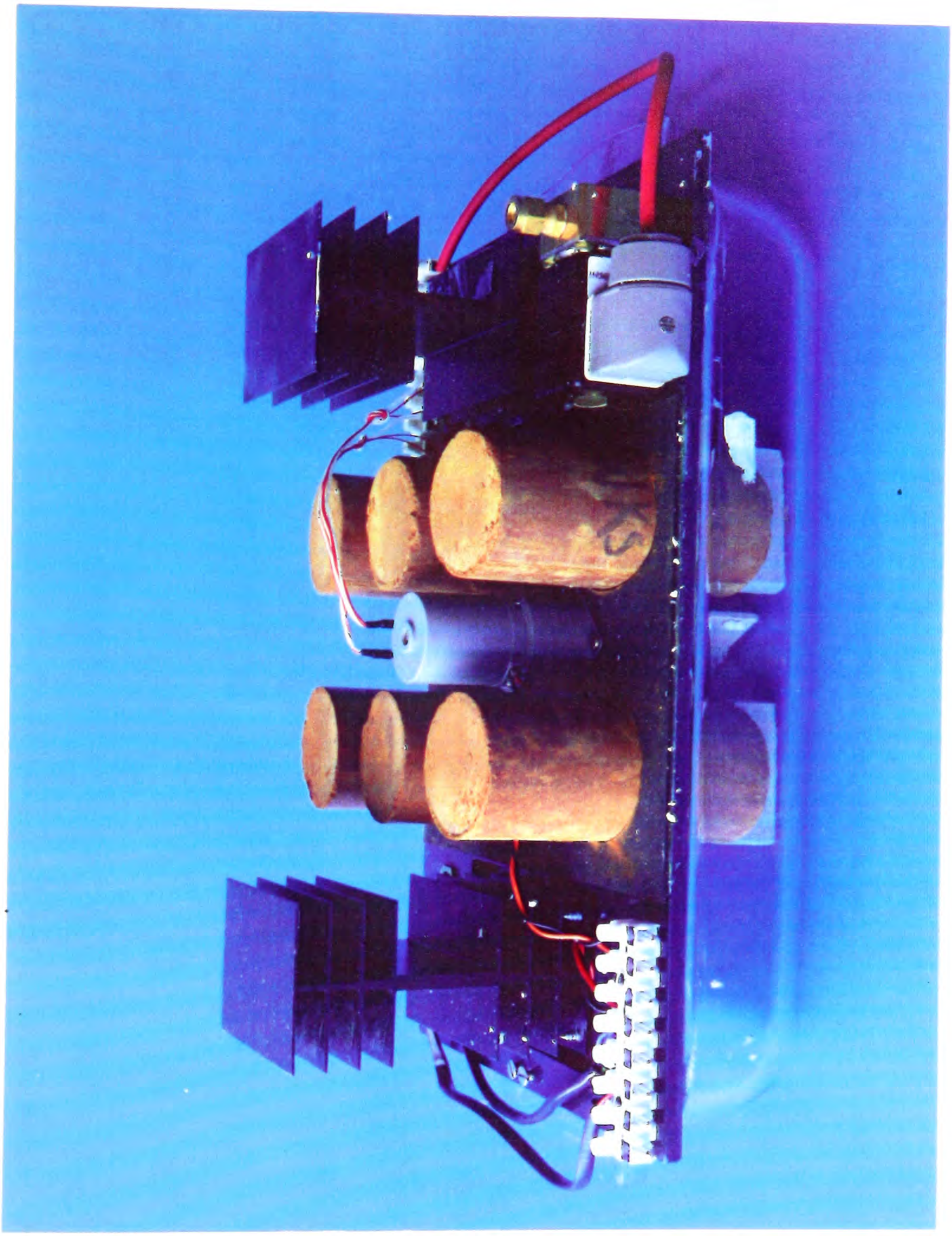
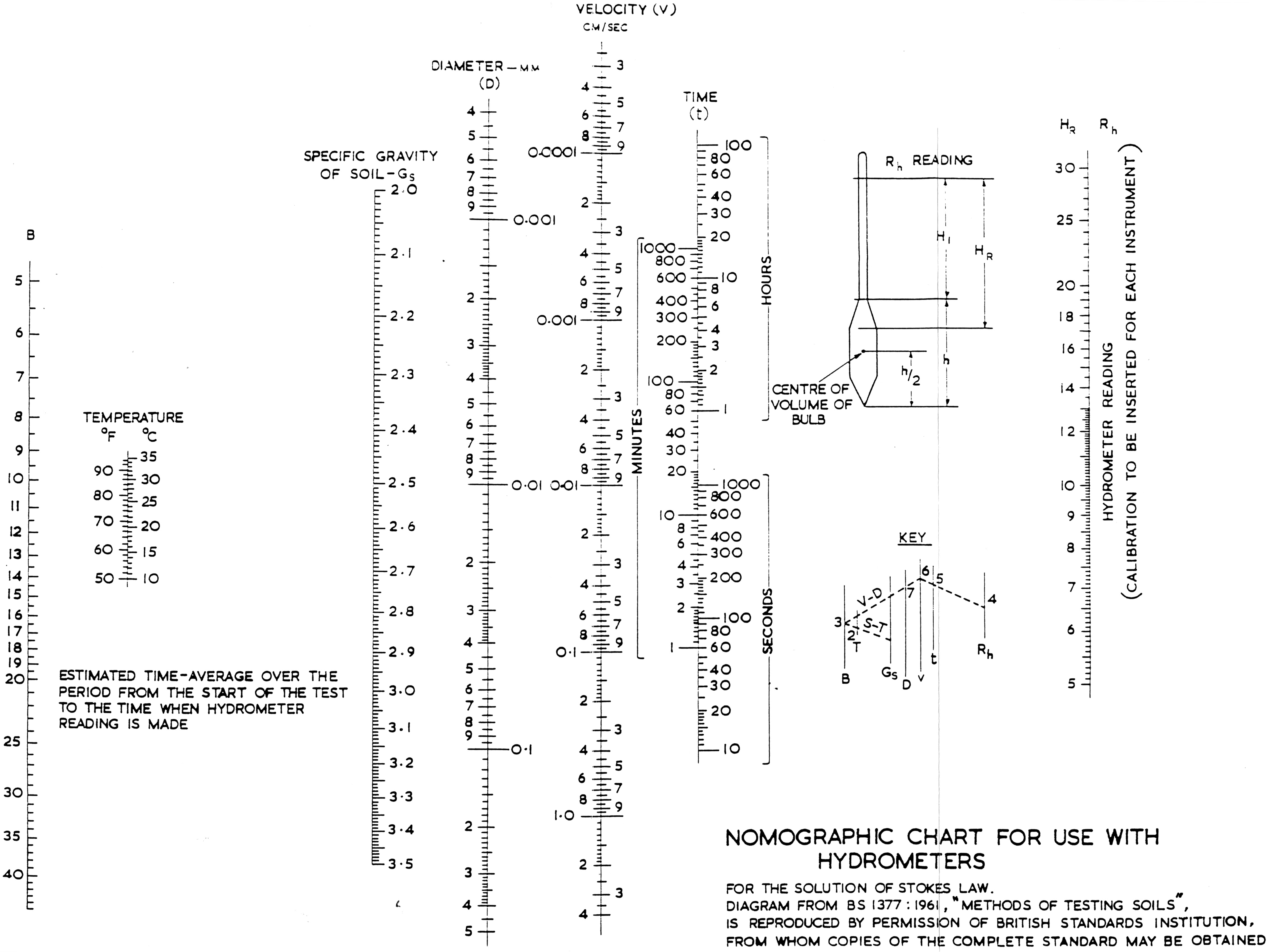


Plate 5.5 Transfer Unit.

Appendix 5.1



NOMOGRAPHIC CHART FOR USE WITH HYDROMETERS

FOR THE SOLUTION OF STOKES LAW.
DIAGRAM FROM BS 1377 : 1961, "METHODS OF TESTING SOILS", IS REPRODUCED BY PERMISSION OF BRITISH STANDARDS INSTITUTION, FROM WHOM COPIES OF THE COMPLETE STANDARD MAY BE OBTAINED

CHAPTER 6

EXPERIMENTAL RESULTS

6.1 Physical characteristics of the raw materials

6.1.1 Particle size distribution and clay content

Determination of particle size and hence clay content of a soil is important in deciding the kind of binder to use in soil stabilisation (see section 3.3). The natural soil, murram used in the current study contained fine particles as well as soft rock particles which could be easily broken by hand. Two methods (i.e. sieving and sedimentation) for determining particle size distribution were used to cover the range of particles in the crushed soil. The SG of the soil was determined for use in the sedimentation method calculation. The value obtained was 2.83. The particle size distribution curve obtained from both sieving and sedimentation methods is shown in Figure 6.1. From this curve it can be seen that the soil contains about 65% clay. This suggests that, according to Webb (9), the soil is not suitable for stabilisation with cement and is probably suitable for lime stabilisation employing heavy compaction to acquire the minimum strength requirements.

An attempt was made to determine the clay content in the soil by using The 'bottle test' (see section 3.2). This was not successful as there was no clear boundary between the different particle sizes.

6.1.2 Shrinkage characteristics

The linear shrinkage was determined for various compositions of clay (kaolinite) and sand to establish a relationship between linear shrinkage and kaolinite clay content. It was intended that comparison of these data with the linear shrinkage data for the murram soil would provide a method of assessment of the amount of clay in the murram.

Linear shrinkage was determined by the method described in Chapter 5 and the linear shrinkage curves for kaolinite-sand mixes are shown in Figure 6.2. Figure 6.3 shows a plot of linear shrinkage versus kaolinite content. Above a kaolinite content of about 30% there is a simple linear relationship between these variables whereas from 0 to 30% kaolinite the relationship is non-linear. This initial non-linear relationship is attributed to the fact that at low clay contents the clay particles principally occupy the void space between the sand particles rather than bridging the sand particles. Therefore shrinkage of the clay has a minimal effect on the behaviour of the bulk material. Above about 30% clay content the clay particles begin to form principal links between sand particles which are themselves non-expansive. Thus the linear shrinkage in this region is directly proportional to clay content. It should also be noted that the higher the clay content, the longer it takes for the soil paste to attain maximum shrinkage.

Linear shrinkage of the murram was determined by employing both the open semi-cylindrical brass mould described in BS 1377:1990 and the open wooden mould. The brass mould gave a linear shrinkage of 12%. Using the wooden mould, the linear shrinkage levelled off after 10 days to a value of 60mm (i.e. 10% linear shrinkage) as shown in Figure 6.4. The difference in linear shrinkage when employing the two moulds (i.e. the semi-cylindrical brass mould and the rectangular open wooden mould) may be attributed to friction in the wooden mould which partially restrains the paste from shrinking. Also included in Figure 6.4 are linear shrinkage curves for murram-sand mixes (i.e. 20wt% and 30wt% sand). The percentage linear shrinkage was reduced (from 10%) to 5.7% when 20wt% sand was added and to 5% when 30wt% sand was added.

Comparison of Figure 6.4 for the murram with Figure 6.2 for the kaolinite-sand clearly indicates that the murram has a high clay content. However using Figure 6.3 to predict the clay content of the murram is not feasible and would in fact indicate a clay content greater than 100%. Clearly even when the soils contain the same clay mineral, the shrinkage characteristics may differ due to variations in the characteristics of the clay mineral itself such as variation in specific surface. Also soils may contain other minerals of high specific surface which may contribute to the shrinkage. The high linear shrinkage (10%) of the murram suggests that the soil, according to Webb (9) would require 8.3wt% cement and 16.6wt% lime (see Table 5.2) for effective stabilisation.

6.1.3 Plasticity characteristics

The Atterberg limits were used to define the plasticity of the murram soil. The liquid limit obtained using the Casagrande apparatus was 64% and that obtained using the cone penetrometer was 60%. The plastic limit of the soil was 43%.

This gives a plasticity index between 17 and 21%, which again indicates a high clay content for the soil (see section 3.2). The high liquid limit and plasticity index obtained indicates that the soil has a high affinity for water and would be more effectively stabilised with lime because lime will modify its plastic properties so that it is less susceptible to moisture movement (21). To confirm this the effects of lime on the Atterberg limits were also determined. In agreement with other workers (see section 4.3.1) the liquid limit was found to decrease as the lime content increased (see Figure 6.5). The plastic limit showed more complex behaviour and increased when up to 5wt% lime was added, remained constant between 5 and 10wt% lime addition and then decreased on further addition of lime (see Figure 6.6). These changes in liquid limit and plastic limit resulted in a sharp initial reduction in plasticity index with lime addition and subsequent levelling off of the index at higher lime contents (see Figure 6.7). It therefore confirms that small additions of lime to the murram soil result in a marked reduction in its plasticity.

6.1.4 Compaction characteristics

Standard Proctor compaction was employed to study the effect of soil stabilisation on the compaction characteristics. To a 30wt% kaolinite-70wt% sand mix, 5, 10 and 15wt% lime were added and for each mix Proctor compaction was carried out. The compaction curves are shown in Figure 6.8. The maximum dry density of the mix decreased as the lime content increased (Figure 6.9), while the optimum moisture content increased as the lime content increased (Figure 6.10).

The compaction curves obtained for murram-lime mixes for both standard and heavy compaction are shown respectively in Figures 6.11-6.12-6.13 and Figures 6.14-6.15-6.16. A similar trend of reduction in maximum dry density and increase in optimum moisture content with increasing lime content is also apparent particularly for heavy compaction where, as might be expected, maximum dry densities are rather higher and optimum moisture contents rather lower than for light compaction. Also for standard compaction the changes in these parameters are less systematic and initially maximum dry density actually shows a slight increase and optimum moisture content a small decrease.

The compaction characteristics of murram-cement under standard compaction (see Figures 6.17-6.18-6.19) are very similar to those of murram-lime under standard compaction and give similar maximum dry density and optimum moisture content values although it must be noted that in the case of murram-cement, cement additions of up to only 6wt% were employed.

6.2 Chemical characteristics of the raw materials

6.2.1 Murram soil

The chemical analysis of the murram is shown in Table 6.1 (a). Also included in the table are comparable data for other Kenyan lateritic soils. The ratio of silica to alumina plus iron oxide is 0.56, which shows that the soil used in the present work is a true laterite. This low ratio is a result of the extremely high Fe_2O_3 content of the soil. The soil has a low loss on ignition value which means a low organic content. The water soluble salt content is also very low (see Table 6.1 (b)), which is another desirable property for effective stabilisation. The pH value of 4.0 obtained indicates that the soil is acidic. This means that the soil will need a high percentage of lime stabiliser to bring the pH value to 12.4, a value that needs to be reached for maximum reactivity (see section 4.2). The mineral components in the soil, determined from X-ray analysis (see Table 6.2) are Kaolinite together with Gibbsite, Haematite, Quartz and Anorthoclase.

Thermogravimetric analysis of the murram and that of pure kaolinite gave thermograms which are compared in Figure 6.20. The DTG trace for murram shows peaks at 50, 300 and 550°C. The weight loss peak below 100°C corresponds to loss of adsorbed water due to the colloidal nature of some of the soil components and that formed at 300°C is due to dehydroxylation of gibbsite (66). The peak at 550°C is due to dehydroxylation of kaolinite to form meta-kaolinite. This confirms the X-ray observation of the presence of kaolinite and gibbsite in the murram soil.

Scanning electron microscopy of the murram was able to show (see Plate 6.1) the microstructure of the murram soil which consists of a large proportion of platy clay particles mainly in the size range 1µm to 20µm.

6.2.2 Lime, gypsum and cement

The hydrated lime ($Ca(OH)_2$) employed, was produced and supplied by ICI (UK), and is commercially available under the trade name "Limbux". Table 6.3 shows the chemical analysis and some of the properties specified by the manufacturer.

The DTG thermogram of the lime is shown in Figure 6.21. Weight losses were observed giving two distinctive weight loss peaks in the temperature range 400-520^{o}C, and 550-750^{o}C, which were identified respectively as a result of dehydroxylation of the lime and decomposition of the impurity carbonate.

The fine gypsum powder used was calcium sulphate di-hydrate ($CaSO_4.2H_2O$) supplied at 98% purity by Aldrich Chemical Co. Ltd. Thermal analysis carried out on the gypsum, showed dehydration taking place between 90 and 210^{o}C reaching its maximum at about 168^{o}C as shown in Figure 6.21. The weight loss of the gypsum is due to the loss of its two water molecules. As a result of dehydration, gypsum forms anhydrite (i.e. $CaSO_4$).

The cement used in the current study was supplied by Blue Circle Industries. Its chemical and physical properties are shown in Table 6.4.

6.2.3 Kaolinite and sand

The kaolinite used in the current study was "Standard Porcelain" supplied by ECC International Ltd., St. Austell, Cornwall. The specifications of the kaolinite given in Table 6.5 were provided by the suppliers. The kaolinite consists mainly of SiO_2 and Al_2O_3 together with minor components such as potassium and iron oxides.

Figure 6.20 compares the derivative thermogram (DTG) of the kaolinite with that of murram. It shows a small weight loss between 30 and 100^{o}C which is attributed to the loss of absorbed water. The weight loss due to dehydroxylation occurs between 425 and 750°C.

'Clean' sand which consisted mainly of quartz was used in the current work. Thermal analysis of this sand showed no weight loss when it was heated to a temperature of 900°C. It was believed that by mixing this sand with kaolinite or murram there was, since quartz is unreactive, no chemical interactions with the soil, the sand only acting as a filler.

6.3 Physical properties of the stabilised soil

6.3.1 Strength development

6.3.1.1 Initial investigations

The investigation of strength development of the stabilised murram was aimed at achieving the minimum strength required by the Kenyan standard (i.e. 1.5N/mm^2 wet strength and at least 3N/mm^2 dry strength) in the most efficient manner with regard to materials, fabrication and curing period. Therefore a wide range of material compositions were investigated (i.e. kaolinite-sand-lime, murram-lime, murram-cement, murram-lime-gypsum, murram-sand-lime and murram-sand-lime-gypsum) using different curing times (i.e. 1 to 4 weeks and in some cases up to 8 weeks) and two compaction pressures (i.e. 'standard compaction' equivalent to 5N/mm^2 compaction pressure and 'heavy compaction' equivalent to 10N/mm^2 compaction pressure).

Initial work was carried out using 'standard compaction' on kaolinite-sand-lime, murram-lime and murram-cement compositions and subsequent studies were then made using 'heavy compaction' on murram-lime, murram-cement, murram-lime-gypsum, murram-sand-lime, and murram-sand-lime-gypsum with the object of improving the strength development. In the former initial study, only wet strengths were determined whereas in the latter study both wet and dry strengths were determined. It should be noted that all the strengths reported are the equivalent cube strengths of the cured cylinders rather than the cylinder strengths themselves (see section 5.3.1). Figure 6.22 shows the development of wet compressive strength with curing time for cylinders of synthetic soil (i.e. 30wt% kaolinite-70wt% sand) containing 5, 10 and 15wt% lime. The wet strengths developed are very low ($<1.5N/mm^2$) and also increases in lime content of greater than 10% do not produce any additional increases in strength. These effects are probably a result of the rather low clay content of the synthetic soil. Figure 6.23 shows a similar set of curves for murram-lime. In this case the wet compressive strengths achieved are substantially greater and there is a systematic increase in strength with increase in lime content. Also the time taken for the ultimate strength to be achieved increases with increase in lime content and for 15wt% lime addition the ultimate strength has still not been reached after 4 weeks of curing. Although in this case quite moderate strengths have been achieved, only the 15wt%

lime addition material cured for at least 3 weeks meets the requirements of the Kenyan standard for wet strength.

Figure 6.24 shows the development of wet compressive strength with curing time for cured murram-cement additions. In this case the strengths achieved are slightly below those for which equivalent amounts of lime have been added and it would clearly require substantially greater cement additions to achieve the minimum strength requirements.

6.3.1.2 Extended studies

On the basis of these initial studies it was decided to concentrate on the murram-lime compositions but to increase the compaction pressure to 10N/mm^2 and also incorporate small additions of gypsum in order to promote strength enhancement and therefore make more efficient use of the lime. Figure 6.25 shows a plot of (a) the wet and (b) the dry compressive strengths of the murram-lime mixes compacted at 10N/mm^2, versus curing time. Comparison of the curves in Figure 6.25 (a) with those in Figure 6.23 shows that the increase in compaction pressure from 5 to 10N/mm^2 has produced strength increases of between 50 and 100%. Also as might be expected comparison of Figures 6.25 (a) and 6.25 (b) shows that the dry strengths are significantly greater than the wet strengths. However with regard to the Kenyan standard relating dry strength to wet strength (dry $\geqslant$ 2 wet) only the 10wt% lime addition material complies, and unfortunately this just fails to meet the minimum requirement of 1.5N/mm^2 wet strength even after 4 weeks of curing.

The addition of small amounts of gypsum however, has a very significant effect on both wet and dry strengths. Figure 6.26 compares the development of (a) the wet and (b) the dry compressive strengths of the murram-lime-gypsum cylinders at various curing periods of up to 6 weeks for lime contents of 5, 10 and 15wt% lime and for a fixed gypsum to lime ratio of 3:10. Comparison of Figures 6.26 (a) and 6.25 (a) show that the small gypsum additions result in strength increases of between 50 and 150% for wet strengths and the effect on dry strength is even more dramatic (see Figures 6.26 (b) and 6.25 (b)) resulting in strength increases ranging from 100-500%. In particular strength enhancement resulting from gypsum additions is most pronounced at low lime contents. Also the Kenyan standard for minimum strength is achieved for all the three lime contents (i.e. 5, 10 and 15wt%) when gypsum is added and the Kenyan standard relating dry strength to wet strength is easily achieved. In fact dry strengths range from 2.5 to 4 times the wet strengths depending on the lime contents.

