EFFECTIVE USE OF INDEGINOUS TECHNOLOGY

WITH PARTICULAR REFERENCE TO EARTH STABIISED MATERIAL FOR RURAL HOUSING IN SINDH

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Abstract

Earth was one of earliest materials used for construction of human shelters. In its raw state, it does not meet the basic physical properties required of a material for use in construction, i.e. compressive strength and durability (water resistance). The raw material can be stabilised to improve these properties through chemical, physical and mechanical methods. Chemical and physical methods involve mixing and compacting the earth with various materials to increase its compressive strength and reduce its propensity to shrink and swell. Mechanical methods of stabilisation involve only compaction of the raw material to produce blocks.

Stabilised blocks have adequate compressive strength and durability for use in low-income housing. They are also easy to handle, can be moulded to a variety of shapes and are suitable for use as structural blocks. The latest developments in the design of moulding machines means that stabilised blocks can be produced on-site at approximately half the cost of the next cheapest construction material (hollow concrete block).

The most important consideration in the stabilisation process is the choice of material for mixing. The choice is based on three criteria: (i) composition of the earth, (ii) local availability of the stabilising material and (iii) cost of the stabilising material. For example, in terms of composition, earth with a high clay content, such as the samples used in this study from Sindh Province, Pakistan, was found unsuitable for construction purposes. This is because the clay minerals cause excessive shrinkage and expansion of the material. However, work conducted in this study found that the effects of clay can be mitigated by correcting particle size distribution and stabilisation.

Specimens of stabilised material were produced to measure the affects of mixing various additives, including cement, lime, linseed oil, and calcium chloride, with earth. The key findings from research carried out on these specimens are:

(a) Cement can not be used without correction of particle size distribution.

(b) Previous research work has found lime to be the most effective stabiliser in terms of improving compressive strength. However, it was found that, in the case of the high clay content earth used in this study, cement provided better results.

(c) In earth stabilised through correction of particle size distribution, linseed oil provided the most improvement to water resistance.

(d) Calcium Chloride is not suitable for use as a stabiliser with earth containing a high proportion of clay minerals. This is because it reacts with the clay minerals to produce water.

(e) A comparative study of the cost and engineering benefits of various stabilised specimens showed that cement provides the greatest improvement to durability, but at the highest cost. Lime was found to be the best stabilising material for high clay content earth in terms of overall cost and engineering benefit. It provides adequate improvement to durability at low cost. Linseed oil was the cheapest stabilising material but, although greatly improving water resistance, it provided little improvement to compressive strength.

Dedicated to

Najeebullah,
Yassir and Mansoor,
Who will always be in my thoughts.....

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Rubina Shaikh
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Introduction to the Study

Earth is the most widely used construction material globally. In Sindh, it has been used in the construction of over 70 % of dwellings. This study investigates the effective use of indigenous technology on earth as a building material. Many techniques have been developed through the ages, and around the world, to utilise earth as a construction material. However, earth is still relevant in the field of construction technology and new techniques for application continue to be developed.

Earth, when used as a construction material, provides inadequate protection against running water, resulting in structural damage to the building. Most earth-based constructions require regular repair, and occasionally reconstruction, after heavy rainfall.

Earth is characterised by four components: clay, silt, sand, and gravel. Clay minerals in earth play a key role in determining the engineering properties of the material. If the clay content is too low, then coarser components in the earth are not bound together adequately for use as a construction material. A lack of clay also creates instability by facilitating the migration of water inside the brick/block. However, if the clay content is too high, then the earth is sensitive to the presence of water and subject to excessive shrinkage and expansion.

For this investigation, earth samples were taken from dwellings in Sindh Province, Pakistan. These dwellings had suffered from structural damage due to water deterioration. The sampled material was analysed and evaluated to determine its suitability for stabilisation with various additives. Analytical test results showed the earth samples to have high clay content. A hypothesis was formulated that addition of stabilising material would improve the construction properties of the earth samples. Therefore, in order to counter the engineering problems associated with this clay, earth stabilisation trials were conducted. Earth stabilisation involves the mixing of additives with raw material and compacting the mix under specific loads. The criteria for choice of additive were made according to the three main parameters: (i) composition of the raw material, (ii) local availability of the stabilising additive and (iii) cost of the stabilising additive. In this study, the earth samples were mixed with various stabilising additives, including cement, lime, linseed oil, and calcium chloride. Individual test specimens were evaluated to for engineering performance.

Research into earth stabilisation is necessary to promote traditional technologies, low energy consumption and harmonisation of new construction with the built environment. It has been found from previous work (1,2) that the production of earth stabilised blocks consumes up to 60% less energy than concrete blocks. The use of earth, a traditional construction material, also facilitates the application of traditional building technologies.

Owing to rapid industrialisation in developing countries, and new innovations in material technology, the substitution of earth by other, more expensive, construction materials is increasing. This trend is occurring despite more than half of the global population living in poverty and without shelter (3). Researchers and intellectuals are involved in studies to solve this escalating problem.

The challenge for today's researcher in construction technology is to bridge the gap between traditional and modern technologies. This study shows that traditional technologies are environmentally friendly, help maintain the identity of a region and bring benefits of low energy consumption. On the other hand, modern technologies, such as steel, glass and concrete constructions, consume more energy and support internationalisation rather than the maintenance of regional identity. In situations where the architect, engineer and planner encounter problems of unaffordable housing, poor infrastructure and unsustainable built environment, an appropriate response is to utilise elements from both traditional and modern technologies. The combined use of both types of technology promotes self-reliance and the preservation of regional identity. This study has been undertaken in the context of delivering effective solutions to construction problems using both traditional and modern technologies.

This thesis contains two sections (see Figure 1):

A. Problem description

B. Problem solution

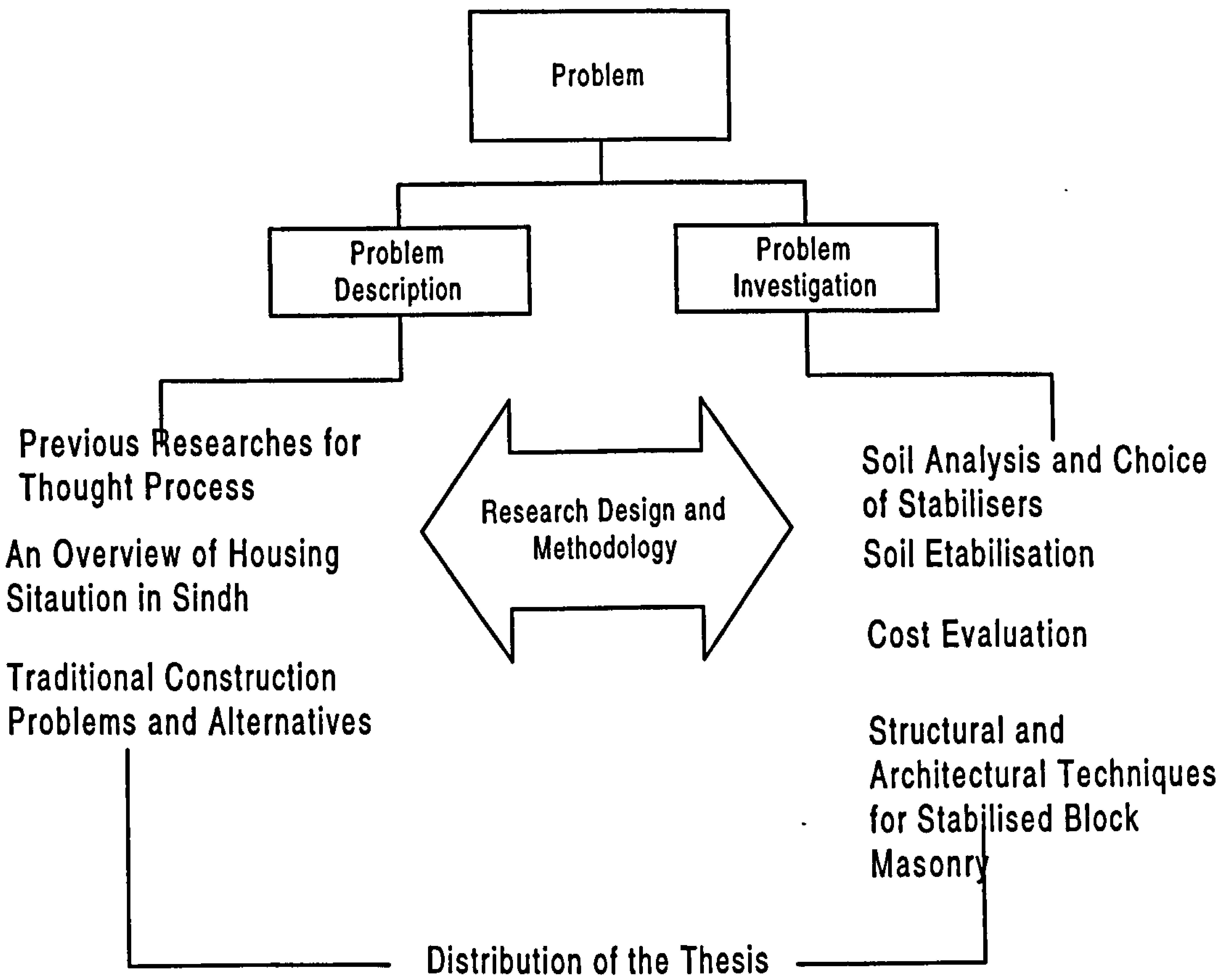


Figure 1. Structure of thesis

A. Problem description

This section comprises an overview of the housing situation in Sindh, together with an investigation of initiatives and research conducted into low-income housing in the province. The review includes a study of existing research into building materials and traditional construction technologies. The properties of earth as a raw material for construction are also examined.

Chapter 1 investigated the existing theories that address the conceptual evolution of appropriate technology. The concept of 'technology blending', i.e. utilising both traditional and modern technologies, for building construction are assessed. This chapter also reviews the projects, which has been successfully constructed with earth stabilised blocks. Finally, the steps necessary to commercialise new, affordable construction materials are recommended.

Chapter 2 contains a profile of a 1989 World Bank survey (4) into the housing situation in Sindh. This survey was conducted to determine the condition of housing throughout Pakistan for implementation of a 'low-income community shelter' project. The types of houses in Sindh, and commonly available construction materials and techniques are identified. The need to identify constraints for the provision of sufficient housing in Sindh in the light of population growth is discussed. The requirement for low cost construction materials and technology is highlighted.

In Chapter 3, The use of traditional and modern construction technologies in Pakistan is studied in order to determine ways in which they might be combined. Technological improvements in construction, as identified by the National Building Research Institute of Pakistan, are also analysed. This analysis provides the basis for the research undertaken in this study on the effective use of traditional technologies. This Chapter also forms the basis for evaluating the results from field work undertaken to determine the cause of damage to three residential units in a compound house in Sindh.

B. Problem investigation

The literature review provides the basis for understanding the strengths and weaknesses of earth as a construction material. Earth is the most commonly used construction material in Sindh because of its widespread availability and low cost. In order to improve the effective use of earth as a construction material, a widely available and low cost solution is required.

Chapter 4 contains the research design and methodology adopted in this study (Figure 2). The key research goal of stabilising earth is placed in context by defining all areas covered by the study. The problem statement has been broken down into sub-problems to facilitate the process of determining solutions. The relationship between two research variables, and their relevance to the study, is identified. On the basis of these variables, a target hypothesis, consisting of four propositions, is put forward.

In order to test the hypothesis, primary data was collected from laboratory tests. These tests, based on British Standards Institute specifications, were carried out in two stages: (i) analysis of earth and (ii) stabilisation of earth with various additives.

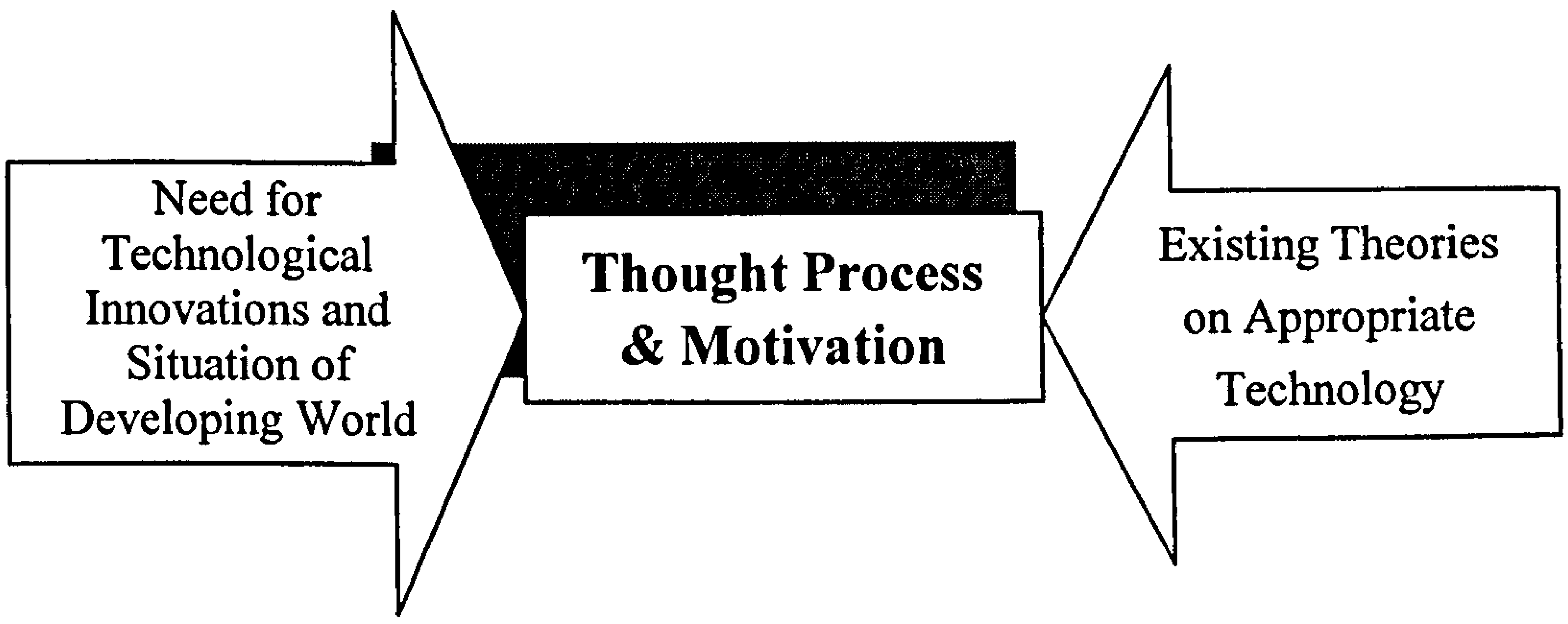
Results of earth analysis are recorded in Chapter 5. They are evaluated in the context of the existing theories and research discussed in this chapter. These results provide the basis for determining the suitability of the earth samples for stabilisation.

In Chapter 6, the stabilisation of earth with various additives, such as cement, lime, linseed oil and calcium chloride, are examined. Compressive strength, water absorption, durability and porosity tests were carried out to evaluate engineering properties of the stabilised specimens. The criteria for the choice and amount of stabiliser used are described. Curing of the test specimens was carried out in a temperature-controlled environment that replicated the climatic conditions of Sindh.

As already noted, the cost of the stabilising material is a critical consideration that can affect the feasibility of a project. In Chapter 7, the cost of producing earth blocks stabilised with the various additives under reviews is calculated. This data is used to determine the material cost requirements for using different types of earth-stabilised to construct a model two bedroom house.

Earth stabilised block are only suitable for use in structural systems where loads are transferred in compression. This is because the blocks have greater compressive strength than tensile strength. In Chapter 8, the various types of structural system compatible with the use of earth stabilised blocks are explored. The ability of blocks to accommodate various structural techniques is discussed, together with their flexibility in terms of shape and form.

Chapter 9 contains the recommendations and conclusions resulting from the research work. The chapter places the significance of the research findings to the field of earth stabilisation into context. The importance of earth stabilisation to the construction industry of developing countries is emphasised.



Chapter One

Previous Research Guiding Author's Thought Process

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1.1 Introduction

In this chapter, regional development is discussed in terms of technologies that are suitable for both the user and the region. Suitability for the user is important when considering regional identity, i.e. architecture and construction techniques, and the available skills base. Suitability in terms of the region is important when considering whether the technology utilises locally available resources. The study presented is based on current theories and concepts for technological development in the developing world.

In many places in the world today, the poor are getting poorer whilst the rich are getting richer (1) and established processes of foreign aid and development planning do little to over come these trends. In many developing countries, there are some industrial sectors that are fully developed and able to compete successfully with those of developed countries. However, these countries are often characterised by a stagnating infrastructure that does not fulfil basic human needs.

Cultural mapping of the world over the last century and a half has ascribed particular meanings to the terms `develop' and `modernise'; they are used to represent the Western influence on national development and urban modernity in developing countries. According to the degree of Western influence, the world has been divided into different groupings: First World, Second World, Third World, East and West*. This charting of the world under a single economic and industrial idea of progress has resulted in the adoption of international technologies and architectural styles. Consequently, the indigenous technologies and regional identities of many developing countries have been eroded.

* The First World comprises developed, industrialised countries; the Second World is a term formerly used to define Eastern block countries behind the Iron Curtain and the Third World constitutes countries previously governed by colonial powers which are now developing and industrialising.

The concepts of 'indigenous' and 'regional identity' provided the initial inspiration behind the thought process of this thesis. The image projected by architecture, as a profession, tends to focus on modern, high cost constructions. The author wished to extend the scope of her professional training and social awareness to address this issue. As such, poor infrastructure for low-income communities in the developing world, particularly in Pakistan, was identified as an issue that has not been adequately addressed by her profession.

Pakistan is one of the most populous countries in developing world, with more than half of the population either homeless or living in very low quality shelter. Since independence, unstable governments and government policies have resulted in a failure to provide or fulfil the basic human requirements of the public. This is especially true in Sindh due to the high rate of immigration into the province since 1947. A further cause of the problem of inadequate shelter has been the lack of innovation in material technology, as described in Chapter 2.

As shelter is a basic human need, the quality, suitability and affordability of dwellings are important criteria to be considered in shelter-related studies. An objective of this study is the promotion of self-sustainable technologies to meet these criteria, with particular reference to shelter in Sindh.

Although earth is one of the oldest and most basic building materials, there has been little research conducted into the effective use of this material for construction purposes. However, initial research findings indicate that the engineering properties of earth are markedly improved by stabilising the material with various additives. Stabilised earth blocks offer a number of advantages over modern construction materials for use in low-income housing and low-rise masonry construction. These advantages include maximising the use of locally available materials, low levels of energy input and relatively simple production processes.

Earth stabilised blocks are used as building materials in India and several other developing countries. The construction of 4000 houses in Haryana State, India was one of the earliest examples of the use of earth stabilised blocks in a developing country. (2) The Haryana project provided the author with the idea of undertaking research into the viability of using earth stabilised blocks in Sindh. Prior research into this subject has provided inconclusive results, whilst the results of this study serve as a platform for further work.

The suitability of earth for use in the stabilisation process is governed by its grading, plasticity, compactability and cohesive strength. It must have an adequate fines content to provide the necessary cohesion for block production, whilst not being overly detrimental to physical characteristics such as strength and durability. If the earth has a high clay content, it is recommended that the fine grain size be eliminated. The author imported clay rich earth from Sindh to determine its suitability for use in stabilised blocks.

Cement, lime, various pozzolanic materials, bitumen, sand, industrial resins, vegetable fibres and extracts have all been recommended as additives to improve the engineering properties of earth. A number of additives were selected in this study, based on local availability and cost parameters.

As the basis of this research work, a number of key studies were consulted. For example, the findings of work by Dr DJ Webb on the use of clay rich earth in stabilised block production were considered. He placed particular emphasis on the use of lime as an additive to clay rich earth. The research findings from studies by CRATerre-Eag (Houben, H.), Dr B Baiche and Prof. P Walker on the use of lime and cement as additives were also considered. It was found that most literature emphasised the addition of only cement or lime to stabilise earth. However, a wide variety of additives can be utilised and so it was decided to determine the effectiveness of adding calcium chloride and linseed oil as stabilising agents.

The challenge is not only to improve engineering properties by stabilising earth, but also to use appropriate structural systems. In the latter case, an understanding of construction systems that apply compressive loads to building elements is required.

The author felt that an important consideration, overlooked in much of the previous research, was that unskilled labour should be capable of undertaking the earth stabilisation and construction processes.

If this technology is to be successfully promoted and widely accepted in low income communities, then future research will also have to consider the implications of ease of use, preservation of indigenous skills and affordability. As Gandhi said,

> 'The poor of the world cannot be helped by mass production, only by production by the masses. The system intensive, high energy-input dependent, and human labour-saving technology, presupposes that you are already rich, for a great deal of capital investment is needed to establish one single workplace. The system of production by the masses mobilises the priceless resources, which are possessed by all human beings, their clever brains and skilful hands, and supports them first-class tools'. (3)

1.2 The Concept of Adoptable Technology

According to the World Bank, by the early 1980s there were over 800 million people living in absolute poverty. These people lack the basic requirements for decent human life, such as an adequate food supply, clothing and housing. They also have no access to basic services, including clean water, energy, schools and health facilities. The pattern of deprivation is almost identical in all developing countries.

Approximately 80% of the population in developing countries live in rural areas, where there is little in the way of employment opportunities and the returns from agricultural work are poor. (1) Therefore, people commonly migrate from countryside to seek employment in urban areas. This has resulted in the explosive growth of urban populations in developing countries and, in many cases, urban industries have simply been unable to keep pace with the demand for jobs.

Urban infrastructure is accessible only to specific sectors of the public - those who can afford to pay to use the amenities. Others, who lack education and relevant skills, earn their living in unskilled jobs, such as shoe shining, selling matches, selling lottery tickets, etc. These jobs provide only subsistence income and do not offer the chance to escape the poverty trap.

Also, as urban populations grow, more and more of the food surplus from the countryside is required to support city dwellers. The burden of supporting the urban food requirements is becoming increasingly difficult for developing countries to meet. This situation is encapsulated by E. F. Schumacher's description of the 'process of mutual poisoning':

> ". . . industrial development in the cities destroys the economic structure of the hinterland and the hinterland takes its revenge by mass migration into the cities, poisoning them and utterly unmanageable". (4)

The solution of any problem lies in the analysis of its cause. The author asserts that poverty in developing countries is not only driven by urban migration, poor education of the workforce, etc but also by the transfer, distribution and use of inappropriate technologies. In many cases, imported technology is applied in circumstances where it is totally unsuitable for the prevailing environment. The money spent on importing modern technology, which is beyond the affordability of much of the population, could be better spent addressing basic human and infrastructure needs. In addition, planners and development policy makers must invest in the upgrading of regional resources and support research into optimising the use of indigenous technology.

Seventy percent of the population in Sindh resides in rural areas (see Chapter 2). In general, rural areas are serviced by poor transportation links and are subject to frequent power failures. These areas are also characterised by a lack of building infrastructure, e.g. scaffolding, concrete mixers, etc. Also, fired bricks tend to be of low quality because of a lack of fuel to fire them. Thus, the potential of earth for use as a building material is clearly of importance.

Local buildings, especially domestic architecture, have traditionally been constructed from earth. However, in order to increase the perception of earth as a modern building material amongst the local population, a long-term strategy involving construction of demonstration buildings for public use is required.

1.3 Technological Improvements

In order to solve the acute housing problem in Sindh, the various technological options for improving the properties of building materials and construction techniques, must be examined. The term 'appropriate technology' has acquired a current popularity in development literature. The concept of an appropriate technology is not new; humans have always combined skills and science to devise methods of solving problems and increasing their productivity. People apply appropriate technology whenever they adopt the resource available to them to create techniques and equipment that are consonant with their particular circumstances. (5)

Any technology is inappropriate if applied literally, and without modification, to fit a physical or socio-cultural environment different from that for which it was originally designed. This has often been the case in development assistance programmes in the less industrialised regions of the world.

It has become very clear that highly complex, costly, capital-intensive processes and equipment are not applicable to the conditions in developing countries. Rather, it is necessary to develop technologies and adapt them to local needs; a process which maximises the use of local skills and resources. Such innovations form the base of what is now commonly referred to as appropriate technology.

Appropriate technology is of particular importance to developing countries because it generally involves low-cost, labour intensive small-scale processes and equipment. It utilises local energy sources, and is characterized by simplicity, facility of maintenance and minimal operating cost. Sometimes it is applied to overcome unemployment and hardship of the rural poor, who have been largely bypassed in many development assistance efforts. (6)

These issues are those which E.F. Schumacher was describing when, in 1973, he first brought the concept of 'intermediate technology' to the attention of the public in his best–selling book, 'Small is Beautiful'. (4) Of course, Schumacher was not the first person to identify the need in developing countries for technologies that have a 'human face'. Such eminent figures as Gandhi (3) and Julius Nyerere (1) have also talked about, and campaigned for, such technologies. However, it was Schumacher who first promoted the idea at an international level when the problems faced by developing countries began to gain prominence. Schumacher's concept of 'smallness', and Gandhi's slogans to promote the 'use of local resources', also became popular in developed and developing countries at this time. Gandhi articulated his philosophy about the use of local resources by defining what he termed the Swadeshi Movement:

> "After much thinking, I have arrived at a definition of 'Swadeshi' that perhaps best illustrates my meaning. Swadeshi is that spirit in us which restricts us to the use and service of our immediate surroundings to the exclusion of the more remote. Thus, as for religion, in order to satisfy the requirements of the definition, I must restrict my self to my ancestral religion. That is the use of my immediate religious surroundings. If I find it defective, I should serve it by purging it of its defects. In the domain of politics I should make use of the indigenous institution and serve them by curing them of their proven defects. In that of economics I should use only things that are produced by my immediate neighbors and serve those industries by making them effect and complete where they might be found wanting". (3)

Schumacher's analysis of the problem and his suggested solution mirrored those of many other writers and philosophers, including Morris, Ruskin, Huxley, Carson and Galbraith. All warned of the danger of environmentally careless growth, and argued for a more humane, ecologically sound and human-scale society.

The concept of appropriate technology has begun to be accepted in developed and developing countries, but the best means for adoption is still under debate. Appropriate technology has been defined as:

> "Appropriate technology become now an generic term for a wide range of technologies characterized by any one or several of following features: low investment cost per work place, low capital investment per unit of output, organizational simplicity, high adaptability to a particular social or cultural environment, sparing use of natural resources, low-cost of final product or high potential for employment". (1)

Where, for example, a village suffers from a shortage of capital and an abundance of unskilled labour, the concept of appropriate technology means choosing a technology from locally available resources that can be used by unskilled labour (or requires an affordable training program). Through the use of appropriate technology, self-reliance can be achieved in terms of resources and labor. By contrast, imported technologies may damage the pool of local resource and lead to unemployment amongst those with traditional construction skills. However, policy and technology decision making is often centralised and does not take account of these issues. Also, overseas training of policy and decision makers inculcating them with a preference for modern technologies.

Development aid mostly comes from the Western world, and it is the author's experience that many office bearers of the aid organisations apply their own western experiences when managing construction projects. It is difficult for those in developing countries to fathom out the workings of 'Western' NGOs, not only because of their secrecy, but also because their ideological and philosophical orientations are products of complex historical forces within their own countries which outsiders cannot fully understand. (7) Crewe provides an anthropologists view on appropriate technology in the developing world by arguing that it could be even harder for those in the West to make sense of these complex forces. She asserts that rather than seeing their ideology as a product of history, the thinking of those in the West is oriented by it. She states that this ideology is:

> ". . . automatically pigmented with the character of objectivity for insiders, while outsiders are constantly reminded that historical forces behind the foreign ideology are very different from their own". (7)

The technology used by the 'informal' sector, which is not driven by policy and planning decisions, is often based more on 'appropriate technology' than in the 'formal', modern sector. However, in one sense both sectors use inappropriate technologies because, whilst the 'formal' sector is too capital-intensive, the 'informal' sector uses too little capital. (8) A possible solution is the use of technology with intermediate capital intensity that can be applied to both formal and informal sectors. This approach will ensure the optimum utilisation of the country's resources and capabilities in all sectors of society.

1.4 Scope of Technological Improvements

The appropriateness of a building material or construction technology can not usually be generalised. This is because not every material is suitable for all regions due to specific social and climatic demands on the building.

Appropriate technology is a philosophy, which constantly evolves according to the experience of those who apply it. (6) However, the following factors assist the assessment of a technology's appropriateness:

- Is the material produced locally or partially imported or entirely imported?
- Has the material been produced in a factory far away (transportation costs)? Does the material require specialised equipment, for example in handling? Can the material be produced at a lower cost on the building site? It should be noted that good quality and durability are often more important than low procurement costs.
- Does its production and use require high-energy input and cause wastage pollution? Is there an acceptable alternative material, which eliminates these problems?
- Are the material and construction techniques climatically acceptable?
- Does the material and construction techniques provide sufficient safety against natural hazards?
- Are the material and technologies understood by the local workers? Are special skills and experience required?
- Are repairs, maintenance, retrofitting and replacements possible with local means?
- Is the material socially acceptable? Is it considered low standard or does it offend cultural beliefs? Does it match the material and construction of nearby buildings? Does it comply with the regional and traditional heritage?

There is a range of options available when searching for the appropriate technological solution to a housing problem. A successful application might contain elements of several of these. Some of the options are outlined below.