In addition to adding gypsum to the murram-lime compositions, the murram was 'diluted' by partial replacement with sand. Excessive dilution would of course be detrimental to strength development because there would not be adequate clay present to react with the lime to produce the necessary cementitious material (e.g. see Figure 6.22) The dilution level chosen was 30% sand to 70% murram. This gives a linear shrinkage of 5% (30mm; see Figure 6.4) which suggests that there is still a moderate clay content present. Table 6.6 compares the four week cured wet and dry compressive strengths of these 'diluted' materials with other materials investigated including a murram-10wt% cement addition material (heavy compaction).

This establishes that the addition of an inert filler such as sand can make more efficient utilisation of the lime by effectively increasing the strength for a particular lime content. In fact the addition of 10wt% lime to murram alone produces a 4 week strength which does not meet the requirement of the Kenyan standard whereas the addition of 10% lime to a 70% murram-30% sand mixture achieves a strength well in excess of this requirement.

Clearly the combination of increased compaction pressure and small gypsum additions to the murram-lime system produces a very marked improvement in strength development and enables the strength requirements of the Kenyan standard to be achieved with quite small additions of lime. Also by substituting part of the murram with sand even more effective utilisation of this added lime may be achieved. However a second important criterion must be taken into account in addition to strength when stabilised earth is used for building, that of durability (see section 4.5) and the fact that a material complies with strength requirements does not necessarily mean that it will also meet the durability requirements. Thus the potentially most promising materials with regard to strength development were also subjected to durability tests.

6.3.2 Durability characteristics

6.3.2.1 Range of durability testing

One aim of this study was to determine the durability of these cured materials. The results obtained can then be used to predict the range of compositions which will best withstand the weathering conditions if used as building materials. All durability tests were carried out on 4-week cured samples as this was normally the time required to achieve maximum strength (see Figures 6.25 (a) and 6.26 (a)) and for the strength requirements to be met.

In the alternate wet-dry tests (see section 5.3.5.1) weights and dimensions of cylinders were noted both before and after each wet and dry cycle. The dimensions (i.e. heights) were measured at fixed and marked points on the cylinders and the wet and dry cycling was carried out over alternate 24 hour periods. Two different wetting methods were employed, one of total immersion in water (full wetting) and the other immersing the cylinders in water to a depth of one quarter the height of cylinders (partial wetting). The former method is important especially if the stabilised material is used for foundation construction. In this case the material is likely to be wetted totally when the ground water level rises (i.e. during the rainy season). The latter method is suitable for building material used in wall construction. It is assumed that one side of the wall is exposed to rather dry conditions while the other side is exposed to alternate wetting and drying. Although this alternate wet and dry cycling over alternate 24 hour periods may not be the real situation in the field, it can be used as an indication of the relative behaviour of different material compositions when exposed to alternate wet and dry weather.

The weight and length changes after first fully soaking cured specimens in water for 24 hours was used to evaluate respectively, the linear expansion and water absorption of the cured samples. Tests for linear expansion/shrinkage and moisture movement should ideally be included in any assessment of the properties of stabilised soils. These tests are necessary because any large movement would lead to cracking of the wall, to failure of applied renderings, or to rain penetration. As mentioned earlier earth walling is inherently sensitive to changes in moisture content, and so, as it loses the water needed for moulding it is bound to shrink. The moisture movement of stabilised soils is still likely to be higher than that of other walling materials such as burnt brick and concrete.

In the spray test artificial rain was generated from a shower head at a pressure of about 1.5kg/cm^2. Samples which had been soaked to a quarter of their height in water during the alternate wet-dry cycles, were placed at 200mm from the shower head with the ends that had been soaked and dried facing and parallel to the shower face. This test is necessary as it is assumed that in a building, the outside wall not only experiences alternate wetting and drying but also stormy rain the force of which can erode the wall material.

Another set of samples were subjected to a brushing test. The samples were soaked in water for 24 hours, then oven dried for at 70°C for 48 hours prior to brushing employing a wire brush. The brush used was not identical to the one described in section 4.5 but this was not considered critical as the test was aimed at assessing relative performance rather than compliance with an absolute standard. Twenty strokes were applied with almost equal force on each sample and the amount of material which was abraded away was determined. The Kenyan standard recommends 12 cycles of soaking in water and drying and brushing but does not place a limit on the amount of material abraded away. Although only one cycle was carried out in the current work, the results obtained did give a useful comparison of the relative weathering resistance of the different materials under investigation. This type of test is important when testing the durability of soil building material for use in arid areas where buildings in these areas are frequently subjected to wind blown sand that erodes the wall surfaces. Also the test is important when checking whether the building material will withstand scratching of walls due to normal household activities.

6.3.2.2 Results of wet-dry cycling

Plates 6.2 (a) and 6.2 (b) shows murram-lime and murram-lime-gypsum samples that were subjected to 14 full and partial wet-dry cycles respectively. Note that there are no comparable murram-5wt% lime, murram-5wt% lime-1.5wt% gypsum and murram-10wt% cement cylinders because these disintegrated during their first full or partial soaking in water.

The murram-10wt% lime and the murram-10wt% lime-3.0wt% gypsum cylinders started roughening especially at their edges, after about 4 cycles of wetting and drying and the gypsum containing samples appeared to be affected more than those containing lime alone for both wetting methods. After about 12 cycles both the 10wt% lime and 10wt%lime-3.0wt% gypsum addition samples that were fully wetted started cracking and eventually broke into pieces (see Plate 6.2 (a)). Although those samples that were partially wetted did not break into pieces, they had lost a considerable amount of material particularly after 28 cycles (see Table 6.7). Note that the specimens containing gypsum performed rather worse than the equivalent specimens without gypsum. This indicates that the addition of gypsum, although significantly increasing the strength, does not improve the durability of the material and appears to make it rather less durable.

The 15wt% lime addition material wihout added gypsum showed the greatest resistance to the wet-dry process for both partial and full soaking. After 7 cycles there was negligible loss of material. As the wet-dry process continued these samples appeared relatively smooth even after 14 cycles. They however started to crack after 14 cycles and those samples that were fully immersed in water eventually broke into pieces after about 25 cycles. Those that were partially immersed in water lost a negligible amount of material even after 28 cycles. The 15wt% lime-4.5wt% gypsum addition specimens tended to lose material earlier than those with 15wt% lime alone. Those that were fully immersed in water during the wetting period broke into pieces after about 20 wet-dry cycles while those that were partially immersed lost a considerable amount of material but less than the 10wt% lime-3.0wt% gypsum addition samples.

The percentage changes in both weight and length for fully and partially soaked samples during the wet-dry cycling process are shown respectively in Tables 6.8-6.9 and Tables 6.10-6.11 and presented graphically in Figures 6.27-6.28 and 6.29-6.30. Although the specimens were subjected to 28 wet and dry cycles over a period of 8 weeks the results only include the first 7 cycles because this was the period over which most of the samples had lost negligible material. Beyond this period, because the samples started losing material, the changes in the measurements were a combination of wetting and drying as well as loss of material and this would not give a true comparison with those measurements obtained at the beginning. Figures 6.27 and 6.29 show respectively, the immediate initial changes in weight and length when the dry samples are first fully immersed in water and the subsequent changes during the wetting and drying cycles. The changes in both weight and length rapidly fall to a fairly constant level as the cycling process progresses. The trend is similar for samples that were partially immersed (see Figures 6.28 and 6.30) except that the immediate initial changes in length are smaller. This indicates that the samples partially immersed in water did not initially reach full saturation even after being soaked for 24 hours. However subsequent changes for both fully and partially soaked samples are almost the same which means that the method of soaking did not have much effect on the weight and length changes. A number of general observations may be made regarding these results. As might be expected the magnitude and direction of the changes in dimensions follow approximately the same general pattern as the changes in weight. In particular for the fully soaked specimens, those specimens which contained gypsum showed greater dimensional changes than equivalent specimens without gypsum, and for the partially soaked specimens those

specimens which contained sand showed smaller dimensional changes than equivalent specimens without sand.
An interesting feature that was observed, which was very pronounced with the samples containing gypsum, was the appearance after several cycles of wetting and drying, of a white deposit (see Plate 6.3) which formed a ring or annulus close to the surface of the cylinder. This was clearly material deposited from solution during the wetting and drying cycles as a result of sub-surface crystallisation or precipitation. Also the material external to this white ring appeared softer compared with that in the other regions. X-ray analysis was carried out on material from the outer region, the white portion and the inner region in order to establish the exact cause of this phenomenon.

Figure 6.31 and 6.32 shows the changes in compressive strength at two week intervals during respectively the full and the partial wetting and drying cycles for the four week cured samples. These show distinct and systematic trends. For fully soaked specimens (Figure 6.31) there is a marked drop in compressive strength after 7 wet-dry cycles for all gypsum containing specimens, whereas the none-gypsum containing samples show a gradual increase in compressive strength as cycling progresses. This latter effect can simply be attributed to a continuation of the curing process with time. The same trends are apparent for the partially soaked specimens (Figure 6.32) but the magnitude of the changes are smaller because of the lower level of saturation of the samples.

6.3.2.3 Water absorption, spraying and abrasion

The static water absorption and linear expansion results for the samples are shown in Table 6.12. The values of water absorption range from 17 to 25% and the highest expansion values are exhibited by specimens containing gypsum and the lowest by specimens containing sand. It should be noted that specimens containing 5wt% lime, 5wt% lime-1.5wt% gypsum and 10wt% cement disintegrated during water absorption and are not therefore included in the results. The Kenyan standard recommends a maximum water absorption value of 15%. The value obtained for 'diluted' murram (16.1) is closest to the Kenyan standard requirement. Although the materials investigated do not satisfy the Kenyan requirement and may not be suitable where low absorption and impermeability are essential, they can still be used above damp proof course level.

The linear expansion values obtained, which could also be used to indicate linear shrinkage, ranged between 0.21 and 0.58. The Kenyan standard does not specify an allowable value for this. A value for drying shrinkage of 0.05% is suggested in BS 2028 as a maximum for precast concrete blocks for common use. Similar specifications based on this standard could be suggested for stabilised soil blocks, although this would be too restrictive due to the fact that soil is much weaker than materials like precast concrete. A value of 0.2% for drying shrinkage has been suggested (67) as an upper limit for stabilised soil blocks.

Table 6.13 compares material washed away when the samples were subjected to partial wetting and drying followed by 6 hours of spraying. Comparing Table 6.7 and Table 6.13 there was very little difference in the material loss before and after spraying. The alternate wet-dry cycling was severe enough to be used as a weathering test and spraying may not be necessary in this case but can be used to assess the durability within a short period.

The weights of material abraded away when the samples were subjected to a brushing test are shown in Table 6.14. Material loss for 5wt% lime and 5wt% lime-1.5wt% gypsum addition samples is significantly greater than that for the other samples indicating again that these samples are weaker. Although the difference in material loss for the other samples is not so great, the diluted murram samples show the smallest amount of material loss indicating that these samples are the most resistant to abrasion.

6.4 Analysis of the stabilised soil

6.4.1 Introduction

Analysis was carried out on selected stabilised soil samples rather than on all specimens, with the object of identifying the new phases formed during the curing period and qualitatively following the reaction of lime and gypsum with the soil.

X-ray powder diffraction analysis was used for the identification of new phases and for this only the 4 week cured murram-15wt% lime and murram-15wt% lime-4.5wt% gypsum specimens were selected in order to give sufficient time for any new phases to be fully formed. The high lime and gypsum content specimens were selected because these should contain substantial amounts of any new phases, making the phases easier to detect.

Thermal analysis was principally used to follow the take up of lime and gypsum during the period of curing and stabilisation. A knowledge of the consumption of these reactants during curing makes it possible to determine whether the reactants are being fully utilised in the stabilisation process or whether they are being added in excess. In addition the thermal analysis results can in some cases be used to confirm the X-ray observations with regard to the identification of the reaction products.

Scanning electron microscopy was used principally to examine the morphology of the new phases formed and to identify any changes in soil fabric on stabilisation.

6.4.2 X-ray diffraction results

Table 6.15 shows the X-ray diffraction data for murram-15wt% lime material cured for 4 weeks at 30°C and 100% relative humidity. Although kaolinite and gibbsite are still present after curing there is no free lime remaining and a weak diffraction line from calcite at 3.033 A shows that a small amount of the lime has carbonated. Two completely new phases are observed to form as a result of the reaction of lime with the murram. One is Strätling's compoumd which is a calcium silicate aluminate hydrate of composition C_2ASH_8 and the second is a carbonate substituted calcium aluminate hydrate based on the composition C_4AH_{13} (44).

Table 6.16 shows the X-ray diffraction data for murram-15wt% lime-4.5wt% gypsum material cured for 4 weeks at 30°C and 100% relative humidity. When gypsum is present the reaction products formed are totally different. Carbonate substituted C_4AH_{13} is not formed although there is evidence of formation of a limited amount of Stratlingite. Instead the principal phase formed is ettringite $C_3A3C\bar{S}H_{32}$ which is a calcium sulpho-aluminate hydrate. Therefore in the high pH environment within the pore solution in the murram, the alumina released from both the kaolinite and the gibbsite forms calcium aluminate and silicate aluminate hydrates when only lime is present but forms mainly calcium sulphoaluminate hydrate when lime and gypsum are present. It should be noted that the formation of these totally different reaction products could result in very different physical behaviour. It was also noted, in section 6.3.2, that when stabilised specimens which contained gypsum were subjected to the alternate wetting and drying durability tests, a white annulus developed within the cylinders (see Plate 6.3). Material within, external to, and internal to, this white annulus was subjected to X-ray analysis. The X-ray results obtained were very similar to those reported in Table 6.15 other than the fact that the ettringite diffraction peaks in the material external to the ring were rather weaker and the calcite peak at 3.03 A very much stronger. Table 17 shows the relative heights of these calcite peaks in the material external to, within and internal to the white annulus. These observations suggest that the process of alternate wetting and drying is initiating rapid carbonation of the ettringite within the outer layers of the specimen. This will release sulphate which is then involved in the formation of the white amorphous product below the outer surface. Each time the specimen dries out the concentration of the sulphate in the pore solution adjacent to the outer surface will increase and more and more of this white product will be deposited in the pore spaces.

6.4.3 Thermal analysis results

Figures 6.33, 6.34 and 6.35 compare the derivative thermogravimetry (DTG) thermograms of the cured murram-lime cylinders at various curing times, for lime contents of 5, 10 and 15wt%. The weight loss peak resulting from dehydroxylation of the lime occurs at about 450°C. This peak is clearly present immediately after mixing when 15wt% lime has been added (see Figure 6.35) and is present at a lower intensity when 10wt% lime has been added (see Figure 6.34), but it is completely absent when 5wt% lime has been added. Also after one week of curing the peak completely disappears from the thermograms of material containing both 10 and 15wt% lime. This indicates that the reaction of the murram with lime is very rapid and begins immediately the reactants are mixed together.

In addition to the weight loss bands due to, adsorbed water at 70-100°C, dehydroxylation of the gibbsite between 300 and 350°C, dehydroxylation of kaolinite at about 570°C and decomposition of calcium carbonate at about 750°C, there are a number of new bands which develop during the curing process. These new bands are strongest and most clearly defined for the murram-15wt% lime material after curing for 4 weeks when the greatest quantity of reaction product has developed. They occur (see Figure 6.35) at 130, 180 and 230°C and from previous reports by Kuzel (45) and Abdi (59) they can positively be identified as being due to dehydroxylation of Strätling's compound. This confirms the

X-ray diffraction observations of the formation of this compound. Carbonate substituted C_4AH_{13} also has weight loss bands in this region and these may be superimposed on the other bands. De Silva and Glasser (68) give the composition of this phase as $C_4AC_{0.5}H_{12}$ and attribute weight loss bands at 150°C and 280°C to this phase.

Figures 6.36, 6.37 and 6.38 give the equivalent DTG thermograms for murram-lime-gypsum cured materials. Comparison of these thermograms with those for gypsum-free material show little evidence of weight loss peaks at 130, 180 and 230°C indicating that calcium aluminate and silicate aluminate hydrates are no longer formed or are formed in very limited quantities. Also the weight loss peak at between 70 and 100°C instead of diminishing with curing time as it does when no gypsum is present actually increases in intensity with curing time and after 4 weeks of curing has developed into a strong sharp peak at between 100 and 120°C. This peak is characteristic of the dehydration of ettringite (69) and is positively identified as such, thus confirming the X-ray diffraction observations. The absence of any weight loss peaks due to dehydration of gypsum (160°C) at curing periods of 1 week and beyond suggests very rapid ettringite formation.

6.4.4 Scanning electron microscopy (SEM) observations

Scanning electron microscopy analysis of the cured murram-lime mix cured for 4 weeks is shown in Plate 6.4. Comparison of this with that of murram alone (Plate 6.1), shows a more continuous microstructure with a much lower abundance of the finer particles. This indicates that the cementitious products that are formed particularly from reaction with the more surface active fine particles link the particles together to produce a more connected microstructure.

Addition of gypsum to the murram-lime samples produces very pronounced modifications in the microstructure of the cured samples (see Plate 6.5). The principal feature observed in the case was formation of 'ettringite' rods. These rods nucleate and grow on the surfaces of the clay particles and subsequently grow into the pore spaces between particles (59). As the micrograph shows the ettringite rods form an interlocking three-dimensional network and this interlocking network will almost certainly result in strength enhancement of the material as it will inhibit relative movement of the clay particles when specimens are subjected to an applied compressive stress.

6.5 Summary

The following major points have been established from the experimental observations.

i) The murram used in the current work has a high clay content. Particle size analysis gives an estimated clay content of 60%. This is reflected in the shrinkage characteristics of the murram which shows a linear shrinkage of 10% and in the plasticity index for the murram which is of 17%.

ii) The addition of lime to the murram significantly reduces the plasticity index to a constant value of 9% for lime additions greater than 10%. Also the addition of sand significantly reduces the linear shrinkage of the murram, the addition of 30wt% sand reducing the linear shrinkage from 10 to 5%.

iii) The addition of lime to the murram reduces the maximum dry density and increases the optimum moisture content when heavy compaction is employed. When standard compaction is used then a less systematic trend is observed when using either lime or cement additions.

iv) Chemical analysis of the murram gives a ratio of silica to alumina plus iron oxide content of 0.56 which establishes that the murram is a true laterite. Chemical analysis also shows that the soluble salt content of the murram (i.e. sulphate, chloride and carbonate) is negligible.

v) The mineralogical content of the murram principally comprises Kaolinite, Haematite and Gibbsite together with minor amounts of Quartz and Anorthoclase.

vi) Stabilising the murram with lime and employing standard compaction, results in a systematic increase in strength with both increase in curing time and increase in lime content. However only specimens with lime contents of at least 15wt% lime cured for 4 and more weeks comply with the Kenyan standard for minimum wet strength of 1.5N/mm^2. Also the addition of cement as a stabiliser appears to be less effective than lime with regard to strength development.

vii) Increasing the compaction pressure from 5N/mm^2 (standard compaction) to 10N/mm^2 (heavy compaction) increases the compressive strength of the cured murram-lime material by amounts ranging from 50 to 100%, although still only the 15wt% lime addition material meets the Kenyan standard for minimum strength, and this material does not comply with the standard relating dry strength to wet strength. However adding small amounts of gypsum to the murram-lime material in addition to increasing the compaction pressure produces very significant increases in wet and dry strength. Strength increases of between 100 and 500% are achieved, the effect being greatest at low lime contents. For these gypsum containing materials the Kenyan standard relating dry strength to wet strength is easily achieved.

viii) Even more effective use of the lime may be achieved by diluting murram with sand. This enables higher strengths to be achieved for the same overall lime content. Diluting the murram with 30wt% sand enabled strength increases of 86% for 10wt% lime addition material and 15% for 10wt% lime-3.0wt% gypsum addition material to be achieved. For both of these materials the Kenyan standard for minimum strength was satisfied and also the dry strength to wet strength requirement was achieved.

ix) Increase in compressive strength of the stabilised materials does not automatically improve the durability of these materials. Although additions of gypsum to murram-lime material increased the strength substantially it did not have a similar beneficial effect on the durability.

x) Cured murram cylinders containing up to 5wt% lime with or without gypsum, or up to 10wt% cement, disintegrated during initial soaking. Cured murram cylinders with higher lime contents which were subjected to alternate wetting and drying showed a pattern of dimensional changes which reflected their changes in weight. Specimens which contained gypsum showed much greater dimensional changes than the equivalent specimens without gypsum whereas specimens containing sand showed lower dimensional changes than specimens without added sand.

xi) The compressive strength of cured murram-lime cylinders which had been subjected to alternate wetting and drying increased gradually with increasing number of wet-dry cycles for samples containing no added gypsum but decreased significantly for specimens containing added gypsum. These changes were more pronounced for fully soaked samples than for partially soaked samples.

xii) The water absorption values for the cured murram/sand/lime/gypsum samples did not meet the Kenyan standard requirement of 15wt% water absorption. Specimens with murram diluted with sand gave values approaching the specified requirement and this could almost certainly be achieved by using the optimum dilution factor.

xiii) In the wire brush abrasion test the addition of gypsum appeared to have minimal effect on the abrasion resistance whereas diluting the murram with sand did produce a significant improvement in abrasion resistance.

xiv) Reaction of lime with murram results in the formation of two distinct products. These are Strätlingite which is a calcium silicate-aluminate hydrate of composition C_2ASH_8 and a carbonate substituted calcium aluminate hydrate of probable composition $C_4A\bar{C}_{0.5}H_{12}$.

xv) When gypsum is present in addition to lime the principal reaction product is ettringite which is a calcium sulpho-aluminate hydrate of composition $C_3A3C\bar{S}H_{32}$. For these compositions no $C_4A\bar{C}_{0.5}H_{12}$ is formed although small traces of C_2ASH_8 are still observed.

xvi) The reaction of murram with lime or with lime and gypsum is very rapid and the additives are normally fully consumed within one week of curing at 30°C and 100 relative humidity although development of the products still continues beyond this period.

xvii) No distinct change in microstructure is observed when lime reacts with murram. The reaction products are thought to be deposited as layers on the soil particles and increase the interconnectivity of the particles. When gypsum is present in addition to lime the ettringite reaction product forms as rods which grow on the soil particle surfaces and out into the pore spaces producing an interlocking three-dimensional network and very different soil fabric. It is this interlocking three dimensional network which is thought to be responsible for the marked strength enhancement when gypsum is present.

xviii) The alternate wetting and drying of the cured gypsum containing samples appears to promote carbonation of the ettringite. The carbonation of the ettringite in the outer layers of the specimen and subsequent release of sulphate results in the development of a soft highly carbonated outer layer. This layer is adjacent to a partially carbonated inner layer which contains a deposit of white amorphous material which itself is adjacent to the principally uncarbonated interior. The formation of the white annulus is thought to result from sub-surface precipitation of a sulphate containing an amorphous product as the outer surface of the specimen dries out and the concentration of sulphate in the sub-surface pores increases.

Component	Murram (Mataara Rd.) (wt%)	Murram * (wt%)	Red coffee soil * (wt%)
Oxides			
SiO_2	29.82	39.15	39.00
Al_2O_3	9.65	11.72	28.84
Fe_2O_3	43.80	30.71	14.43
Loss on ignition	7.25	9.10	12.94
pH	4.0	-	-
SiO_2/R_2O_3	0.56	0.92	0.88

$R_2O_3 = Al_2O_3 + Fe_2O_3$

* Data after Webb (9)

Table 6.1 (a) Chemical analysis of the murram compared with some other Kenyan laterites.

Component	wt%
Ca^{2+}	0.006
Mg^{2+}	0.006
K^+	0.020
Na^+	0.039
SO_4^{2-}	0.048
Cl^-	0.15
CO_3^{2-}	Nil

Table 6.1 (b) Water soluble salts in the murram used.

Observed d-spacing Å	Minerals
7.176	Ka
4.833	Gi
4.439	Gi/Ka
4.160	Gi/An
4.027	?
3.583	Ka
3.339	Gi/Qu
3.235	An
3.199	An
2.709	Ha
2.564	Ka/Ha
2.495	Ka
2.430	Gi
2.334	Ka
2.298	Ka
2.233	Ka
2.198	Ha
2.156	An
2.039	Gi
1.991	Ka
1.819	Qu
1.763	?
1.750	Gi
1.698	Ha
1.686	Ka
1.670	Ka
1.542	Ka/Qu
1.488	Ka/Ha
1.452	Ka/Ha
1.281	Ka
1.236	Ka

Ka-Kaolinite, Gi-Gibbsite, Ha-Haematite, Qu-Quartz An-Anorthoclase.

Table 6.2 X-ray diffraction data for murram soil.

Chemical analysis

Compound		Weight (%)
Calcium hydroxide	$Ca(OH)_2$	96.79
Calcium carbonate	$CaCO_3$	1.36
Calcium sulphate	$CaSO_4$	0.06
Magnesium oxide	MgO	0.83
Ferric oxide	Fe_2O_3	0.06
Aluminium oxide	Al_2O_3	0.10
Silica	SiO_2	0.46
Excess moisture	H_2O	0.34

Grading analysis

Nominal aperture size (µm)	% weight passing
500	100
355	99.99
250	99.98
180	99.93
125	99.74
90	99.59
63	94.71

Table 6.3 Chemical and grading analysis of the lime used.

Physical properties:

Particle size (μm)	15
Surface area (m^2/kg)	350-500
Bulky density (kg/m^3)	1300-1400
Specific gravity	3.14

Chemical composition:

Chemical symbol	% weight
SiO_2	20.9
Fe_2O_3	2.2
Al_2O_3	4.5
CaO	64.0
MgO	2.3
$Na_2O + K_2O$	0.9
Impurities + LOI	4.7

Table 6.4 Chemical and physical properties of the cement used.

Mineralogical composition:

Mineral	% weight
Kaolinite	84
Micaceous material	13
Feldspar	1
Other minerals	2

Chemical analysis:

Chemical symbol	% weight
SiO_2	48
Al_2O_3	37
Fe_2O_3	0.65
TiO_2	0.02
CaO	0.07
MgO	0.03
K_2O	1.60
Na_2O	0.10
Loss on ignition	12.51
Sulphate content	200-400 parts/million
Atomic ratio Al/Si	0.908

Particle size distribution:

Particle size	% weight
>53µm	0.03
>10µm	4
<10µm>2µm	23.7
<2µm	70

Table 6.5 Chemical and grading analysis of kaolinite used

Composition	Four week cured wet	dry compressive strength (N/mm^2)
M10L	1.4	5.0
Kenyan standard	1.5	at least 3.0
M10C	2.4	7.5
*70M30S10L	2.6	6.7
M10L3.0G	3.3	9.8
*70M30S10L3.0G	3.8	9.7

* note that the lime and gypsum are expressed as a percentage of the weight of the diluted murram (i.e. murram plus sand).

Table 6.6 Comparison of the wet and dry compressive strengths of stabilised murram and stabilised murram diluted with sand.

Composition of mix	Material loss (g) after 7		14		28 cycles	
	F	P	F	P	F	P
M10L	2.0	1.0	2.2	3.0	-	10.0
M15L	1.0	1.1	1.8	2.0	-	3.0
M10L3.0G	4.4	3.2	-	9.6	-	18.9
M15L4.5G	4.8	4.3	-	4.9	-	10.8
70M30S10L	1.0	0.6				
70M30S10L3.0G	1.8	1.2				

F-Full immersion - specimen disintegrated
P-Partial immersion

Table 6.7 Material loss after the wet-dry cycles for samples that were fully immersed in water.

M10L-Murram-10wt% lime
M15L-Murram-15wt% lime
M10L3.0G-Murram-10wt% lime -3.0wt% gypsum
M10L4.5G-Murram-15wt% lime -4.5wt% gypsum
M10C-Murram-10wt% cement
70M30S10L-70wt% murram -30wt% sand -10wt% lime
70M30S10L3.0G-70wt% murram-30wt% sand-10wt% lime -3.0wt% gypsum

Sample	M10L	M15L	M10L3.0G	M15L4.5G	70M30S -10L	70M30S -10L3.0G
% changes in weights	+24.6	+23.8	+21.8	+22.0	+17.4	+16.1
	-12.5	-8.7	-12.0	-11.3	-11.1	-11.6
	+13.0	+8.6	+12.2	+11.7	+11.0	+11.7
	-14.6	-11.9	-11.8	-12.5	-11.2	-13.2
	+14.4	+10.8	+11.5	+12.3	+11.2	+13.2
	-10.6	-9.5	-10.5	-10.7	-11.2	-13.2
	+10.6	+9.6	+10.4	+10.6	+11.2	+13.3
	-10.7	-10.0	-11.0	-9.6	-10.4	-13.0
	+10.7	+9.9	+10.4	+9.6	+10.4	+13.0
	-10.1	-7.5	-9.4	-9.8	-7.7	-10.2
	+10.2	+7.5	+9.0	+9.8	+7.7	+9.9
	-8.2	-6.0	-9.2	-9.7	-7.6	-9.5
	+8.3	+6.4	+9.1	+9.6	+7.8	+10.3
	-8.4	-6.5	-9.3	-9.6	-8.0	-10.0

note -ve sign means change when sample dries and +ve sign means change when sample is soaked in water.

Table 6.8 Weight changes expressed as a percentage of original dry weight of samples soaked (full) and dried for 7 cycles.

Sample	M10L	M15L	M10L3.0G	M15L4.5G	70M30S 10L	70M30S 10L3.0G
% change in weight	+20.0	+15.6	+16.3	+15.0	+15.1	+13.2
	-11.4	-8.2	-9.0	-6.4	-10.9	-10.9
	+14.0	+11.7	+12.6	+10.6	+12.2	+9.4
	-15.1	-11.1	-13.0	-11.1	-12.3	-10.7
	+14.7	+11.0	+13.8	+12.5	+12.5	+10.2
	-12.8	-9.2	-9.8	-10.1	-12.0	-9.3
	+13.0	+10.9	+10.0	+11.1	+8.7	+8.4
	-13.1	-7.8	-9.3	-9.3	-11.0	-10.1
	+13.3	+8.1	+9.5	+9.8	+8.5	+8.6
	-10.9	-9.4	-11.8	-11.3	-7.7	-6.2
	+11.0	+7.8	+11.9	+11.5	+7.5	+5.6
	-10.8	-7.9	-12.0	-9.5	-7.7	-6.0
	+10.9	+7.6	+11.9	+9.7	+8.0	+5.8
	-10.4	-7.6	-11.8	-9.4	-7.8	-6.2

Table 6.9 Weight changes expressed as a percentage of original dry weight of samples soaked (partial) and dried for 7 cycles.

Sample	M10L	M15L	M10L3.0G	M15L4.5G	70M30S 10L	70M30S 10L3.0G
% change in length	+0.39	+0.41	+0.58	+0.44	+0.21	+0.32
	-0.28	-0.2	-0.45	-0.3	-0.17	-0.29
	+0.27	+0.2	+0.42	+0.3	+0.15	+0.08
	-0.21	-0.22	-0.44	-0.26	-0.17	-0.22
	+0.16	+0.18	+0.28	+0.22	+0.19	+0.16
	-0.2	-0.21	-0.24	-0.27	-0.21	-0.21
	+0.21	+0.19	+0.23	+0.24	+0.23	+0.21
	-0.15	-0.18	-0.32	-0.22	-0.13	-0.21
	+0.15	+0.17	+0.35	+0.13	+0.14	+0.26
	-0.13	-0.21	-0.29	-0.13	-0.10	-0.14
	+0.12	+0.16	+0.3	+0.15	+0.11	+0.12
	-0.11	-0.17	-0.32	-0.16	-0.10	-0.09
	+0.13	+0.18	+0.36	+0.18	+0.12	+0.09
	-0.14	-0.19	-0.32	-0.23	-0.12	-0.12

Table 6.10 Length changes expressed as a percentage of original dry weight of samples soaked (full) and dried for 7 cycles.

Sample	M10L	M15L	M10L3.0G	M15L4.5G	70M30S 10L	70M30S 10L3.0G
	+0.36	+0.2	+0.15	+0.09	+0.10	+0.13
% change in length	-0.17	-0.24	-0.14	-0.08	-0.20	-0.18
	+0.2	+0.24	+0.14	+0.19	+0.18	+0.14
	-0.25	-0.30	-0.11	-0.21	-0.14	-0.16
	+0.21	+0.11	+0.16	+0.24	+0.16	+0.21
	-0.14	-0.12	-0.18	-0.17	-0.14	-0.18
	+0.16	+0.25	+0.23	+0.17	+0.17	+0.20
	-0.13	-0.25	-0.21	-0.13	-0.16	-0.19
	+0.15	+0.17	+0.22	+0.14	+0.18	+0.20
	-0.16	-0.16	-0.22	-0.19	-0.15	-0.22
	+0.10	+0.15	+0.20	+0.20	+0.18	+0.20
	-0.18	-0.14	-0.19	-0.18	-0.18	-0.16
	+0.14	+0.11	+0.16	+0.19	+0.19	+0.23
	-0.15	-0.10	-0.13	-0.20	-0.20	-0.18

Table 6.11 Length changes expressed as a percentage of original dry weight of samples soaked (partial) and dried for 7 cycles.

Composition of mix	Water absorption (%)	Linear expansion (%)
M10L	24.6	0.39
M15L	23.8	0.41
M10L3.0G	21.8	0.58
M15L4.5G	21.5	0.44
70M30S10L	17.5	0.21
70M30S10L3.0G	16.1	0.32

Table 6.12 Water absorption and linear expansion of four-week cured cylinders.

Composition of mix	Material loss (g) after		
	7	14	28 cycles
M10L	1.0	3.2	10.4
M15L	1.2	2.1	3.2
M10L3.0G	3.6	10	20.4
M15L4.5G	4.4	5.3	11.2
M10C	-	-	-
70M30S10L	0.8		
70M30S10L3.0G	1.3		

Table 6.13 Material loss after wet-dry cycles followed by spraying for 6 hours for samples whose quarter heights were immersed in water during the wetting period.

Composition of mix	Material loss (g)
M5L	5.67
M5L1.5G	5.80
M10L	2.7
M10L3.0G	2.66
M15L	3.2
M15L4.5G	2.56
70M30S10L	2.1
70M30S10L3.0G	2.08

Table 6.14 Material loss after brushing.

Observed d-spacing Å	Mineral
12.538	Strt
8.117	$(C_4AH_{13} + \bar{C})$
7.225	Ka
6.321	Strt
5.639	Gi
4.928	Strt
4.835	Gi
4.407	Strt
4.230	Qu
4.181	Strt
3.863	$(C_4AH_{13} + \bar{C})$
3.345	Qu/Gi
3.238	An
3.033	Ca
2.882	Strt
2.749	$(C_4AH_{13} + \bar{C})$
2.694	Ha
2.614	Strt
2.559	$(C_4AH_{13} + \bar{C})$
2.508	Ka
2.292	$(C_4AH_{13} + \bar{C})$
2.201	Ha
2.084	?

Strt-Stratlingite, Ka-Kaolinite, Gi-Gibbsite $(C_4AH_{13} + \bar{C})$-Carbonate subsituted calcium aluminate hydrate (Glasser re), Ca-Calcite, Ha-Haematite, Qu-Quartz, An-Anorthoclase.

Table 6.15 X-ray diffraction data for murram-15wt% lime cured for 4 weeks at 30°C and 100% relative humidity.

Observed d-spacing Å	Mineral
12.13	Strt
9.67	Et
8.6	Et
7.16	Ka
6.42	Strt
5.54	Et
5.03	Et
4.93	Strt
4.83	Gi
4.65	Et
4.44	Gi/Ka
4.36	Ka
4.22	Gi
4.12	Gi
3.83	Et
3.66	Et
3.56	Ka
3.46	Et
3.32	Qu/Gi
3.24	Et/An
3.01	Et/Ca
2.91	?
2.85	Strt
2.76	Et
2.66	Ha
2.63	Et
2.55	Et
2.49	Ka
2.41	Ka
2.78	Gi
2.33	Ka
2.31	Ka
2.19	Et
2.17	An
2.14	Et
1.91	Gi
1.84	Ha
1.68	Ha
1.49	Ha/Ka

Et-Ettringite

Table 6.16 X-ray diffraction data for murram -15wt% lime-4.5wt% gypsum cured for four weeks at 30°C and 100% relative humidity.

Position	Relative estimate of calcite level*
centre	3
white deposit	6
outer	41

* level assessed from peak height above background of the 3.03Å diffraction peak.

Table 6.17 Relative estimate of calcite level at the centre, in the white deposit and in the outer areas of a gypsum addition samples that had undergone wet-dry cycles.

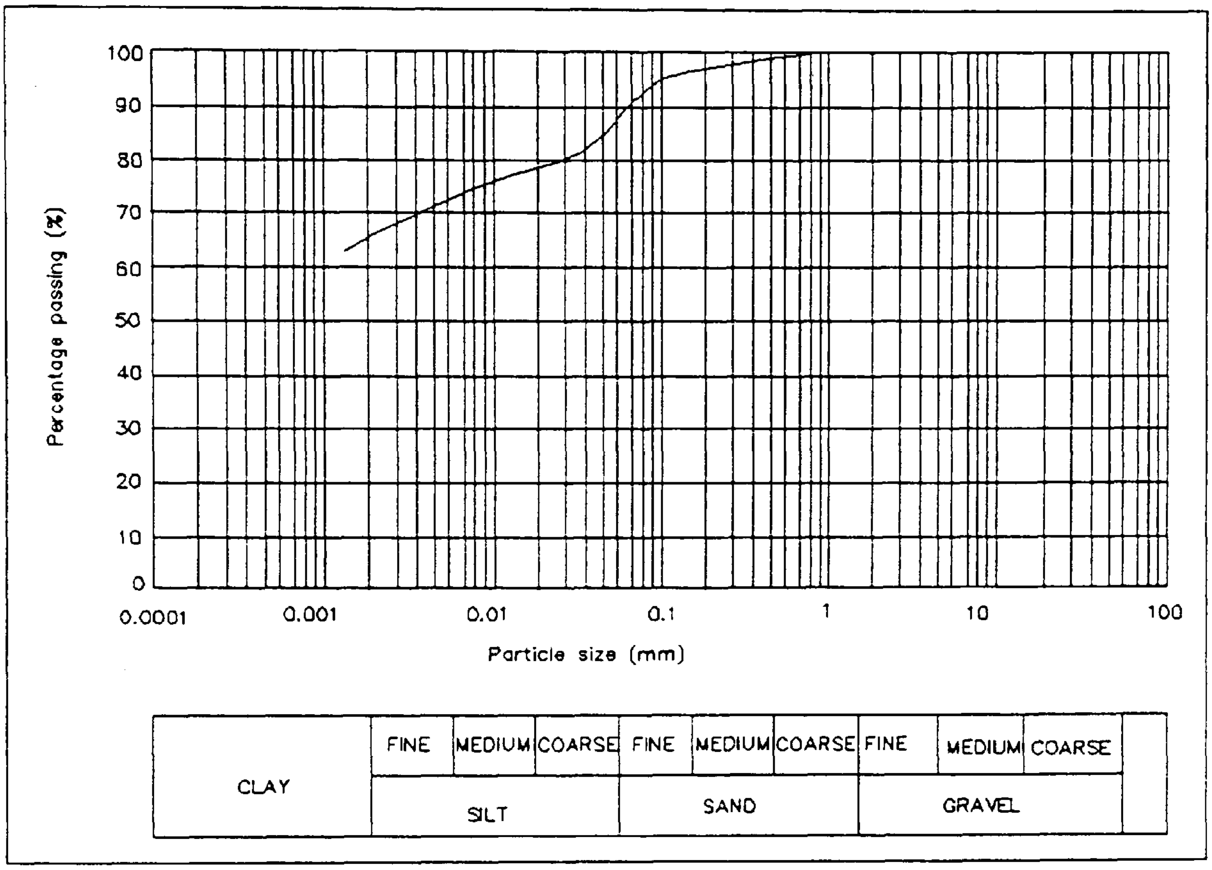


Figure 6.1 Percentage passing versus sieve size for crushed murram soil used.

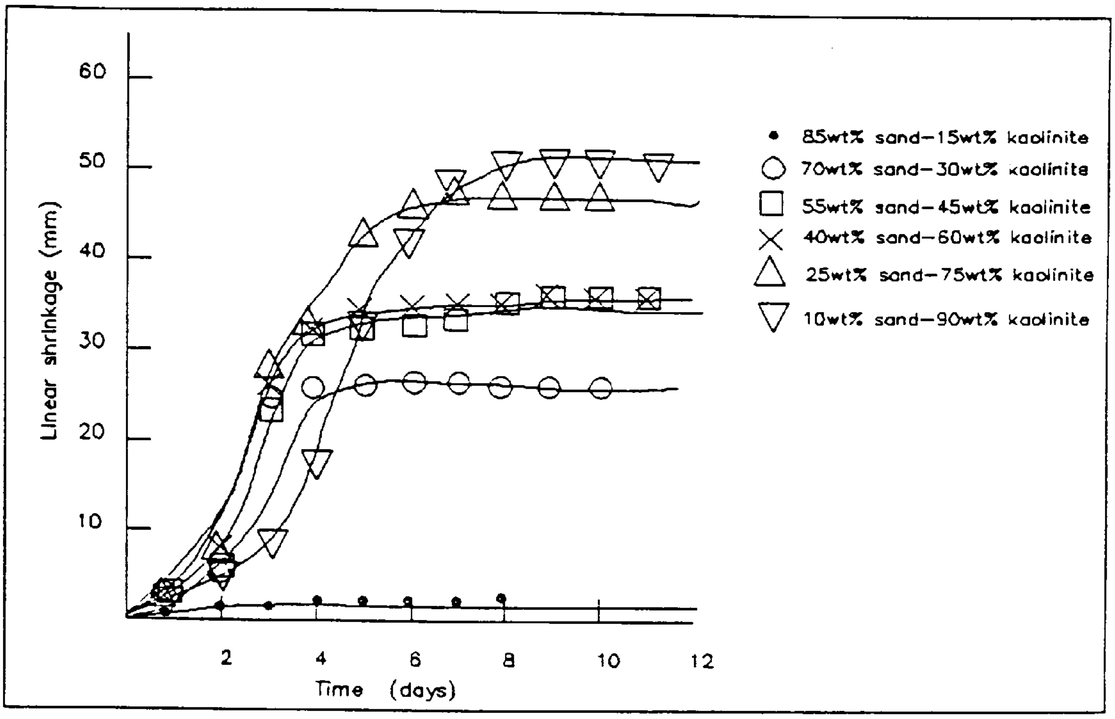


Figure 6.2 Linear shrinkage versus time for kaolinite−sand mixes.