I. Adopting or improving the traditional indigenous technology

Existing crafts and small-scale processes potentially offer technologies well suited to the needs of the region. These tools and techniques should be studied systematically, and an organised effort has been made towards improvement in their efficiency and productivity. As an example, the traditional all-wooden rotary harrow of Malaysia has been slightly modified by replacing several wooden parts with metal. This has given the traditional implement a greatly improved efficiency and a much longer life. (4)

II. Accepting a scientific "modern" technology

In some instances, modern technology without adaptation may be acceptable, particularly in the more industrialised sectors of developing economies, e.g., in the petrochemical industry. However, the possibilities of this type of application are quite limited. (4)(5)

III. Reviving technology

The revival and adaptation of some of the older technologies used by industrialised societies when they were developing appears to have some potential for solving certain problems. Examples of these might include water wheels and windmills for the production of mechanical shaft power. Generally, these were developed at a time when labour was plentiful, and sophisticated machinery less available. (6)

IV. Adapting a modern technology

In many cases it might be appropriate to adapt a modern technology, for example an electric motor can simply be a labour saving device. Substitution of the hand lever for an electric motor represents both a financial saving and reduces manpower input. It also extends application of the equipment to unelectrified areas and simplifies the problem of maintenance. (6)(7)

V. Developing a new technology

There is great scope for both new research, as well as blending of past and present techniques, to develop a new innovation. (3) The definition of the problem and statement of needs will have to come from engineering and research institutions, especially in developing countries themselves and from interpretation and adaptation of the great wealth of technical and scientific knowledge available. The development and introduction of methane or bio-gas plants in rural India to help resolve fertiliser and fuel shortages provides an example of successful application.

VI. Transferring technology within or among developing regions and countries

Often technologies used in one developing area can offer significant improvements over local tools and technologies in another area. For example, bamboo piping, used for centuries for transporting water in South-Asia, is now finding significant application in parts of Africa and Latin America. (5)

1.5 The Adoption of 'Blend Technology'

In 1965, a general assembly resolution at the United Nations recommended that governments of developing countries should take all necessary measures to develop a building materials industry by utilising local raw material as much as possible. (1)

Since the adoption of this resolution at the world body, which is based on strong socio-economic principles, much interest has been generated across the globe for the development of new, alternative and innovative building materials, particularly through use of indigenous resources. Research is being undertaken at leading institutes and universities around the world, with an aim to develop alternatives and innovative building materials. (2)

Various developing countries have adopted technology as a means to resolve technical problems associated with the development of new techniques to support traditional methods. Following these technological innovations, Pakistani researchers and universities are also involved in finding suitable and affordable technologies with which to address the housing problem in their country.

Most innovation and research is still in the experimental stage because of the lack of marketing, specification, sponsoring bodies and poor communication of information about innovations to user. One of the key problems is the lack of information produced in a form that users can directly employ.

The author argues that a primary activity of Research and Development (R&D) institutes should be to develop a direct interface with end users in order to determine their exact requirements. Research should be focused on those areas where such direct links with the end-user exist. This could entail end-users themselves approaching the R&D institutes for solutions to their needs. In other words, the research activities should be market-driven and not based only on 'pure' research.

In addition to undertaking development work, R&D institutes facilitate technology transfer from external sources. Some modern technologies are suitable for local conditions and can be adopted immediately by end-users. Other modern technologies may be used in conjunction with indigenous technologies to provide significant improvement to the characteristics of the indigenous technologies.

1.6 Common Criticisms of Appropriate Technology

The concept of appropriate technology is criticised by some who feel that a lack of modern technologies in construction accentuates perceptions of 'backwardness'. The adoption of high technology is often seen as the sign of a modern country. Furthermore, it can be argued that by concentrating the use of the latest technologies in only the most wealthly countries, they become less accessible to developing countries due to spiraling costs and sophistication. In this scenario, the use of advanced technology is inevitable, even though it may not be ideally suited to the needs of developing countries. The superior efficiency of advanced technology will outweigh its inappropriateness.

Appropriate technology is a relative term depending on the circumstances of the user. To a large extent, the economic wealth of a nation determines the 'appropriateness' of a technology. Wealthy countries can afford the latest technologies, which means that these technologies are deemed 'appropriate' to their needs. However, the same technologies are often too expensive for developing countries and so deemed to be 'inappropriate' to their needs. The ideal solution for developing countries is for production of modern, efficient technologies to be geared to their specific resources and requirements.

The terms 'appropriate' and 'intermediate' technology are interchangeable. However, intermediate technology is sometimes mistakenly interpreted as a technology of intermediate specification. For example, earth stabilised block might be called intermediate technology because it is of lower specification than concrete block but higher than adobe brick. This is an incorrect usage of the term because intermediate technology simply describes one that is best suited to the circumstances where it is used. Therefore, the author recommends that, in order to avoid confusion, the term 'appropriate' technology be used rather than 'intermediate' technology.

Some researchers criticise appropriate technology for being only a transitional solution rather than a permanent one. However, the author argues that once an appropriate technology is adopted by a developing country, it becomes the de facto choice and, thus, a permanent solution. As developing countries become more developed, differences in the appropriateness of technologies between countries will diminish and perhaps finally disappear.

1.7 Basic Needs and Appropriate Technology

It was stated in Section 1.2 of this chapter that, along with food, water and energy, shelter is one of the basic human needs. Figure 1.1 shows the relationship between basic human needs and technological improvements. For every type of human need that must be addressed in regional development planning, policymakers must consider the technological improvements required. It other words, the use of appropriate technology improves the ability of planners to address basic human needs in any region where deficiencies exist.

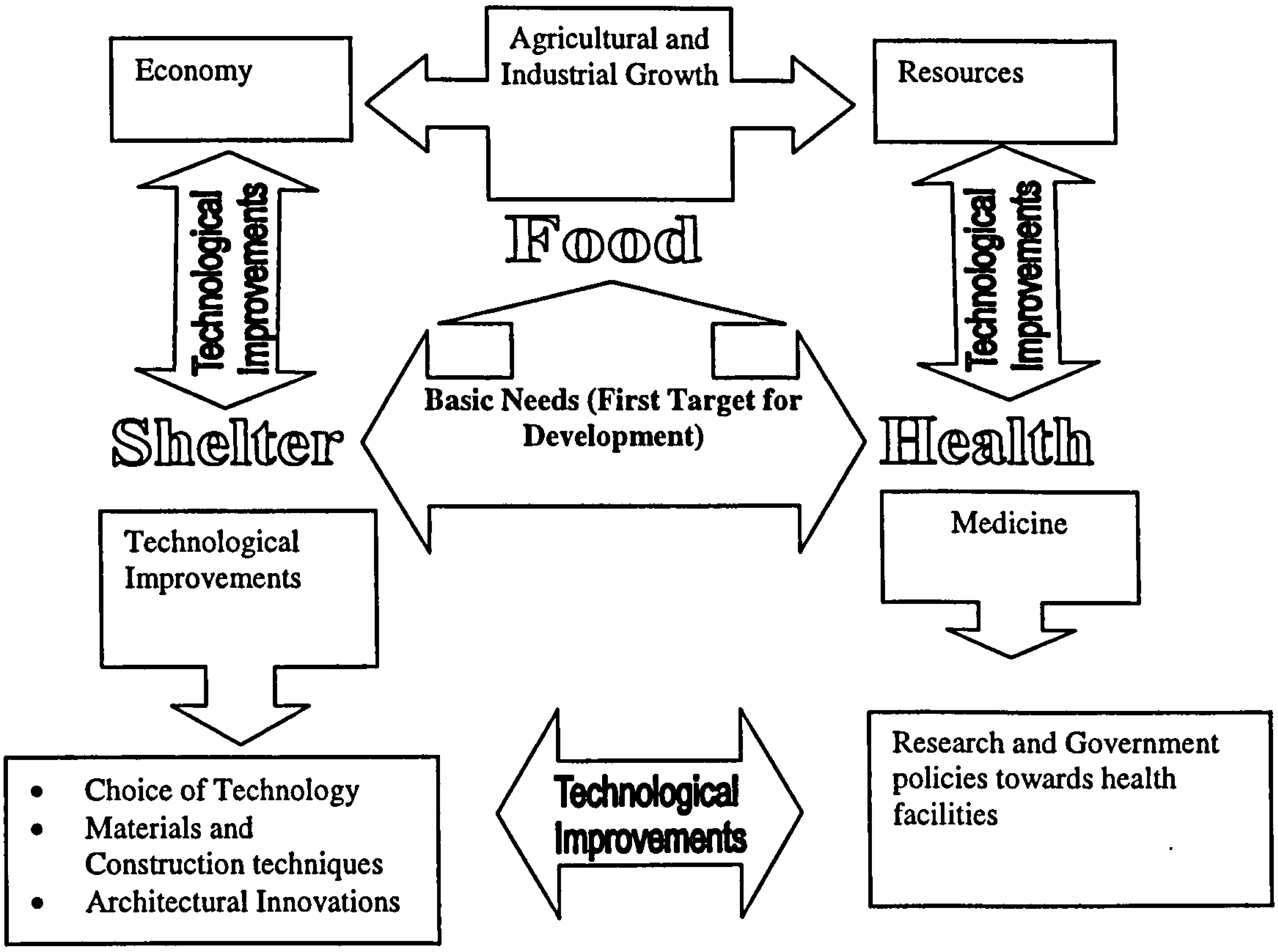


Figure 1.1 The development process cycle.

The importance of technological improvement is further explained by a recent UNIDO report:

> "If the poorer sections of the community are to be helped to build structurally durable and functionally adequate houses, the focus of attention will have to be on the provision of suitable building materials to them at cost they will be able to bear. The materials should be such as are available locally and that do not require specialised skill in their use". (8)

This statement supports the assertion that it is unrealistic to propose the use of expensive modern technologies in subsistence economy where cash is always in short supply. There are insufficient resources in the world to build houses for everybody according to conventional standards, but it is not necessary to adopt those standards. There are many traditional and improved techniques and materials, which can provide rural and urban fringe communities with decent accommodation at a fraction of the cost of conventional methods. This study has focused on the use of local materials, skills and techniques that make housing more accessible to all sectors of society.

The current rate of housing construction in most developing countries is insufficient to meet the needs of the poor and is heavily dependent on the importation of materials and equipment. (8) The author sees the reduction of overall investment per unit and the greater use of local materials and resources as ways of alleviating these problems. The work of Fathy, who provided early insights into the use of appropriate technology, supports these solutions. He described examples of low-cost alternatives to conventional housing strategies and talked of the dignity and beauty of mud bricks, as well as the simplicity and naturalness of artisanal masonry techniques. (9)

In the 1950s, Ramirez developed compressed earth blocks in Colombia. From that time on, Latin America and Africa led the development of earth stabilised blocks. Research and development on the material, construction techniques and architecture were conducted by organisations from Africa (Adau, LBTP Abidjan), Australia (CEBS), USA (Adobe Today, MIT, VITA) and Europe (CRATerre). (10) Also, during the past few decades, earth architecture has been developed in India by research organisations such as CBRI (Roorkee), ASTRA (Bangalore) and Development Alternative (New Delhi), as well as social organisations such as Mud Village Society (New Delhi). (10)

1.8 Background of Earth Architecture

Most of the world's population still lives in houses constructed from earth, benefiting from the transfer of skills and knowledge of countless generations of urban and rural peoples. The process has been one of constant assimilation, reinvention and improvement of these building techniques. Earth construction has passed the test of time, proving its merits and adaptability to the most diverse cultures, geographical conditions and climates. Examples of earth architecture are to be found on every continent; they are found not only in the form of historical and archaeological remains but also in the innumerable towns and villages where the multicultural heritage, enriched by exchanges between the most varied civilisations, are perpetuated daily.

Recent developments, such as the energy crisis due to the population explosion, seem to invite us to continue this vital cycle of renewal of earth architecture. Since earth has heat-retaining capacity, buildings built with it have the great advantages of insulation against high external temperatures. (1)(2)

Through the centuries, earth has been used to build beautiful edifices all over Asia, Africa and in Muslim countries such as Morocco, Turkey, Saudi Arabia, Iran and Pakistan. That so many such buildings survive to the present day, is a testimony to the incredible durability and sculptural potential of earth. It is an extremely versatile material allowing walls to be built in many different ways.

Sun -dried brick masonry is the most common earth construction product, but rammed earth walls with earth applied in layers are also used successfully in many countries. Another variation is the use of earth as a fill and finishing material on a frame of logs and reeds. The architecture of urban Sindh, for example is primarily based on wood and earth, and is a variation on the theme of 'earth construction'. Although the basic structure was camouflaged with richly decorated facades using stucco, the internal skeleton is covered with earth in Sindhi towns like *Thatta.* (3)

Craftsman who worked on the *Thatta* houses to give an appearance of stone construction material used tremendous skill and expertise. The basic square form of the houses was diligently worked on, square inch by square inch, to transform a simple structure into an expression of extreme elegance and charm (3).

It was the extraordinary quality of earth that allowed the application of decorative elements to transform simple houses into beautiful mansions. Earth can be used as a construction material in numerous ways, and a dozen or so fundamentally different building methods have been identified. Even then, there are close to a hundred variations on these basic themes.

The use of the molded earth linked to the evolution of humankind which took place between the agricultural revolution of the Neolithic age and the urban revolution and corresponds to an advanced stage in the evolution of societies, and in the organization of material production and the building of dwellings.

The progression from moulded earth techniques to the compacted earth block corresponds to a logical improvement in the material. The increased density and reduced porosity resulting from compression improve the behaviour of the earth block in the face of harmful effect of water. This compression technique was first practised manually using a tamp inside the moulds. Machines were then developed for moulding and producing the blocks. The evolution of earth construction techniques from use of adobe, to compacted earth block and then compressed earth blocks remains a logical progression in many regions.

1.9 Architectural Realisation of Earth Stabilised Blocks

The Indian Institute of Building Construction and CRATerre-Eag have recently produced remarkable housing schemes and public buildings in various parts of world. The 1950s were marked by the research into the use of earth stabilised block as construction materials. The scope of research activity in terms of architectural realisation has continued to grow, both in industrialised and developing countries. The following two case studies are considered to highlight the successful architectural realisation of earth stabilised blocks.

Case Study 1: Low-Cost Housing at Mayotte (11)

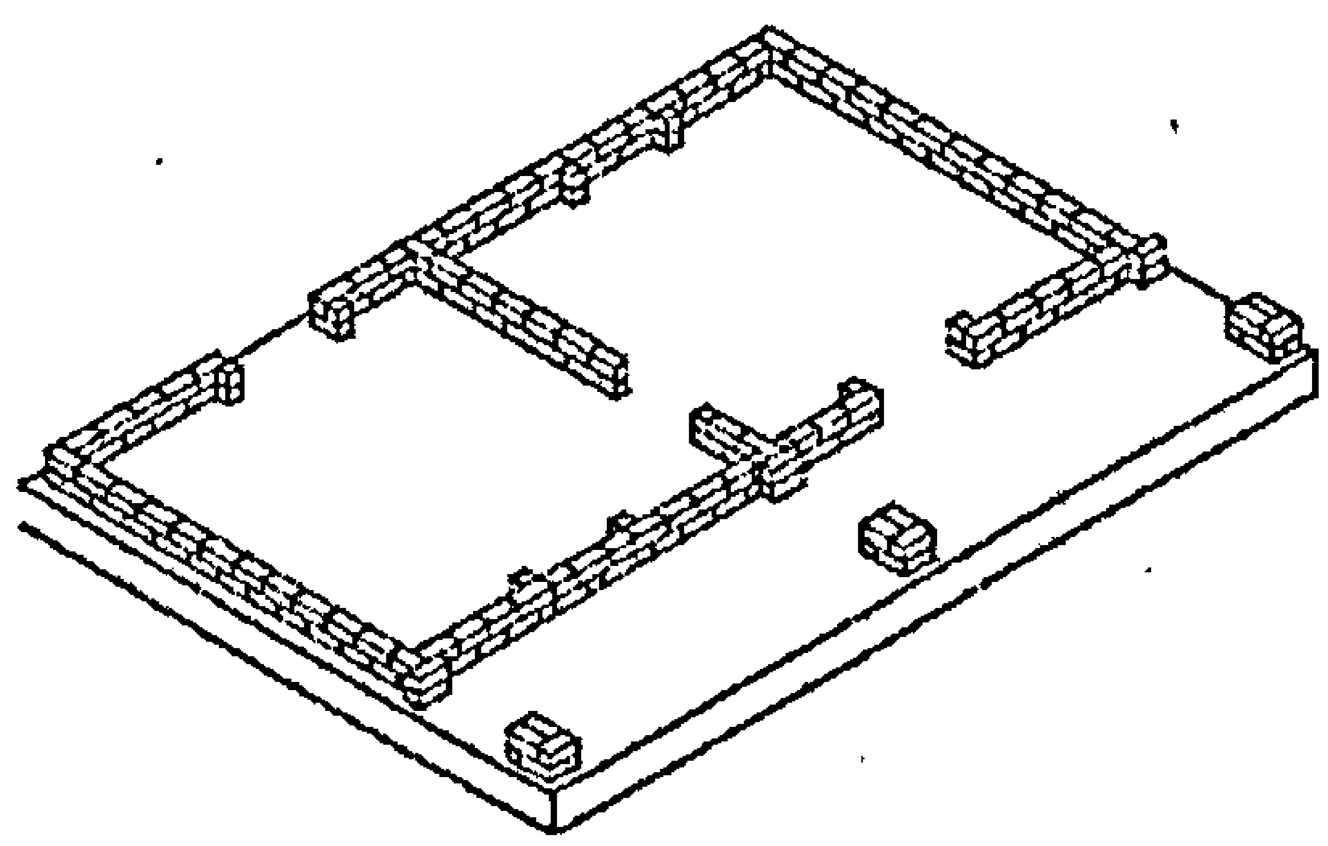
In 1978, the Mayotte project was launched to renew the housing stock at a rate of 750 housing units per year for ten years, to install sanitary and educational facilities in all communes and to open up the villages of the island. Mayotte Building Company took responsibility for this project and had built nearly 6,000 low-cost houses and 500 rental units by 1990. This project, considered by experts as reference due its successful implementation, provided the means for private ownership to low income families.

General features of the units:

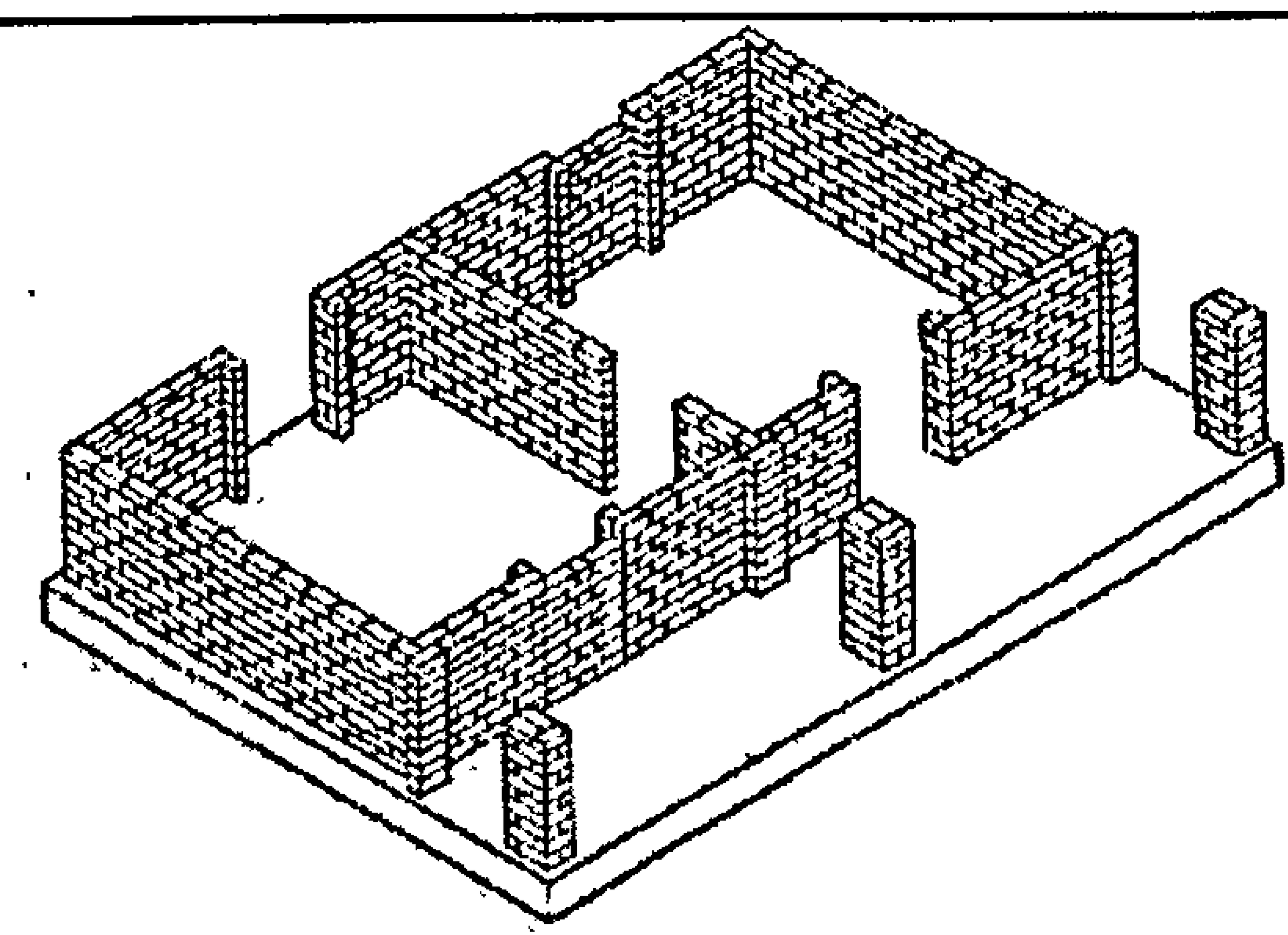
- Covered surface area: 33.6 m2
- Total surface area: 40 m2
- Number of Rooms: 2 bedrooms of 11.7 m2 each
- Veranda: 1, surface area 10.2 m2

Construction:

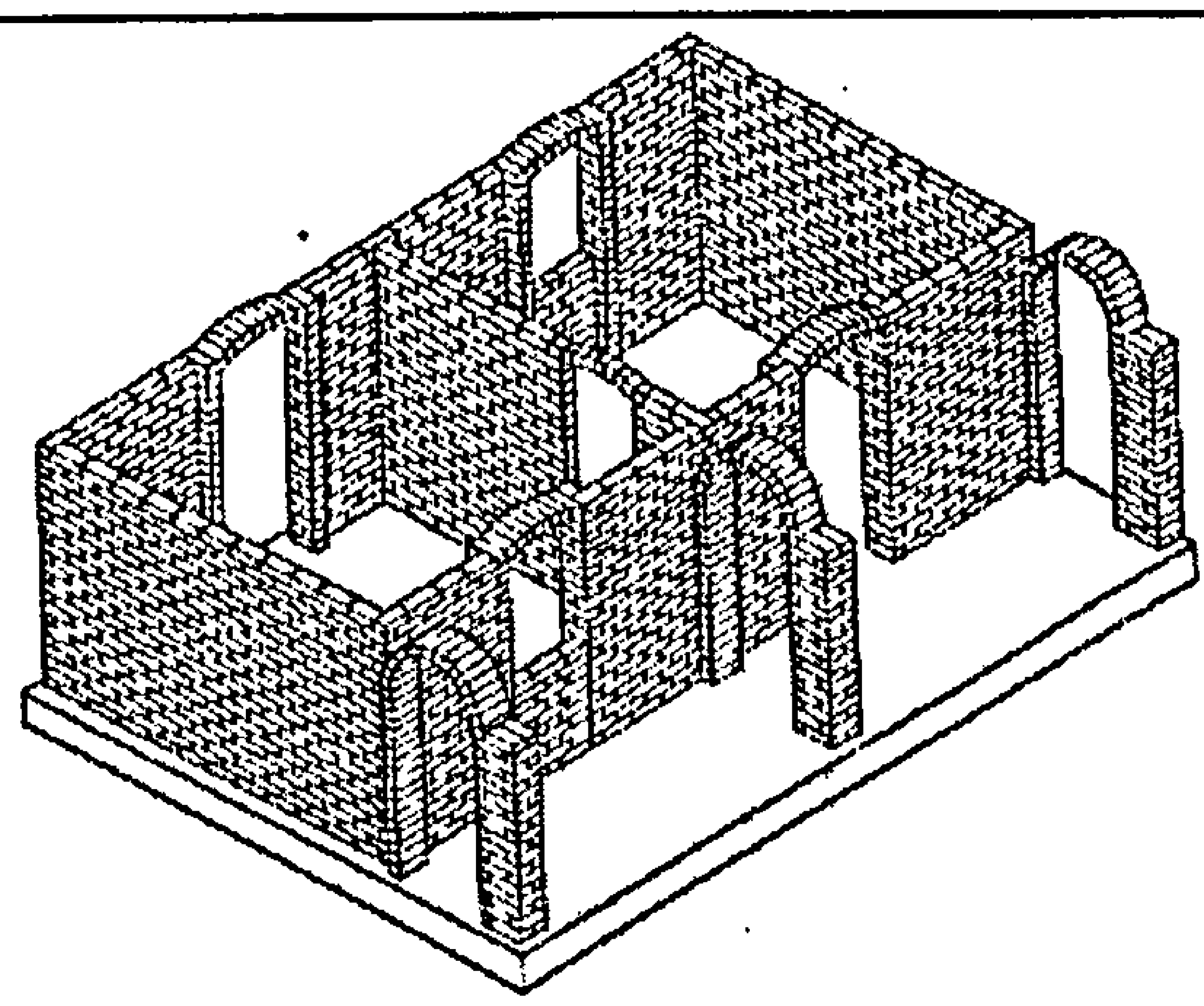
- Local skilled labour and building craftsman
- Nominal dimensions of the earth stabilised blocks: l x w x h = 29.5 x 14 x 9 cm
- Thickness of wall: 14 cm. Bonding pattern: stretches
- Stability of walls: projecting buttresses alongside door and window reveals bonded in to the wall.
- Ring beam: all the way round the peripheral and partition walls; made of reinforced concrete with a single layer of iron rods; poured in lost formwork made from earth stabilised blocks.
- Roofing : swan wooden purlins resting on the gale-end walls and the partition walls. Evas purlin anchored to the ring beam on waiting rods laid during the pouring of the ring beam. Covering: galvanized steel roofing sheets bolted through the purlins. (See Figure 1.2)



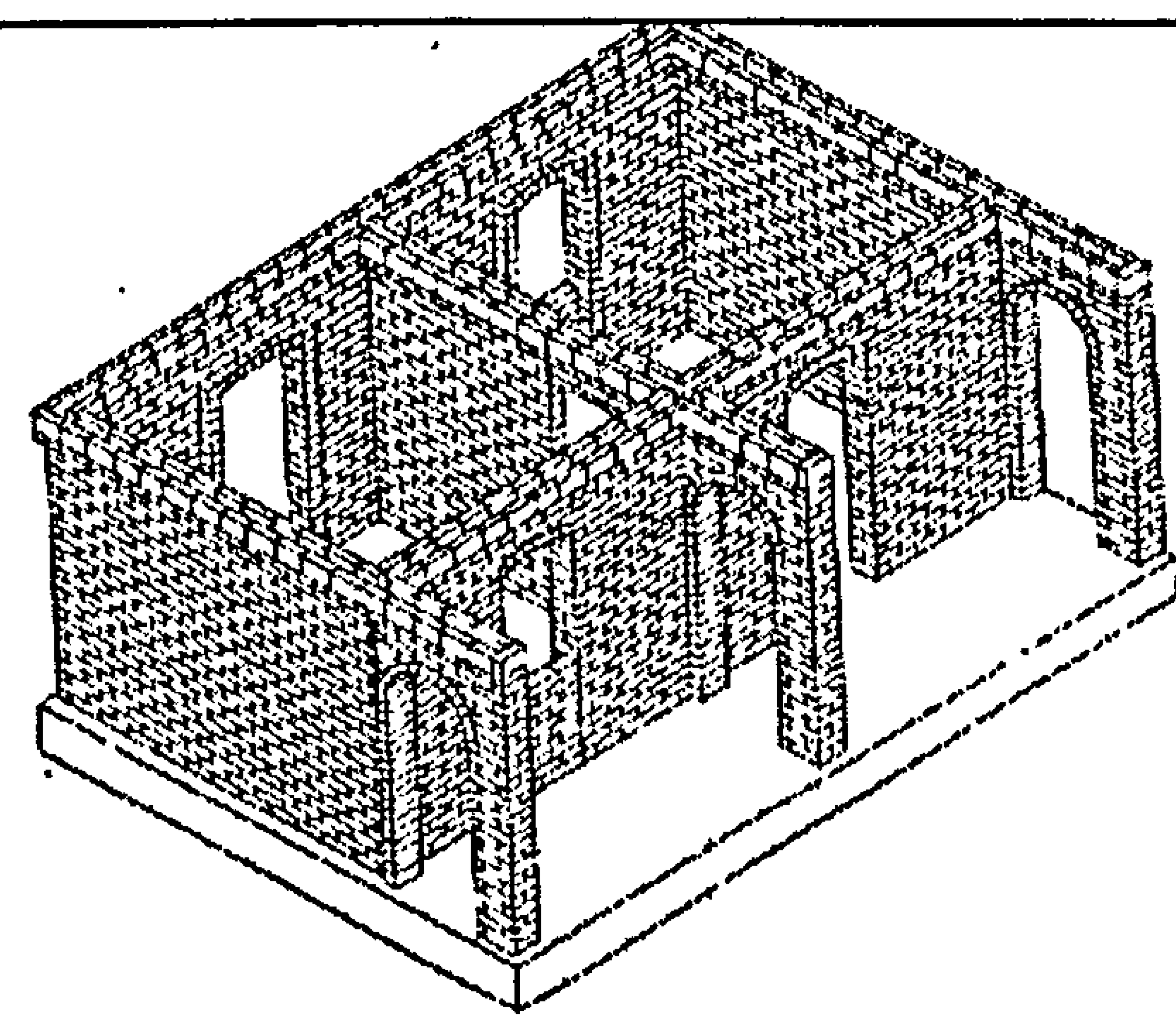
Masonry of the second course of compressed block