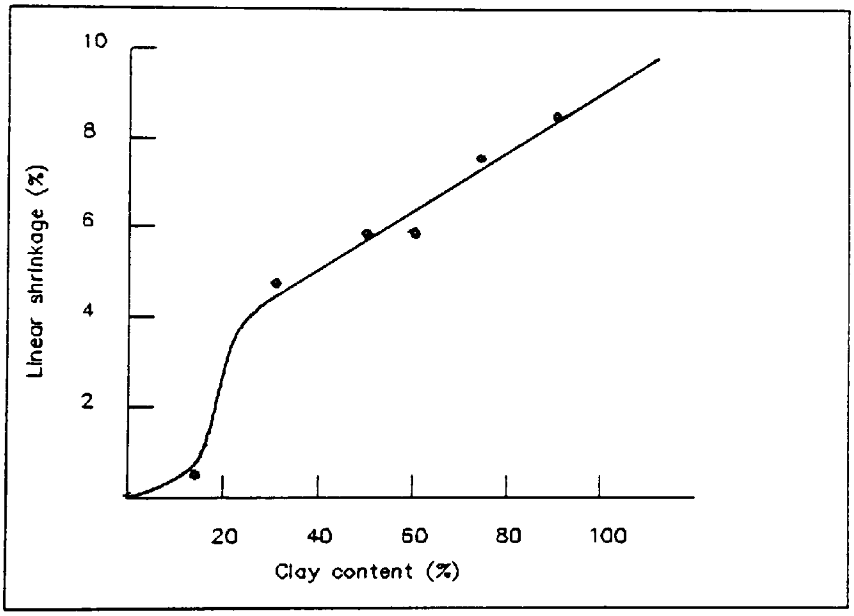


Figure 6.3 Linear shrinkage versus clay content for kaolinite−sand mixes after 10 days.

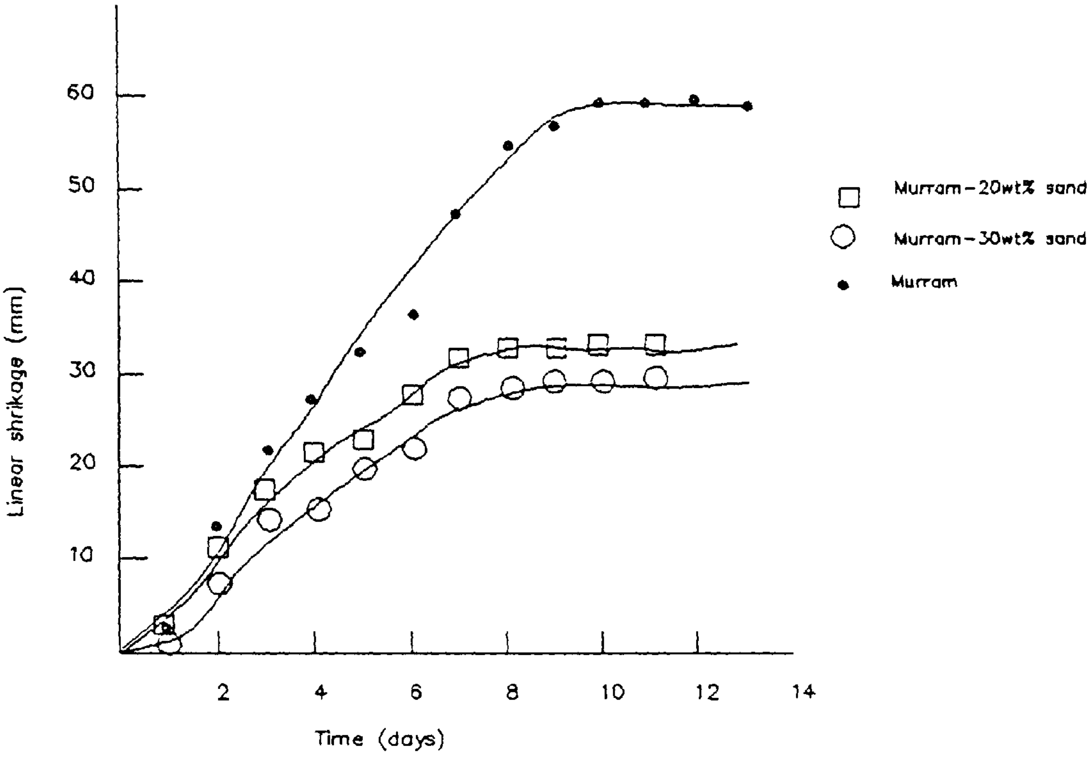


Figure 6.4 Linear shrinkage versus time for murram and murram-sand mixes.

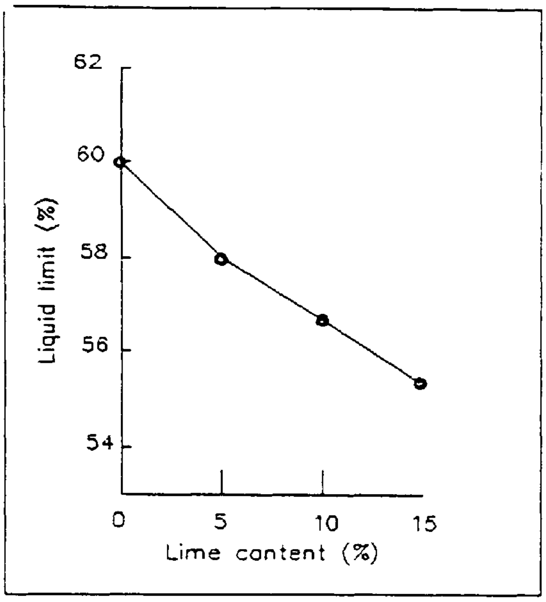


Figure 6.5 Liquid limit versus lime content for murram–lime mixes.

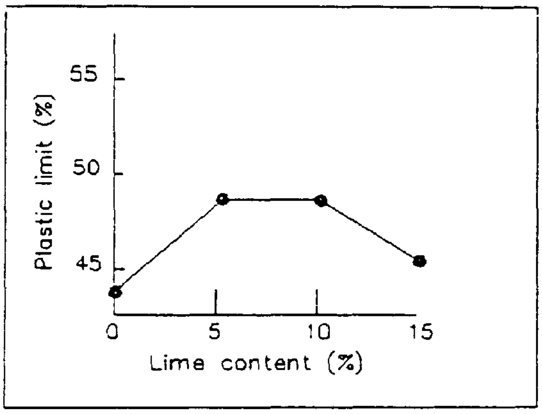


Figure 6.6 Plastic limit versus lime content for murram–lime mixes.

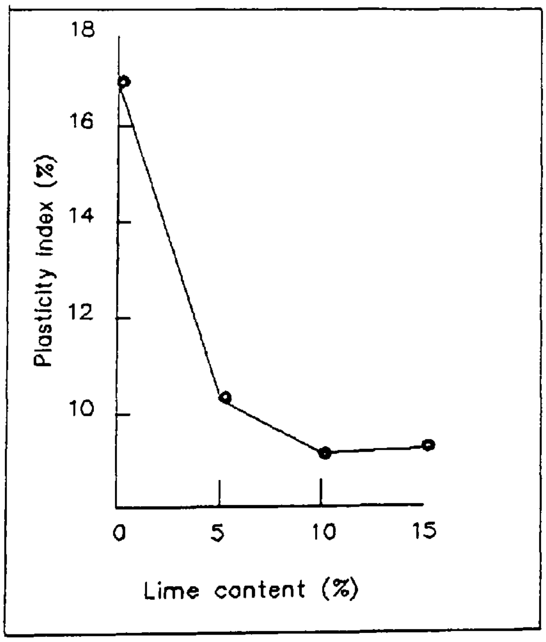


Figure 6.7 Plasticity index versus lime content for murram–lime mixes.

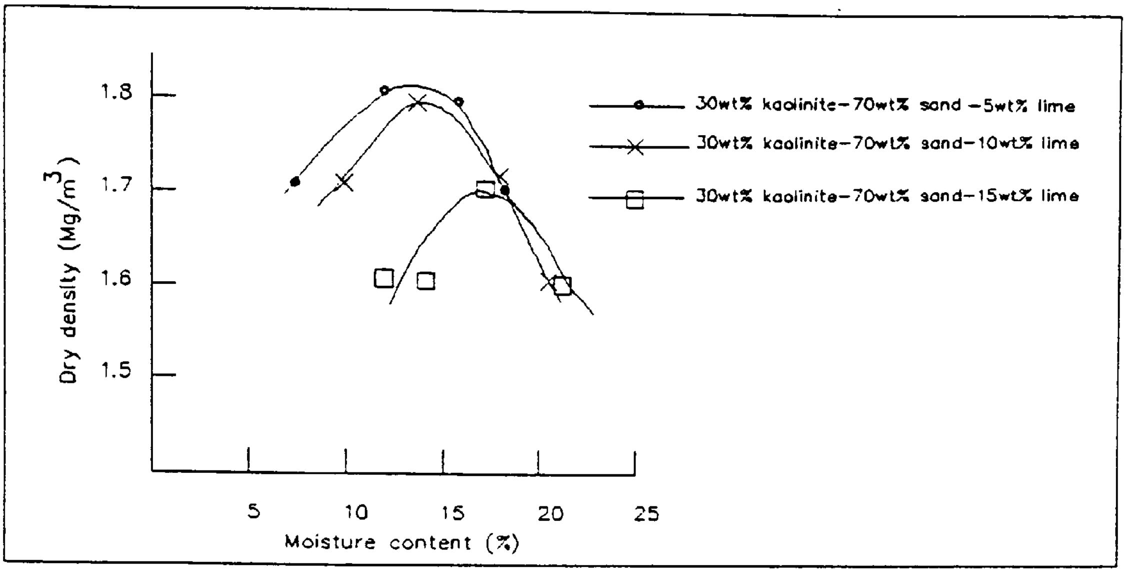


Figure 6.8 Dry density versus moisture content for kaolinite-sand-lime mixes at standard compaction (2.5kg rammer).

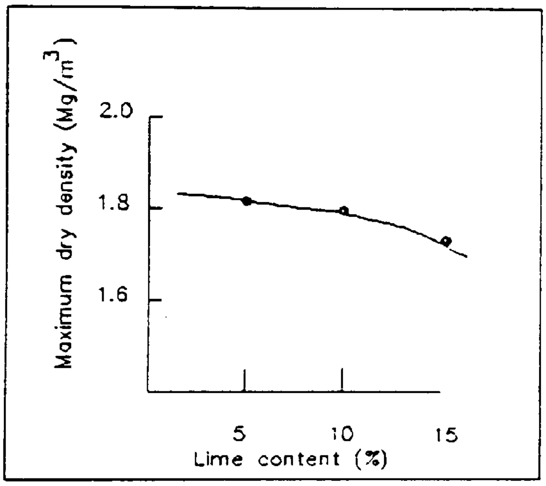


Figure 6.9 Maximum dry density versus lime content for kaolinite-sand mixes at standard compaction.

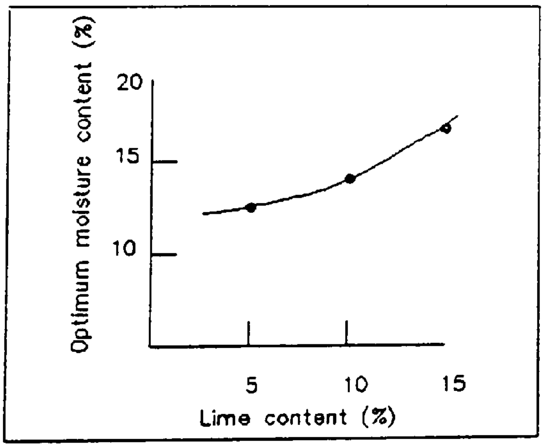


Figure 6.10 Optimum moisture content versus lime content for kaolinite-sand-lime mixes at standard compaction.

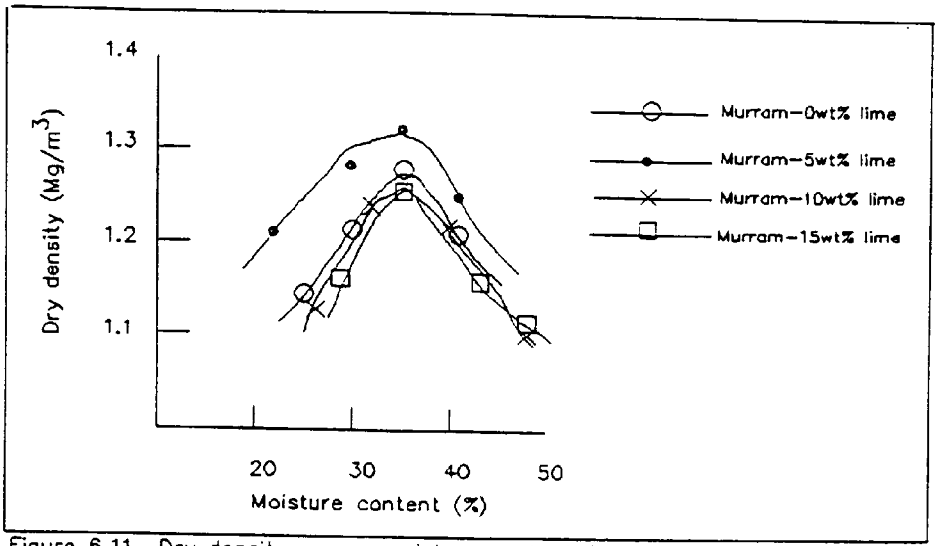


Figure 6.11 Dry density versus moisture content for murram–lime mixes at standard compaction (2.5kg rammer).

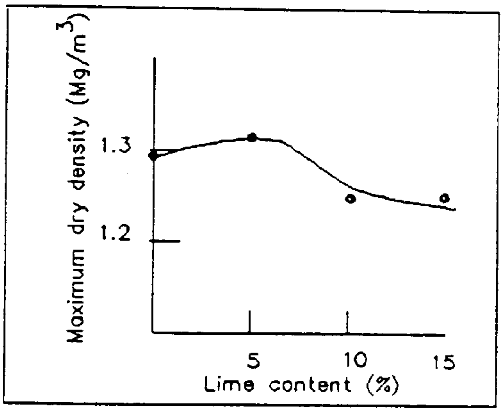


Figure 6.12 Maximum dry density versus lime content for murram–lime mixes at standard compaction.

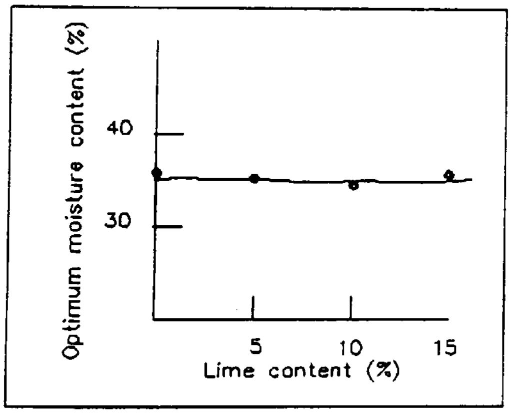


Figure 6.13 Optimum moisture content versus lime content for murram–lime mixes at standard compaction.

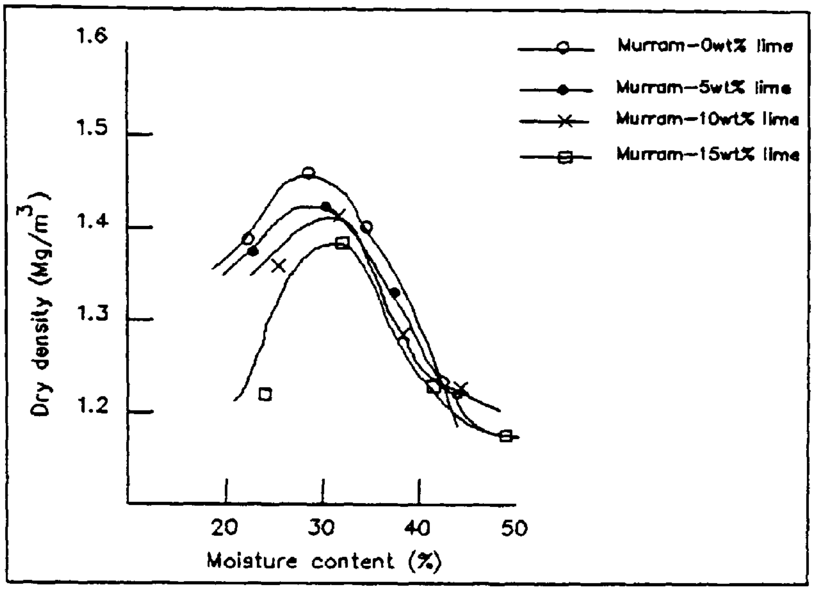


Figure 6.14 Dry density versus moisture content for murram–lime mixes at heavy compaction (4.5kg rammer).

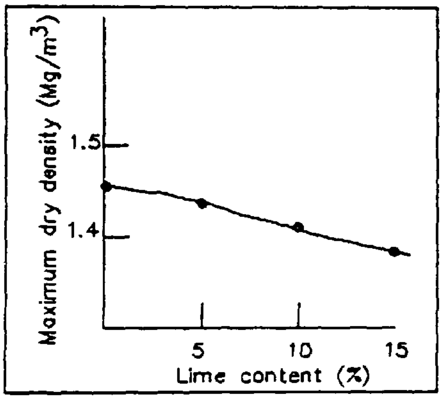


Figure 6.15 Maximum dry density versus lime content of murram–lime mixes at heavy compaction.

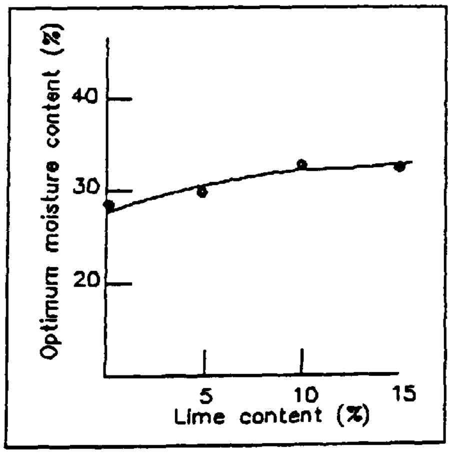


Figure 6.16 Optimum moisture content versus lime content of murram–lime mixes at heavy compaction.

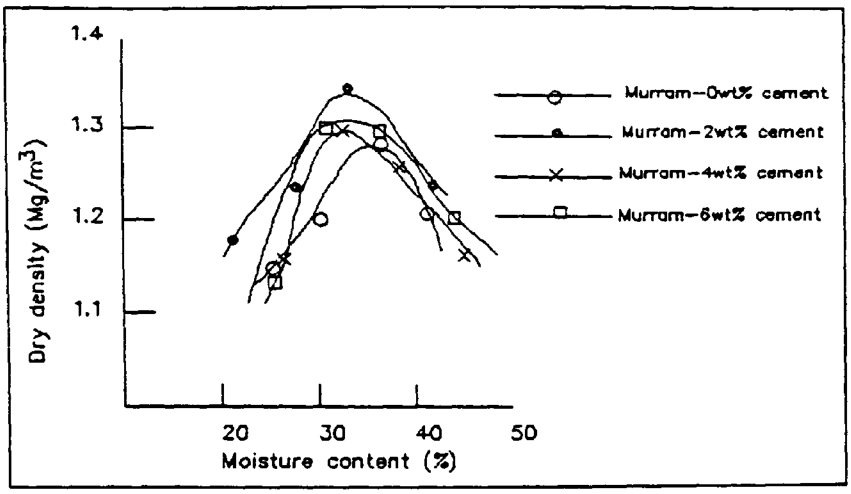


Figure 6.17 Dry density versus moisture content for murram-cement mixes at stanard compaction (2.5kg rammer).

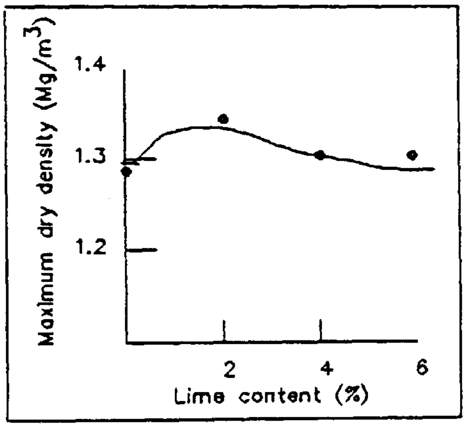


Figure 6.18 Maximum dry density versus lime content for murram-cement mixes at standard compaction.

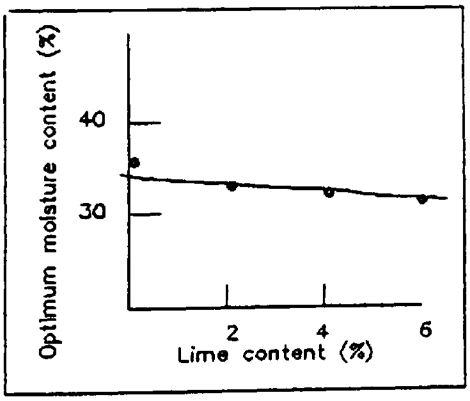


Figure 6.19 Optimum moisture content versus lime content for murram-cement mixes at standard compaction.

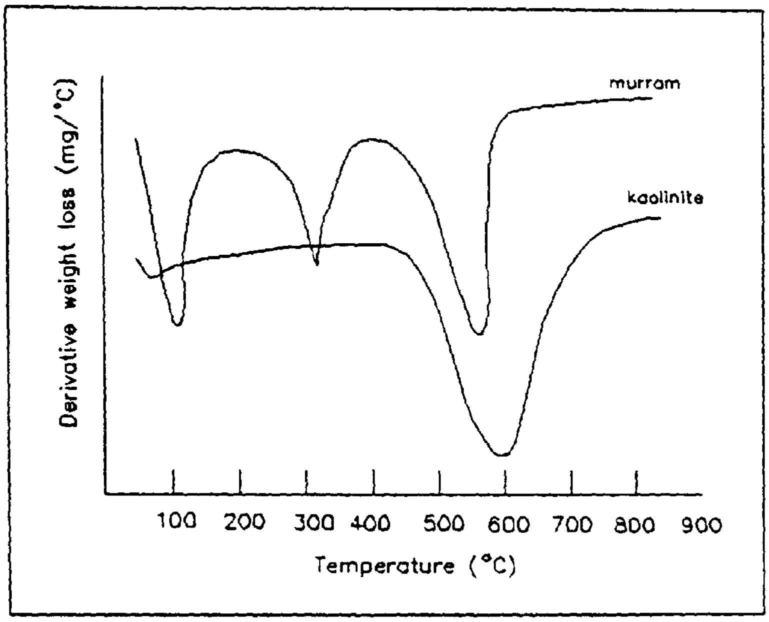


Figure 6.20 Derivative thermogravimetry of murram and kaolinite.

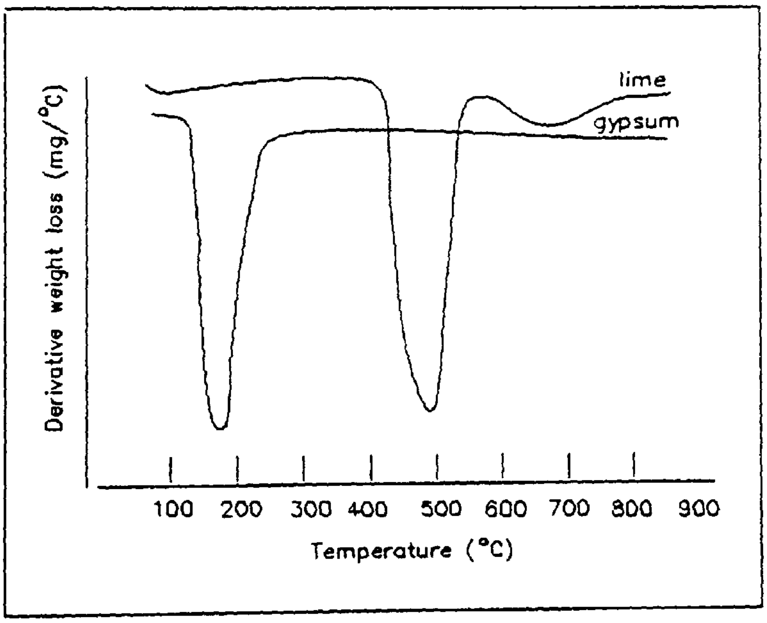


Figure 6.21 Derivative thermogravimetry of lime and gypsum

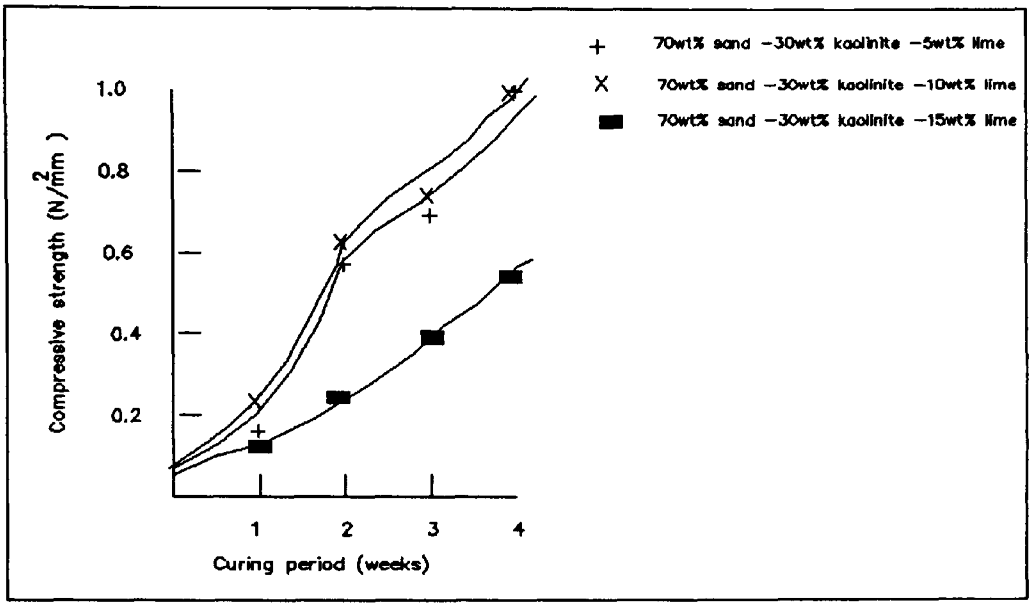


Figure 6.22 Wet compressive strength versus curing period for kaolinite-sand-lime mixes compacted at $5N/mm^2$ pressure

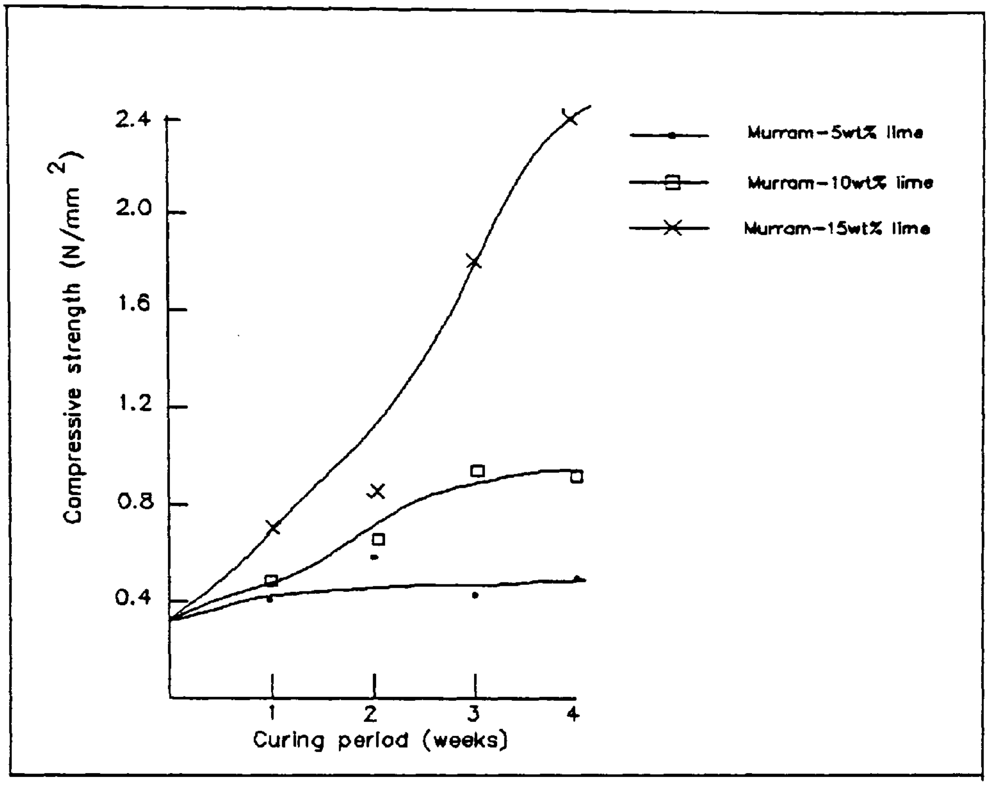


Figure 6.23 Wet compressive strength versus curing period of murram-lime cylinders compacted at 5N/mm^2 pressure.

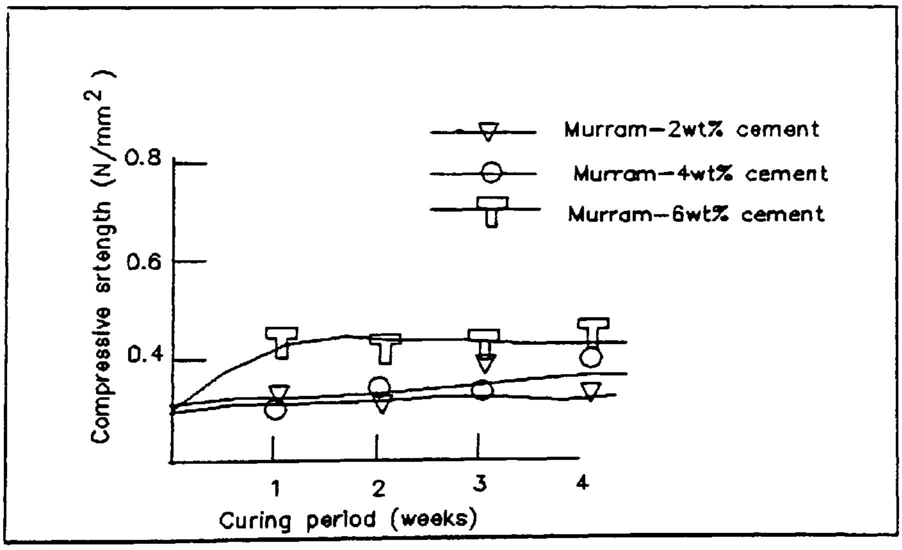


Figure 6.24 Wet compressive strength versus curing period of murram-cement mixes compacted at 5N/mm^2 pressure

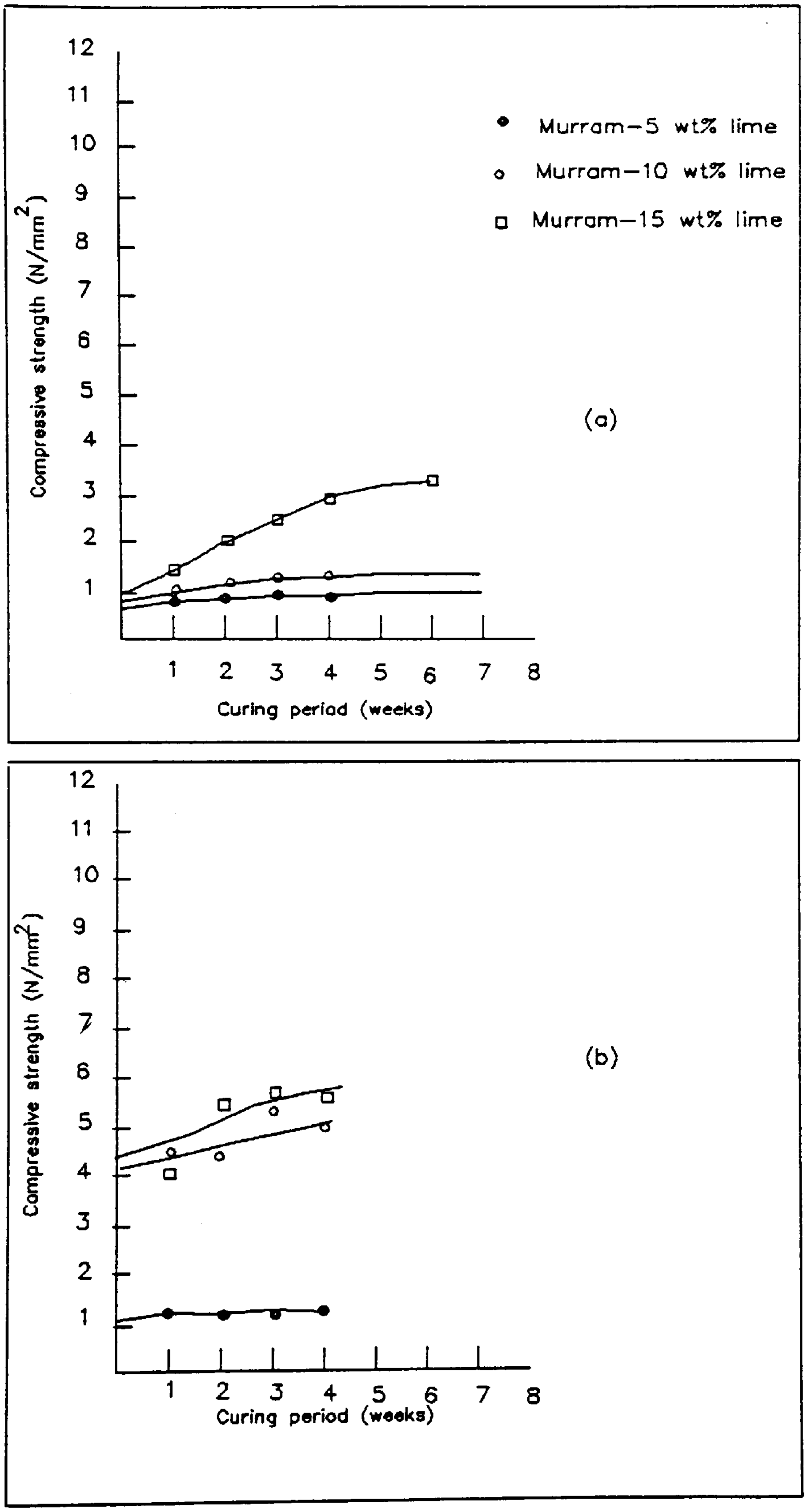


Figure 6.25 Compressive strength versus curing period of (a) wet and (b) dry murram–lime cylinders compacted at 10N/mm^2 pressure.

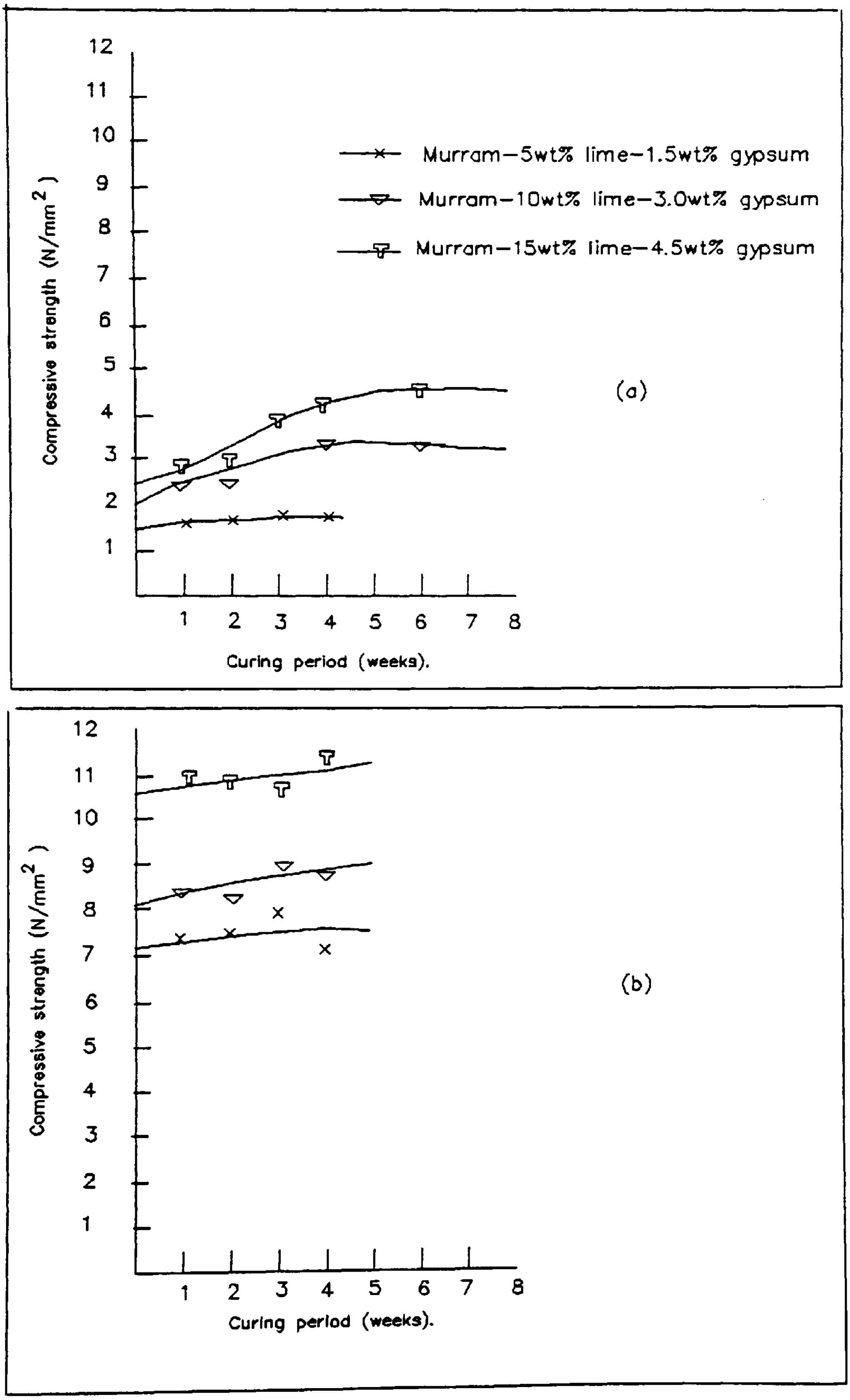


Figure 6.26 Compressive strength versus curing period of (a) wet and (b) dry murram–lime–gypsum cylinders compacted at 10N/mm^2 pressure.

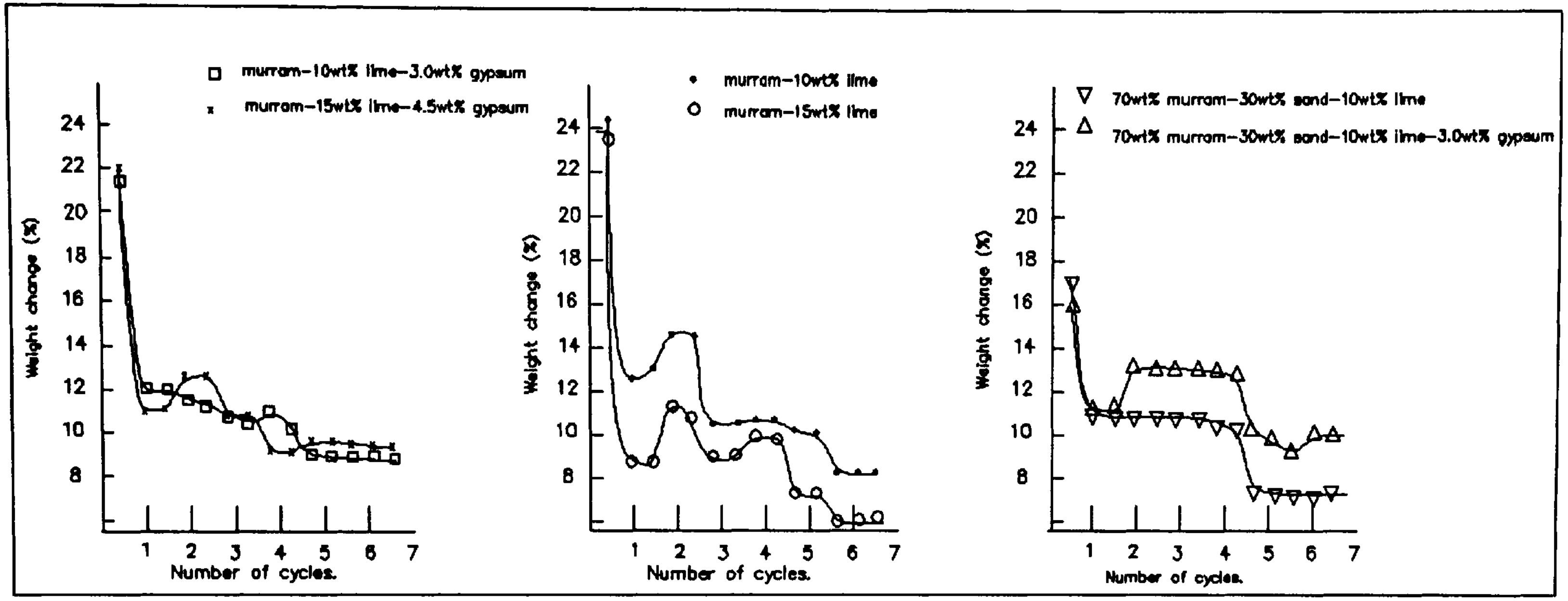


Figure 6.27 Percentage weight changes versus number of wet-dry cycles for samples fully soaked in water during the wetting period.

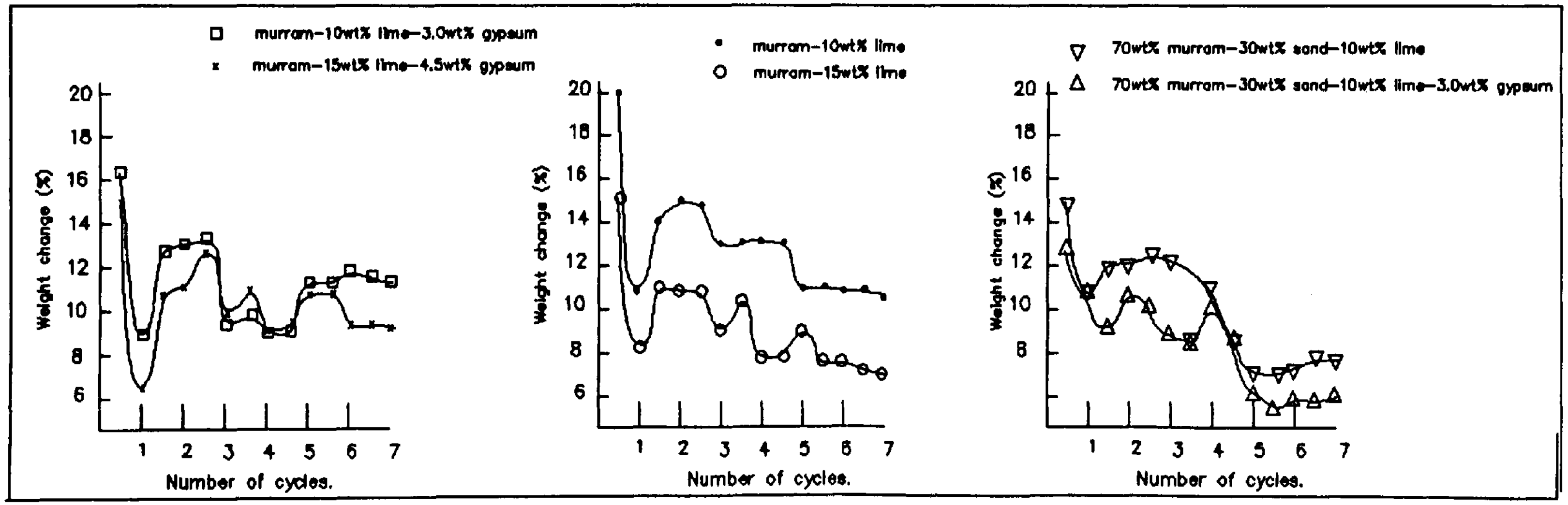


Figure 6.28 Percentage weight changes versus number of wet-dry cycles for samples partially soaked in water during the wetting process.