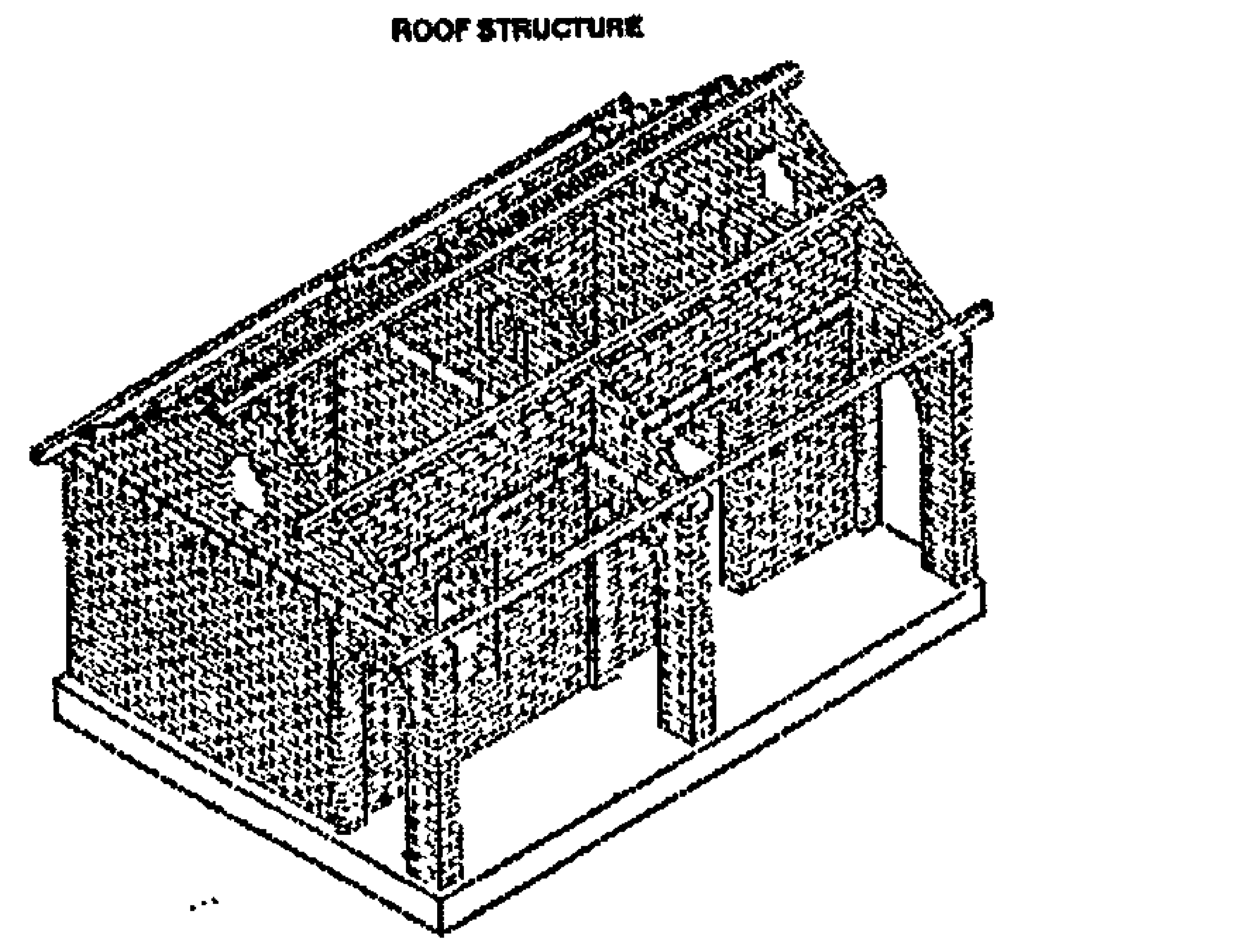
Raising the masonry to the level of the window sills



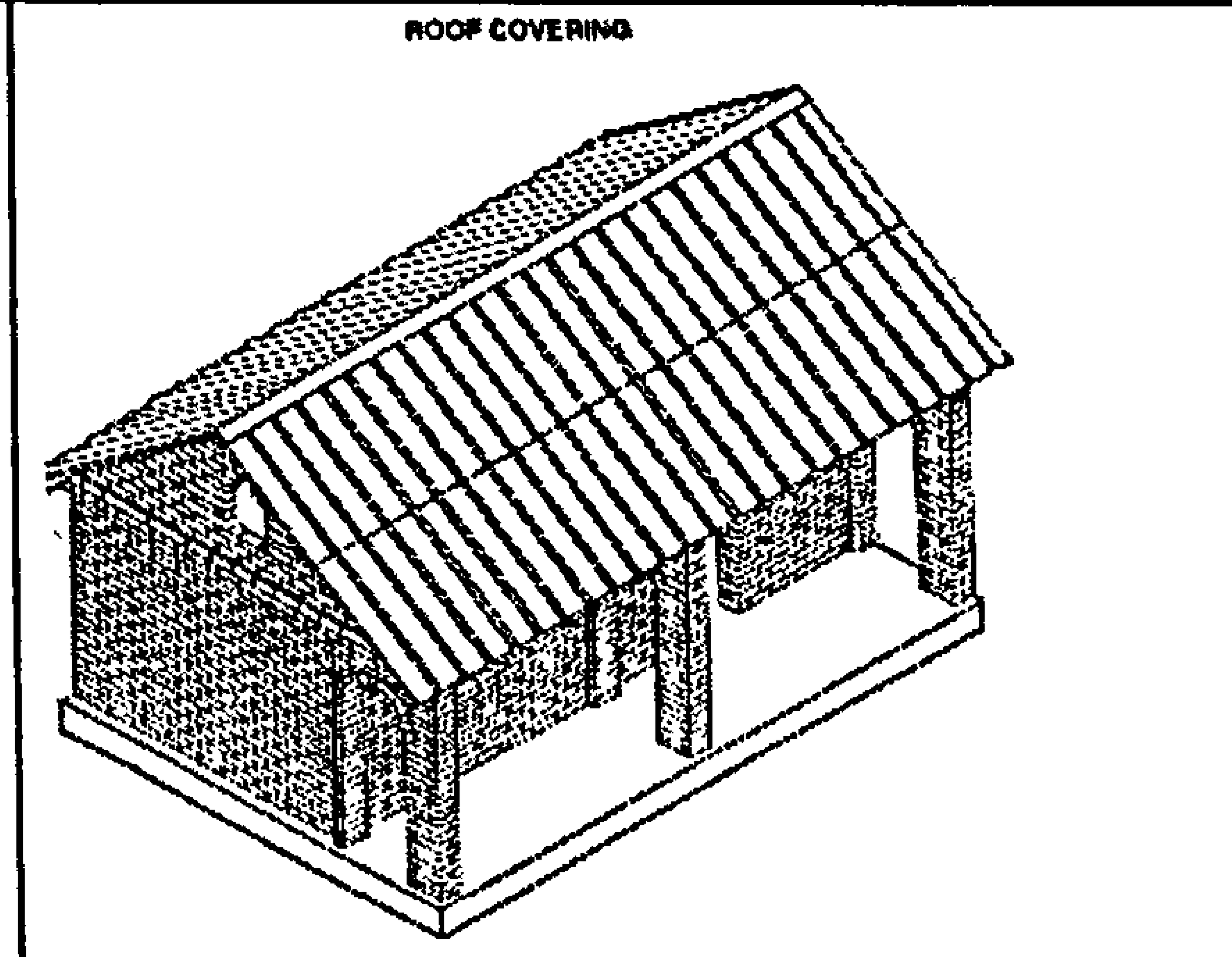
Masonry raised as far as the top of the door and window arches



Masonry of the lost formwork for the ring-beam using header blocks



Laying the purlins from gable wall to gable wall



Roof covering of galvanised steel roofing

Figure 1.2 Construction of the Units.

Author's view on the Mayotte Project

This project is the one of the best examples of appropriate technology being successfully implemented. The project managed to preserve traditional identity and ensure that harmony with the environment was maintained. Before starting this project, a survey was conducted by ethnologists and architects to find out the traditional way of living and users living patterns. The two bedrooms and the veranda were identified as the main spatial requirements, together with basic facilities such as kitchen and toilet.

During construction, a cyclopean masonry foundation system was adopted. As construction was undertaken in a tropical region, the Moyette buildings had to withstand the effects of water and so cement was used in the foundations. As little cement as possible was used in order to minimise the cost implications. However, cement was also used in the ring beam and as an 8% addition to earth stabilised blocks.

The architectural concept of 'good boots and a good hat' was adopted because of the severe climatic conditions that prevail. Thus, all foundations comprise a single masonry block raised above ground level and extended to a drainage ditch; the use of floated cement mortar ensures that water runs-off along the walls.

Up to the window level, masonry patterns were designed so that stretchers shift along and avoid the creation of vertical joints. The window breasts were built, using earth blocks, under the principle of totally independent masonry. Dry joints were constructed between the breast and the buttresses at the reveals of the openings. In order to fully exploit the principle that earth block masonry is best suited to compressive loading, whilst at the same time seeking to attain economical use of reinforced concrete, the openings were spanned with shuttered arches.

In terms of roofing, local timber was found to be of inadequate quality for such use. Consequently, in order to reduce the amount of imported timber required, the roofs were designed according to the principle of purlins running directly from the gable wall (including transverse partition).

The Mayotte project inspired many other residential projects to use appropriate technology.

Case Study 2: Exhibition Pavilion in Saudi Arabia.(11)

This project was agreed in December 1987, with collaborative partners including the French Embassy at Riyadh and the royal commission of Jubail and Yanbu. The project was undertaken to provide facilities at a traditional national festival held each year. A large number of people participate in the festival, coming from nearly every corner of Saudi Arabia.

It was recognised that earth is a traditional building material that complements regional identity. Stabilised compressed earth block was thus considered suitable to meet the criteria for maintaining regional identity, as well as having an ability to withstand climatic conditions.

General features:

- Pavilion: covered space area of 200 m^2
- Design: Ibrahim Aba-Alkhail, architect from Riyadh
- Implementation: CRATerre-Eag with the help of Saudi enterprise and masons.

Construction:

- Reinforced concrete ground beams were used for foundations
- Reinforced concrete in floors
- Stabilised earth blocks measuring 29.5 x 14 x 9 cm. Load bearing walls 29.5cm thick using a header and double stretcher bonding pattern. 45cm thick pillars supporting interior arches or reinforced concrete lintel beams over the interior patio. 14cm thick roof parapets. Masonry walling system was adopted.
- Mixed system of terrace roofs, using compressed earth block vaulting, reinforced concrete girders, and compressed earth blocks cupolas (at each corner of the building) on penditives. Waterproof render using bitumen and cement mortar over mesh.

Author's View on Exhibition Pavilion at Saudi Arabia.

The requirement of this project was to accommodate a large number of people and to exhibit traditional identity. A further key requirement was that the building should be naturally ventilated. The designer proposed a traditional form for the building - an exact square with open auto courtyard for circulation and ventilation (see Figure 1.3). Small openings in elevations were provided to circulate the air in the courtyard (see Figure 1.4). The wall mass and domed roofs provided thermal resistance in keeping with principles of natural cooling.

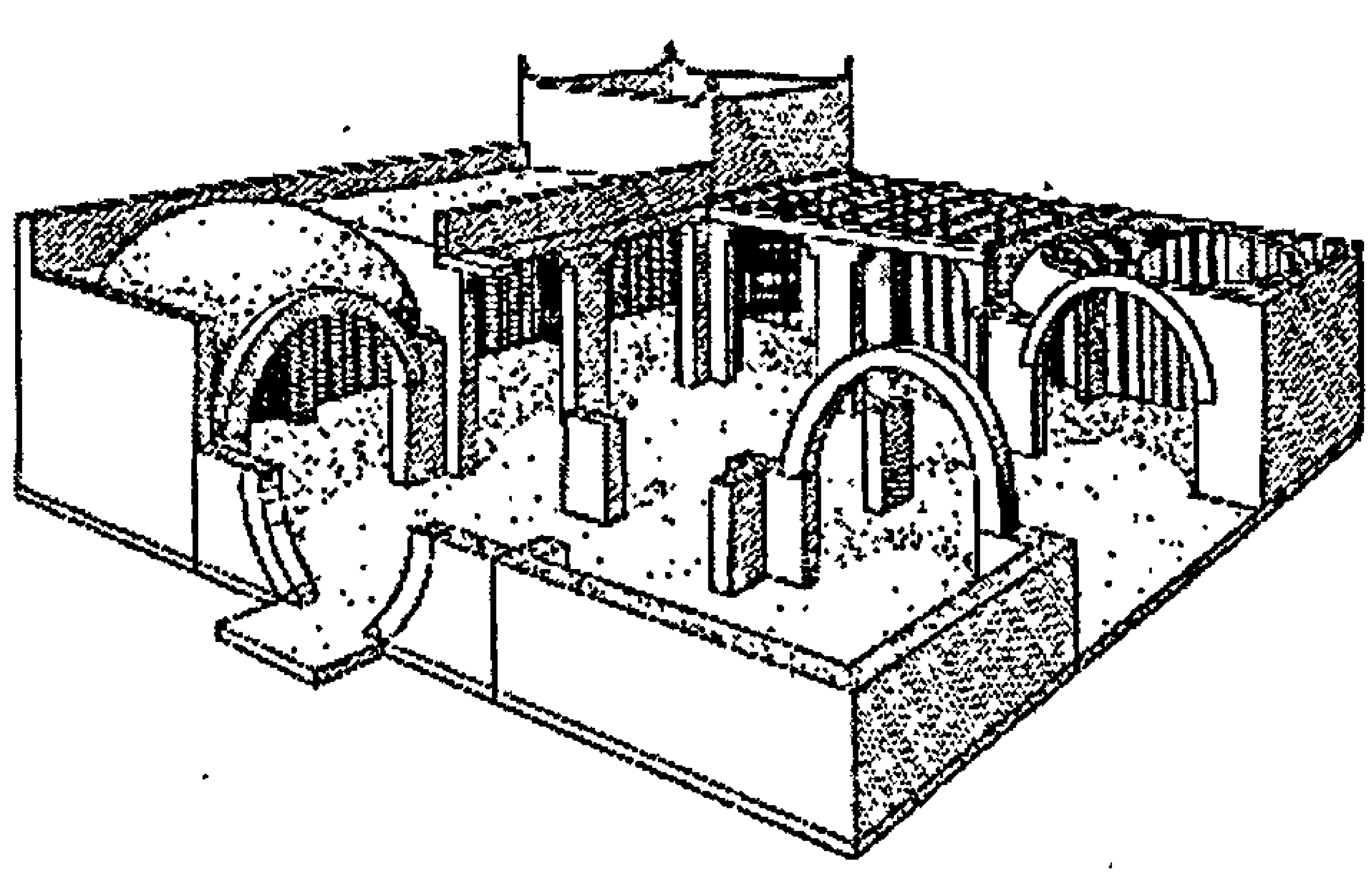


Figure 1.3 Elevation of Exhibition Pavilion in Saudi Arabia (11)

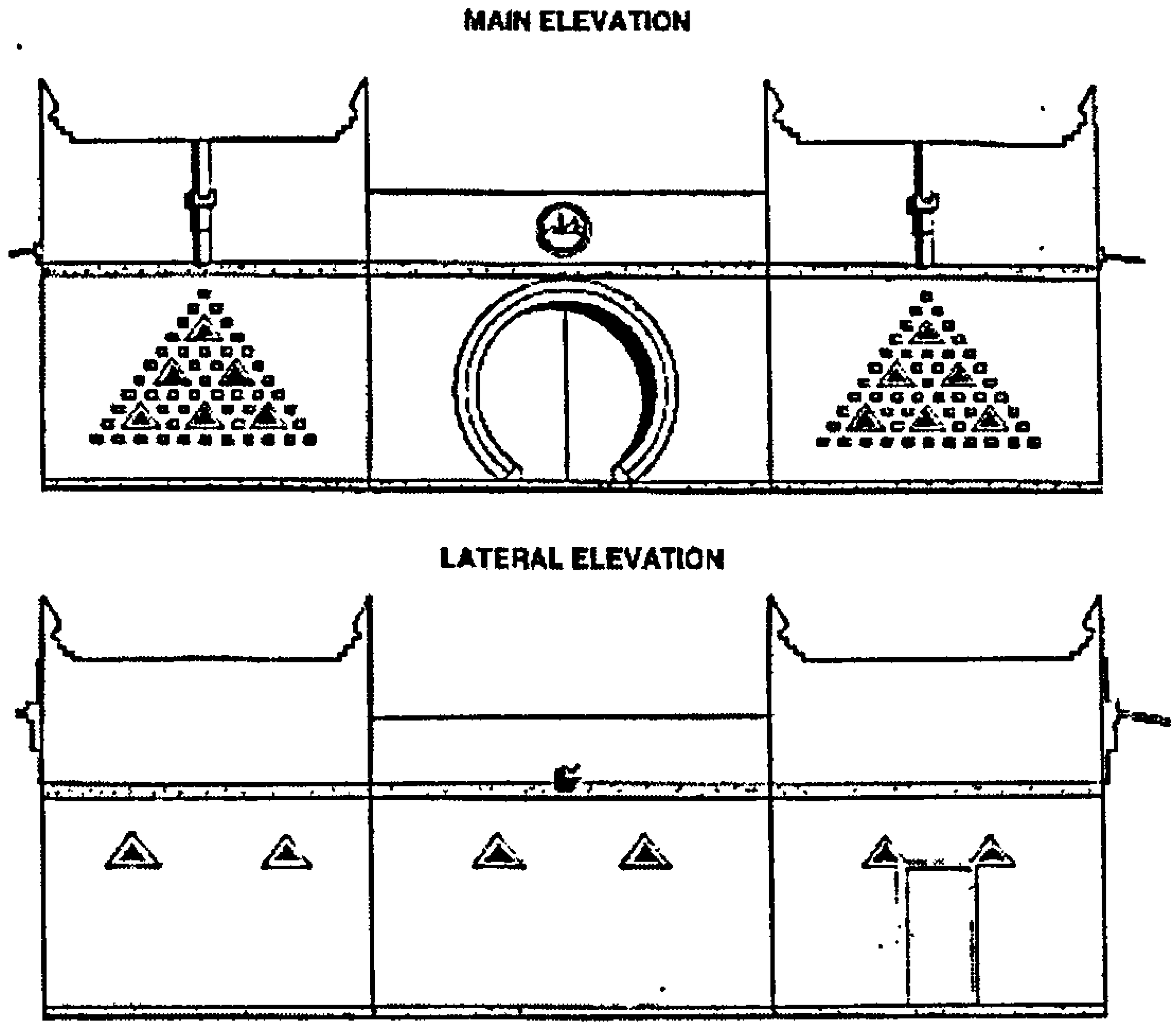


Figure 1.4 3D View of Exhibition Pavilion in Saudi Arabia (11)

The ring beam was used to support the heavy load of the copula roofs and flat terraced roof. Special ring beam blocks were produced with 2 layers of 8mm diameter rods and 6mm stirrups every 30cm. The roof was tamped with layers of stabilised earth, cement and bitumen to provide water proofing. Waterspouts were constructed in order to provide water drainage conduits from roof.

This project is a good example of appropriate technology supporting regional identity and optimum use of traditional construction techniques and materials. The use of earth stabilised block increased the functionality of the building by providing good thermal insulation.

1.10 Summary

The selection of appropriate technology and identification of suitable target groups for implementation is a revolutionary approach to construction in developing countries. It is revolutionary because of the continuing need to gain social acceptance for the adoption of appropriate technology.

In general, people still need convincing about the effectiveness of appropriate technological solutions. This is necessary because the general public, i.e. the users of the technologies, have a fascination with modernisation and high technology. Most of time, the public forgets that modern/high technology is a form of appropriate technology within its context. This is because technology adopted by the developed countries is suitable in terms of their resources and user needs.

Two case studies were reviewed with reference to the implementation of appropriate technology. These case studies looked at how some organisations are encouraging the use of low energy input construction techniques. Stabilised earth blocks exhibited remarkable functionality and aesthetic properties that harmonised with the surrounding environment.

The following challenges still have to be addressed in the field of earth construction:

- Researching the engineering and architectural properties of earth used for construction purposes.
- Reducing the level of sophistication associated with on-site tests methods so that they can be undertaken by unskilled labour. The simplification of the earth stabilisation process can be achieved by focusing research on methods for on-site analysis of earth.
- Transferring the theoretical knowledge acquired by research organisations to the field.
- Developing more efficient equipment capable of producing high quality material on-site.
- Improving the blend of modern and traditional architecture and establishing appropriate architectural and construction guidelines.
- Promoting the use of earth as a building material to decision-makers and the public (contractors, self-builder, etc.) in order to gain more widespread acceptance of the material in construction.

Perhaps the most urgent of the above challenges is to gain mass acceptance of appropriate technology, with particular reference to the use of earth as a building material. This will involve overcoming widely held preconceptions and prejudices that earth is a building material for poor and underdeveloped areas. Therefore, social researchers, who are involved in the implementation of appropriate technology, will need to raise social awareness about the merits of using earth.

The parameters of technological improvement provide a framework for making quick decisions about the most appropriate solution to rural housing problems, as discussed in Section 1.6. Six technological options are available to meet specific housing needs: (i) adopting or improving the traditional indigenous technology, (ii) accepting a scientific "modern" technology, (iii) reviving technology, (iv) adapting a modern technology, (v) developing a new technology, (vi) transferring technology within or among developing regions and countries.

The scope of technological improvements and their implementation can be achieved in two stages: (i) through study of the problems and needs and (ii) through the study of local resource availability. This approach enables the problem situation to be resolved and the appropriate solution to the need identified.

In Chapter 2, an overview of the housing situation of Sindh is presented. The need for, and supply of, housing in the region is also evaluated, together with the availability of material resources for construction.

1.11 References

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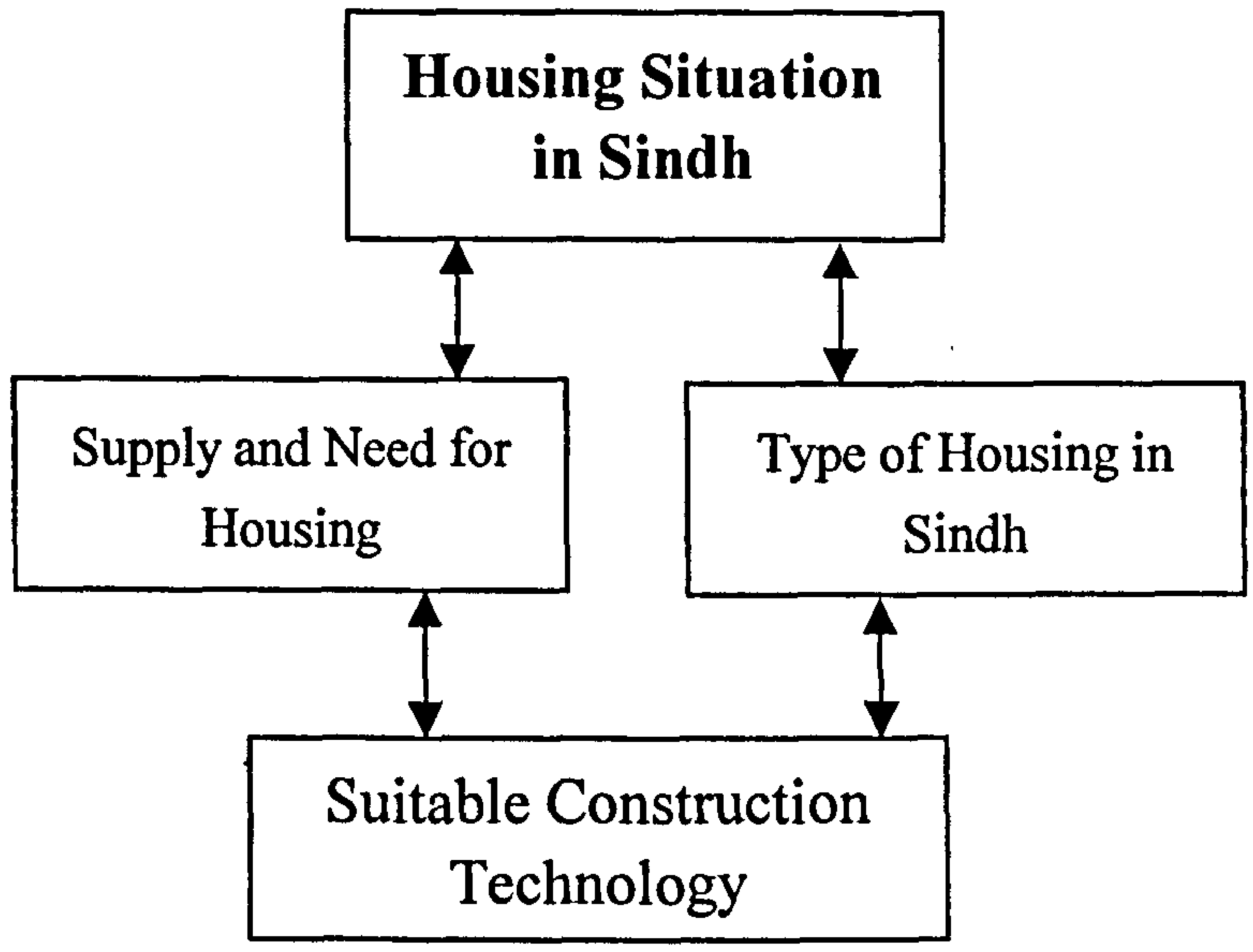


Chapter Two

An Overview of Housing Situation of Sindh

Chapter Two

An Overview of Housing Situation in Sindh

2.1 Introduction

This chapter presents a study on housing situation for low-income communities in Sindh. It also investigates the initiatives, which have been carried out by the Government of Pakistan and Non-Governmental organisations (NGOs) for improving the housing situation in Sindh. The study of housing situation and needs in Sindh provide a better understanding of problems or constraints which makes housing so dear to the region or inmates. The inquiry of these constraints will guide the researcher that whether these issues relate to the unavailability of affordable material, policy document or other causes is explored. In this chapter, the key housing issues are studied using existing survey data obtained through literature research.

In 1989, the World Bank conducted a survey of the housing situation in Sindh for the implementation of a 'low-income community shelter' project. This survey provided major source of information for the research findings presented in this chapter.

The World Bank provides the primary survey source of data for the literature review because this is a paucity of current information on rural housing in Sindh from other sources. The last population census in the region was undertaken in 1981. After this date, due to the volatile political situation in Pakistan in general, and in Sindh in particular, neither the federal nor the provincial government have ever again encouraged the conducting of a census. The World Bank project team surveyed the fifteen districts of Sindh in 1989. Villages with populations of over 500 and 100 inhabitants were considered for this survey.

Housing units were classified according to their construction techniques and the material used. The source of finance for house construction and improvement is considered in the analysis government policy and their initiatives towards the fulfilment of housing loans. The effect of the number of persons per household on house size is also investigated. The review of the 1989 survey and its comparison with the 1981 census provides a valid basis for forecasting future demand and supply for housing in Sindh.

2.2 Preface to Sindh

Sindh is the second biggest economic region in Pakistan. It was the cradle of an ancient civilisation that was well organised and highly developed as early as 5000BC. The manifestation of such a mature form of community organisation in terms of town planning and construction techniques can be seen at the site of Mohen -Jo - Daro (a metropolitan city of Indus Valley Civilisation). (1) It is located between 23 and 37 degrees north latitude and 61 and 76 degrees east longitude.

The majority of people in Sindh are still living in rural areas. They have developed their own style of architecture and practise the vernacular use of indigenous material. Sindh extends over some 140914 square kilometres and according to the 1981 census, has a population of 19,029 million. Of the total population, 10,786 million people live in rural area. (2)

Rural settlements in Sindh were developed historically clans or tribes who lived in their own 'Para' (hamlet) within the Goth (village). Houses are grouped together leaving an open space in the centre, which is used by women and children for communal purposes. Usually, a mud or wattle wall surrounds the whole settlement. An important aspect of the traditional cultural norm is the unique relationship between the male and female sectors of society, where the two sectors are discouraged from intermixing and interacting in public spaces. This gender arrangement brings about two divergent spatial orders, which one may call introverted and extroverted spaces. These are the outcome of religious and cultural beliefs and values. (3) Houses normally have a single entrance leading to a vestibule, or passage, with a right-angled turn so that the main living quarters are not visible from the entrance. In rural Sindh, differences can be observed between a farmer's house and land lords (*Zamindar's)* house in terms of the construction materials and house pattern. Most dwellings are characterised by thick walls usually made of mud, and flat roofs. During the hot season, people sleep on rooftops or in open courtyards. Houses are often designed to face inwards onto a patio or courtyard. (4)

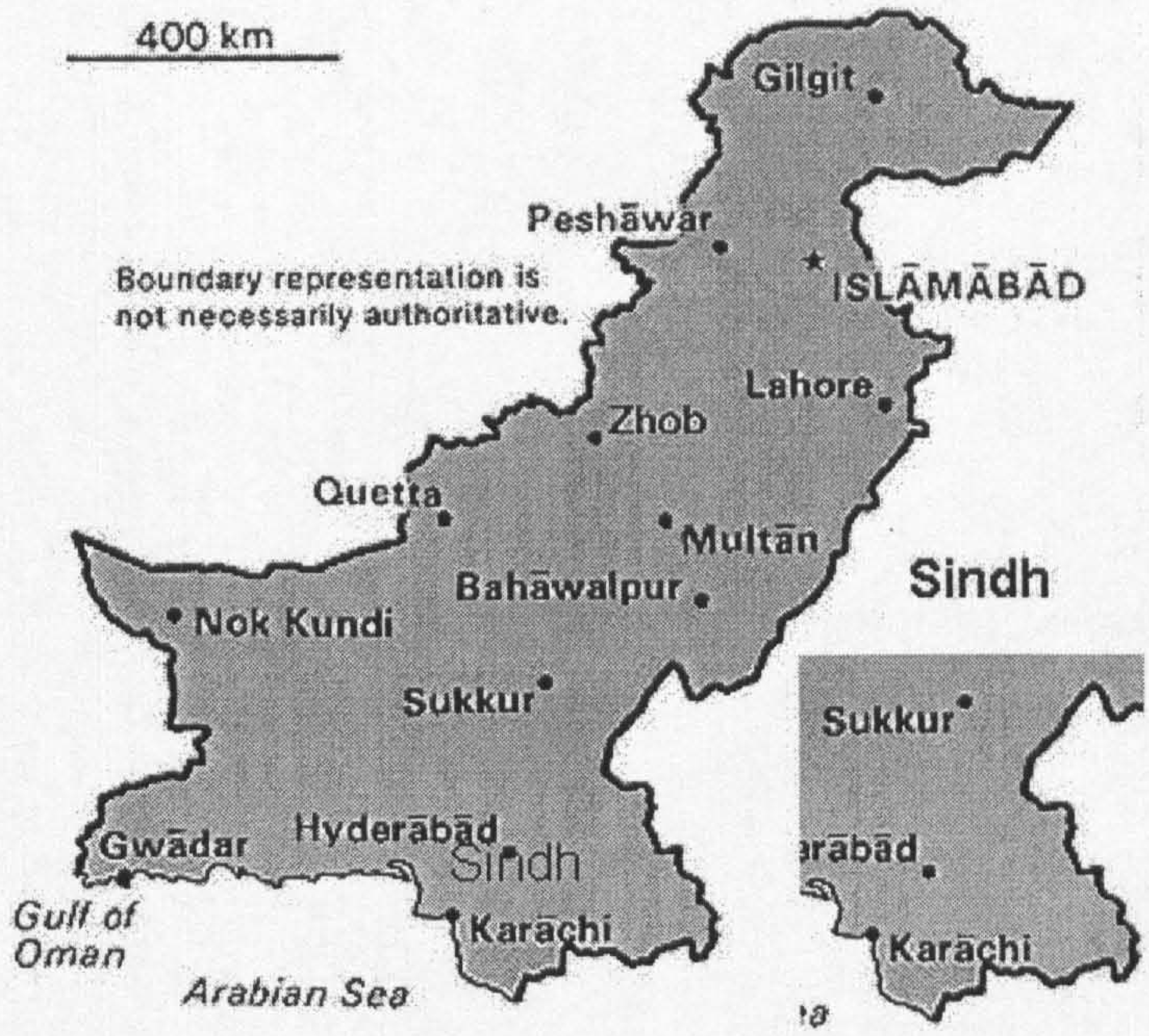


Figure 2.1 Map of Pakistan and location of Sindh as Province. (5)

2.3 Categories of Housing in Sindh

In order to determine the methods of construction for shelters being used by low income inhabitants across Pakistan, both Katchi Abadis (illegally occupied land and structures constructed there on), and planned low-income areas are considered.

Generally speaking low-income shelter all over Sindh and Pakistan can be classified into three categories based upon the materials used in construction and structural integrity. The structures are classified as follows: (6)

- Katcha Shelter Construction
- Semi-Pucca Shelter Construction
- Pucca Shelter Construction

2.3.1 Katcha Shelter Construction

Katcha shelter or Katchi construction is usually built from locally available materials with low durability, e.g. mud, thatch, shrubs, stone and raw timber etc. Katcha shelter is subject to damage from weather changes and requires a lot of regular upkeep and maintenance. Usually the following materials and structural techniques are used for Katchi construction.

a) Walls: Wattle and daub construction is used. A woven frame of wattle (a twig or flexible rods) is smeared, or daubed, in an unaltered state with plastic earth. Moist earth is rammed into forms to make mud walls. Villagers mostly use wattle as basic material for house construction because of its plastic nature.
b) Roofs: Flat roofs made of tree branches, covered with reed mats, wooden joint beams. In the case of two ways pitches roof, branches covered with date palm fibber or reed mat and finished with thatch.
c) Floors: Compacted earth is covered with mats of date fibre. The floor is usually levelled, plastered and maintained with clay washes.

Amongst the low-income community, short life, or katcha, shelter is used predominantly, both in urban and rural areas of Pakistan. According the 1991 report on the low-income group shelter project (as shown in Table2.1 and Figure 2.2), katcha shelter construction accounts for 75% of shelter in both rural and urban areas.

2.3.2 Semi - Pucca Shelter

Semi - Pucca shelter does not require frequent maintenance and can withstand weather extremes. Such shelter is usually of permanent construction except the roof, which is either made of thatch and clay top or is partially permanent, depending upon the type of construction material used in different portions of the roof assembly.

The following materials and structural systems normally used for semi-pucca construction.

a) Walls: Mud layer walls and sun dried brick wall are common. Sometimes the lower portion of the wall is thicker or made of burnt brick to protect it from water
b) Roofs: Flat roof, covered with reed mats and thatch supported by timber beams.
c) Floors: burnt clay floor tiles laid in various patterns, plastered with mud, then clay wash.

Semi- pucca construction is, more or less, used equally in both rural and urban and constitutes 19% of shelter on an overall basis. (6)

2.3.3 Pucca Shelter

Pucca shelter is maintenance-free for years and can fully withstand extremes of climate. It is usually made of processed building material, such as burnt bricks, shaped stone, cement or cement concrete blocks, or a combination of all these building materials. Permanent Pucca construction is, however, more common in urban areas as compared to rural areas. It comprises of 36% of shelter in urban areas and only 6 % in rural areas. (7) The following materials and structural systems are normally used for Pucca construction:

a) Walls: Sun dried bricks finished with lime mortar. Also, burnt bricks with mud mortar or cement mortar and mud bricks plastered with Gara (made of mud and straw).

b) Roofs: Flat, steel 'I' and 'T' sections with burnt clay roof tiles.

c) Floors: Suspended floors are finished with floor clay tiles, ground floor consists of brick soling and 1:2:4 flooring or glazed and unglazed tiles.

While categorising the above-mentioned classes of shelter, it has been assumed that internal finishes do not largely contribute towards structural stability, durability and nature of the shelter.

Table 2.1 Major Types of construction countrywide

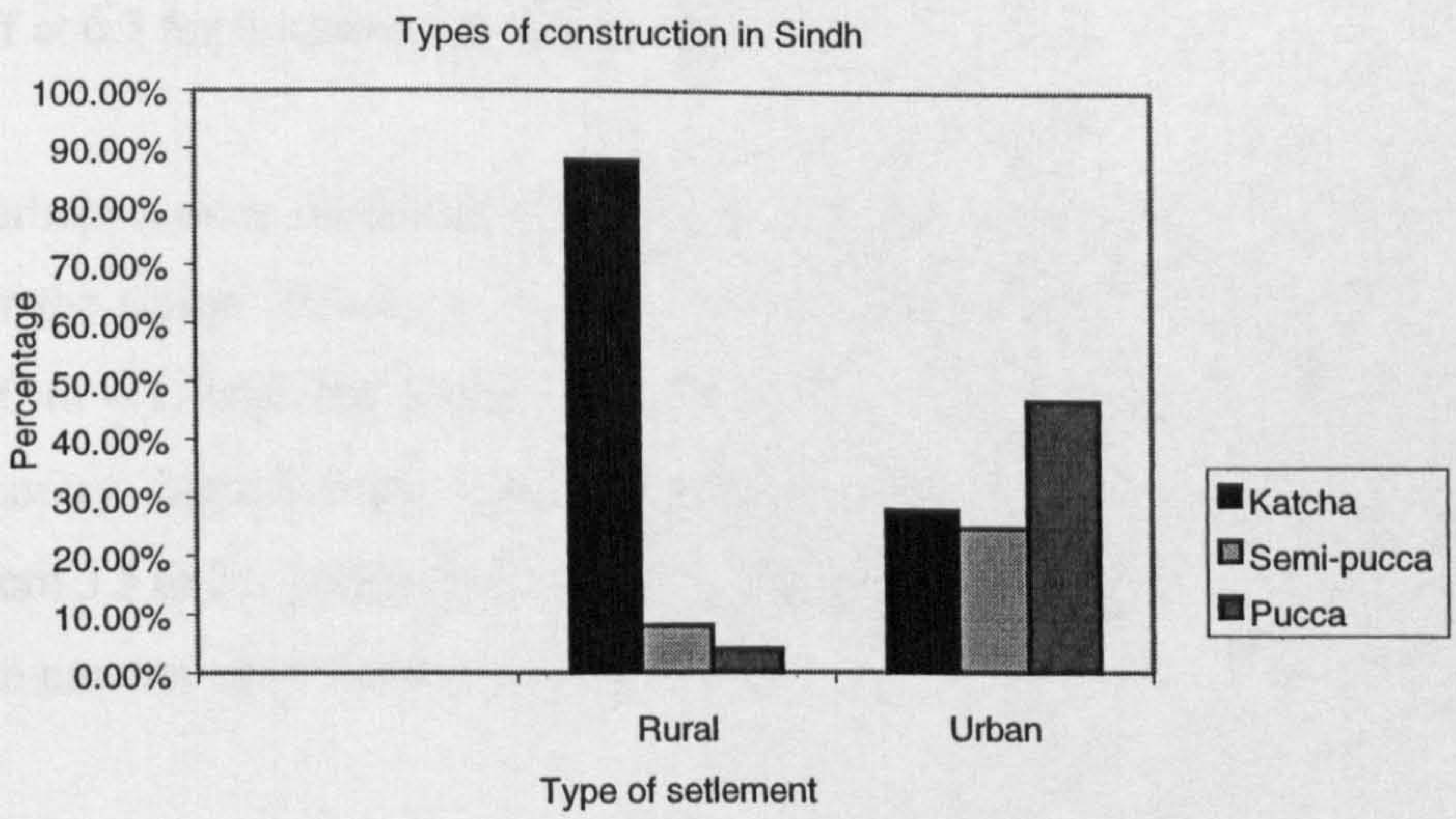
TYPE	RURAL	URBAN
Katcha	75%	45%
Semi-Pucca	19%	19%
Pucca	6%	36%

Source (8)(9)

2.4 Construction in Sindh

In Sindh, Katcha construction is the dominant type of housing, especially in rural areas, where it is used for more than 80% of houses. The Predominance mainly of Katcha construction is due to the lack of accessibility to new and stable construction materials, and the poor financial situation of households and practice of new material for construction. Usually rural housing in Sindh is based on self-help, although sometimes local labour is used to construct houses. In rural Sindh the women's contribution to construction of houses is also observed, especially in maintenance work of walls and the kitchen. This maintenance work is usually undertaken twice a month to improve the look of the outer skin of the walls and floor.

There is an additive nature to houses in rural areas. The rural house is perhaps, never complete; as each extended family grows, so does the house, thereby reflecting the history and family structure of a number of generations. As individual members of the family become economically independent they reside as nuclear families in individual dwellings but near to their parents i.e. always within the same courtyard. (8) Figure 2.2 shows the percentage of the types of construction in rural and urban settlements of Sindh.



Produced by author: Data Source (9)

Figure 2.2 Major Types of construction province of Sindh on rural - urban basis.

In urban Sindh settlements, Pucca construction is dominant, with Semi-pucca and Katcha construction having almost equally prevalent

2.5 The Existing Housing Condition in Sindh

The rural-urban dichotomy in Sindh is put into clearer perspective by the comparison of housing conditions in each sector. The availability of the results of the 1989 Survey housing allowed provincial teams to make these comparisons, as well as gauge the improvement in the housing stock since 1980. The results from the survey can also be used an indicator of the current housing scenario. The following four measures have been considered as indicators of the housing situation in Sindh in this study.

i. Through an increase in population.
ii. Through changes in the size of the house units.
iii. Through the type of construction materials used.
iv. Through changes in tenure.

2.5.1 The Measurement Through Increase in Population

The most commonly used indicator of the housing situation is the number of persons per housing unit, which is directly proportional to population growth. Figure 2.3 (a) and 2.3 (b) shows between 1980 and 1989, that, the number of persons per housing unit levelled off at 6.7 for the nation as whole, and remained at about 7.0 in Sindh. (10)

Perhaps a more meaningful measure is persons per room, which declined from 3.5 to 3.3 for the nation. However, in Sindh the person per room figure it increased slightly from 4.0 to 4.1, with the figure in rural areas increasing from 4.7 to 4.9-the highest in the country. Significantly, urban Sindh followed the national pattern by falling somewhat from 3.3 to 3.2 persons per room (5). Figure 2.3 (a) and (b) shows the overall increase in the number of persons per room and house.

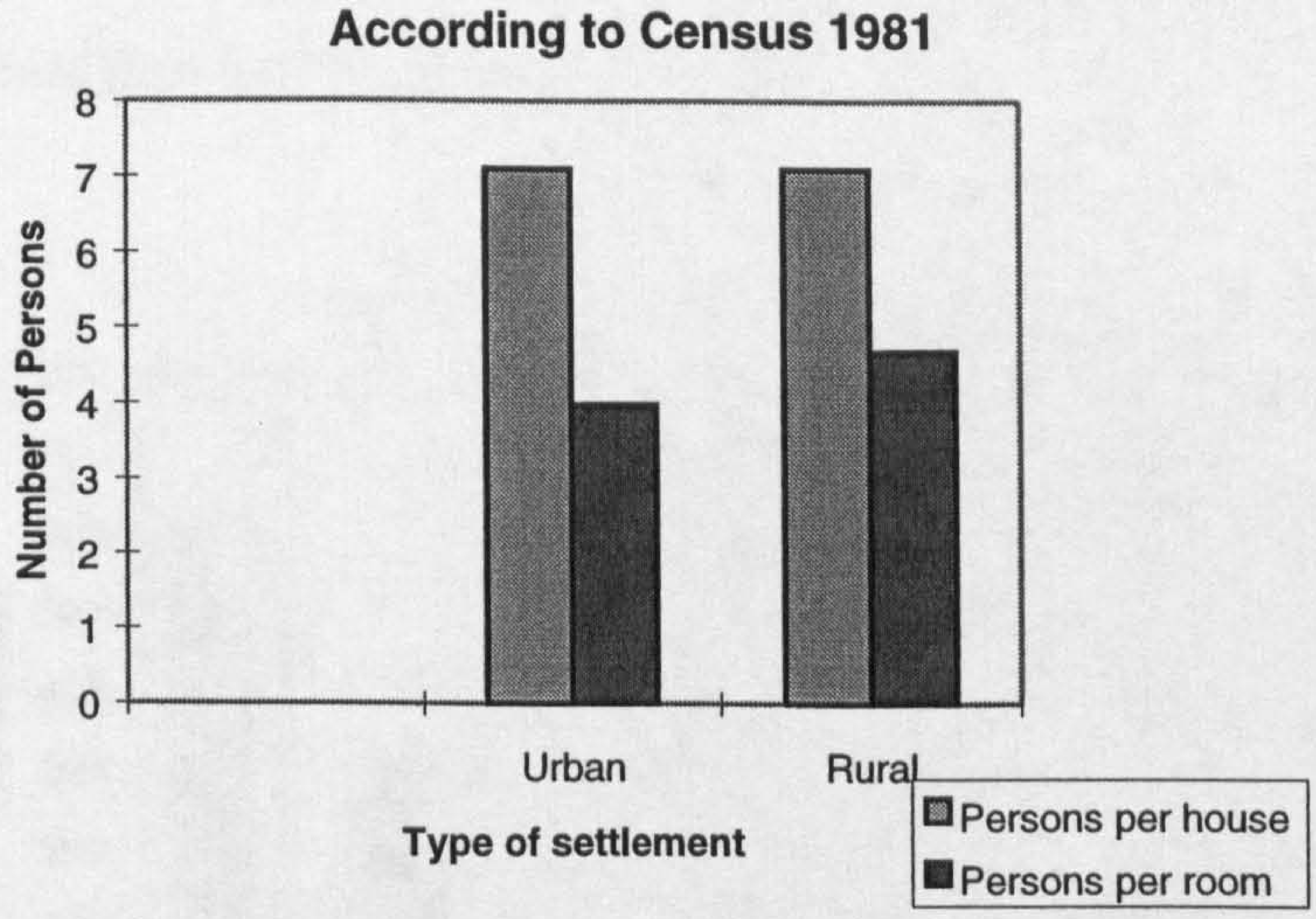


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Figure 2.3(a) Representation of the persons per housing unit and persons per room

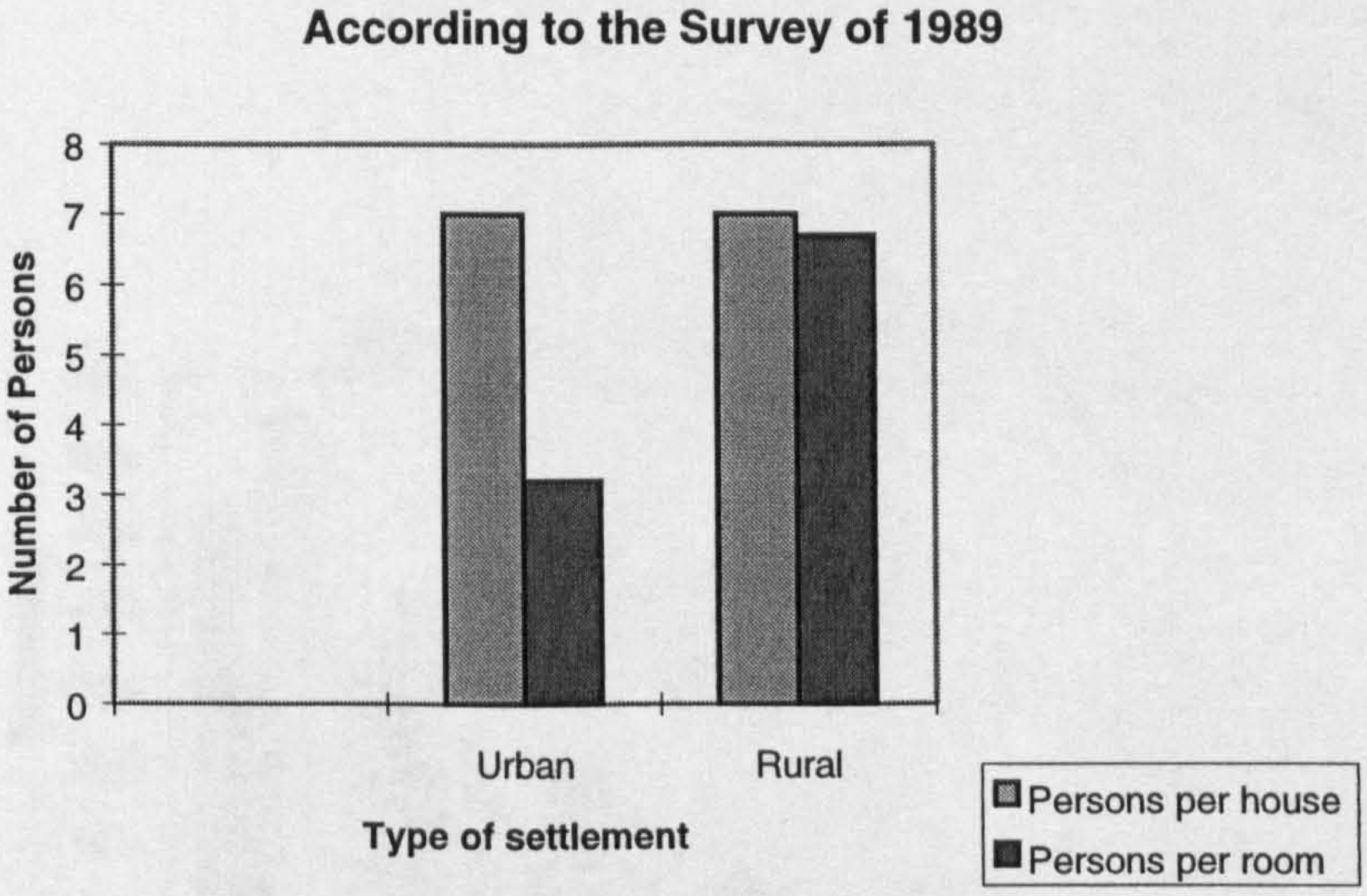

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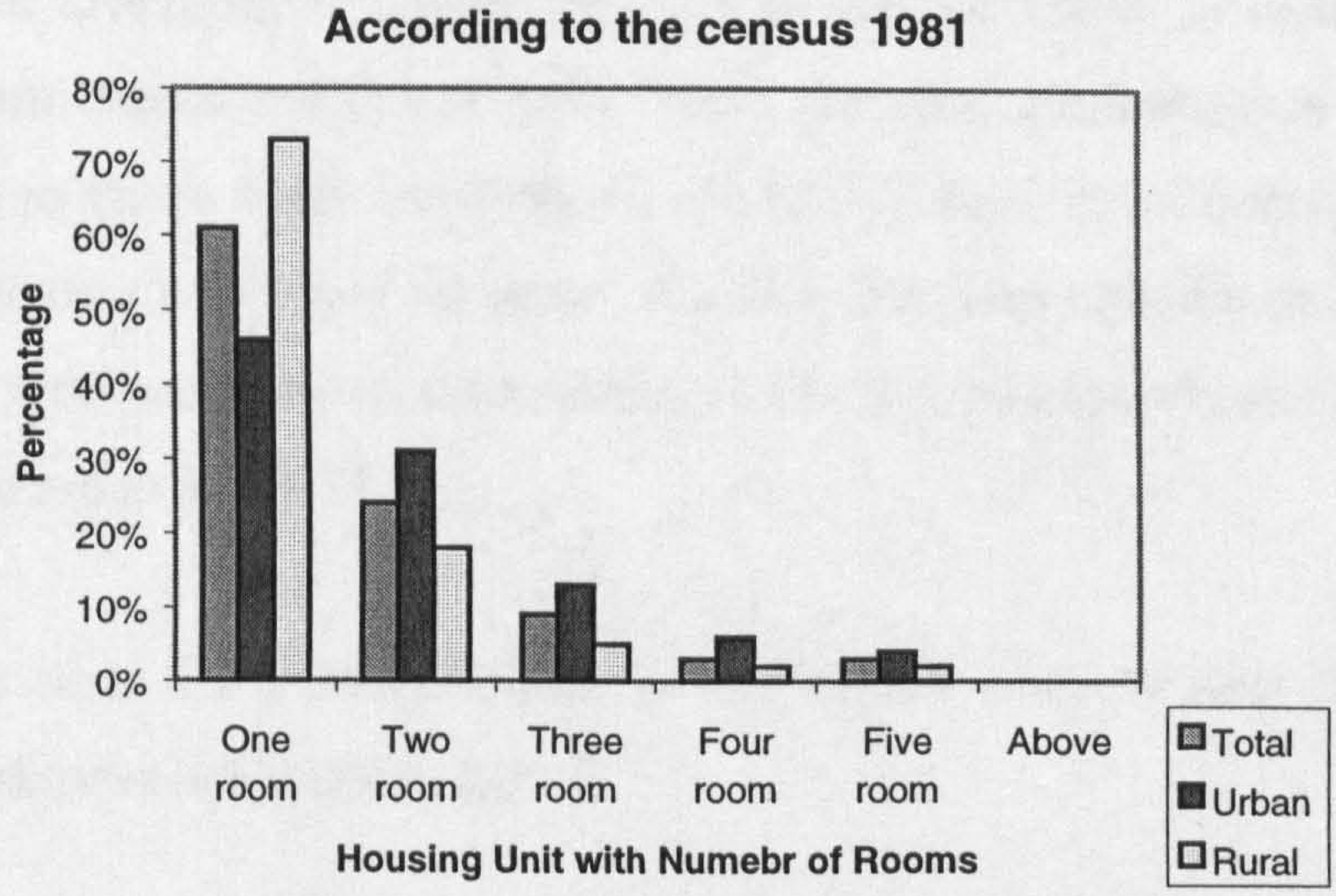
Figure 2.3(b) Representation of the persons per room and persons per house

2.5.2 Measurement through Change in Size of the Housing Unit

Changes in the size of the units are also indicative of the housing situation. According to the survey report, the number of one-room units declined nationally by 15% during the intercensal period, whereas it only decreased by 9 % in Sindh. (11) The rural-urban difference can be clearly seen in Figure 2.4 (a) and (b). One room units in rural Sindh declined by only 8% to 65% of the rural stock, whereas urban one room units declined by 17% to 29%, less than half of the rural percentage. (11)



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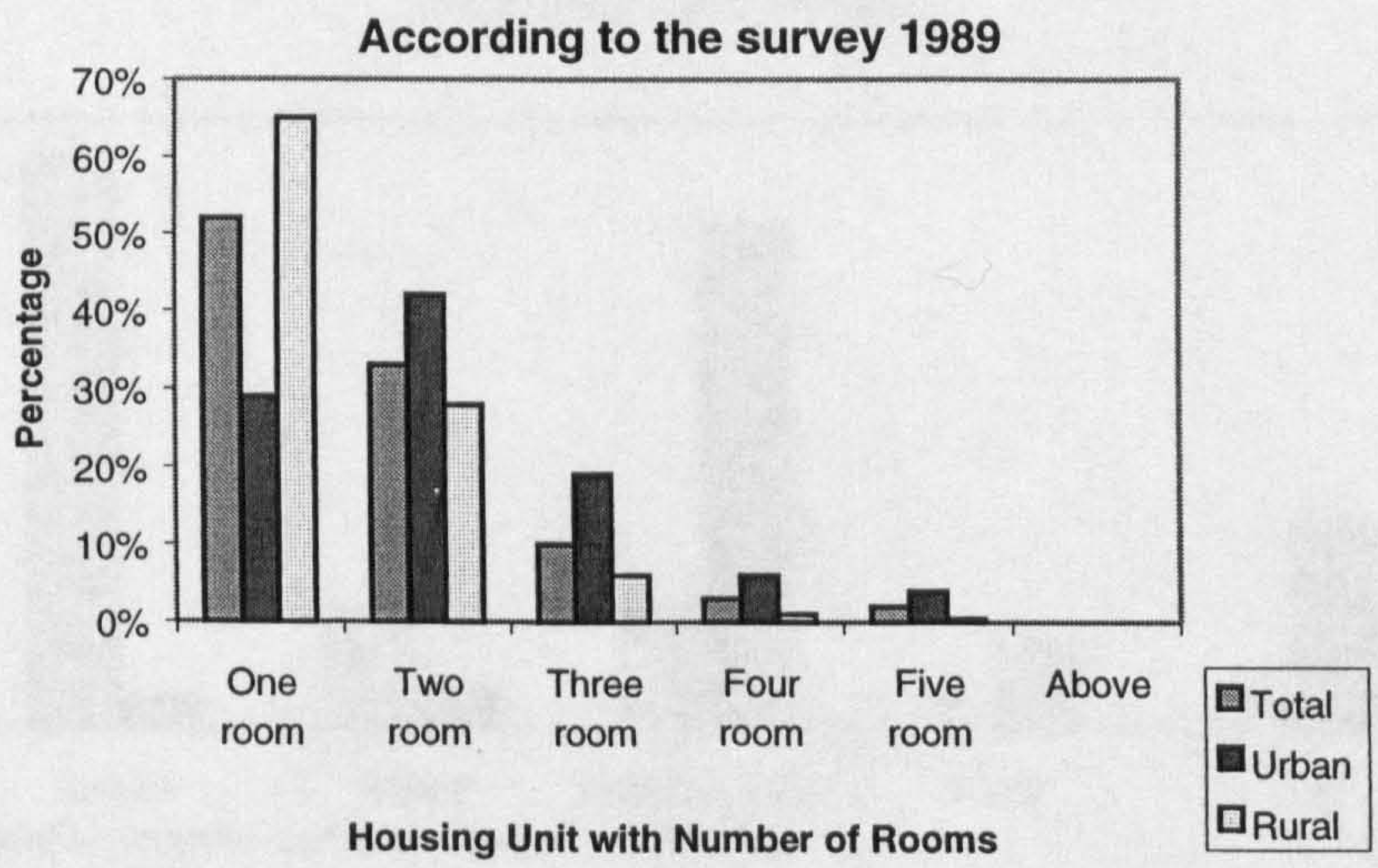

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Figure 2.4 (a) & (b) Sindh: rural housing unit according to the surveys

2.5.3 Measurement through the Type of Materials Used

A third major indicator of the condition of the housing stock is the type of material used in construction. Although in the Figure 2.5 (a) and (b) clearly show the rural-urban split highlighted by other measures, especially in the percentage of the units with Pucca walls in 1980 and 1989.