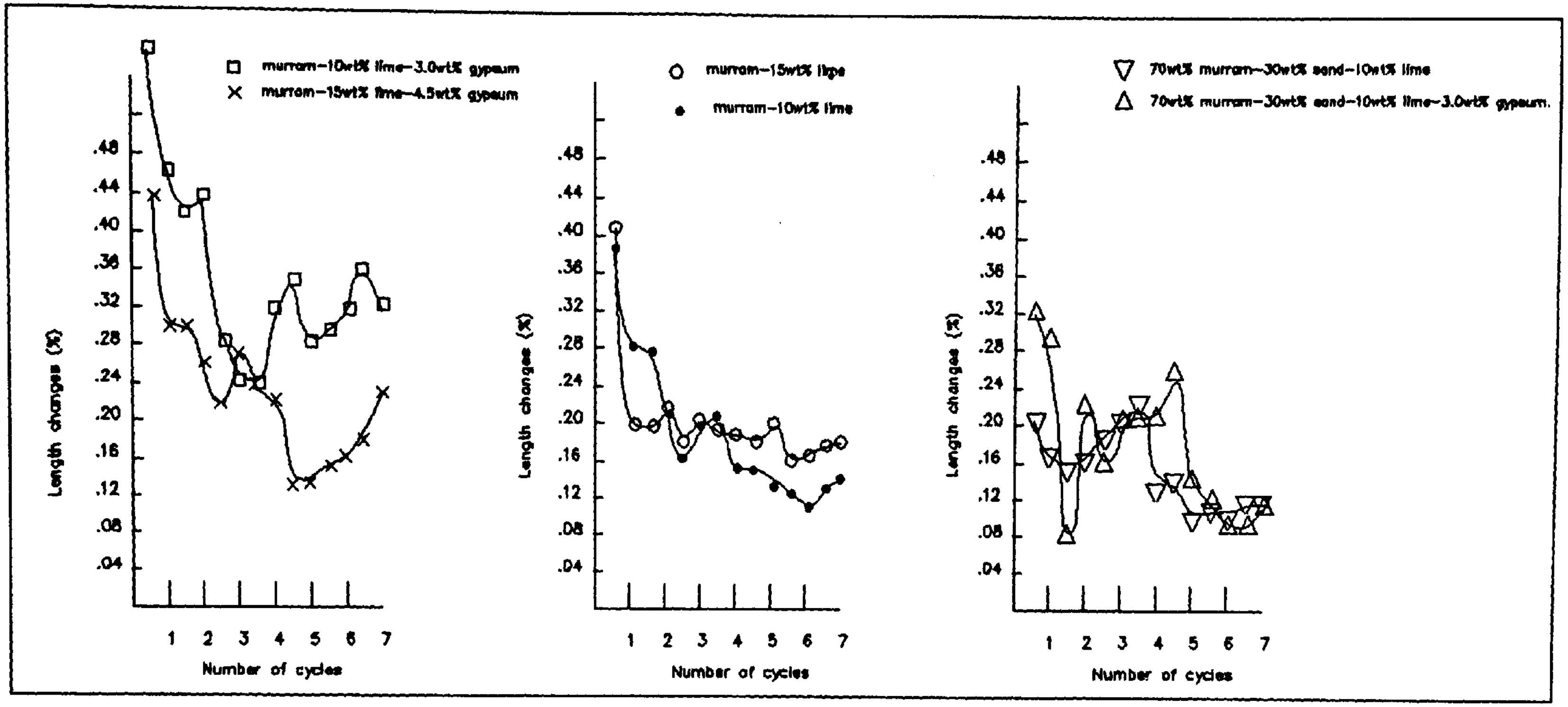


Figure 6.29 Percentage length changes versus number of wet-dry cycles for samples fully soaked in water during the wetting period.

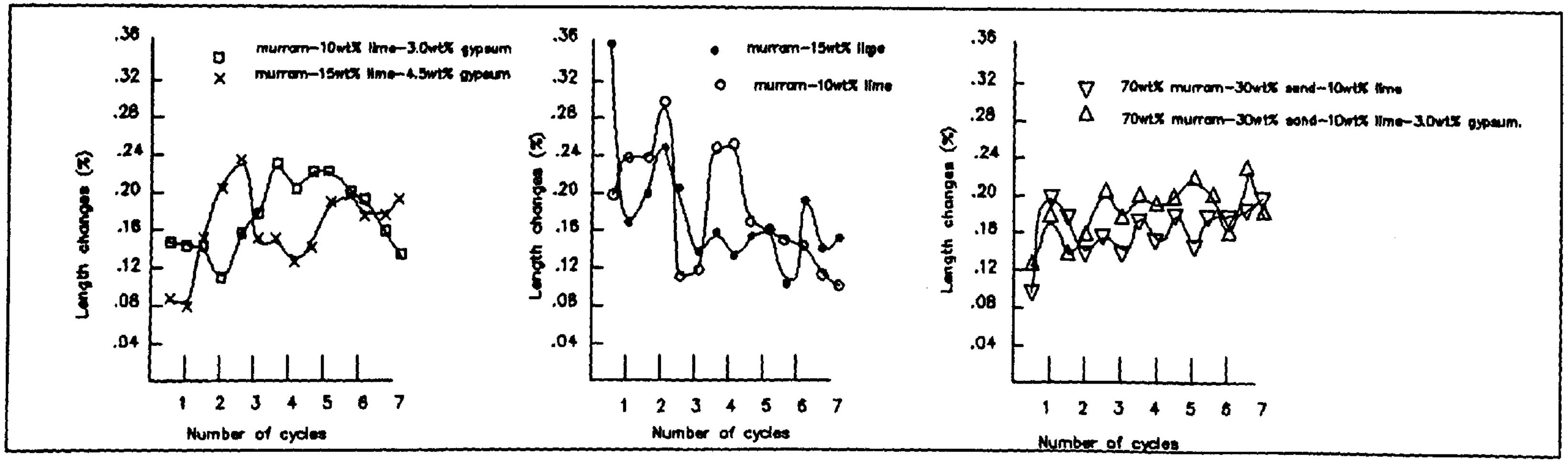


Figure 6.30 Percentage length changes versus number of wet-dry cycles for samples partially soaked in water during the wetting period.

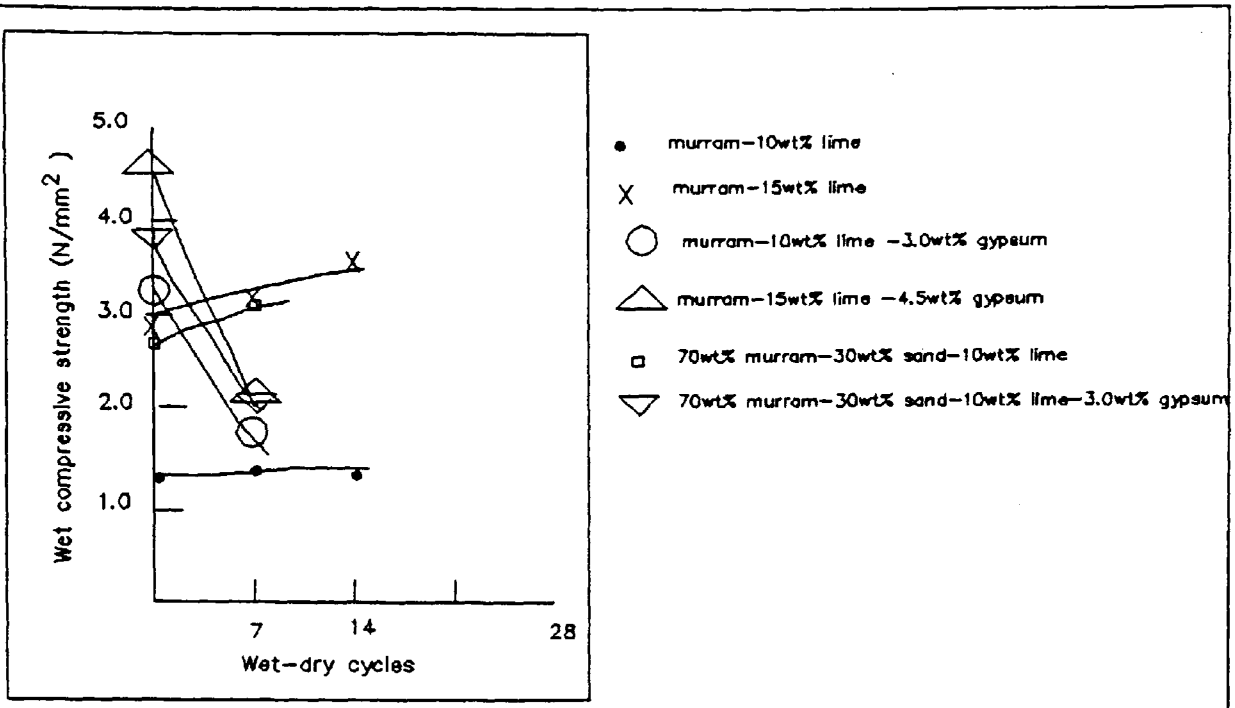


Figure 6.31 Wet compressive strength versus wet–dry cycles for samples that were fully soaked in water during the wetting period.

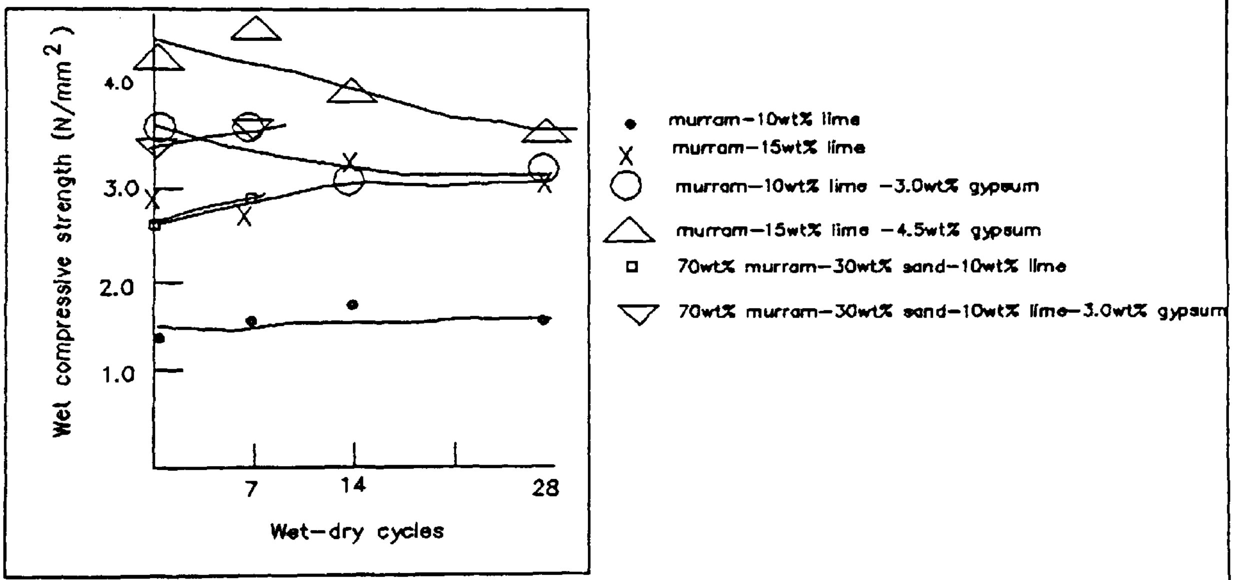


Figure 6.32 Wet compressive strength versus wet–dry cycles for samples that were partially soaked in water during the wetting process.

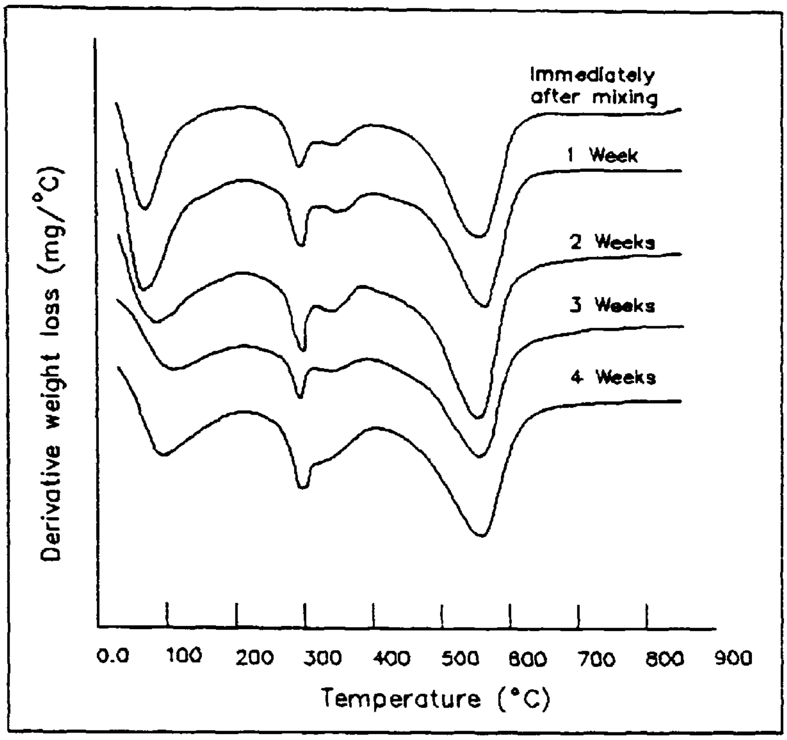


Figure 6.33 Derivative thermogravimetry of murram—5wt% lime cured at 30°C for various curing periods.

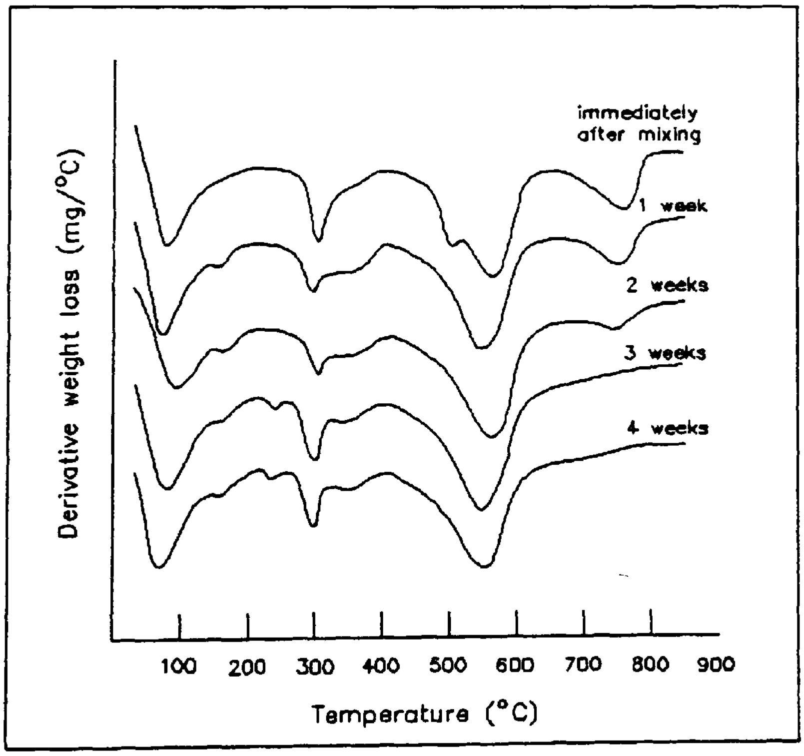


Figure 6.34 Derivative thermogravimetry of murram—10wt% lime cured at 30°C for various curing periods.

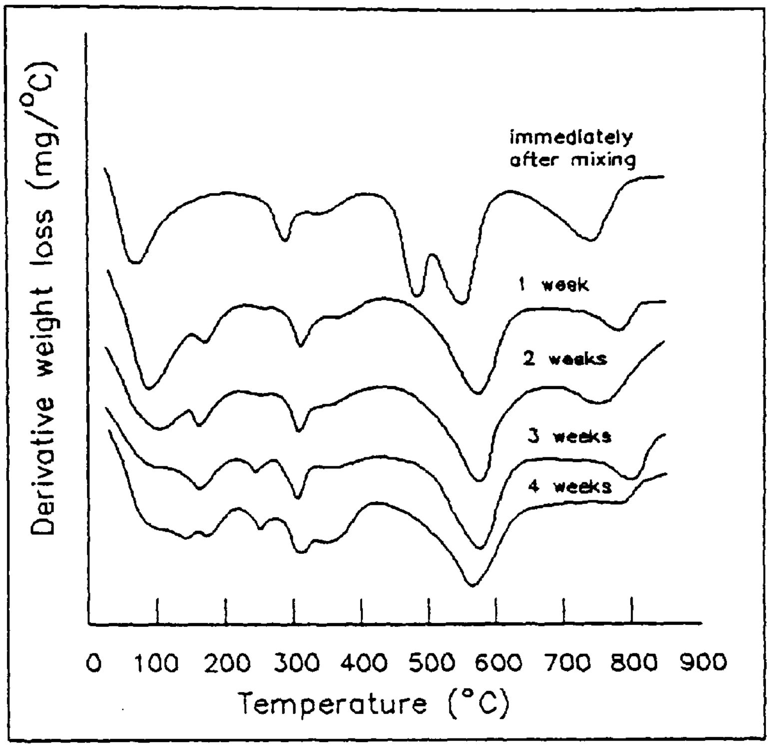


Figure 6.35 Derivative thermogravimetry of murram –15wt% lime cured at 30°C for various curing periods.

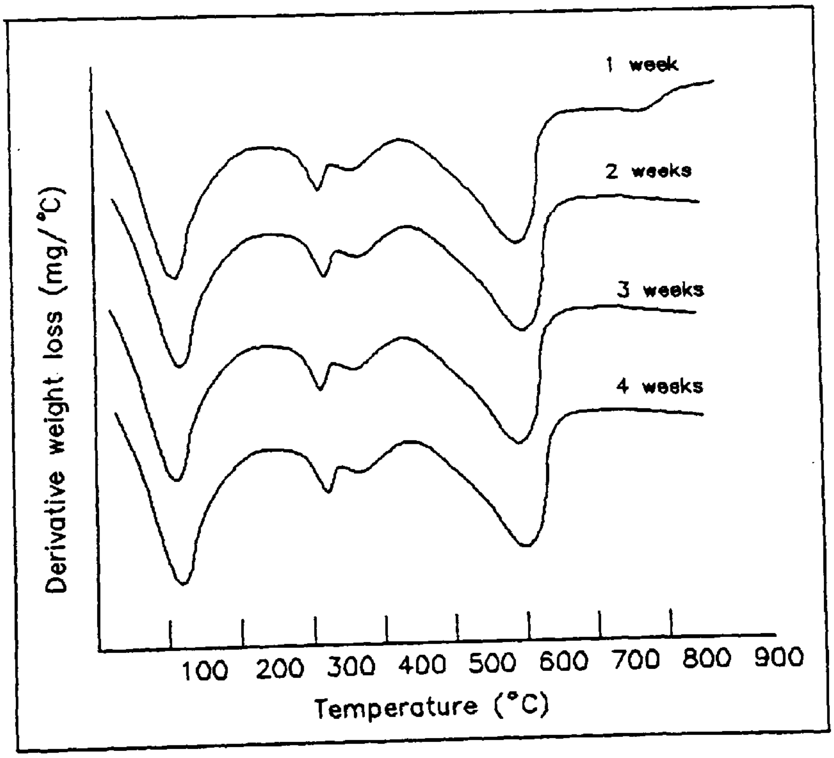


Figure 6.36 Derivative thermogravimetry of murram –5wt% lime–1.5wt% gypsum cured at 30°C for various curing periods.

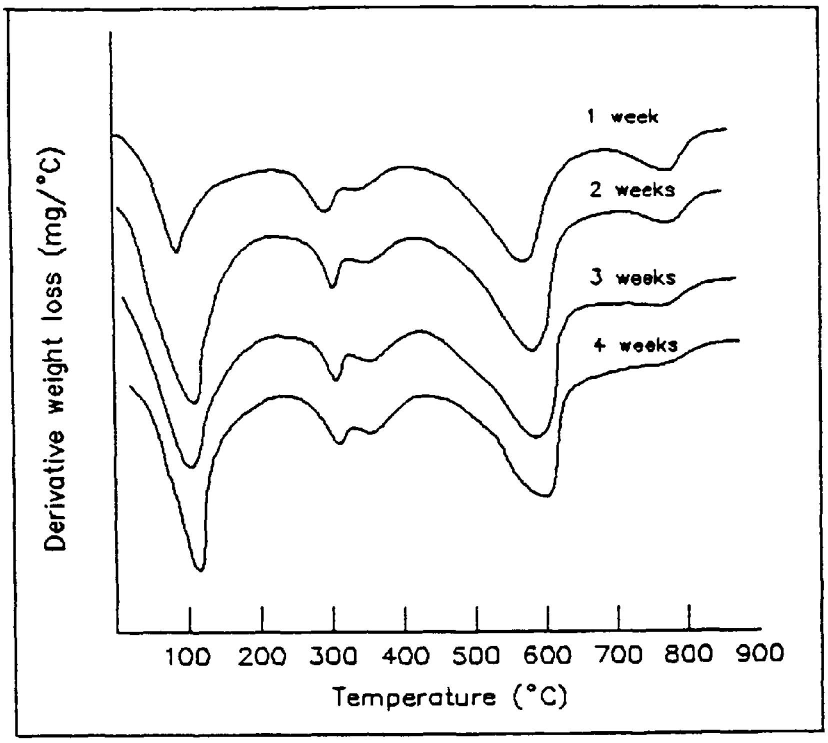


Figure 6.37 Derivative thermogravimetry of murram—10wt% lime —3.0wt% gypsum cured at 30°C for various curing periods.