A more detailed investigation reveals that 11% of Katcha houses in rural areas were improved to semi-Pucca and Pucca walls, while the same percentage in urban areas were improved to Pucca walls and roofs by the help of local development authorities. (8) However, Figures 2.6 (a) and (b) shows that there has been virtually no upgrading to Pucca roofs in rural areas, the total remaining at 1% percent of stock, as against a 10% improvement in urban Sindh. (8)

There has also been a 2% improvement in semi-Pucca roofs in rural Sindh with a corresponding decline in Katcha roofs. (8)

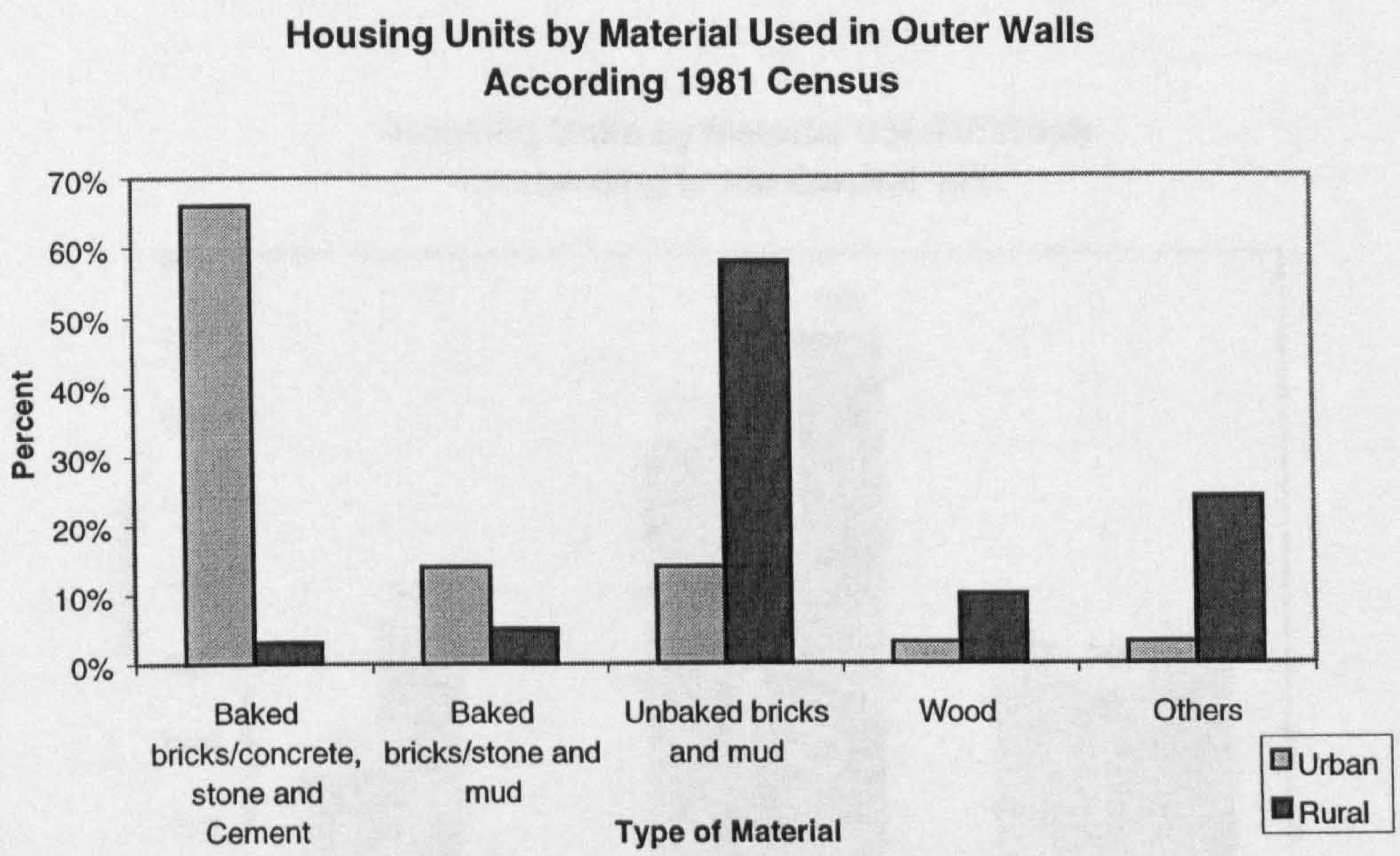

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Figure 2.5 (a) Housing units by material used in outer walls according to the census of 1981.

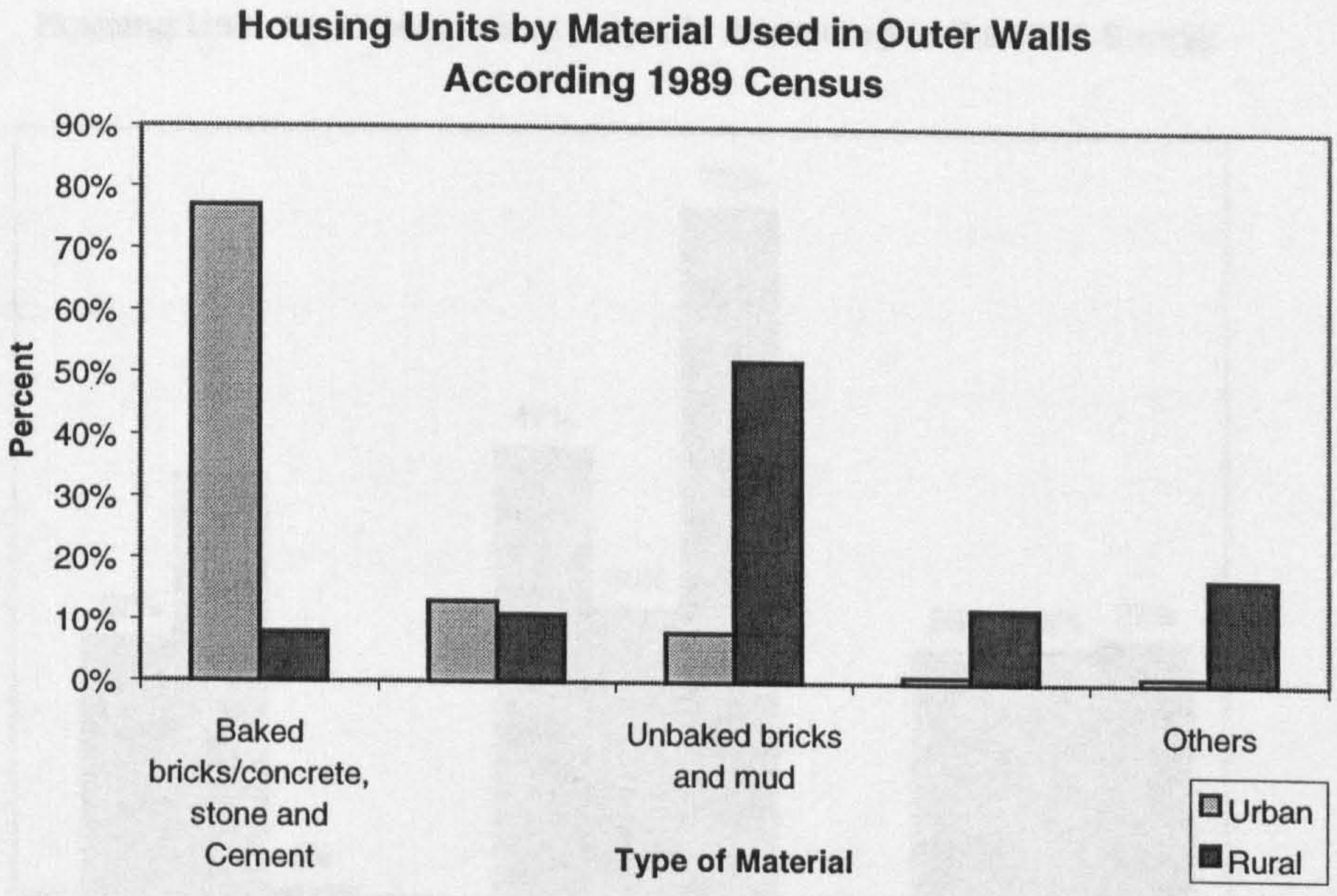

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Figure 2.5(b) Housing units classified by material used according survey 1989

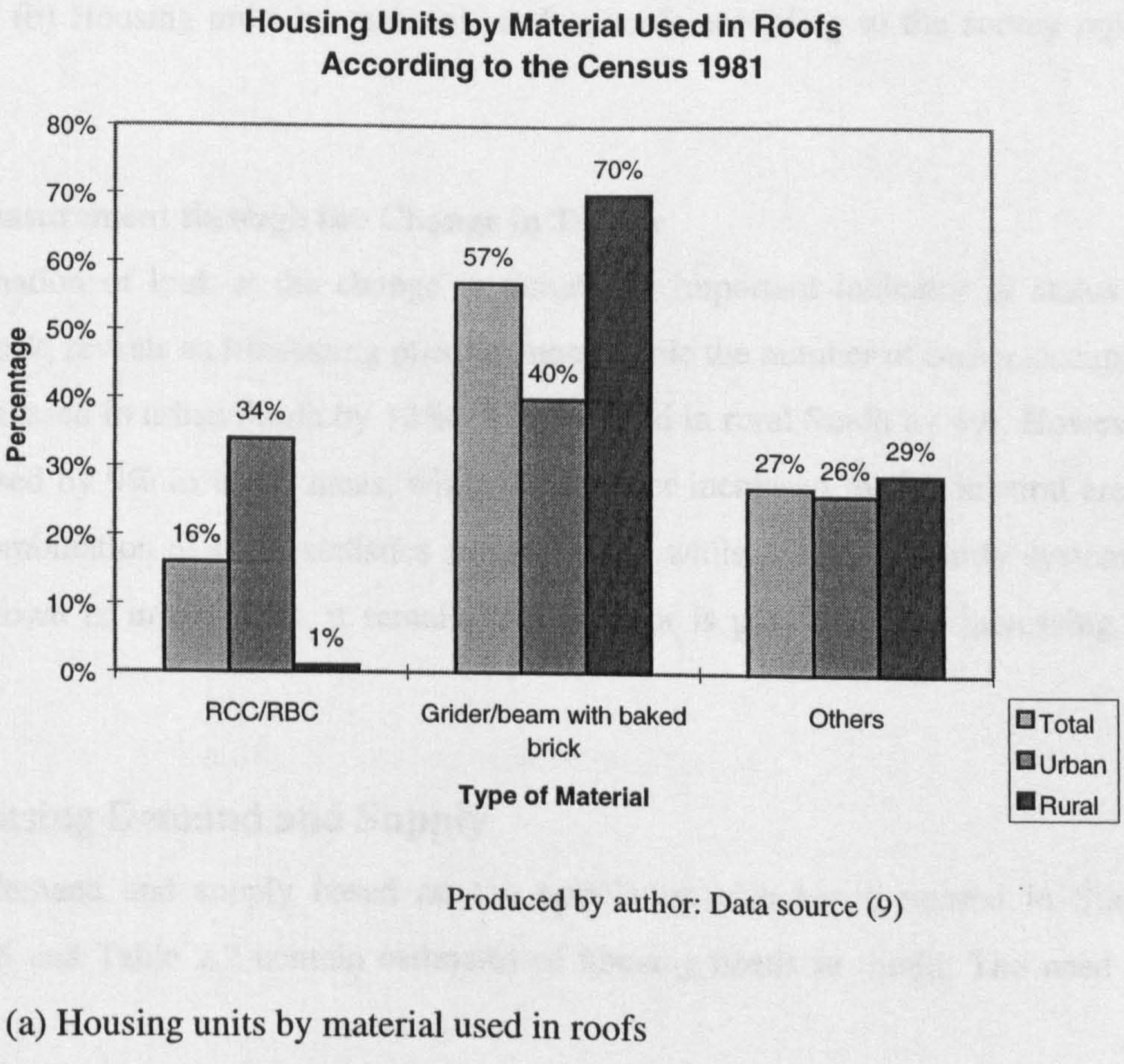

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Figure 2.6 (a) Housing units by material used in roofs

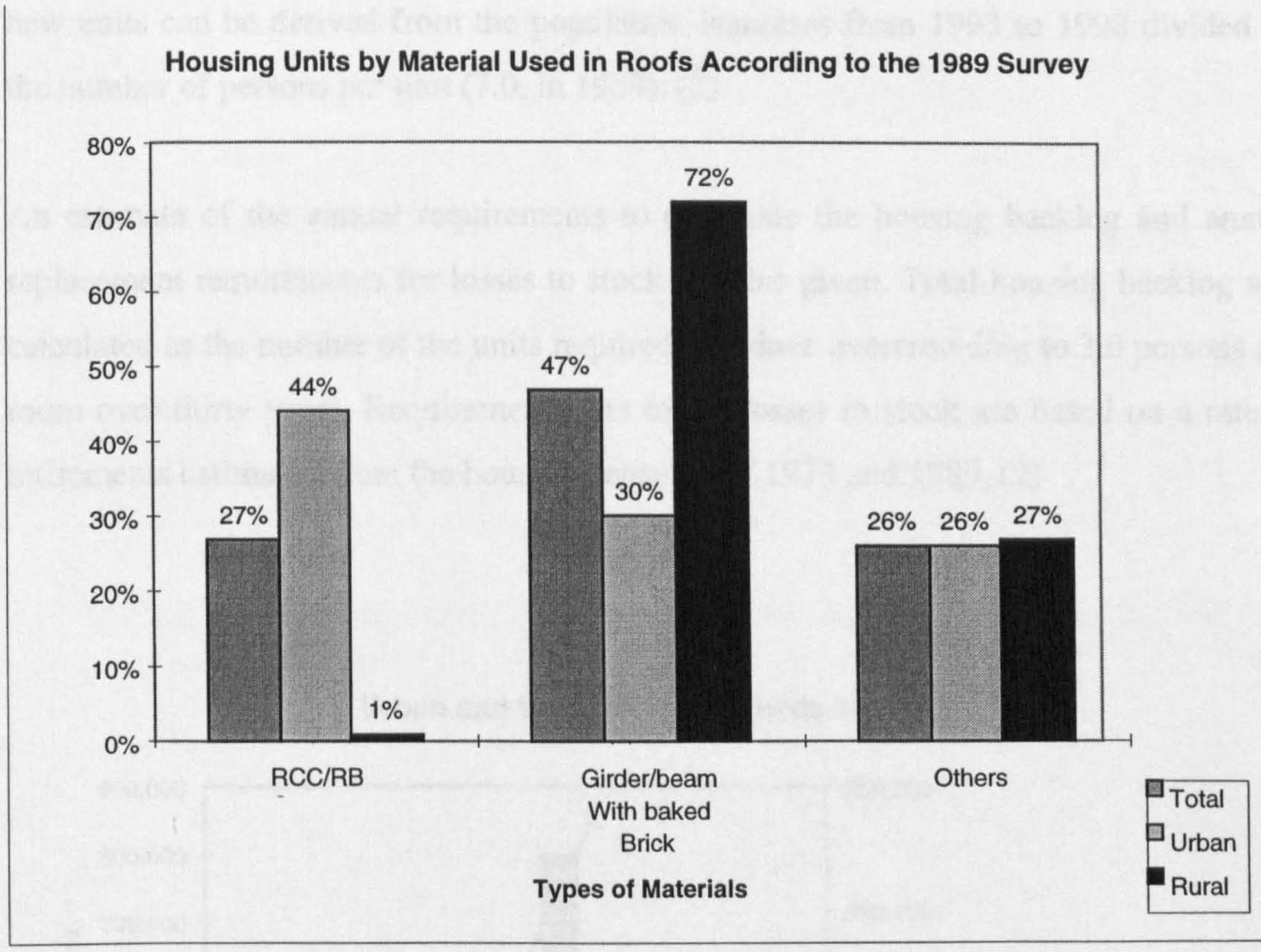

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Figure 2.6 (b) Housing units by material used in roofs according to the survey report 1989.

2.5.4 Measurement through the Change in Tenure

An examination of look at the change in tenure, an important indicator of status of housing stock, reveals an interesting phenomenon. While the number of owner-occupied houses increased in urban Sindh by 12%, they declined in rural Sindh by 4%. However, the decreased by 9% in urban areas, while the number increased by 4% in rural areas. (6) The combination of these statistics suggests that, whilst the joint family system is breaking down in urban areas, it remain prevalent, or is possibly even increasing, in rural areas.

2.6 Housing Demand and Supply

Housing demand and supply based on the population size has increased in Sindh. Figures 2.6 and Table 2.2 contain estimates of housing needs in Sindh. The need for new units can be derived from the population increases from 1993 to 1998 divided by the number of persons per unit (7.0, in 1989). (5)

An estimate of the annual requirements to eliminate the housing backlog and annual replacement requirements for losses to stock are also given. Total housing backlog was calculated as the number of the units required to reduce overcrowding to 3.0 persons per room over thirty years. Requirements due to the losses to stock are based on a rate of retirements estimated from the housing censuses of 1973 and 1989. (2)

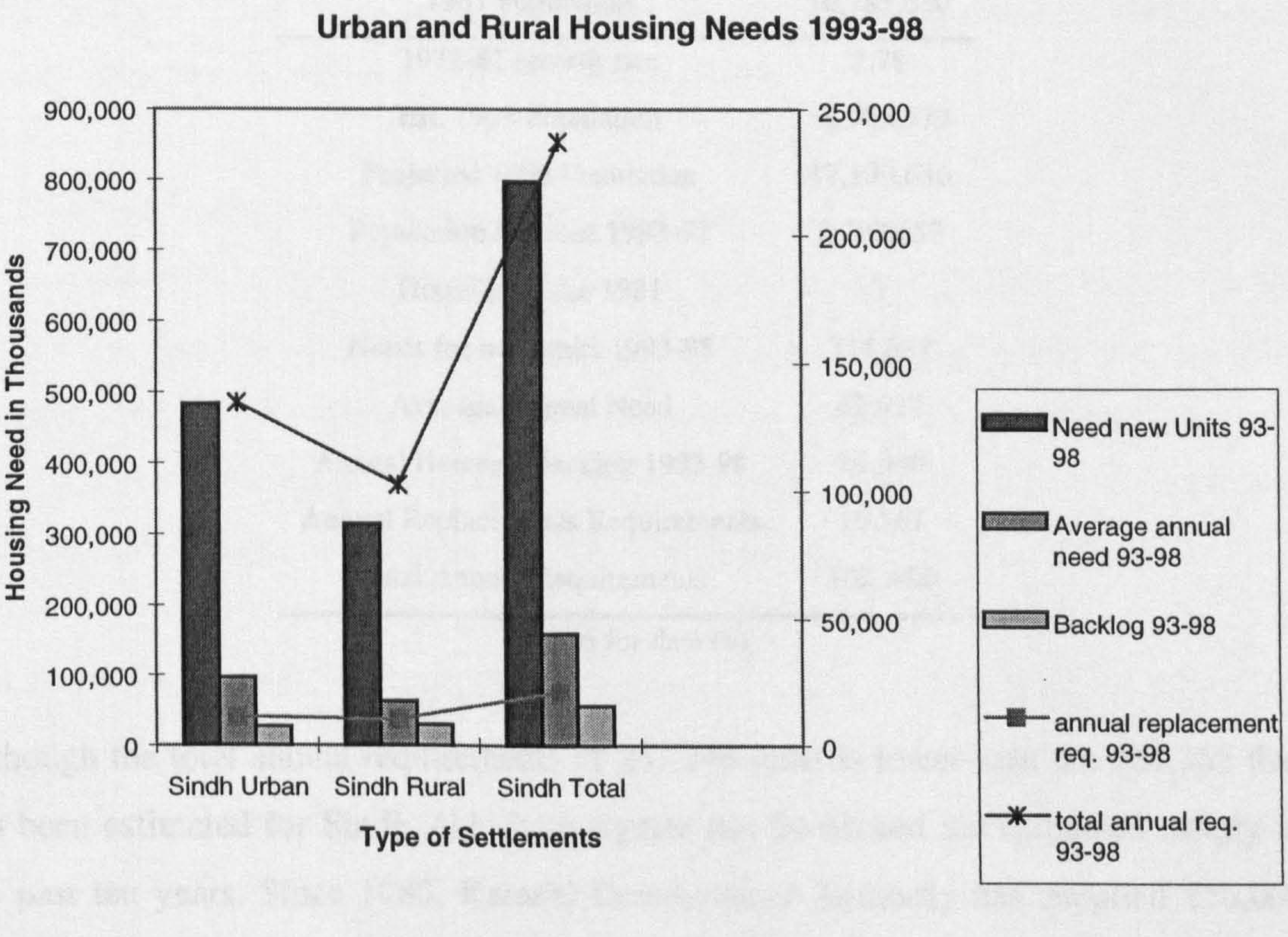

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Figure 2.7 Housing demand and supply

Table 2.2 Sindh: Urban and Rural Housing Needs- 1993 to 1998

	Need for new units 1993/98	Average annual need 1993/98	Annual housing Backlog 1993/98	Annual replacement req'mnts 1993/98	*Total annual Req'mnts 1993/98*
Sindh Urban	483,060	96,612	26,680	11,356	*134,648*
Sindh rural	314,637	62,927	29,506	10,167	*102,600*
Total Sindh	797,697	159,539	56,186	21,523	*237,248*

Table 2.3 Sindh Rural Population Projection and Housing Needs 1992-97

1981 Population	10,785,630
1972-81 growth rate	2.78
Est. 1993 Population	14,988,179
Projected 1998 Population	17,190,636
Population increase 1993-98	2,202,457
Household size 1981	7
Needs for new units 1993-98	314,637
Average Annual Need	62,927
Annual Housing Backlog 1993-98	29,506
Annual Replacements Requirements	10,167
Total Annual Requirements	102, 600

Source for data (5)

Although the total annual requirements of 237,248 units is lower than the 261,355 that has been estimated for Sindh, (11) both figures are far exceed the estimated supply in the past ten years. Since 1980, Karachi Development Authority has supplied 156,000 plots, including Scheme 33, and the Hyderabad development Authority a further 57,000. In addition, there have been about 7,800 building permits approved annually in Karachi over the past three-year. (12)

The gap between formal supply and total demand highlights the fact that occupant households construct most of the new housing stock, informally and incrementally. However, in rural Sindh, this means of construction is twice as prevalent as in urban areas (3). Thus in rural Sindh, overcrowding has increased to 4.9 persons per room, 44 % higher than the national average. (12)

2.7 Government Programmes for Rural Housing

According to the National Housing Policy of Pakistan, many agendas have been considered to improve the rural housing situation. Most of them were influenced by political ideology and undemocratic dismissals of assemblies-factor, which have constrained the implementation of housing policy.

Thirteen agendas, or issues, were described in the National Housing Policy for Rural Development. (4) The Seven Marla Scheme is currently being implemented and some of the initiatives have been taken from the working bodies.

2.7.1 Plot Development (Seven Marla Scheme)

Given the priority of rural housing in Sindh, the Seven Marla Programme was converted to the Goth-Abad Scheme under which landless village households were issued titles (Sanads) to their house plots. However, it is uncertain whether the priorities of the rural poor lie in the provision of the better services, i.e. water, drainage, sanitation and access roads, to their village, or within the provision of plots and building loans. (9)

The Sindh Goth - Abad Directorate has issued over 770,000 Sanads to landless rural households since 1987. In order to ascertain the priorities of the villagers, the Sindh Team undertook a rural housing survey in 67 villages in every district of the province. (9) The survey determined that, while village services such as drainage and health were a priority, there was also a significant demand among villagers for housing improvement and extension loans. The results of the survey therefore became part of the justification for the proposed rural housing loan programme by the low-income community shelter project.

Table 2.4 shows the findings of the survey team in rural Sindh.

Table.2.4 The representation of facts and figures of the surveyed villages

Housing Characteristics	Villages population with over 1000	Villages population with over 500
Number of Districts	15	15
Number of Taluka	69	69
Number of settlements	958	3,543
Population	1,527,572.00	3,269,979
Households	201,012.00	447,691
Household size	7.6	7

Source Human settlements Survey Housing Typologies in Taluka/ District with population Greater than 1000 and 500 (1981).

2.8 Community Profile: Problems and Priorities Villages

The survey report of shelter for low- income communities shows that, community participation is greater in areas where holdings are small than in areas with large holdings. The response from households proves the presence of community and village organisations. The majority of these organisations are working in the field of education, basic health facilities, industrial home credit and promotion of cleanliness in the community. The types of resource available for future development in housing related were also investigated. The survey found that 43 % of responses centred on voluntary participation in the form of labour, 35% towards donating land and 22 % showed their willingness to contribute cash. (9) Further survey shows the following findings in Table 2.5.

Table 2.5 Villages with and without community groups

Community Groups	No. in Sample (100)	Percentage
Villages with Comm. Groups	26	26
Villages without Comm. Groups	74	74
Total	100	100

2.9 Housing in Relation to Other Problems in Rural Sindh

Rural Sindh is relatively developed area, and general policies by governmental and non-governmental organisations aim to address the severe lack of infrastructure, which was highlighted by survey. (9) The provision of housing has been historically neglected by most organisations. This is due to a stereotypical image of villagers needing a health service, drainage or water supply etc. rather than the provision of housing. The need for housing should be given the some priority as for health and other basic amenities.

In terms of the other problems e.g. drainage, water, electricity, health and etc, the housing problem on a household level has been found to be about 20% and the village level the problem reaches 11%. (13)

2.9.1 The priority given to 'the need for housing' by villagers

The data from the survey of low-income communities' revealed the presence of a hierarchy of needs among villagers in rural Sindh. The results show that 68 % of surveyed people give first priority to the provision of housing and loan construction (Figure 2.7). Other facilities are on the same overall level of need. (2)

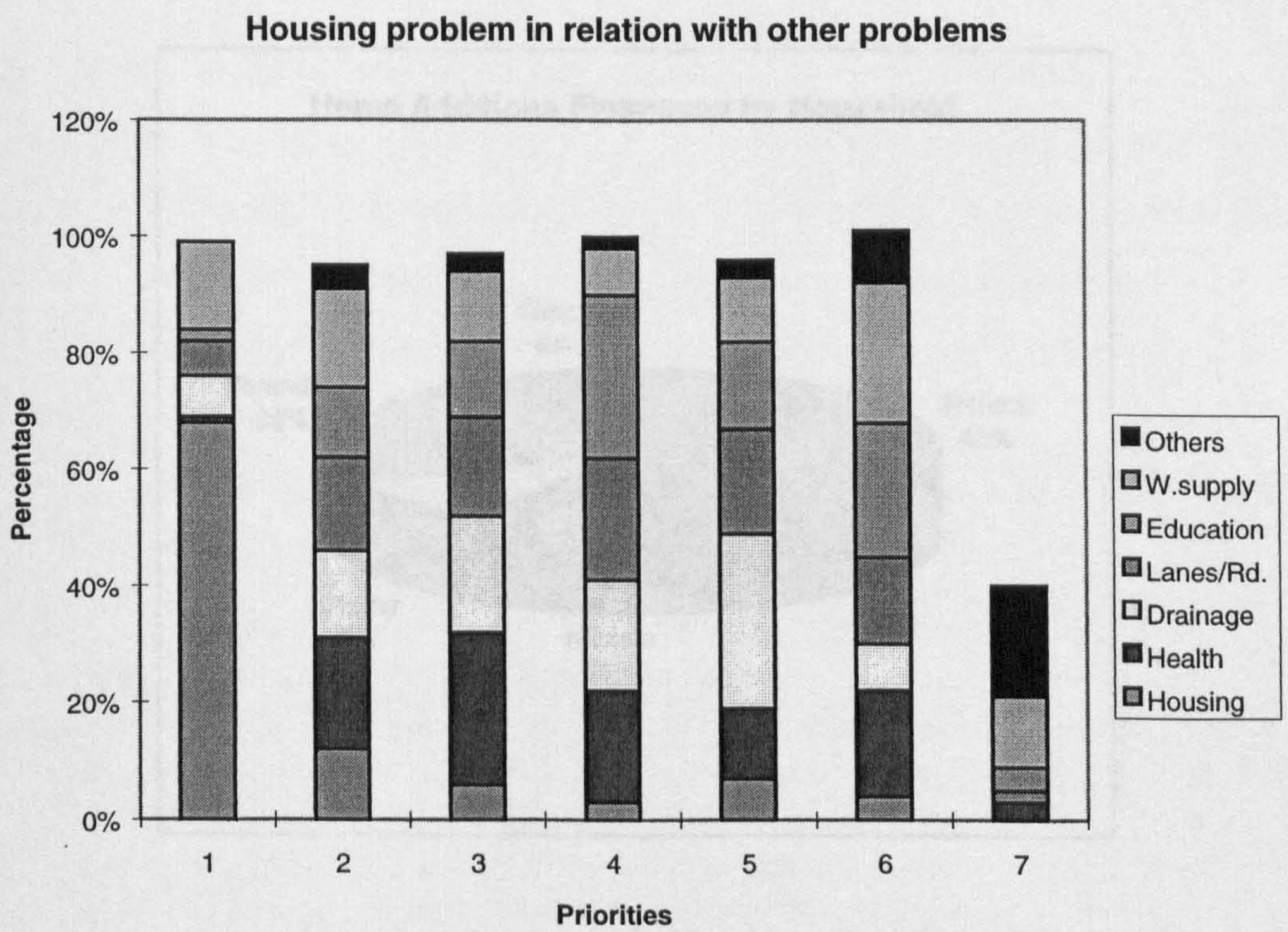

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Figure 2.8 Problems and status of the problem with reference to priorities

2.10 Home Additions and Improvements: Financed by Householders

Most improvements and extensions are usually financed and carried out by the household. Occupants of house usually carryout in maintenance, such as uplifting the outer skin and other seasonal maintenance requirements. This seasonal maintenance is necessary because of the instability of the construction material.

The percentage of improvements to existing structures is higher than for home extensions; 88% of households reported undertaking some formed face lift to their dwelling of these housholds (16), 36 % made improvements in roof structure and 34% to plaster work. (2) Also, 21% reported other improvements, such as storage space, boundary wall, veranda and latrine. (5)(13) (Refer the figure 2.8 (a) and (b)

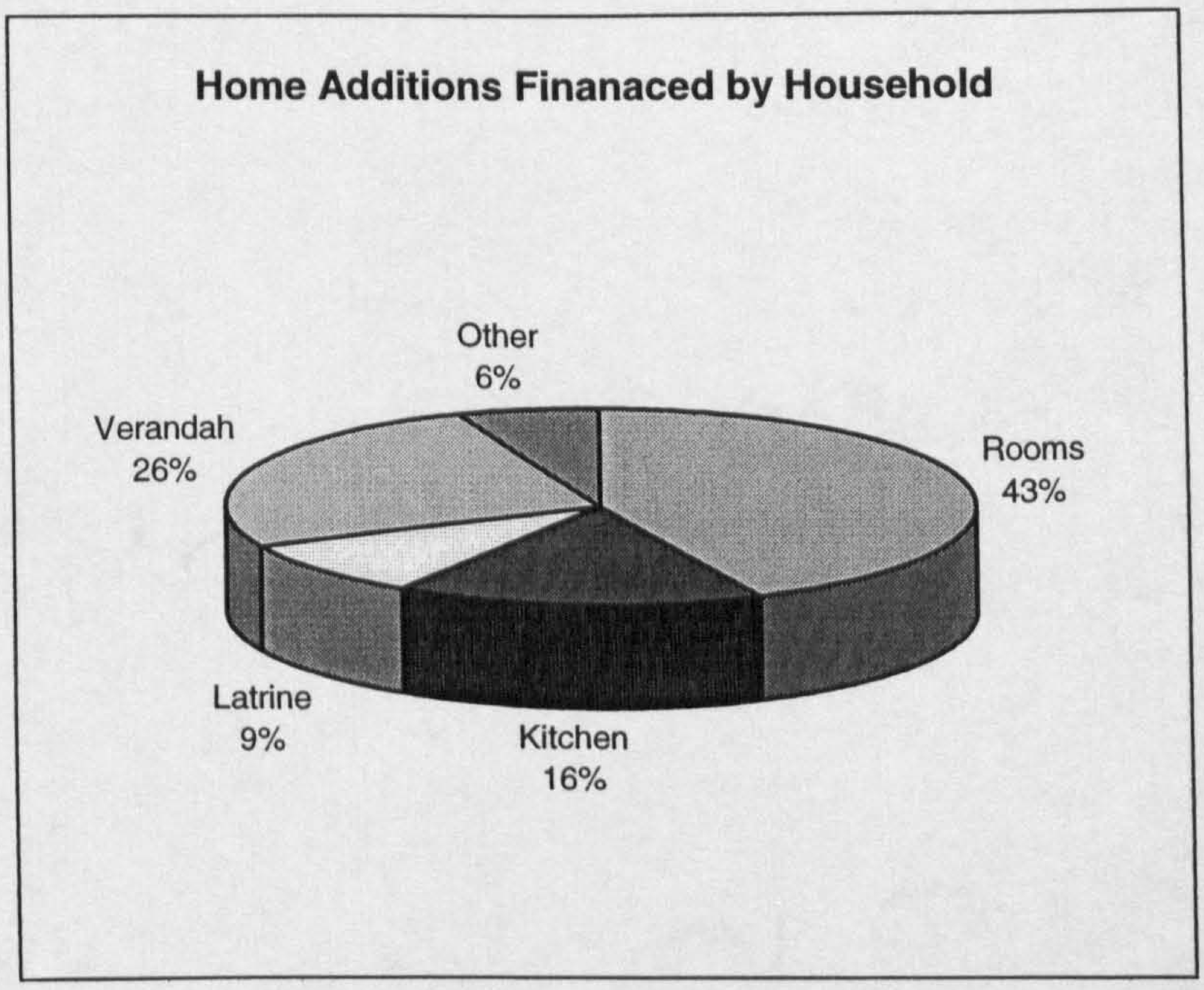

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Figure 2.9 (a) Home additions financed by household

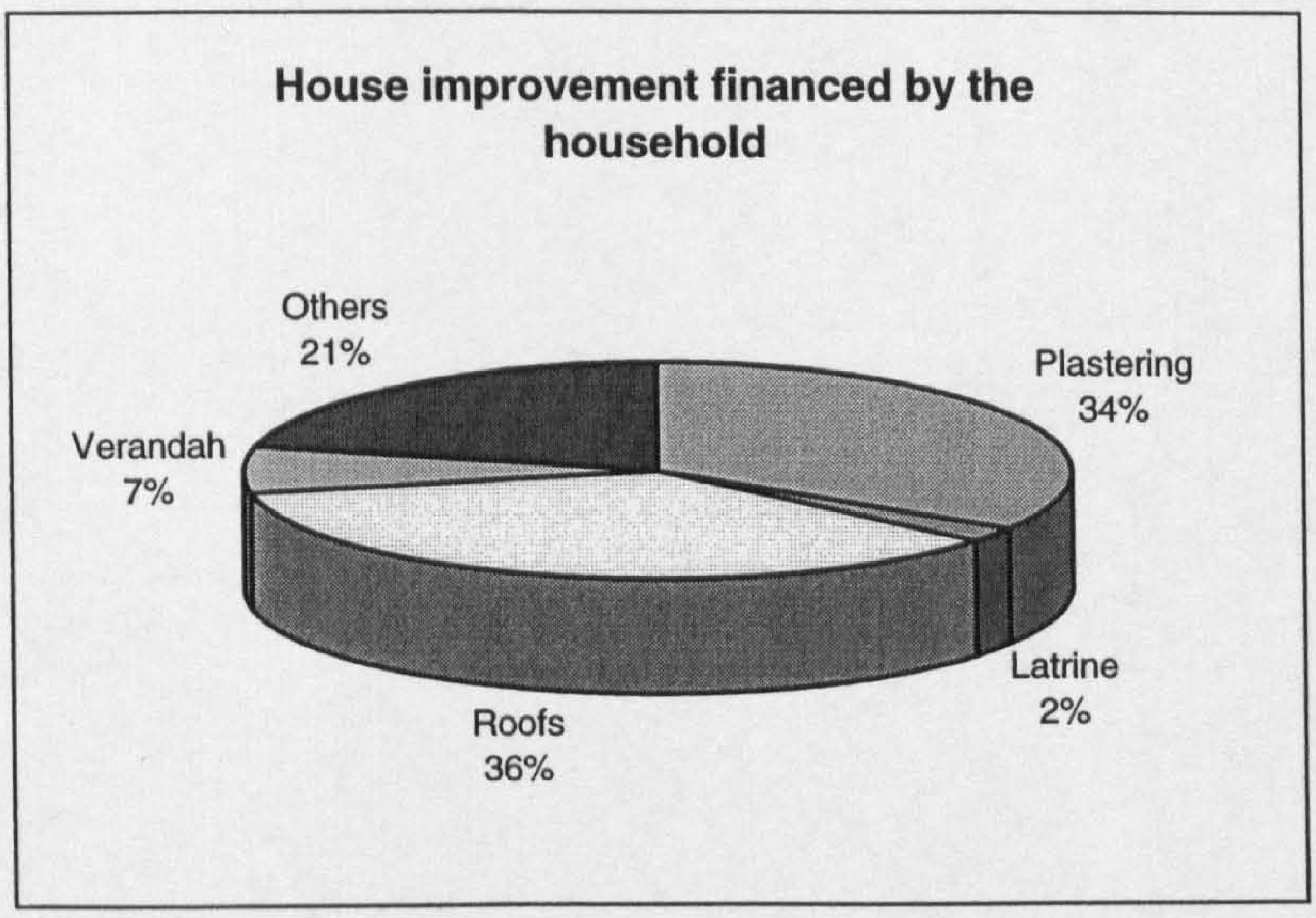

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Figure 2.9 (b) House additions and improvements financed by household

2.10.1 Other sources of finance for home addition and improvement

The finance for the extensions or improvements comes from a variety of sources. The main source of finance is personal savings, with, to lesser extent, help being provided by official institutes. The mandate for institutional lending is clearly written in the housing policy document (Rural housing policy, Point 5 Institutional Credit') as follows: (14)

> **" To provide institutional credit for the construction and maintenance of rural housing, the following steps are recommended:**
>
> a) Commercial banks should also extend their loan facilities for house construction and improvements in rural areas;
> b) Formation of rural housing co-operative societies should be encouraged which will entitle of these societies to secure house construction loans from the provincial co-operatives Bank;
> c) The small business finance corporation's charter should be amended so that it can advance loans for home improvements in the rural areas;
> d) Savings and mutual guarantee associations should be established to encourage savings and loans;
> e) The possibility of giving loans in the form of building materials for village improvements or house building should be studied."

The following Figure 2.10 represents the involvement of various factors for financing housing improvement and extension.

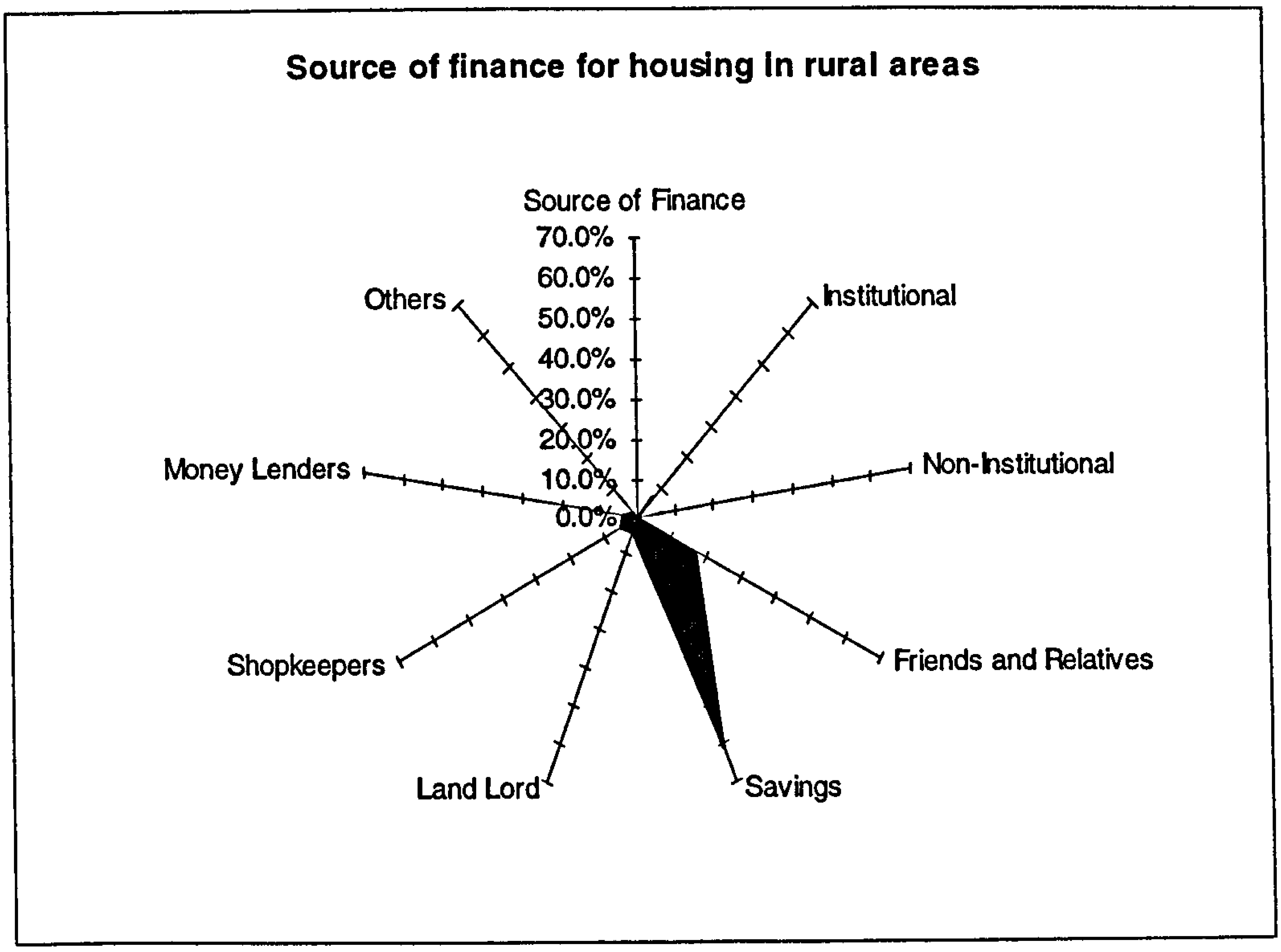

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Figure 2.10The source of finance for housing in rural areas.

These findings reflect a pattern of incremental construction in rural areas, irrespective of household income. The increase in the number of relatives, especially in joint households, is also seen as a contributory factor to the growth in construction of extensions and home improvements. (9)

2.11 Investment and Improvement on Housing in Surveyed Villages

Loans have been issued to villagers by the development authority according to the housing policy (Seven Marla Scheme). Table 2.6 shows the distribution of loan finance to villagers in the surveyed villages for improvements and extension of the household.

Table 2.6 Amount invested for improvement and extension of the household

Amount in Pakistani Rupees		Percentage
up to 10,000	£200	38
RS. 10,000-30,000	£200-400	28
RS. 30,000-40,000	£400-500	11
RS. 40,000-60,000	£500-800	7
Above 60,000	£800	16
Total		100

It is evident from the survey data that households have relied on non-institutional sources, mainly savings (61%), for home extensions and improvements. However, majorities of those households undertaking new construction have obtained loans from institutional sources such as the HBFC (Housing Building Finance Corporation) and ADBP (Agricultural Development Bank Project). (7)

Table 2.7 Loans obtained for construction, addition and Improvement

Housing Construction	Percentage
Loans obtained for New construction	14
Loans obtained for Home additions/improvements	86
Total	100

The percentage of sample households that borrowed money for new construction low (14 %) compared to loans for home additions/ improvement 86% (16).

Table 2.8 Sources of finance for construction

Source of finance for new construction	Percentage
H.B.F.C	37
Friends and relatives	25
Employer	19
Shopkeepers	13
Money Lenders	6
Total	100

(9)

Table 2.9 Amount borrowed for construction

Amount borrowed for new Construction		Percentage
Up to RS. 30,000	£600	31
RS.30,000-40,000	£600-800	19
RS.40,000-50,000	£800-1000	13
Above 50,000	£1000	37
Total		100

(9)

According to the above tables, 66 % of respondents spent up to Rs. 30,000 (£1.00 = 83 Rs.) on home additions and improvements whereas 50% borrowed up to Rs. 40,000

(£1.00 = 83 Rs.) for new construction. This indicates the positive impact of the **Sanads** on rural households. They have not only given them a sense of security, but also provided against loans from institutional sources can be secured.

Although rural dwellers have to go through a bureaucrat procedure for obtaining loans, usually accompanied by demands for illegal payments at each and every step, many households have no other choice but to apply to institutional sources such as HBFC. (9) HBFC usually takes interest rates on loans as follows in Table 2.10.

Table 2.10 Interest rates on the loan

Interest Rates	Source
UPTO 12 percentage	H.B.F.C
12-24 Percentage	Money lender

2.11.1 Credit and Savings

The sources and pattern of financing for both new construction and additions/improvements to existing dwellings include both institutional sources (such as HBFC, ADBP, commercial banks and co-operatives) and non-institutional sources (private loans, savings, moneylenders, shopkeepers, etc.). It can be seen in Figure 2.9 that 94% of credit is raised from non-institutional sources. This compares to a figure of 62% of credit needs being financed by savings in rural areas. (8)

The proportion of self-financing of home improvements rises as income level increases (See Table 2.11).

Ten percent of home improvement loans in low-income group come from savings- a figure that rises to 26% and 25% in the lower middle and upper lower income groups, respectively. (7)

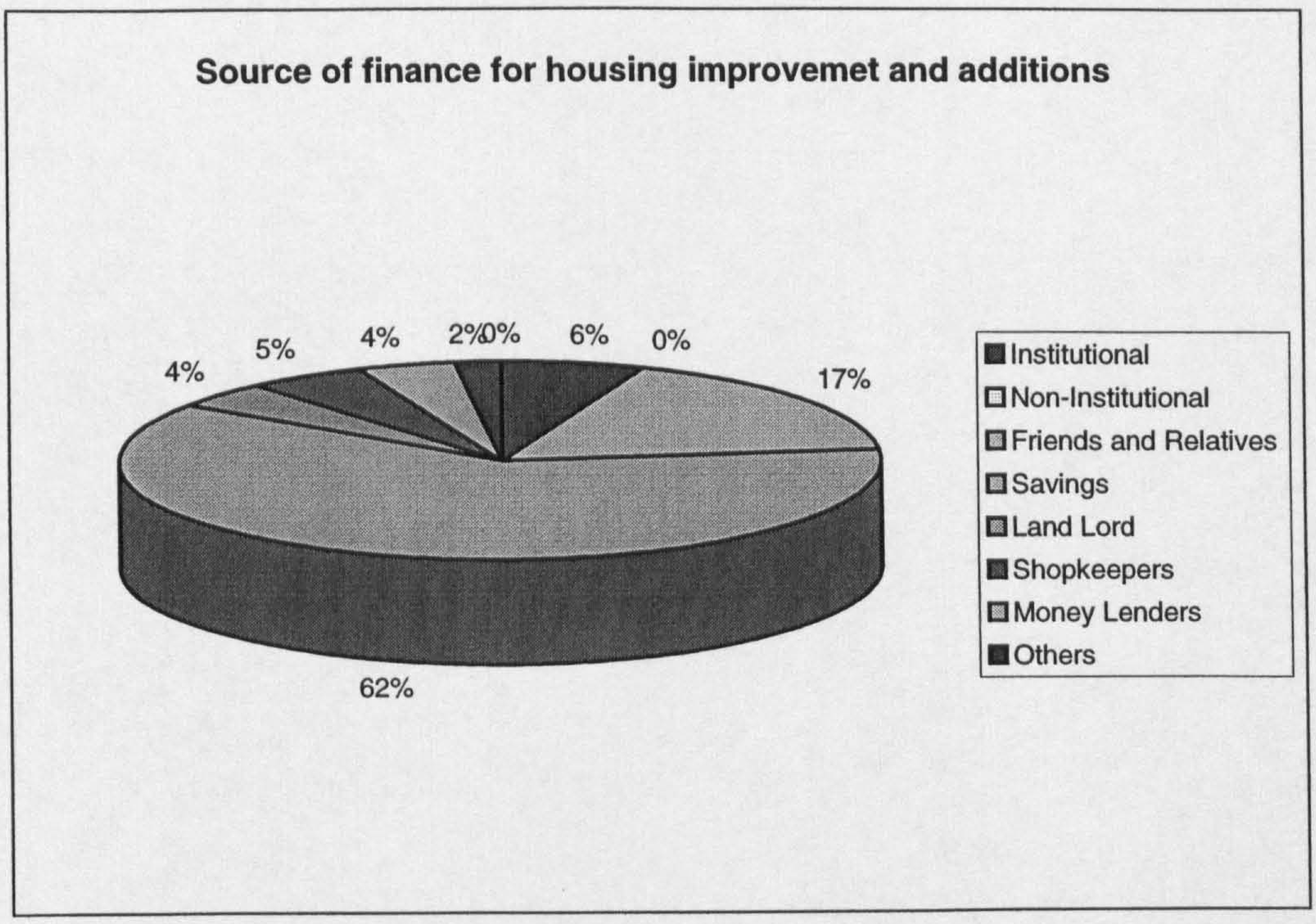

Figure 2.11Sources of finance for home improvements and additions. (Produced by author)

Table 2.11 Loans from various sources according to income group

Sources	Lower(Rs.1000) £20.00	Middle (Rs.1001-2000) £20.01-40.00	Upper (Rs.2001-2500) £40.01-50.00)	total
Banks	1%	3%	2%	6%
Friends & Relatives	5%	9%	2%	17%
Savings	10%	26%	25%	61%
Landlords	2%	2%	-	4%
Money Lender	3%	1%	-	4%
Shopkeeper	3%	2%	1%	6%
Other	1%	1%	-	25

(6)

However, 9% of home improvements loans to lower middle income households comes from friends and relatives, whereas only 5% of home improvement loans in the group originated from this source. It is also worth noting that among the 4% credit share of moneylenders, 3% was borrowed income from families'. (10)

2.12 Rural Housing Improvements

'Rural housing' is often a loosely defined term. However, it must be specifically defined for the purpose of effective policy formulation. It is necessary to recognise the following factors in defining the 'rural housing':

- Formative processes of religion, culture and social norms.
- The nature of the building processes practised (construction organisation, supervision, material acquisition and use of building skills).
- The nature of the building design processes.
- The use of long existing models and the influence of new house design and construction models.
- The relationship of dwellings to settlement pattern and rural regional development.

Analysis of the survey findings presented above has confirmed the importance of incremental extension and structure improvements to the rural household. Thus in shaping of any housing policy, the importance of considering incremental extension and structural improvement, as well as maintenance can be seen.

Contextual recognition leads to a transformation in perceptual understanding of the house which has been 'observed'. The objective of any housing policy must be to narrow the gap between the perceptions of the rural owner builders and the urban-focused agencies that seek to help them.

By collating general categories of housing form and the building processes that shape them, with classification of types of rural area, the approaches required in housing policy can be determined. (10)

a) Indigenous dwellings of the rural periphery

The rural peripheries are the less accessible areas of Sindh where the folkways are still in the ascendant. The limited range availability and affordability limits the options for varying the design form of housing, but permits a strongly identifiable model for the form of 'the house'. In this situation constant change dominates. Most houses in this group are locally called Katcha. Some however are built in stone and can be classified as semi-pucca or pucca. (9)

b) Vernacular dwelling of the rural heartland

These areas are less isolated that those in category (a). They comprise the green lands and semi- arid areas of Sindh, each distinctively different. There is a widening but still limited range of design and building process options.

Some materials and fashions construction ideas are imported from the adjacent modernising rural regions but continuity is still more significant than change. Most dwellings are semi-pucca, although there is still a significant proportion of Katcha. (9)(12)

c) Popular housing of the transforming rural regions

Popular housing (influenced by international style) is located near the rainy areas and irrigated lands close to national highways and the bigger cities. Here the national economy rather than a local/regional economy are in the ascendant. There is an uncritical absorption of new materials particularly Pre-cast concrete, which is often placed in traditionally conceived structures. Often structural continuity between old and new materials is weak and junction strength poor. Poor site drainage, flooding and earthquakes can lead to building failure. The design intention here is to build pucca dwellings. (12)

d) Urban type houses of modern materials built in rural region.

It is important to mention these types of houses, since they are influential in shaping the aspirations of those now in indigenous, vernacular or popular housing. Although well beyond the affordability of rural households, these 'imported' dwellings set the ideal standards. A situation is created in which it becomes difficult to get households and helpers to focus on 'real' housing needs and ensure that are met in an affordable way. The pucca house has become an icon of aspirational housing and is detracting focus from more realistic that drives out ''the good', i.e. what is and affordable types of housing.

There are profound differences between category (d) and the other three. Category (a), (b), and (c), are based on design approaches that seek to adapt to existing conditions. Alternatively the design approach of (d) is to modify the conditions themselves, e.g. drain the site, bring water to the house by pipe, and use permanent materials. A new niche in the local environment is created. For example, the structural design used in category (d) attempts to resist the effect of earthquakes, whilst in the other categories the approach is to accommodate the effect of earthquakes through safe, partial collapse and repairable failure of the buildings. (12)

The move from adapting to local conditions to resisting local conditions of climate, geology and site is a major change of design intent. It is an expensive change- one that costs three to four times more than the cost of improving a traditional type house structure constructed on the old philosophy of accommodation and adaptation.

Considering the low-income status of the rural households the main way of achieving improvements in rural housing for the foreseeable future will be the design principle of adaptability rather than resistance. That means that where earth walls are used the effort should be focused on trying to improve their stability and resilience. The move to brick work or concrete block as a walling substitute may represent a cost increase of three to four times over.

There is clearly a need for innovation in order to provide low-cost building material as an alternative to concrete and other high cost, high-energy consumption materials. The specification for such technological innovation of construction materials should comprise of the three main factors:

a) Ease of use
b) Availability
c) Low-cost construction and maintenance costs

In the context of Sindh housing problem, which appears to result from a lack of appropriate construction materials, the solution should focus on the integration of two sources of technology, i.e. traditional and the imported technologies. This concept was discussed in Chapter 1.

2.13 Summary

In order to determine the construction methods in Sindh the low income shelter project classified housing according to the use of construction materials and structural soundness. Three types of construction were identified: (i) Katcha Construction, (ii) Semi-Pucca Construction, (iii) Pucca Construction.

According to the study Katcha construction comprises 80% in rural Sindh due to the lack of finance and availability of stable material.

Based on an examination of the housing situation in Sindh, an 'evaluation' model is proposed. This model, which comprises four measures, or parameters, that are used as indicators of the housing scenario:

(I) The first measure is based on findings that housing stock is directly proportional to population growth. Comparing data from two studies, it has been found that the number of person per house and per room increased in rural areas of Sindh between 1981 and 1989.

(II) The second measure is based on changes in size of the housing unit. In rural Sindh, one room units declined by only 8% to 65% of the rural stock, whilst in urban Sindh, one room units declined by 17% to 29%, less half of the rural percentage.

(III) The third measure is based on the use of construction materials. Earth construction predominates in rural areas of Sindh, although some houses also comprise some timber construction. (but regular uplifting has been observed) From 1980 to 1989 the 11% of Katcha walls were upgraded to semi -pucca walls with the help of developing authority but virtually no upgrading to pucca roofs in rural areas has been undertaken.

(IV) The fourth measure is based on the tenure situation in rural Sindh. Whereas, from 1980 to 1989, the number of owner-occupied dwellings has increased in urban Sindh. The number of owner-occupied houses has decreased by 45% in rural areas.

The housing need and supply is dependent upon population growth. Within the period 1993-98, an additional 314,637 housing units have been needed in rural areas of Sindh, an average increase of 62,927 units per year. The Annual housing backlog is estimated to be 29,506, and the annual replacement requirement is 10,167. The total annual requirements are 102,600 for 1998.

It has also been also found that there is poor implementation of housing policy in rural areas. Housing problems have been a major priority by policy makers in the Government. The Government's involvement in the provision of plots made a considerable improvement to the housing situation, which clearly shows that financial and technical assistance may improve living quality.

'Sanada' not only provides a sense of security for rural villagers regarding housing, but also acts as a source of collateral against which they can obtain loans from institutional sources.

In low-income residential areas, most of the shelter and related services are provided through the informal sector i.e. construction or materials agents. There is a need to replace these with service agencies. Which are mostly inadequate and eventually costly. It is possible through community organisations, by hiring the services of trained engineers, who guide the community workers on how to build drainage lines and improved roads, how to build stable houses, and what material would be most appropriate for a given location.

Four main approaches have been adapted to improve the housing situation in Sindh, see section 2.9. These approaches depend upon the housing type, location access to urban settlements and economic factors. Analysis of survey findings has shown that three approaches are geared towards the structural improvement of buildings with regards to safe, partial collapse and repairable failure. The other approach seeks to modify environmental the conditions, e.g., drain the site, pipe water to the house, use permanent materials, etc.

Using materials and construction technique currently available replacement of mud construction with high technology materials will result in a huge increase in the cost of housing. Affordability of materials is the main problem in the provision of housing. In order to determine the resources used by the Government of Pakistan to solve the material problem, the author presents a the study in Chapter 3 of existing research and materials technology in Pakistan.

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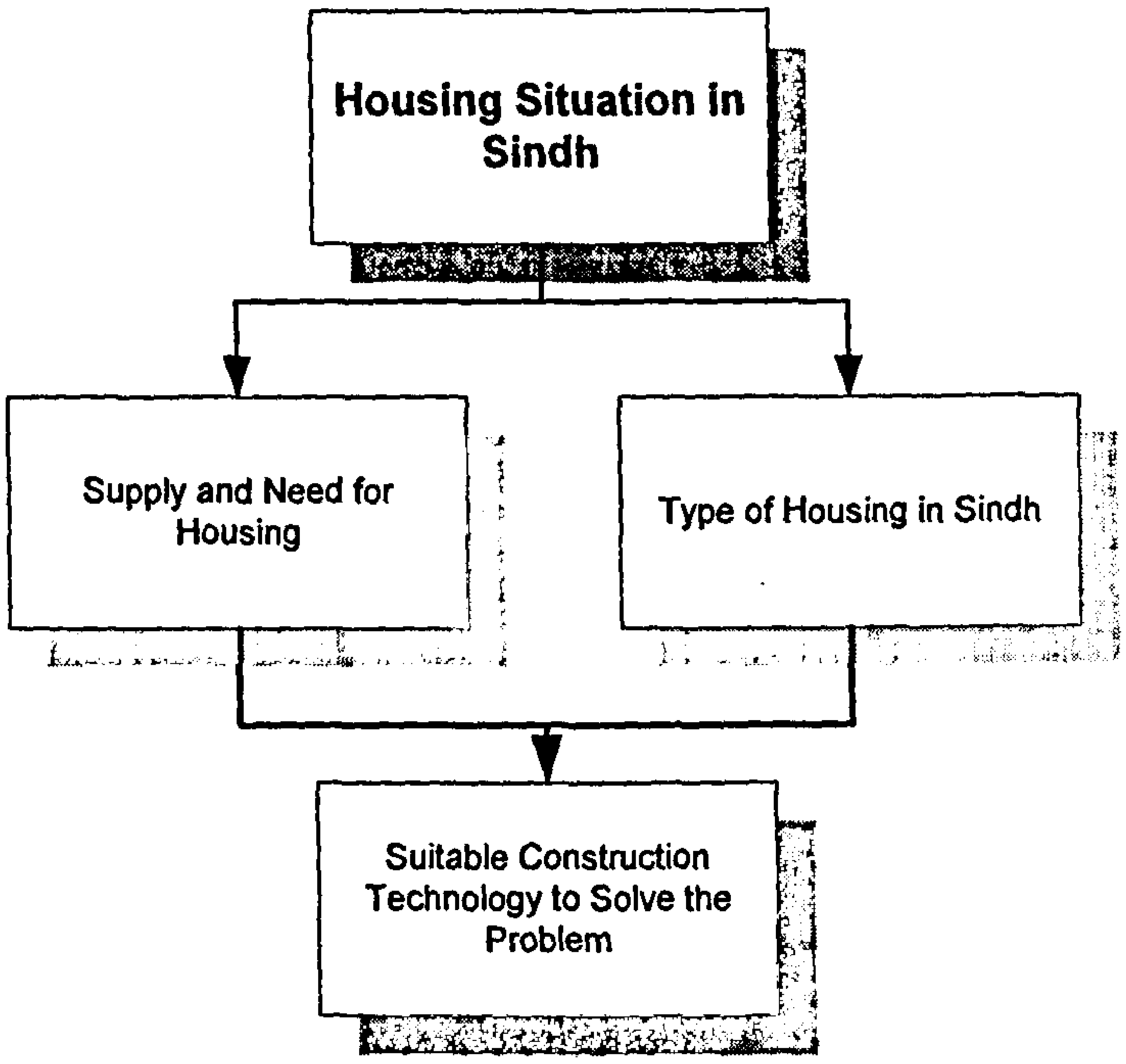


Chapter Three

Traditional Construction: Problems & Alternatives

Chapter Three

Traditional Construction: Problems and Alternatives

3.1 Introduction

This chapter presents the investigations of effective technical solution to the problem of rural housing in Sindh. The detailed analysis of the use of traditional construction technology and its current status in rural areas is also presented. The motivation for blending technologies is to propagate the optimum use of indigenous materials, to promote local technology and to reduce transport and energy cost.