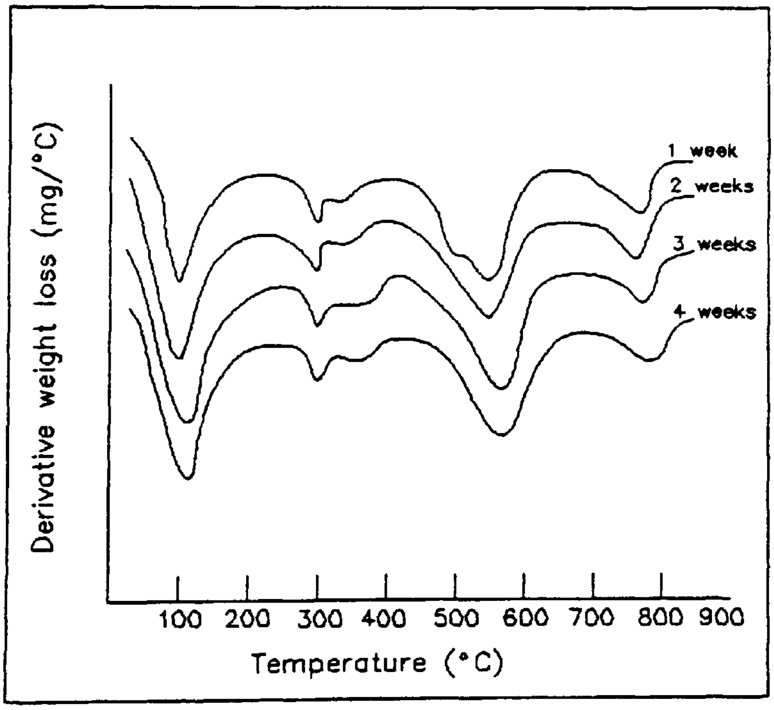


Figure 6.38 Derivative thermogravimetry of murram—15wt% lime —4.5wt% gypsum cured at 30 °C for various curing periods.

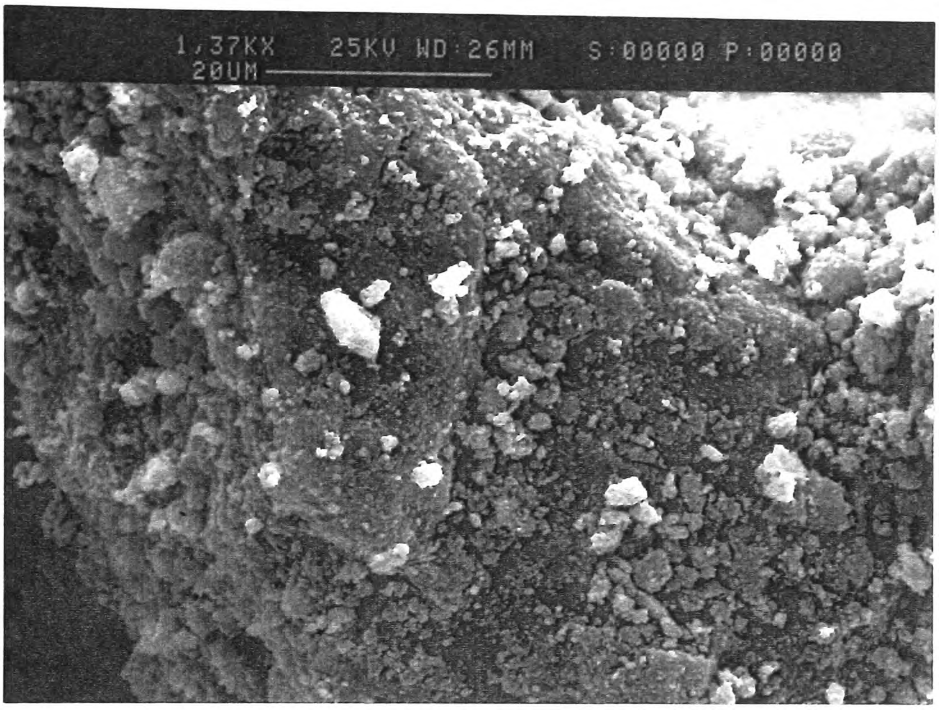


Plate 6.1 Scanning electron micrograph of murram soil.

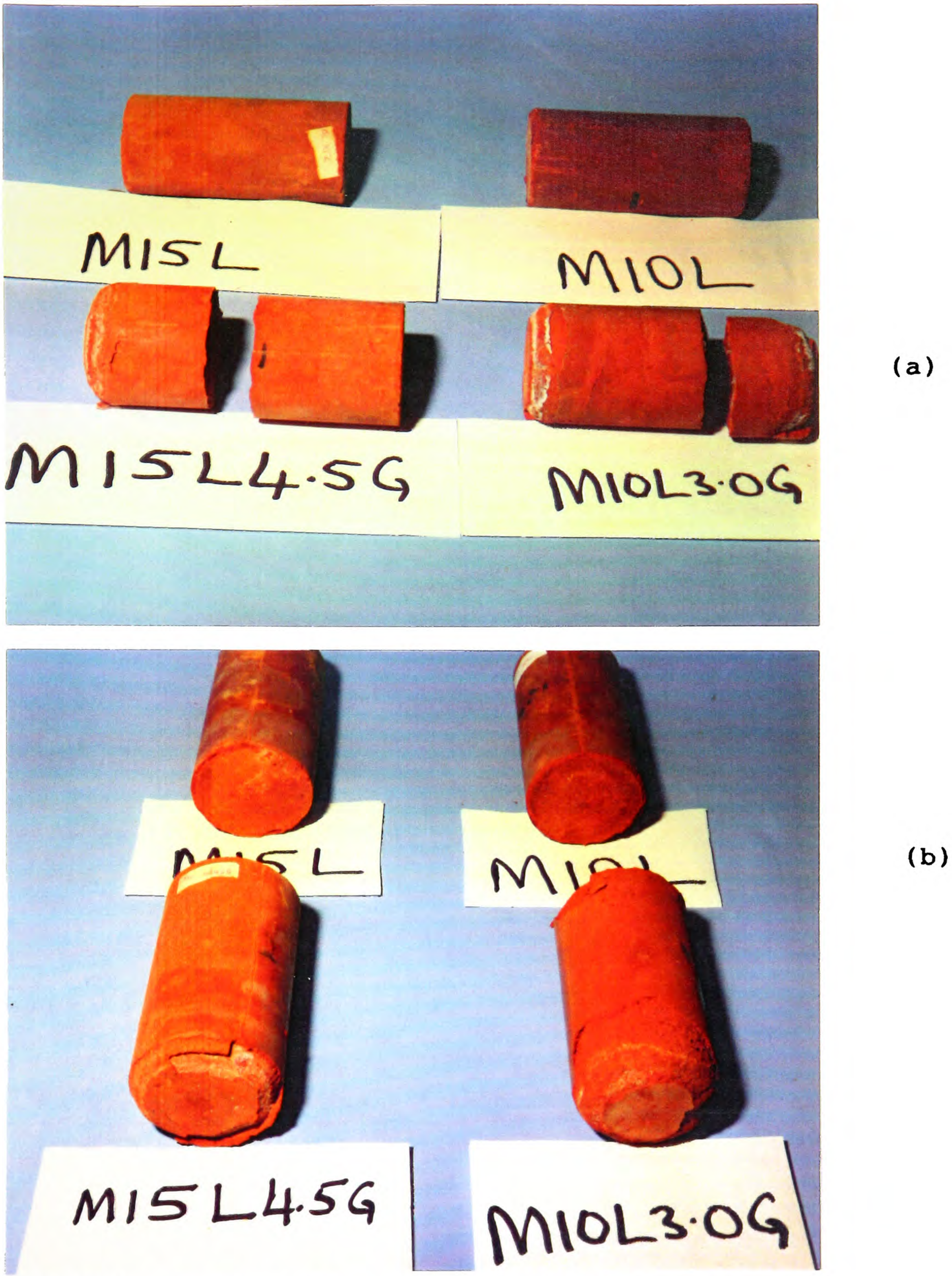


Plate 6.2 Murram-lime and murram-lime-gypsum samples subjected to 14 cycles of (a) full and (b) partial wetting and drying.

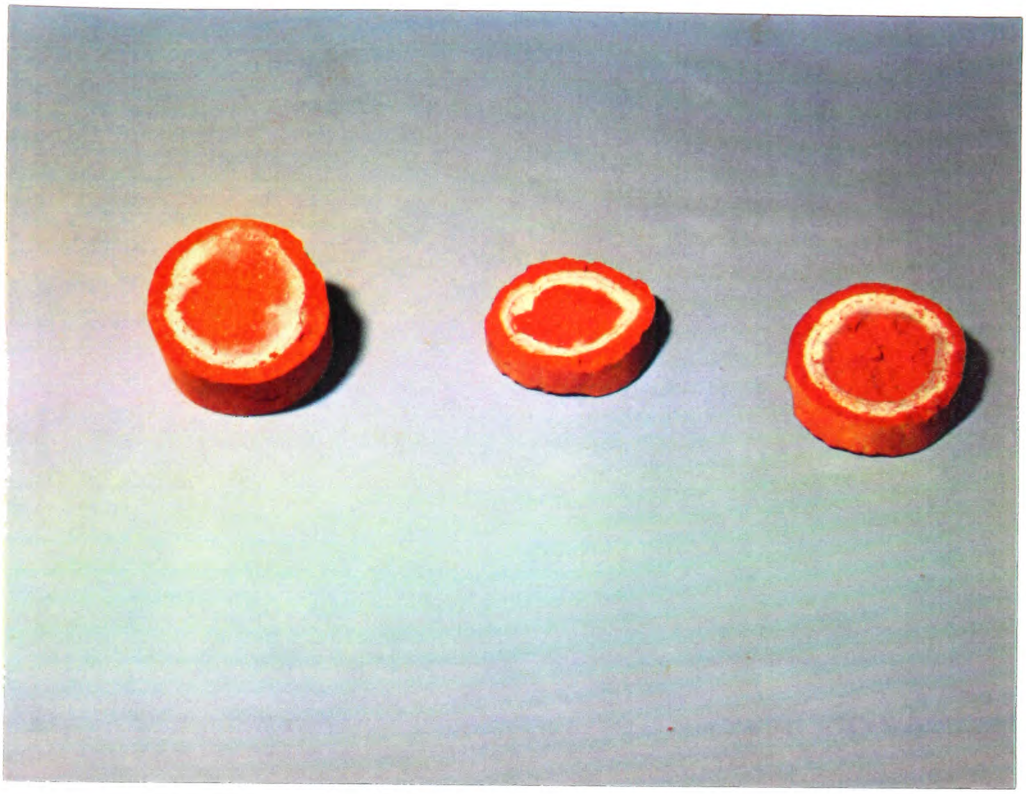


Plate 6.3 White annulus formed in murram-lime-gypsum samples after several wet-dry cycles.

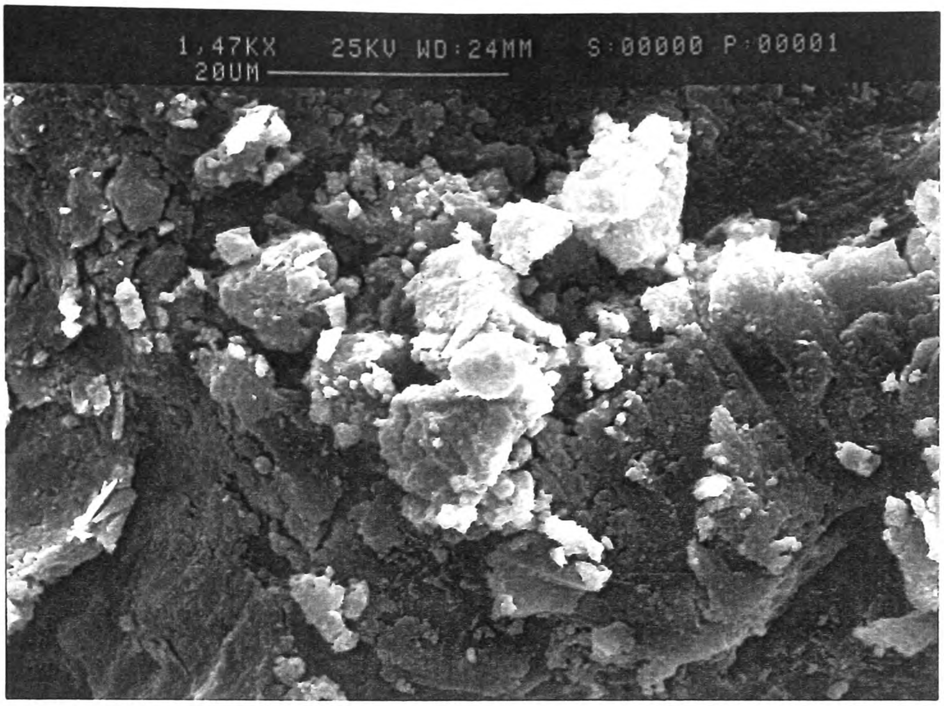


Plate 6.4 Scanning electron micrograph of murram-15wt% lime cured for 4 weeks at 30°C.

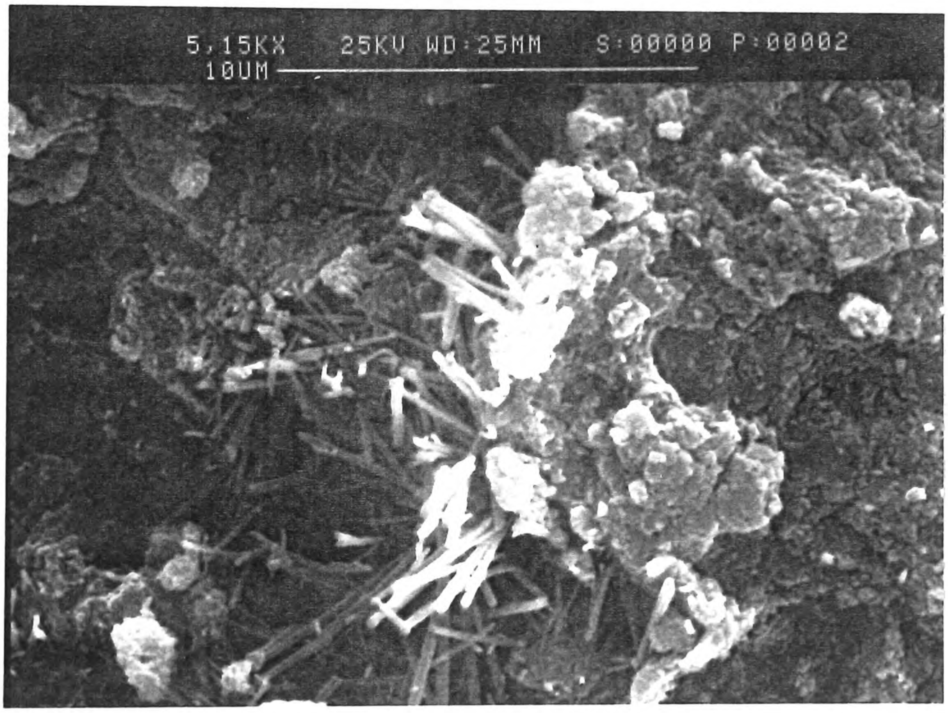


Plate 6.5 Scanning electron micrograph of murram-15wt% lime-4.5wt% gypsum cured for 4 weeks at 30°C.

CHAPTER 7

DISCUSSION

7.1 Introduction

Many of the problems associated with inadequate housing in Kenya could be largely overcome by the use of cheap and readily available building materials such as soil and by applying simple technologies. Although soil as a building material is unpopular because of its low strength and poor durability, this problem can be overcome by mixing the soil with a binding agent or stabiliser and then compacting the mix. It has been found (9) that blocks made out of this soil-stabiliser mix could be more than 50% cheaper than the concrete variety. The blocks can be made solid and smooth using block making machines such as the Brepak. With this kind of building material good housing can be achieved even by the low income groups and the medical hazards resulting from poor living conditions could be overcome.

Currently soil is being used in many parts of the country as a building material in different types of construction: wattle and daub (where a vertical weaving of wooden poles, branches, twigs and reeds is 'chinked' with mud); rammed earth (where moist soil is forced between heavy wooden shafts to form a wall); layering (which is similar to rammed earth except that no shafts are employed); adobe block construction (where mud blocks, formed in a moulding process in which wet mud is placed into a mould by hand and allowed to dry in the sun, are used to build walls). These methods produce good durable structures in dry climates, but in wet weather conditions they lose their stability and erode. Constant maintenance is required to combat linear shrinkage cracks which form an ideal breeding ground for vector-borne diseases.

Stabilised soil blocks, where good choice of soil and stabiliser have been made, can serve as good building materials which are comparable with other building materials such as concrete. Good choice of soil can only be made after studying its nature. This helps in predicting its behaviour when stabilised and hence its performance when used as a building material. In the current study murram soil which was obtained from Kenya was analysed both physically and chemically and its stabilised state assessed. This was important in choosing the kind of stabiliser that would turn the soil into a good building material when subjected to some compacting pressure.

7.2 Lime stabilised murram

The word murram is used widely in Kenya to refer to laterite soil with a large proportion of iron stones. This murram has been utilised extensively in road base construction but not much in building construction. Depending on locality the murram soil contains varying proportions of clay. The murram soil studied in the current work was obtained from Mataara road alignment in the Kiambu district of Kenya. The different samples collected along the road, as representative of murram were mixed together, dried and crushed.

The mixed and crushed soil was found to contain about 65% clay. Webb (9) worked with murram soil from Kawangware near Nairobi which contained only about 15% clay. This clearly shows that the clay content in the murram depends on locality. With this high proportion of clay (65%) the appropriate stabiliser is lime. Also the linear shrinkage of 10% indicated that the soil could be stabilised effectively with lime.

The plasticity of the soil was reduced when lime was added. This confirms what other workers (33, 34, 35, 36, 37, 38) have found. This reduced plasticity makes the soil friable and easy to work with.

Addition of lime also resulted in decreased dry density and increased optimum moisture content especially when the murram-lime mixes were subjected to heavy compaction. This decrease in dry density may be attributed to aggregation/flocculation of the soil particles which occupy a greater volume, and hence alter the effective grading of the soil. Also the specific gravity of lime (2.23) is lower than the specific gravity of the murram soil (2.83) which contributes to a further reduction in density. The increase in moisture content may be attributed to the increase in the fines content as a result of lime addition which increases the affinity of the mix for water.

When lime reacts with murram the principal reaction products are calcium silicate hydrate represented as C_2ASH_8 and carbonate substituted calcium aluminate hydrate represented as C_4AH_{13}. The development of these cementitious products results in an increase in strength of the stabilised murram. When small amounts of gypsum are added the formation of these products are however suppressed due to depletion of the available alumina by the formation of ettringite. The development and growth of the ettringite rods to form an interlocking network produces an enhancement in strength. This enhancement in strength does not however improve the durability of the stabilised soil. When the stabilised murram-lime-gypsum material is exposed to alternate wet and dry conditions it starts to disintegrate. This is attributed to the fact that under alternating wet and dry conditions these specimens show greater dimensional instability than those in which gypsum has not been added. The fluctuating dimensional changes weaken the internal bonding between particles and result in a sharp decline in strength. This loss in integrity of the material is enhanced by surface carbonation and decomposition of the ettringite. Nishikawa et al (70) have suggested a mechanism by which this occurs. In contact with water, which contains carbonated ions and shows a low pH, ettringite and the liquid phase will not be in equilibrium. Calcium and sulphate ions will therefore immediately dissolve in the liquid from the surface of the ettringite. The loss of calcium and sulphate leaves the ettringite crystals coated with alumina gel although their size and morphology do not change compared with the the original ettringite. The carbonation proceeds by a diffusion controlled step through this layer. In the current work it is suggested that the dissolved ions released into the liquid are consumed to form well-crystallised calcium carbonate and an amorphous sulphate containing product (white deposit).

7.3 Economic consideration

Achieving the right quantity and type of stabiliser for a suitable soil which gives the required strength and durability is not the sole consideration in soil construction. Some other factors such as availability and cost have to be considered. Economic consideration in any industry is very important as it renders the industtry competitive and viable and also enables the user of the product to choose from the available alternatives which will satisfy his/her need.

The current study was aimed at turning murram soil into an effective building material by using a suitable stabiliser. This objective has been achieved. The problem that remains is how to encourage the people to use this product. Note that this is a product which will mainly serve the majority of the Kenyan population living in rural areas with limited income of about 3000 Kenyan shillings (50 pounds) per month. The building material that will therefore be most accepted is that which is affordable by the majority. This section evaluates the economic viability of the materials studied in current work as building materials. The materials considered are

A. murram-15wt% lime

B. murram-10wt% lime-3.0wt% gypsum

C. 70wt% murram-30wt% sand-10wt% lime

D. 70wt% murram-30wt% sand-10wt% lime-3.0wt% gypsum

E. murram-10wt% cement.

Although these alternatives chosen did not all meet all of the Kenyan standard requirements, they had recommendable properties and depending on where they are used they can be utilised as building materials. Alternative A meets the wet strength requirement although it does not meet the requirement relating wet strength to dry strength. The material however showed good resistance to durability tests. Alternatives B, C, D and E meet the Kenyan standard requirement for wet strength and that relating dry strength to wet strength. Alternatives B, C and D were still complete after 7 cycles of wetting and drying although the strength for B and D had deteriorated. Alternative E disintegrated when soaked in water. Alternatives C and D have low water absorption and low linear expansion.