Three residential units of a house in Sindh have been examined as part of an investigation the causes of damages to earth buildings. This field study was undertaken in the Goth '*Tori*' District of Shikarpur, Sindh (Pakistan). The map and plan of the house is attached in Appendix A. The main construction material used in the house is earth, taken from a near by pond. Bamboo and palm trunk fibres are incorporated used into for thatch roofing which covers one unit of the house. Sun dried bricks and earth plaster have been used for walling of this single story building. The construction method is wattle and daub. Two major types of damage were observed (i) damage due to the presence of water and (ii) damage due to the structural defects.

Current research in building technology by the National Building Research Institution (NBRI) Pakistan is examined. Such research can be classified according to the alternative choice of suitable raw materials and according to their suitability for use in the construction of disparate building elements. This research provides the basis for accessing available expertise in blending the two building technologies used in Pakistan, i.e., and 'indigenous' and 'imported' technology. It also enables the effectiveness of the new methods to be gauged when adopted for the solution of the Sindh housing problem.

The modification of earth as a building material, through different methods of improvement, can increase the functionality of earth as a basic material for housing. The parameters for promoting the material are also studied in this chapter. Earth stabilisation using a combination of modes is also investigated. The selection of cement and lime as stabilisers was based on the results of the literature review, whilst the selection of linseed oil and calcium chloride was based on cost and local availability.

In this part of study, a current picture of Pakistan's state-of-the-art developments on the subject is presented. The information and data used have been extracted from research literature, papers, reports and other related publications gathered from various institutes, individual professionals. Before discussing new research work, it is necessary to provide a brief introduction to indigenous construction materials and techniques. This is because most new researches into construction materials are based on indigenous technology.

3.2 Indigenous Construction Material and Techniques

In Sindh, various types of building materials and techniques of construction have evolved. The production and cost of buildings in Sindh varies enormously They are a function of building materials, construction technologies and techniques, site location, complexity of design as well as the political and socio-economic status of the client.

Various types of material and techniques of construction can be used, depending on climate. There are two classes of such techniques: firstly, the outcome of experience over generations and, secondly, the results of architectural development. Locally trained craftsmen, who mainly use indigenous materials and traditional building techniques, carry out the construction of buildings in rural Sindh. Some traditional building materials and techniques suitable for the climate of rural Sindh have been used for generations and are discussed below:

3.2.1 Earth and Clay

Earth and clay have been used since ancient times for the construction of walls and in some areas, to cover the wooden structure of roofs. Today, the majority of houses in rural areas still have mud walls built by locally trained craftsmen. Hence the demand for burnt clay products is very small. As a low cost material, which is frequently used in rural construction, mud walls stand on a bed excavated into the ground. Mud has lower strength than other commonly used construction materials and so mud wall is built thicker. Mud wall heat up more slowly during the day, impeding heat flow, so that internal air temperatures are above those prevailing outside. The Figure 3.1 shows that typical example of shelter made of traditional material such as mud, thatch and bamboo.

Produced by author during mud house investigation at field trip to Sindh

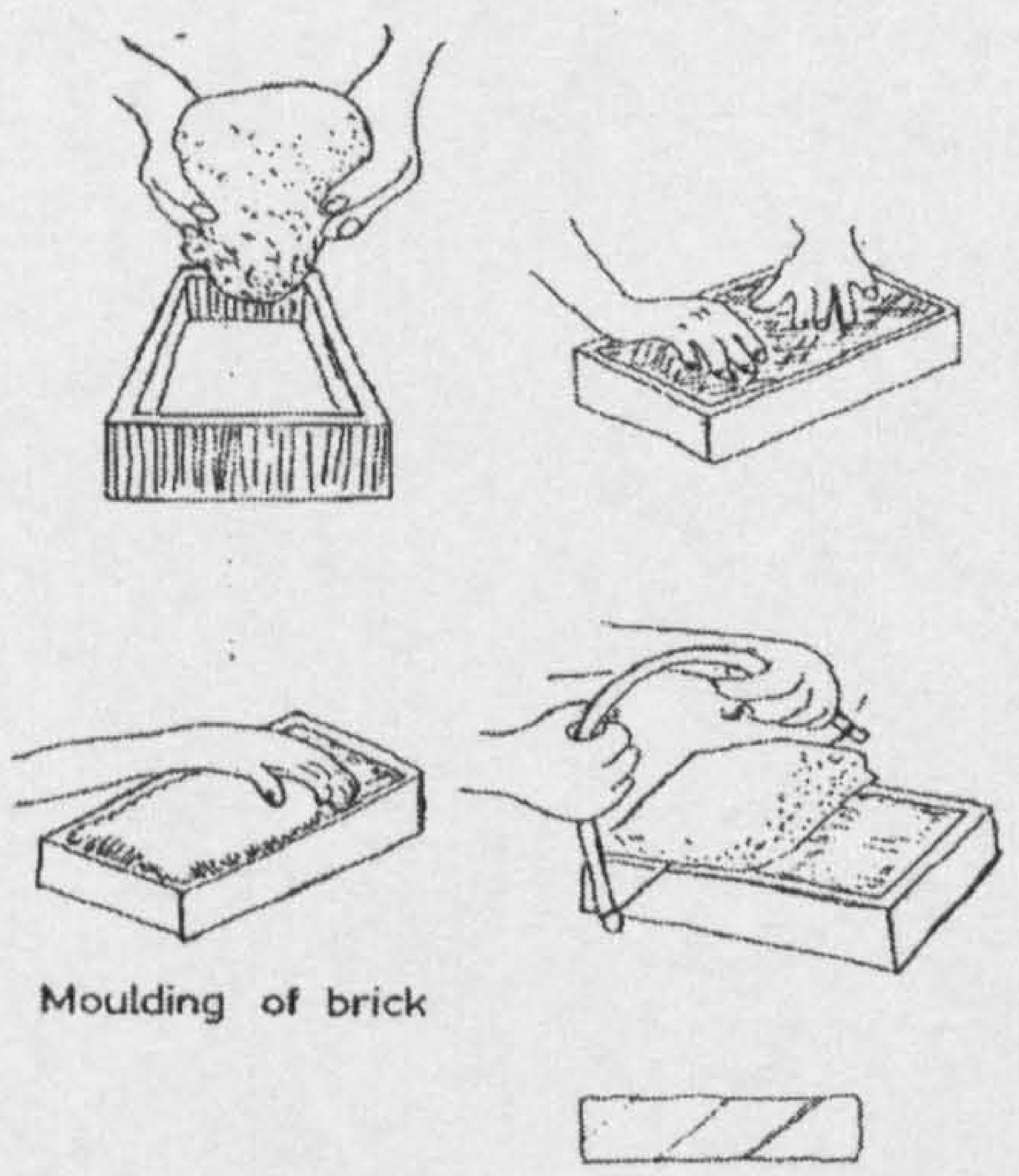
Figure 3.1 Typical Sindhi house with thatch roof and mud walls

Mud is also used for roofing, which is usually constructed by placing wooden joists at suitable intervals, covered by planks or bamboo. Twigs and leaves are then superimposed and covered by mud, which is tamed, screened and plastered.

Mud requires periodic maintenance but recent experiments have shown that by combining mud with new materials, the life span of mud structures increases. For example earth stabilised with cement and bitumen has shown greater strength and resistance to damage. Earth, or clay/mud, is usually used in the following forms:

I. Mud bricks

In rural areas of Sindh, mud bricks have great potential for use in domestic and public buildings. This type of brick is very suitable for the climate of Sindh and is easily manufactured. A mixture of earth and water simply moulded into brick form and allowed to dry in the sun. (See the Figure 3.2) Bricks are stacked on top of each other in various patterns and binds together using mud or mortar. As mud bricks are small and can be cut and trimmed easily, they allow great flexibility during the process of construction.



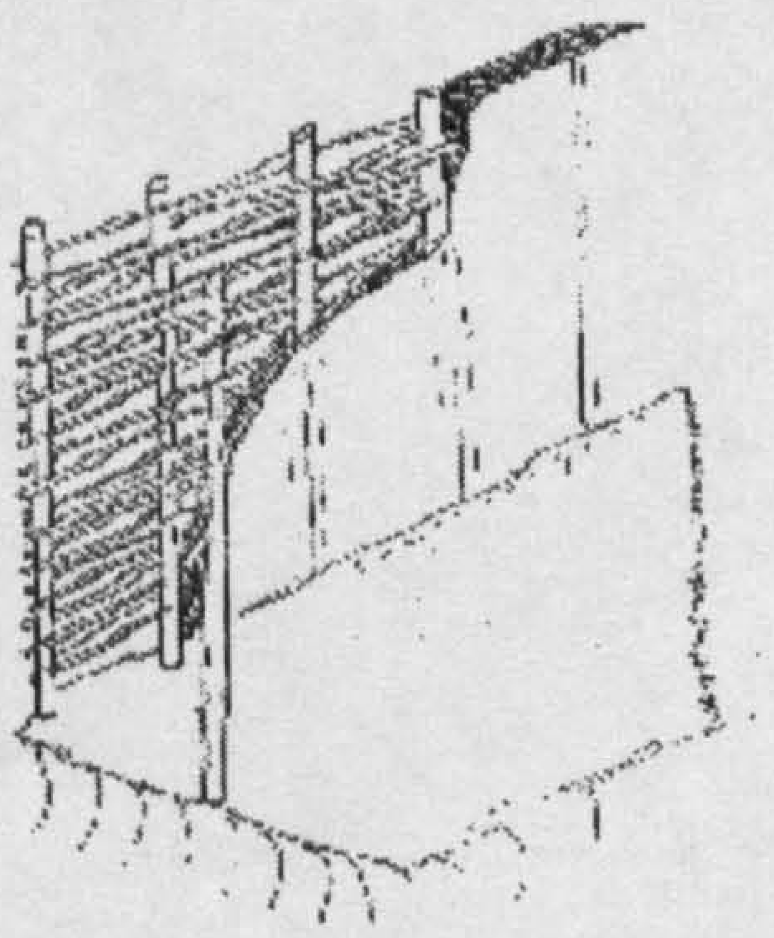
(3)

Figure 3.2 Moulding of brickwork

Mud bricks or other mud constructions withstand only compression and cannot withstand tension due to mud's brittle quality. However, mud bricks are cheaper than cement blocks.

II. Wattle and Daub

This method of construction is highly suitable for the Sindh climate, especially with a mud covering. Crude, mature or light framework of wood is built to reinforce the basic material of construction. (Refer the Figure 3.3) The mud is then poured in this wooden reinforcement and the thickness is built up to provide a sound and water proof shelter.

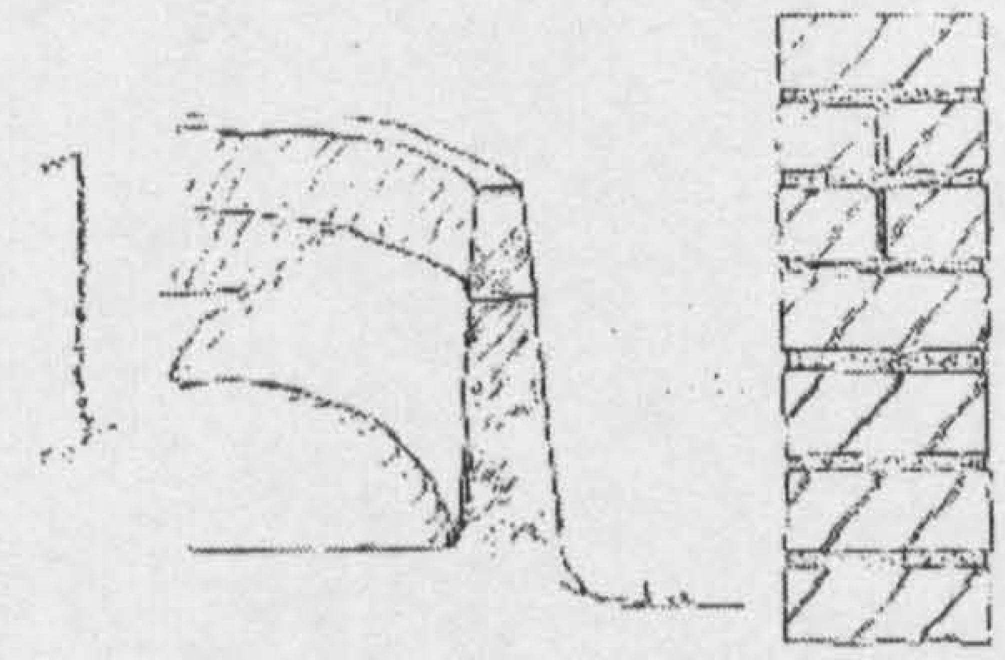


(3)

Figure 3.3 Wattle and daub construction

III. Puddle form of mud

The material is used in a liquid or semi-liquid form. Layer upon layer is built up, resulting in a laminated wall as shows in Figure 3.4. The strength of the wall depends on the density achieved with the rough mixing. This type of wall construction is mostly used in boundary walls and locally as ' ODKI BHITT'. Puddle mud construction can also be applied internally in the form of rammed earth or pies. In this method, puddle mud is poured into a movable frame.



(3)

Figure 3.4 Puddle form of earth wall construction

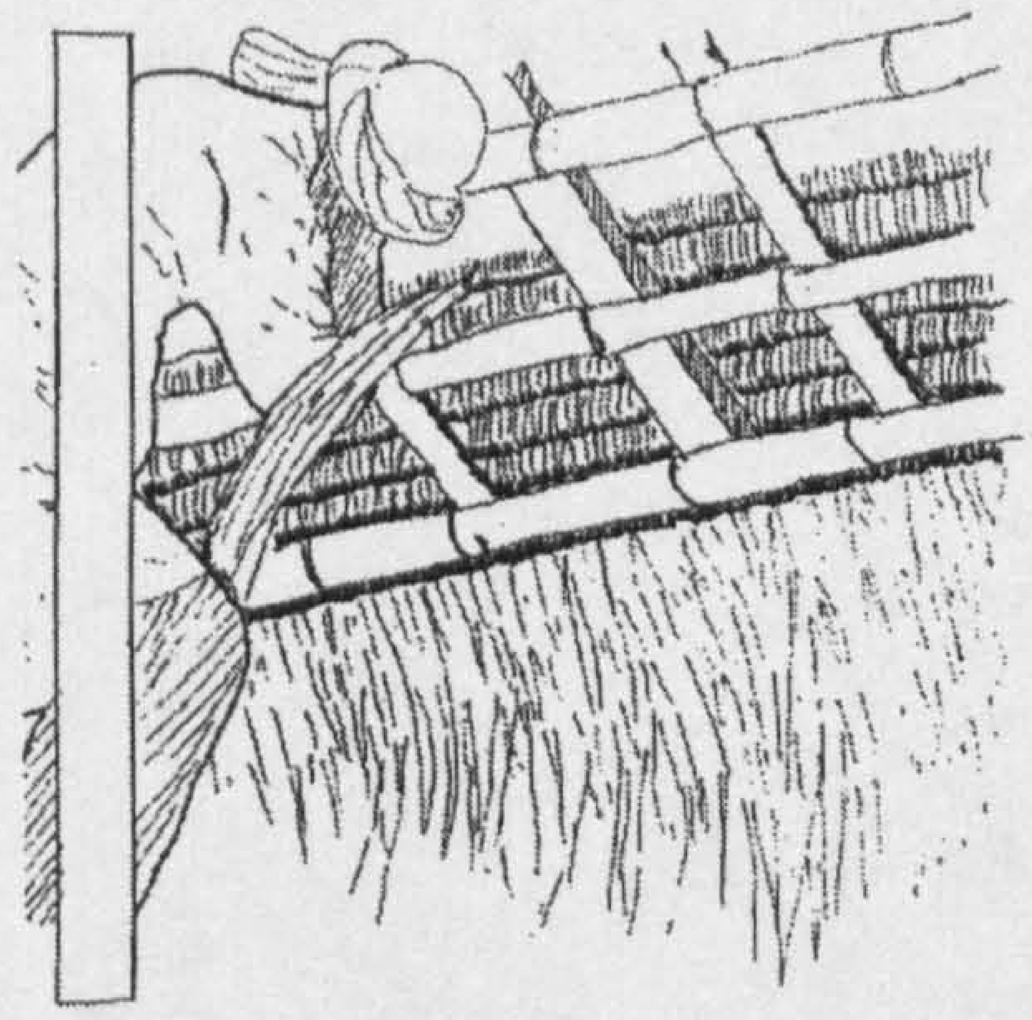
3.2.2 Mud Plaster (*Lepai*)

TORI (long *Boosa* or straw) is mixed with mud and makes a mortar for laying and plastering. The water content in this case is less than that required for brick making.

Mud plaster is applied by trowel as in normal plastering. Only one coat, approximately half an inch thick, is required, but it must be applied slowly and carefully. For the best result, gobar (cow or buffalo dung) is mixed with the mortar. The mixing with gobar helps to give the plaster a smooth surface and also improves it water-resistance.
Normally, no other work is needed when applying the mud plaster, although it must be renewed after the rainy season. If lime plaster is used The water-resistance of the mud surface is further improved.

3.2.3 Thatch

Thatch is a common roofing material in houses of rural Sindh. Wooden planks are laid upon the walls and then thatch mates are laid over it. Finally, is the structure is completed by applying straw and mud plaster. (See in Figure 3.5 and 3.6) Many techniques are employed for the construction of roofs on mud walls, but thatch remains popular in areas where cost is a major consideration.



(1)

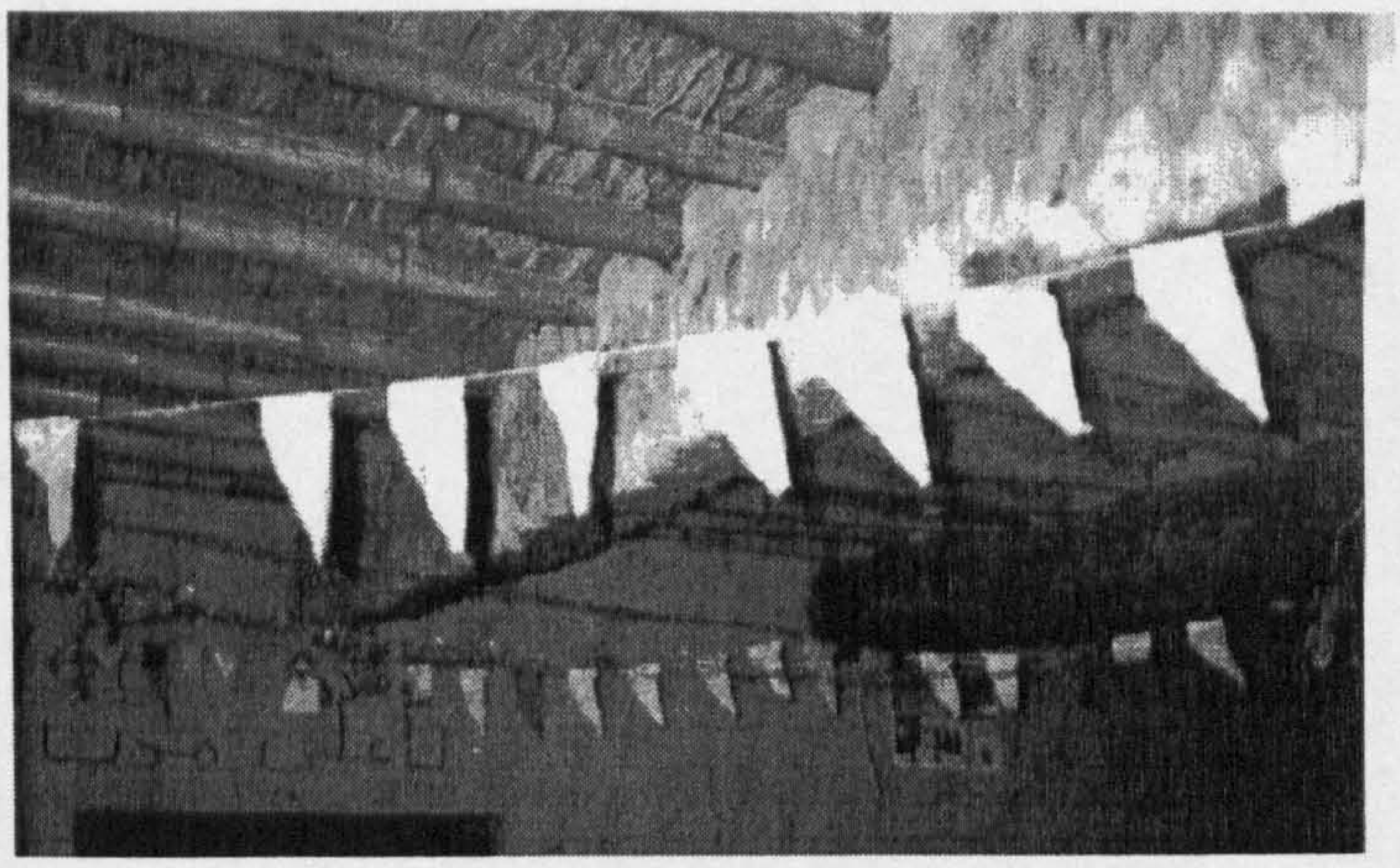
Figure 3.5 Pattern of Thatching with support of Bamboo

Produced by author during field trip to Sindh

Figure 3.6 Use of Thatch as walling material in Sindhi village.

3.2.4 Bamboo

Bamboo is widely available in rural areas of Sindh and is used as a building material. The main characteristics of bamboo are low elasticity, low concrete adhesion, a limited range of practical culm diameter and length, and a wide variability in moisture content. (Refer to the Figure 3.7)



Produced by author during site investigation

Figure 3.7 Bamboo supported roof with palm trunk (A typical Sindhi house construction)

Most housing in developing countries is built through 'self help' and is not depend very little on contingent upon either building materials industries or on building firms. The conventional perception of self-help is that the builder, the builder's family and neighbours procure the materials and carry out the all construction tasks themselves. Indeed, there are some cases, particularly in rural housing, and temporary urban dwellings, where the technologies are basic enough, and social ties are strong enough, to enable this to happen.

3.3 Causes of Damages to Earth Buildings - A Case Study

It is important to study the causes of damage to earth houses before taking investigating ways to improve earth as a building material. For this reason, three dwellings in an earth-built house have been studied. (See Appendix (A) and (B).

Earth constructions are well known for their sensitivity to moisture, with much damage to earth buildings being caused by migration of moisture. This under lines the necessity of first examining the causes of damage to earth buildings before looking at ways to improve construction properties. For further information on earth as raw material see Appendix B(I).

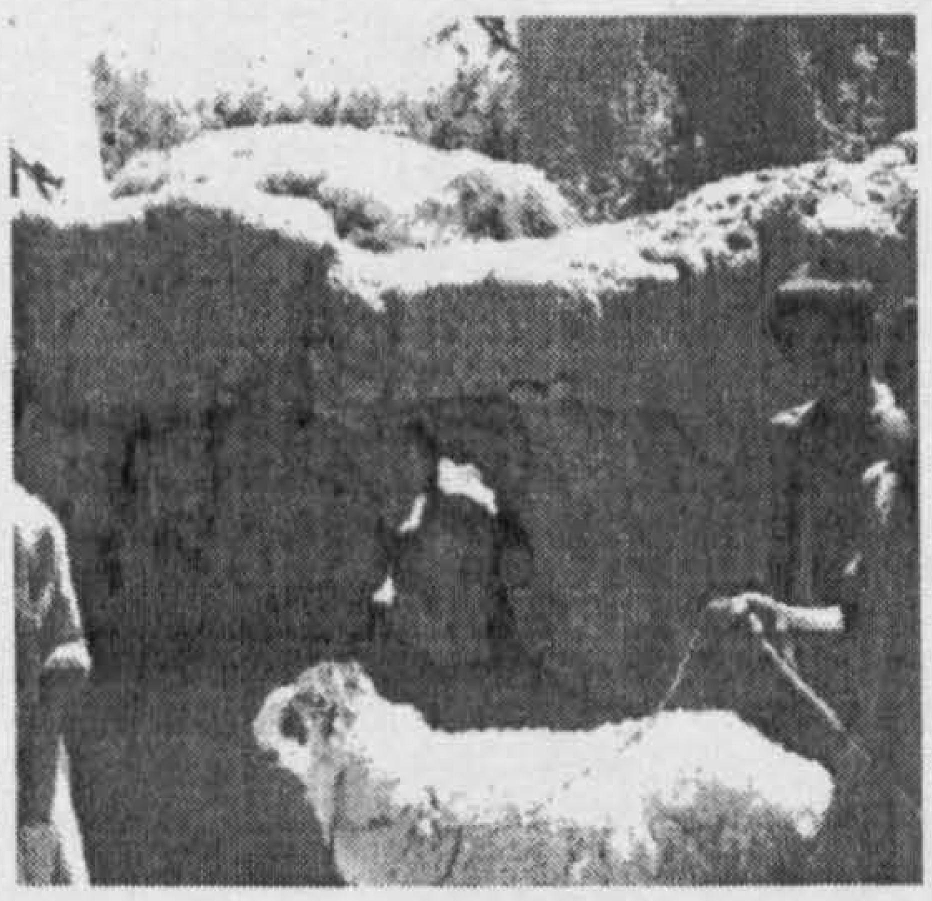
Two main causes of damage have been observed in earth buildings:

a. Presence of water in the building
b. Inadequate engineering properties of construction materials

Most earth structures are vulnerable to the action of water (see Figure 3.4). When water penetrates a building, from nearby standing water for example, it can create an uncomfortable, or even unhealthy, environment inside and increases the risk of rapid structural deterioration.

There are three main conduits for water to penetrate a building:

1. Presence of water on the surface of the building
2. Presence of physical openings
3- Presence of forces that act on the building e.g. capillary action, gravity and other pressures that facilitate the passage of water through openings.



Produced by the author during the field trip to Sindh

Figure 3.8 Earth wall deterioration due to rainfall and wind load

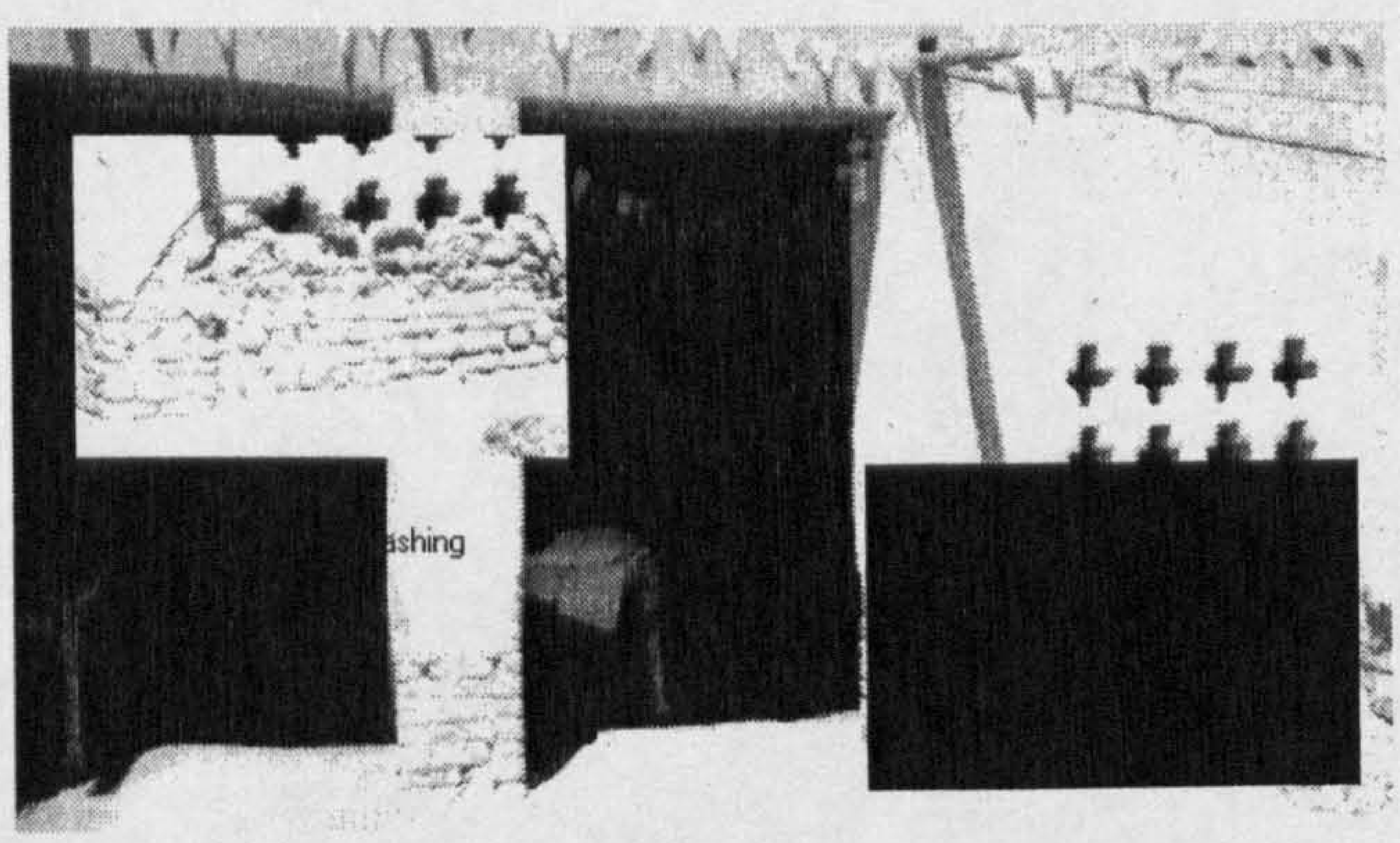
3.3.1 Mechanisms of damage due to water

There are six main mechanisms by which water damages earth buildings:

1. It has been observed that a rise in the level of ground water may reduce the safe bearing capacity of earth and that a fall in the level of the ground water may cause differential settlement of structures. There are several reasons for water to rise by capillary action at base of walls and enter foundations: seasonal changes in the ground water table, retention of water by roots of shrubs, defective sewers, a lack of

drains for the building, and standing water at the foot of walls. Persistent dampness can also cause weakening at the base of walls. (4)(5)

When earth walls encounter water, they pass from a solid to a plastic state and can no longer bear loads. This increases the risk of the building collapsing. It also has been found that dampness encourages efflorescence of salts, such as $NaCl_2$, $CaSO_4$ and $NaSO_4$, which causes hollows to form. Insects and rodents are attracted by damp conditions and cause further deterioration of the wall. Considerable seasonal changes in moisture content can occur, causing the clay to pass through cycles of shrinkage and swelling. Figure 3.5 shows the effects of erosion due to absorption of floodwater.