In this evaluation it is assumed labour, equipment and water are constant variables. Consider a typical house of $50M^2$ plan. This will require approximately 3000 stabilised blocks for the walls. Consider that each block has dimensions 290 X 140 X 100 mm.

Sample calculation

Consider alternative

A. Murram-15wt% lime

Using lime alone as a stabiliser the soil could effectively be stabilised with 15wt% lime.

Material needed for one block

volume = $0.29 \times 0.14 \times 0.1\ M^3$

$= 4.06 \times 10^{-3}\ M^3$

bulky density = $1.896 Mg/M^3$

therefore total weight = $4.06 \times 10^{-3} \times 1.896 \times 10^{+3}$ kg

= 7.7 kg

= soil + 15wt% lime + 32wt% water

= soil + 15% soil + 32% (soil + 15% soil)

(note that the water is expressed as a percentage of soil plus lime)

therefore

Soil = $7.7/\{1 + 0.15 + 0.32(1 + 0.15)\}$

= 5.075kg

Lime = $0.15 \times 5.075 = 0.695$kg

Water = $0.32 \times (5.075 + 0.695) = 1.870$kg

Material required to make 3000 blocks

soil = 15225kg

lime = 2085kg

water = 5616kg

The table below shows the amount of materials needed in each alternative to make 3000 blocks for a typical house. The current prices of the following materials were obtained, through private communication, from Housing Research and Development Unit (HRDU), University of Nairobi.

Soil - Kshs. 112.5/M^3

Sand - Kshs. 600/M^3

Cement - Kshs. 185/50kg

Lime - Kshs. 150/25kg

Gypsum - not given*

Comparable costs of using each alternative are also shown in the table below.

Alternative	A	B	C	D	E
Materials					
Bulky density (kg/m^3)	1896	1920	1996	1996	1948
Murram (kg)	15225	15690	12270	11940	16920
Sand (kg)	-	-	5250	5130	-
Lime (kg)	2085	1569	1740	1710	-
Gypsum (kg)	-	471	-	513	-
Cement (kg)	-	-	-	-	1692
Water (kg)	5615	5670	5010	5100	5460
Cost (Kshs.)	13684	10623 + *	12945	12704 + *	7564

Although lime, in the current work is the most effective stabiliser, from an economic point of view it is expensive compared to cement. Lime stabilised material proved to be more resistant to weathering tests. For example while the cement stabilised material disintegrated when soaked in water, the lime stabilised one could stand the alternate wet-dry test for at least 7 cycles. Thus, where durability of the material is of importance, cement stabilisation of the soil studied in the current work is not recommended. Considering also the gypsum addition material, because of the dimensional instability in alternating wet and dry conditions, the addition of gypsum is not recommended in the production of lime stabilised murram building products. However, depending on the clay content of the murram the addition of sand is recommended as this improves dimensional stability and if added in the appropriate quantity also enhances strength and abrasion resistance. However it is important to carry out a number of initial trial tests to ensure that both lime and sand are added in the optimum amounts required to maximise strength and durability.

7.4 Energy considerations

When considering ~~what kind~~ the type of stabiliser to use in soil stabilisation a number of factors are likely to influence the decision. The factors considered so far include performance, availability, suitability and cost. One other factor which needs consideration in the current climate is the amount of energy which is consumed in the production of the stabilisers, as the amount of energy required is not always fully reflected in the cost of the final product. Efficient use of energy is becoming increasingly important with concerns about depletion of energy reserves and global warming. The energy consumption in the production of stabilisers such as Portland cement and lime which are in common use need to be considered. In the current section, energy consumption in the production of lime is considered. Lime is produced by the dissociation of limestone or calcium carbonate which is an endothermic reaction and by the hydration of the resultant quicklime which is an exothermic reaction. The energy changes involved in these reactions are calculated as follows:-

Heat of dissociation of calcium carbonate ($CaCO_3$)

$$\overset{\Delta H1}{CaCO_3} \longrightarrow \overset{\Delta H2}{CaO} + \overset{\Delta H3}{CO_2}$$

$\Delta H1$ $\quad Ca + C + 1.5O_2 \longrightarrow CaCO_3 \quad$ -1207 kJ/mole

$\Delta H2$ $\quad Ca + O \longrightarrow CaO \quad$ -635.5kJ/mole

$\Delta H3$ $\quad C + O_2 \longrightarrow CO_2 \quad$ -393.5kJ/mole

$$\Delta H = (\Delta H3 + \Delta H2) - H1$$

$$= (-393.5 + -635.5) - (-1207)$$

$$= +\ 178 kJ/mole$$ (+ve means heat is absorbed)

1 mole $CaCO_3$ = 40 + 12 + 48 = 100g

178kJ of heat are needed to dissociate 100g of $CaCO_3$

therfore heat absorbed = (178/100) kJ/g = 178 X 10^6 kJ/ton

= 1780MJ/ton

However 100g of calcium carbonate only produces 74g $Ca(OH)_2$

Therefore the figure has to be multiplied by 100/74

= 1780 X 100/74 = 2405MJ/ton of $Ca(OH)_2$

Also the thermal dissociation of $CaCO_3$ requires the material to first be heated from room temperature (20°C) to 1000°C. Thus if the heat capacity of limestone is L_H J/kg/°C, then the heat required is

$980 \text{ X } L_H$ J/kg $= 980 \text{ X } 10^{-6} \text{ X } L_H$ MJ/tonne

$L_H = 800$ J/kg/°C

Therefore the heat required

$= 980 \text{ X } 800 \text{ X } 10^{-3} = (784/0.74)$ MJ/tonne

at 1200°C this is $1.2 \text{ X } 784 = (941/0.74)$ MJ/tonne

This added to the previous heat requirement is

$2405 + 1059 = 3464$ MJ/tonne at 1000°C

and $2405 + 1271 = 3676$ MJ/tonne at 1200°C.

Note that a lime kiln may operate at between 1000 and 1200°C

Heat of hydration of lime

$\Delta H1 \quad \Delta H2 \qquad \Delta H3$

$CaO + H_2O \longrightarrow Ca(OH)_2$

$\Delta H1 \quad Ca + O \longrightarrow CaO \quad -635.5$ kJ/mole

$\Delta H2 \quad H_2 + O \longrightarrow H_2O \quad -285.8$ kJ/mole

$\Delta H3 \quad Ca + O_2 + H_2 \longrightarrow Ca(OH)_2 \quad -986.6$ kJ/mole

$\Delta H = \Delta H3 - (\Delta H1 + \Delta H2)$

$= -986.6 - (-635.5 + -285.8)$

$= -65.3$ kJ/mole (-ve means heat is evolved)

1 mole of $Ca(OH)_2 = 40 + 34 = 74$g $Ca(OH)_2$

-65.3 kJ of heat are released in forming 74g of $Ca(OH)_2$

heat released $= 65.3/100$ kJ/g $= (65.3 \text{ X } 10^6)/74$ kJ/ton

$= 0.882 \text{ X } 10^6$ kJ/tonne = 882MJ/tonne

This heat output is not insignificant as it is equivalent to approximately 25% of the heat input required to produce the quicklime. This energy generated on hydration of the quicklime which is exothermic could be utilised in heating the raw limestone feed before it is fed into the kiln. This would then compensate for the energy advantage in cement production where the exothermic reaction of the lime with the alumino-silicates reduces the overal energy consumption of the process (71).

7.5 Conclusions

The current work has demonstrated that murram with a high proportion of clay can effectively be stabilised with lime and be made into building blocks which meet the Kenyan standard requirements. Additions of small amounts of gypsum greatly increases the strength of lime stabilised murram and also reduces the amount of lime needed for stabilisation. Although this addition of gypsum impairs the durability of the lime stabilised soil in wet climates, it could possibly be utilised in damp proof areas in a house. However because of the potential problems which could arise, the use of gypsum in lime-stabilisation is not recommended and soils containing significant amounts of sulphate should be rejected for stabilisation purposes. In the case of lime-stabilised blockworks which shows a good resistance to alternate wetting and drying (e.g. 70wt% murram-30wt% sand-10wt% lime material) it is probably desirable to construct the base of the wall with concrete or stone up to a height of at least 250mm (23, 72) before laying the lowest course of the soil blockwork.

At present the cost of lime-stabilised blocks would be significantly more expensive than cement-stabilised blocks. There are a number of reasons why cement is currently less expensive to purchase than lime. Cement production has developed into a large scale, technologically advanced highly efficient process. The worldwide demand for the product means that it is a high volume product which has the advantage of economy of scale. However there is nothing in the production requirements of lime which make it an inherently more expensive process than cement production given the same conditions. Also lime can be produced locally using simple technologies and as long as its quality is controlled it may turn out in relation to future trends to be a cheaper material compared to cement whose production is quite sophisticated. As cement is produced in centralised large-scale production plants, its cost will increase due to transport requirements. This factor becomes more significant if the cement is transported hundreds of kilometres from the manufacturing site.

*

In conclusion soil stabili~~s~~zation requires a study of the nature of soils which helps in choosing a suitable soil for stabilisation. Good soil is that which contains a range of particles i.e. sand, silt and clay, is low in organic matter content and does not contain sulphates. After a suitable soil has been found, the next step is choosing a stabiliser. The choice of soil stabiliser will depend on the type of soil, availability and cost. The users need to have some knowledge of the basic chemistry of the stabiliser in order to handle it correctly and avoid any health hazards and also to understand the reactions which occur when the materials are processed for quality control purposes.

7.6 Recommendations for future work

The aim of this project was to turn murram soil into a building material that would perform well in the Kenyan environment and which is economically viable. These objectives have been achieved. However, in the course of doing this work, several questions have arisen which could form a basis for future work

1. It was found that diluting murram with sand and then stabilising it with lime and lime-gypsum improved greatly its performance. For each soil the optimum sand content needs to be determined to ensure the most effective use of lime.
2. The work carried out was mainly to evaluate the potential of murram as a walling material. More work needs to be done to evaluate its performance and viability as a roofing or a rendering material.
3. Probably the most critical property for these materials is their durability. Much better durability tests need to be

developed, possibly based on the prototype developed in this study, that can reliably predict the long term performance of these materials. Such testing should be carried out along with actual testing in the true environment to compare relative performance and assess the validity of the laboratory tests. The durability assessment ought to be done on a prototype building exposed to actual weathering conditions. This will help in judging how long the actual building constructed would continue to perform effectively.

REFERENCES

1. Republic of Kenya, "Statistical Abstract, Central Bureau of Statistics", Ministry of Planning and Development, Kenya, 1990.

2. National Council for Population and Development, "Demorgraphic and Health Survey", Ministry of Home Affairs and National Heritage, Inc. Nairobi, Kenya, 1989.

3. R.J.S Spence and D.J Cook, "Building Materials in Developing countries", John Wiley and Sons Ltd, 1983.

4. C. Buckle, "Landforms in Africa, An introduction to Geomophology", Longman, 1978.

5. Republic of Kenya. "Development Plan 1989-93", Government printers, Nairobi, Kenya, 1989.

6. E.S Munoko, "Project proposal on potential of Murram as a traditional building material in Bungoma District", Private communication, Civil Engineering Department, University of Nairobi, Kenya, 1990.

7. Republic of Kenya, "Housing Strategy for Kenya 1987-2000", Report of the steering committee, Housing Department, Ministry of Works, Housing and Physical Planning, 1987.

8. D.J.T Webb and A.J Lockwood, "BREPAK Operators Manual", Building Research Establishment Client Report, BRE, Garston, Watford, U.K, 1987.

9. D.J.T Webb, "Stabilised soil building blocks", PhD Thesis, University of Newcastle Upon-Tyne, 1988.

10. S, Denyer, "African Traditional Architecture", Heinemann Educational Books Ltd, 1978.

11. E.F.A Adam, "Stabilised soil blocks for low cost housing in the Sudan", MPhil Thesis, Hatfield Polytechnic, 1982.

12. R.F Carrol, "Disease reduction by improved house construction", Overseas Building Note 194, Building Research Establishment, Garston Herts, U.K, 1990.

13. W.H Dennen and B.R Moore, "Geology and Engineering," W.C Brown Publishers, 1986.

14. J.K Zumberge and C.A Nelson, "Elements of Geology", John Wiley and Sons. 1972.

15. P.W Bikeland, "Pedology, weathering and geomorphological research", Oxford University Press, 1974.

16. Z. Wilum and K. Starzewsski, "Soil mechanics in foundation engineering. Properties and site investigation", Vol.1, Surrey University Press, 1975.

17. S.A Ola, "The potentials of lime stabilisation of lateritic soils", Engineering Geology, Vol.11, 1977, pp 305-317.

18. C.A O'Flaherty, "Highway engineering", Vol.2, Edward Arnold (Publishers) Ltd, 1974.

19. F.G Bell, "Engineering properties of soil and rocks", Butterworths, 1981.

20. M. Arabi, "Fabric and strength of clays stabilised with lime", PhD Thesis, Polytechnic of Wales, 1987.

21. O.G Ingles and J.B Metcalf, "Soil stabilisation", Butterworths, 1972.

22. N.M Al-Rawi and A.A.A Awad, "Permeability of lime stabilised soils", Proc. ASCE, Transportation Engineering Journal, Vol. 107 n.1, 1981, pp 25-35.

23. M.G Lunt, "Stabilised soil blocks for building", Overseas Building Note No. 184, BRE, U.K, 1980.

24. Overseas Information Paper 2, "Choosing soil for blockmaking", Practical construction advice for developing countries, BRE, U.K, 1990.

25. J.E.O Okwero, "Kenya specification for stabilised soil blocks", Kenya Bureau of Standards, Nairobi, Kenya, 1989.

26. J.R Coad, "Lime stabilised soil building blocks", Building Research and Practice, BRE, U.K, 1979.

27. G.E Bessey, "Production and use of lime in developing countries", Overseas Building Note No.161, BRE, U.K, 1975.

28. H.N Atkins, "Highway materials, Soils and Concrete", Reston Pub. Co., Virginia, 1980.

29. A. Kedzi, "Stabilised Earth Roads", First edition, Elsevier Science Publication Co., 1979.

30. Habitat, "The use of selected indigenous building materials with potential for wide application in developing countries", United Nations Centre for Human Settlements (UNHS), Nairobi, Kenya, 1985.

31. Shelter-Afrique, "Study of building materials in Africa: Kenya", Shelter Afrique Publications, Nairobi, Kenya, 1989.

32. R. Tuts, "Potentialities and Constraints for using pozzolans as alternative binders in Kenya", Paper presented at the 1st International seminar on lime and other

alternative cements, Stoneleigh, Warwickshire, U.K., 9-11 Dec., 1991.

33. S. Diamond and E.B Kinter, "Mechanics of soil-lime stabilisation", Highway Research Record No. 92, 44th annual meeting, Jan., 1964, pp 83-94.

34. J.B Croft, "The process involved in the lime-stabilisation of clay soils", Proceedings second conference, Highway and Traffic Research Institute, University of New South Wales, Vol.2, part 2, 1964, pp 1169-1200.

35. F.G Bell, "Stabilisation and treatment of clay soils with lime", Ground Engineering, Jan., 1988, pp 10-15.

36. S. Diamond and E.B Kinter, "Mechanism of soil-lime stabilisation", Highway Research Record, Public Roads, Vol.33, No.12, 1966, pp 206-273.

37. State of the Art, "Lime stabilisation, reactions, properties, design, construction", Transportation Research Circular, No.180, Sept., 1976.

38. F.G Bell and J.M Coulthard, "Stabilisation of clay soils with lime", Mun. Engr. Vol.7, Jun. 1990, pp 125-140.

39. R.E Grim, "Clay mineralogy", 2nd edition, McGraw Hill Book Co., New York, 1968.

40. G.H Hilt and D.T Davidson, "Lime fixation in clay soils", Highway Research Record, 1960, pp 20-32.

41. M. Arabi and S. Wild, "Property changes induced in clay soils when using lime stabilisation", Mun. Engr. Vol.6, April 1989, pp 85-99.

42. S. Wild, M. Arabi and G. Leng-Ward, "Soil-lime reaction and microstructural development at elevated temperatures", The Mineralogical Society, Vol.21, 1986, pp 279-292.

43. S. Wild, M. Arabi and G. Leng-Ward, "Fabric development in lime treated clay soils", Ground Engineering, Vol.22, No.3, 1989, pp 35-37.

44. M. Arabi and S. Wild, "Microstructural development in cured soil-lime composites", Journal of Materials Science, Vol.21, 1986, pp 497-503.

45. H.J Kuzel, "Crystallographic data and thermal decomposition of synthetic gehlenite hydrate, $2CaO.Al_2O_3.SiO_2.8H_2O$", N. Jb. Miner. Mh., 1976, pp 319-325.

46. K.E Clare and A.E Cruchley, "Laboratory experiments in the stabilisation of clays with hydrated lime", Geotechnique, Vol.7, 1957, pp 97-111.

47. B.K Akoth and G. Singh, "Some geotechnical properties of a lime-stabilised laterite containing a high proportion of aluminium oxide", Ground Engineering, Jan. 1988, pp 10-15.

48. M. Maeteous, "Soil-lime research at Iowa State University", Journal of Soil mechanics and Foundation Division, SM2, 1964, pp 127-153.

49. M.J Dumbleton, "Investigation to assess the potentialities of lime for stabilisation in the United Kingdom", Road Research Technical Paper No.64, London, 1962, pp 1-75.

50. J.K Mitchel and D.R Hooper, "Influence of time between mixing and compaction on the properties of lime-stabilised

expansive clay", Highway Research Board Bull. 304, Washington, DC, 1961, pp 14-31.

51. S. Wild, M. Arabi and G.O Rowlands, "Relation between pore size distribution, permeability and cementitious gel formation in cured clay-lime systems", Materials Science and Technology, Institute of Metals, Vol.3, 1987, pp 1005-1011.

52. J.J Allen, D.D Currin and D.N Little, "Mix design, durability and strength requirement for lime-stabilised layer in air field pavements", Transportation Research Record, No.641, 1977, pp 34-41.

53. M.R Thompson, "Lime reactivity of Illinois soils", Journal of Soil mechanics and Foundation Division, Proc. ASCE, SM5, Vol.92, Sept. 1966, pp 67-92.

54. P.T Sherwood, "Effects of sulphates on cement and lime-stabilised soils", Highway Research Board Bull. 353, 1962, pp 98-107.

55. M.R Abdi, "Effects of gypsum on lime-stabilised kaolinite", PhD Thesis, Polytechnic of Wales, 1992.

56. P.K Mehta and S. Wang "Expansion of ettringite by water adsorption", Cement and concrete Research, 12, 1982, pp 121-122.

57. J.K Mitchel and D. Dermatos, "Clay-soil heave caused by lime-sulphate reactions", ASTM symposium on Innovations and Uses of lime, San-Francisco, June 1990.

58. P.K Mehta and A. Kevin, "Investigation on the hydration products in the system Ca.$3Al_2O_3.SO_3-CaSO_4-CaO-H_2O$", Highway Research Board, special report No.90, pp 328-352, 1966.

59. Overseas Building Note No.145, "Durability of materials for Tropical Buildings", BRE, Garston, U.K, 1972.

60. R.H Ottewill, "Chemistry of colloidal silicates and cements", Phil. Trans. Roy. Soc. Lond. A310, 1983, pp 67-78.

61. K.H Head, "Manual of Soil Laboratory Testing, Soil classification and Compaction Tests", Vol.1, Pentech Press Limited, 1980.

62. T.H.Y Tebbut, "Principles of Water Quality Control", 3rd edition, Pergamon Press, 1982.

63. R.W Grimshaw, "The Chemistry and Physics of Clays and other Ceramic Materials", Ernest Benn Ltd, 4th edition, 1971.

64. A. Blazek, "Thermal Analysis", Van Nostand Reinhold series in Analytical Chemistry, 1973.

65. O.H Ingles, "Soil stabilisation", Ground Engineer's Reference Book, Ed by F.G Bell, Butterworths, London, 1987.

66. C.M George, "The hydration kinetics of refractory aluminous cements and their influence on concrete properties", Transport Journal, British Ceramic Society, 79, pp 82-90, 1980.

67. M.G Lunt, "Lime stabilised soil blocks for low-cost housing in developing countries", Note No.N15/79, BRE, UK, 1979.

68. P.S de Silva and F.P Glasser, "Hydration of cement based on metakaolin : thermochemistry", Advances in Cement Research, Vol.3, No.12, pp.167-177, 1990.

69. M. Hadi, "Factors influencing strength development in pfa-lime systems," PhD Thesis, Polytechnic of Wales, Pontypridd, UK, April 1990.

70. T. Nishikawa, K. Suzuki and S. Ito, "Decomposition of synthesized ettringite by carbonation", Cement and Concrete Research, Vol.22, pp.6-14, 1992.

71. Basin-News, "Portland cement or alternative cement : a question of energy", Building Advisory Service and Information Network, Issue No.3, pp.15-20, Jan. 1992.

72. Habitat, "Earth construction technology; Manual on Design and Construction Techniques", UNCHS, Nairobi, 1986.

British Standards

BS 1377:1990 "Methods of test for soils for civil engineering purposes".

BS 1924:1975 "Methods of test for stabilised soils".

BS 1881:1970:Part 4 "Methods of testing strength of concrete".