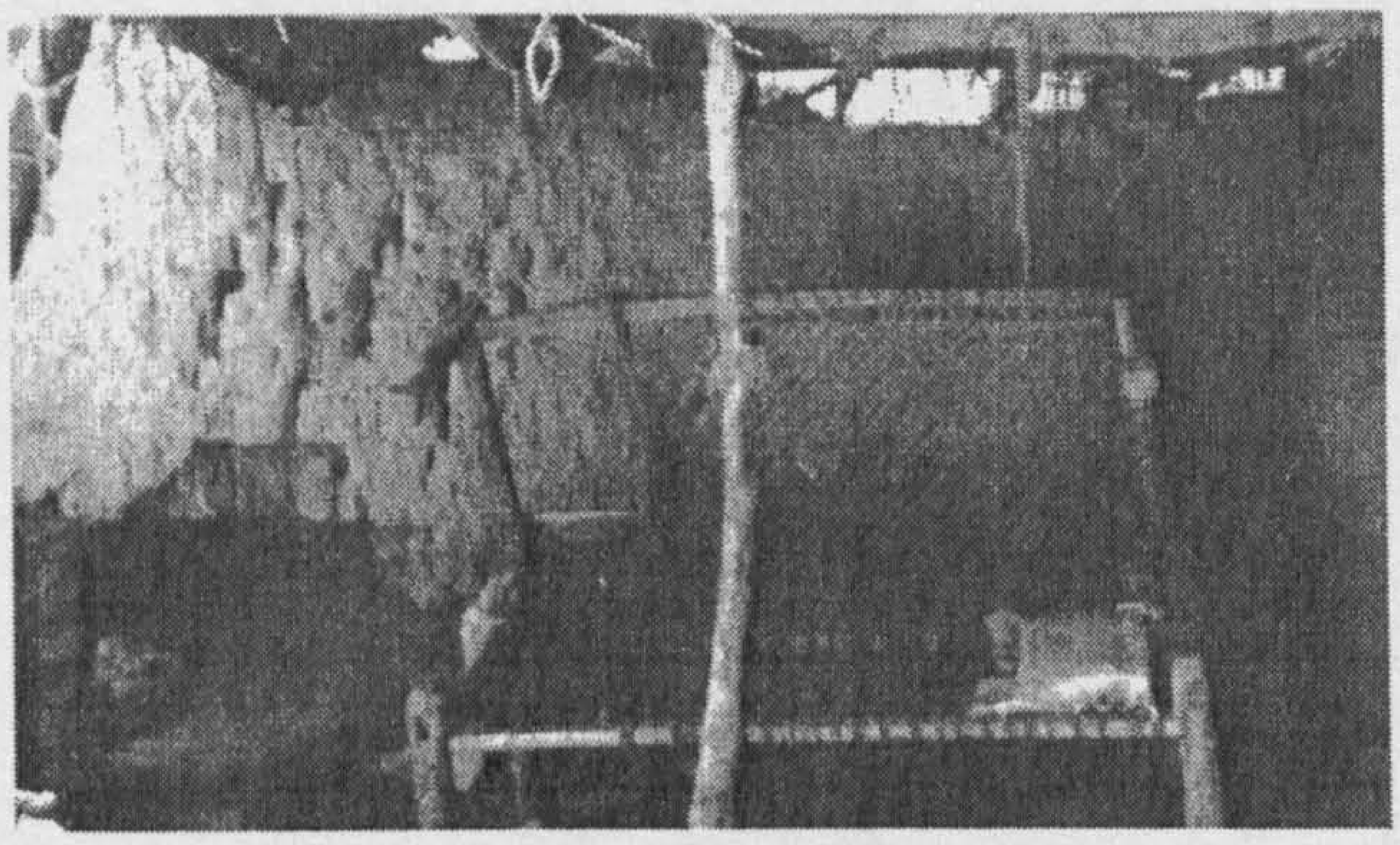
Produced by the author during the field trip to Sindh

Figure3.9 Erosion due to moisture migration from foundations

2. Above ground level, the base of walls can be eroded as a result of any of the following (5)(6):
    - Water splashing from drainpipes
    - Water thrown up by passing vehicles
    - Washing of inside floors
    - Surface condensation (morning dew) running off at the foot of the wall when gutters are too close to the wall
    - Surfaces being rendered impermeable, such as waterproof walkways, which prevents evaporation and encourages condensation between the earth wall

and the waterproof rendering. This results in the growth of parasitic flora, such as moss, and efflorescence.

3. Walls are the most exposed elements of a building and so are highly susceptible to damage by water. The water may infiltrate through structural cracks (caused by settlement and/or shearing), shrinkage cracks (caused by repeated day-wet cycles), unfilled holes left by work clamps, and hollows in the walls.
4. Water that runs off at the junctions of reveals, earth walls, supports and lintels, may infiltrate surrounding masonry or wooden frames causing localised deterioration.
5. Climatic changes, e.g. temperature or rainfall, can cause decomposition of earth by washing out clays and, thus, reducing cohesion. When an earth wall is protected by rendering to prevent the movement of water vapour, condensation on the cold surface of the walls (indoor walls in summer; outside walls in winter), or between the wall and the rendering, causes the wall to deteriorate. In addition, water penetrates at the point where floor or roof beams pass through earth walls, see Figure 3.6. & 3.7. It may also penetrate where poorly designed gargoyles pass through walls at unprotected entry and exit points. Accumulation of earth can block drainpipes, resulting in standing water, absorption and capillary action.



Produced by the author during the field trip to Sindh

Figure 3.10 Wall erosion due to unprotected roofing

6. In some cases, where parapets are unprotected by a projecting cap, or where they are cracked or covered with defective rendering, water penetration may occur. Objects placed against parapets, such as plants that require watering, and poorly drained terraces can cause dampness.

Produced by the author during the field trip to Sindh

Figure 3.11 Damage to an earth staircase due to water run off

3.3.2 Principal causes of structural defects in earth buildings

Earth buildings may suffer from structural defects, which occasionally result in irreversible damage. However, codes of practice have been developed, for use of earth as a construction material and the building systems, which must be followed accurately. It should be noted that structural defects may result from causes other than the type of raw material used. (6)(7) These may include problems related to the site, e.g. settlement and earth slippage, and natural disasters, such as earthquakes and hurricanes. They can result in serious structural damage, particularly where buildings are poorly designed, badly built and carelessly maintained. The following factors cause structural defects in earth buildings: (8)(9)

1. Unsuitable stresses on the material, such as tensile and bending stresses. Earth only functions well in compression. Other types of stress require the use of different materials, e.g. wood, concrete, and steel (used as ties, lintels, etc.)
2. Chronic damp, which reduces the strength of the material, even in compression.
3. Construction on a poor site, which cannot stand up to the loads transmitted to it, or on moving ground that is subject to slippage, uneven settlement, heave or swell.
4. Climatic influences, e.g. wind action on damp walls and loss of material through wind erosion
5. The action of living organisms, e.g,. plants parasites, rodents and insects.

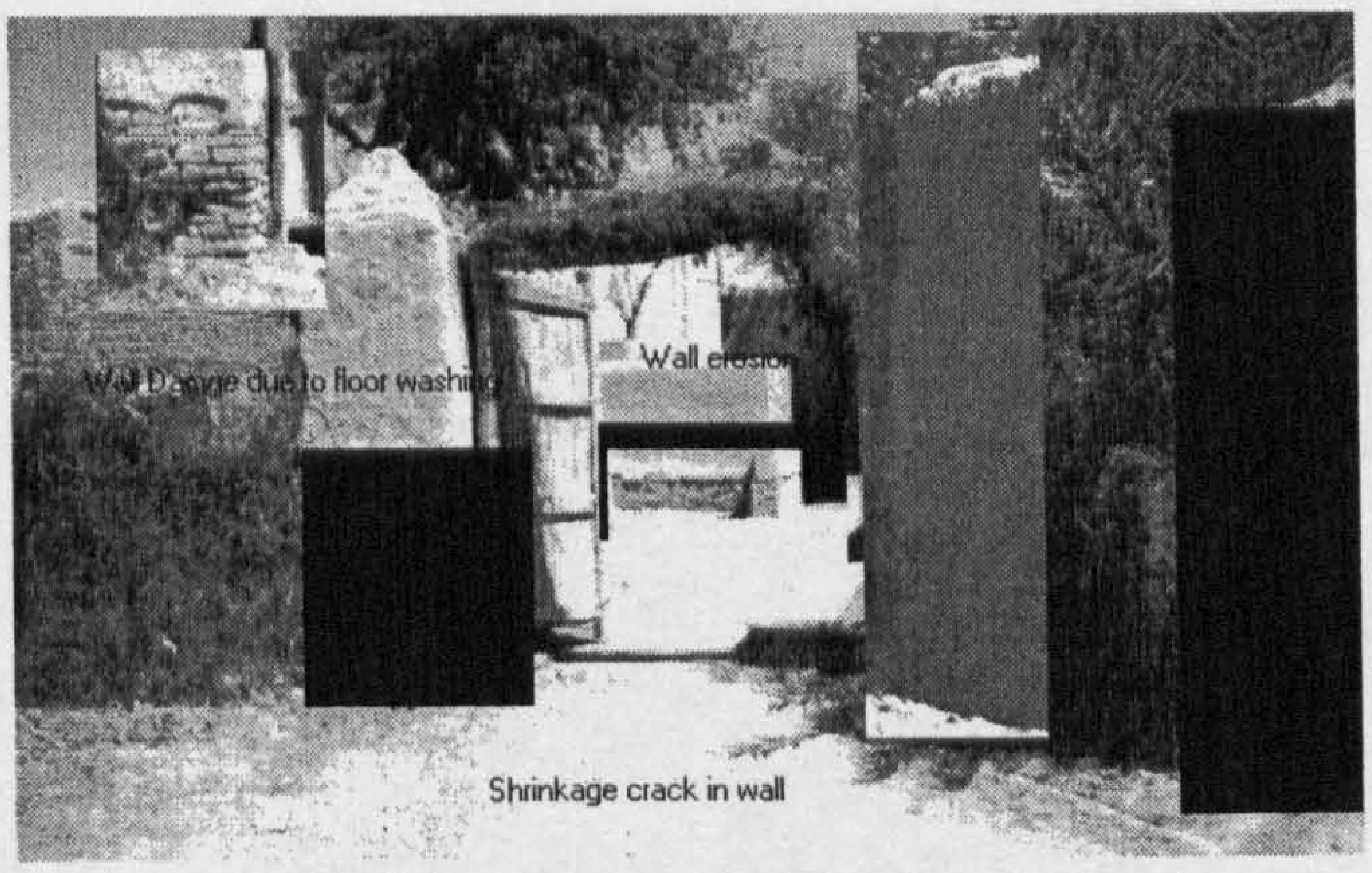
6. Design flaws such as:
   - Under-designed or off-centre foundations
   - Inadequately braced walls, untied walls, walls which are too high, walls with too many openings, walls made of composite materials, etc
   - Excessive loads in the form of floors, roofs, occupancy and point loads
   - Construction systems unsuited to the use of earth as building material (e.g. unsuitable earth or poor quality bricks)
   - Poorly implemented construction techniques (e.g. mistakes in the bond or vertical cracking along joints)
   - Incorrectly mixed mortar
   - Poorly designed openings, without ties, and an absence of a protective damp course at top and bottom of walls.

3.3.3 A study of typical structural defects

Typical structural defects of the earth houses studied include cracks, faults of a physico-chemical nature (i.e. decomposition of the material) and defects due to external agents, such as the action of living organisms. The following damage was found in the surveyed earth houses:

1. Structural cracking due to construction defects, subsequent modification to the building or accidents. The capacity of the material to resist mechanical stress had been exceeded. Such stress includes compression, penetrating tension forces, bending and shearing (see Figure 3.8). They are probably localised (e.g. bonds between earth and various 'hard' materials, downward load due to floors, openings, etc.) or exerted in the body of the walls, e.g. ground subsidence or poor foundations. (10)
2. Shrinkage cracking, which is characterised by a vertical and regularly spaced appearance, e.g. every 0.5-1m in the earth wall. These cracks are usually the result of poor quality control, either in terms of the earth used, e.g. excessively clayey earth, or during construction, e.g. the earth was too moist or dried too quickly. Shrinkage cracks may also have resulted from variations in relative humidity, causing repeated cycles of wetting and drying. (10)

3. Swelling of walls due to high mechanical stresses, which may have resulted from sudden forward movements of adjoining walls or excessive localised loads. Distortions caused by swelling are often accompanied by cracking - although not always because earth accommodates significant creep. (6)(10)
4. Collapse of structures probably provoked by a build-up of stresses that weakened them, or by a loss of strength of the material, e.g. caused by chronic moisture. Occasional or accidental stresses may also have played a role, e.g subsidence, caving-in, or earthquakes. (5)
5. Decomposition of the earth. There was evidence of rain water, ground water, heat and frost causing chemical and mineralogical structural changes to the earth. This resulted in the earth losing its coherence and disaggregating.



Produced by the author during the field trip to Sindh

Figure 3.12 Structural cracks in a main entrance wall

3.4 Research & Innovation in Construction Technology in Pakistan

Pakistan has an ambitious research community, which has made some contribution to the development of innovative building materials. Some of its research results could be used to reduce in the cost of construction for low-income communities.

3.4.1 Alternative materials

This section outlines research into 'substitute' materials. The substitution of the following basic building materials is examined here:

A. Alternatives for cement

B. Alternatives coarse aggregates

C. Alternatives for reinforcing material

The need to develop substitute materials is imperative for two – reason: (7)

1. Non-availability of conventional materials in some parts of the country because of location, either in terms of distances from the sources of material or geography (arid or mountainous).
2. Conservation of scare resources to ensure future demands can be met, or to prepare for the post-depletion situation.

It is important to note that, these are the primarily technical substitutes and a commercial and/or practical exercise of the same is yet to be made in Pakistan.

A) Alternative for cement

(i) Rice husk Ash (RHA)

Although rice is not a staple food, it is grown in large quantities in Sindh and the Punjab. Research at NBRI (National Building Research Institute) has shown that the Rice husk Ash (RHA) is a potential pozzolanic (cement replacing) material. RHA can replace up to 35% cement without impairing the strength of concrete. (8)

RHA can also be used with lime to produce cementitious products. RHA-PC (Portland Cement) mix can be safely used in the structural concrete and the RHA-lime mix can be used for plaster and mortar purposes. (8) Refer the Table 3.1.

Table 3.1 The Salient features of Rice husk Ash. (7)

Properties	Responses
Special properties	Resistant to acid and sulphate
Comparison with conventional materials	Initial strength low, long term strength comparable
Demerits	Adulteration
Availability(Quantum)	Adequate
Regional limitations	Sindh and Punjab only
Climatic limitations	None
Special skills required	None
Special equipment required	Production plant required
Stage Experience	Experimental
Economical Aspects	Low to medium

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

(ii) Sugar Cane Bagasse Ash (SCBA)

Bagasse is available from sugar mills following the crushing of canes, which are usually burnt in boilers to utilise their energy values. The ash produced by burning up cane creates a waste and disposal problem. However, researchers at NBRI have found that SCBA is a, potential pozzolana. This is particularly pertinent to housing in Sindh and Punjab, where most sugar mills in Pakistan are located. For rural construction, finely ground SCBA may be gainfully utilised to cut consumption of cement and, hence, the cost of construction. (10) Table 3.2 shows the properties of SCBA.

Table 3.2 The salient features of the. SCBA. (7)

Properties	Response
Special Properties	Resistant to acid and sulphate attack
Comparison with conventional materials	Initial strength low, long term strength comparable
Demerits	Possibility of adulteration
Availability (Quantum)	About 700 tonnes per day
Regional Limitations	Sindh, Punjab and parts of NWFP
Climatic limitations	None
Special skills required	None
Special equipment required	Production Plants Required
Stage of experience	Experimental
Economical aspects	Low to medium

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

(iii) Surkhi (brick bat) and Lime

Surkhi (ground brickbat) and lime are traditional building materials, but have been superseded by the use of Portland cement. Since cement is becoming too expensive for the poor rural communities to use, the readopting of Surkhi and lime may be considered. Significant research on the use of Surkhi and lime has been carried out by NBRI. (10) The Table 3.3 shows the properties of Surkhi and lime.

Table 3.3 Salient Features for the Surhki and Lime. (7)

Properties	Response
Special properties	Resistant to acid and sulphate attack
Comparison with conventional	initial strength low, long term strength comparable
Demerits	Possibility of adulteration
Availability (Quantum)	Quantity not known
Regional limitation	All four provinces of Pakistan and Kashmir
Climatic limitation	None
Special skill required	None
Special Equipment required	Ball mills for grinding
Stage of experience	Experimental
Economical Aspects	

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

(B) Alternatives for Coarse Aggregates

(i) Air-cooled Boulder Slag (ACBS)

When molten blast -furnace slag cools in air, it is known as air-cooled boulder slag and has hardness comparable to that of igneous rocks. It is available in substantial quantities, with excess of 100 tonnes per day being produced by the iron-making plants of Pakistan Steel Mills. Research has been conducted at NBRI using air-cooled boulder slag as a coarse aggregate in concrete mix. (10) The properties of crushed aggregates from ACBS as shown in Table 3.4 were found to be comparable with those of limestone crushed aggregates. It is economically viable to utilise crushed aggregates from ACBS for construction work around the Pakistan Steel Mills, Pipri and for KDA (Karachi Development authority) schemes, such as Shah Latif Town and the Khanto scheme. (7)

Table 3.4 Salient Feature of the Air Cooled Boulder Slag (7)

Properties	Response
Special properties	None
Comparison with conventional material	Physical and engineering properties are comparable
Demerits	Medium to high absorption
Availability (Quantum)	100 tonnes per day
Regional limitations	Karachi, Pakistan steel Mills
Climatic limitations	None
Special skills requirements	None
Special equipment required	Crusher Plant required
Stage of experiment	Experimental
Economical aspects	Low cost

Note: The properties indicated above are not inherent and are subject to proper design and construction practices

(ii) Bagasse Clinker as Light Weight Aggregate

Clinker, a waste product from boiler houses of sugar mills and particleboard mills, is an expanded light weight aggregate. Research at NBRI shows that light weight clinkers can be used as walling materials and to produce light weight roofing planks for low cost housing. (4) Table 3.5 shows the properties of BC as lightweight aggregates.

Table 3.5 Salient features of the Bagasse Clinker. (4)(5)

Properties	Responses
Special properties	Light weight, Insulate material
Comparison with conventional materials	Physical and engineering properties are comparable
Demerits	High absorption low abrasion resistance, flaky
Available (Quantum)	Quantity not known
Regional limitation	Sindh, Punjab and parts of NWFP
Climatic limitation	None
Special equipment required	Crusher Plant Required
Special skills required	None
Stage of experience	Experimental
Economical	low cost

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

(iii) Bloated Clay Aggregates

At Lahore Building Research Station, research has shown that Bloated Clay can be used successfully as A coarse aggregate in concrete mixes. Softballs of clay are first prepared and then allowed to dry in the sun. These balls are then fired, a process that bloats and hardens them. The hardened, bloated balls of clay can then be used as a substitute for coarse stone aggregates in concrete mix (7). The properties of Bloated Clay Aggregates are shown in Table 3.6.

Table 3.6 Salient feature of the Bloated Clay Aggregates (4)

Properties	Responses
Special properties	Light weight, insulate material
Comparison with conventional materials	Physical and engineering properties are comparable
Demerits	High absorption, low abrasion resistance, flaky
Availability (Quantum)	Quantity not known
Regional limitation	All provinces of Pakistan
Climatic limitation	None
Special skills required	None
Special equipment required	Rotary kiln
Stage of experiment	Experimental
Economical aspects	Medium to high cost

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

c) Alternatives for Reinforcing

(i) Hard - Grass Reeds

Hard-grass reeds, popularly known as *sarkanda*, are commonly found in areas of overgrown vegetation. Research NBRI shows that Hard-Grass Reed can be use for the construction of low cost housing as a substitute material for reinforcing steel in small span roofing planks and beams. (5) Properties of Hard-Grass Reeds are shown in Table 3.7.

Table 3.7 Salient feature of the Hard-grass reed (5)(7)

Properties	Responses
Special properties	None
Comparison with conventional materials	Strong in tension but poor in fatigue and toughness
Demerits	Poor durability
Availability (Quantum)	Quantity not known
Regional limitation	Sindh and Punjab
Climatic limitation	Dry climate only
Special skills required	None
Special equipment required	None
Stage of Experiments	Experimental
Economic Aspect	Low cost

Note: The properties indicated above are not inherent and are subject to proper design and construction

3.4.2 Innovative Building Elements

In this section, The research by various Pakistan institutes into innovative building elements is reviewed (7):

A) Foundations

No significant innovations in foundation materials have been made. However, NBRI has built some model houses in which earth stabilised blocks (stabilised with cement) have been used. The earth stabilised blocks prepared by NBRI are not suitable for use where the where foundation might be exposed to flooding or high ground water levels. (5)

B) Floors

Not many innovations regarding floors are reported in published or unpublished literature, by the Government of Pakistan. However, rammed, stabilised earth has been used in one or two NBRI model houses. Surkhi-lime floor tiles have also been developed at NBRI for possible use as flooring materials in low-cost housing. (4)

C) Walls

The following significant innovation included:

(i) Soil blocks

Soil blocks produced on a CINVA RAM machine have been used by the NBRI for experimental stage. (7) A number of demonstration model houses have incorporated these blocks as load bearing members. The blocks use locally available soil stabilised by cement. Normally they are produced in dimensions of 4" x 5" x 9", w x d x h, although, any size and shape can be produced with a little modification to the moulds of the CINVA RAM machine. The properties of soil blocks are shown in Table 3.8.

It should be noted that NBRI did not carryout analysis of soil constituent of the blocks and so the properties of the soil were not determined. Soil for block making should undergo analytical testing to determine the amount of cement required to stabilise the block and the effects of the stabiliser on variations of soil composition. (10) It is important to note that Karachi soil, which has been used for experimental blocks at

NBRI is completely different from the interior Sindh soils (soil which is imported from interior Sindh for research work). Karachi is located on the seashores and interior Sindh is considered a hot and dry region so the properties of soil and use of soil is different.

Table 3.8 Salient Features of Soil Blocks. (4)

Properties	Responses
Special properties	Easy to manufacture
Comparison with conventional material	Compares well in strength
Demerits	Poor durability
Regional limitations	Limited to place where soil and binders are easily available
Climatic limitations	Dry climates only
Special skills required	None
Special equipment required	CINVA-RAM
Resistance to earthquake	Poor to medium
Resistance to wind storms	Poor to medium
Resistance to rain	poor to medium
Resistance to insects	Poor to medium
Stage of experience	Experimental
Economical Aspects	Low to medium cost

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

(iii) Soil lime Surkhi sandwich block

Soil lime Surkhi sandwich blocks have been developed at NBRI using CINVA RAM machine. The shape and sizes of the blocks are similar to those containing stabilised soil. However, the soil used in soil lime sandwich blocks is not stabilised but, instead, has protective layers, both top and bottom, of Surkhi-lime mixture. These protective layers prevent water or moisture from travelling into the body of the blocks. Such blocks are therefore more resistant to rain water attack than the ordinary soil stabilised blocks. (10) The properties of soil lime Surkhi sandwich blocks are shown in Table 3.9.

Table 3.9 Salient Features of the Soil Lime Surkhi block (4)

Properties	Responses
Special properties	Good aesthetics, improved durability
Comparison with conventional materials	Compares well in strength
Demerits	Poor handling stress resistance
Regional limitations	Places where soil and binders are easily available
Climatic limitations	Dry climates only
Special skills required	None
Special equipment required	CINVA-RAM machines
Resistance to wind storm	Poor to medium
Resistance to rain	Poor to medium
Resistance to insects	Poor to medium
Stage of experience	Experimental
Economical Aspects	low to medium

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

(iii) Pre cast stone blocks

Pre cast Stone Blocks are similar in shape and size to cement-concrete blocks, but contain, by volume, more than 50% ordinary-grade stone. The concrete enveloping these low-grade stone blocks is very and has cement to coarse sand ratio of 1:12 or 1:18.

These type of blocks have been used successfully by NBRI and are a viable building material where is expensive and stone is cheaply and abundantly available. Where they are economically viable to use, this is because they reduce dependence on transported materials and exploit indigenous (locally available) resources. (11) The properties of Pre-cast stone blocks are shown in Table 3.10.

Table 3.10 Salient features of the Pre-cast Stone Block (7)

Properties	Responses
Special properties	Lightweight, insulating material
Comparison with conventional materials	Compares well in all respects with similar lightweight materials
Demerits	High absorption capacity
Regional limitation	Limited to Sindh, Punjab where sugar mills are located
Climatic limitations	None
Specials skills	None
Special equipment Required	None
Resistance to earth quake	good
Resistance to wind storm	good
Resistance to rain	good
resistance to insects	good
stage of experience	Experimental
Economical Aspects	Low-cost

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

D. Roofing Elements

(i) Pre-cast ferro-cement barrel shell planks

At NBRI, research has been conducted on the use of thin section pre-cast ferro-cement barrel shell planks. These planks can be laid on walls or beams, side by side, to form either roofing or flooring elements. The polar height of the barrel shells varies between 6 to 8 inches, depending upon the span and loads.

The recommended width is 12 inches. They are lightweight and easy to manufacture even by villagers themselves. However, the ferro-cement may not be easily available to villagers. (11) The properties of pre-cast ferro-cement bared shell planks are shown in Table 3.11.

Table 3.11 Salient features of Pre cast Ferro cement barrel shell. (7)

Properties	Responses
Special properties	Lightweight
Comparison with conventional materials	Compares well in strength and life expectancy
Demerits	None
Regional limitations	Limited to places where cement, crushed stone and sand are easily available
Climatic limitations	None
Special skills required	None
Special equipment required	None
Resistance to the earth quakes	good
Resistance to wind storms	good
Resistance to rain	good
Resistance to insects	good
Stage of experience	experimental
Economical Aspects	low cost

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

(ii) Ferro cement Hollow slabs

Ferro cement hollow slabs may comprise ferro-cement ribbed-slabs with bottom skin-plates. They have been developed at NBRI and can be used in appropriate, situations if further research would conducted on the its structural appraisal. The properties of ferro-cement Hollow-slabs are shown in Table 3.12.

Table 2.12 Salient Feature of the Ferro-cement Hollow Slab. (4) (7)

Properties	Responses
Special properties	Good insulation
Comparison with conventional materials	Comparable wall in strength and life expectancy
Demerits	Cumbersome to manufacture
Regional limitation	Limited to the places where cement and crushed stone are easy available
Climatic limitation	None
Special equipment required	None
Special skills required	None
Resistance to earth quakes	Good
Resistance to wind storm	Good
Resistance to rain	Good
Resistance to insects	Good
Stage of experience	Experimental
Economical Aspects	Medium to high

Note: The properties indicated above are not inherent and are subject to proper design and construction practices.

(iii) Pre-cast hollow planks

At NBRI, small reinforced concrete hollow planks have been developed as roofing elements for low cost housing. They are easy to manufacture; the cavities are simple to incorporate. The properties and responses of pre-cast hollow planks have not been measured.

(iv) Fibre-Reinforced corrugated sheets

Organic and inorganic fibre, mixed with Surkhi has been used at NBRI to produce fibre reinforced corrugated sheets. Asbestos sheets manufactured commercially in Pakistan but are expensive. In areas where asbestos sheets are not readily available, fibre - reinforced corrugated sheets make a suitable alternative for use as roofing elements in low cost housing.

Fibre-reinforced corrugated sheets are easy to produce and are cost effective (7). The properties of these sheets have not yet been analysed due to the early stage of research into them.

(iv) Clay-tile reinforced panels

Ordinary burnt-clay tiles, readily available in Sindh and Punjab (Provinces of Pakistan), have been used to produce Clay-reinforced tiles for use as roofing elements. They can be used in combination with reinforced concrete joists or timber or steel joists. Clay-tile reinforced is lightweight, easy to produce moderately low-cost. They have been developed at NBRI and are in the early stages of development.

(v) Pre cast reinforced brick concrete (RBC)

Pre-cast panels have been developed by NBRI using bricks joined together by thin reinforced concrete ribs. They comprise a pre cast panel and can be used as roofing planks as an alternative to burnt clay tile reinforced panels. Experiments have used both mild steel and Hard-Grass Reed as reinforcing material. Also, burnt clay bricks and lightweight clinker blocks have been used. The properties of RBC are under investigation. (10)

3.5 Earth Stabilised Blocks as a Solution for Rural Housing

The choice of stabilised blocks for rural housing or any other low-income shelters makes use of both the available technologies i.e. traditional and modern technologies. Construction is after agriculture, the most important economic activity in rural areas. Construction activities are essential to providing employment and improving the quality of rural life. However, despite this fact, the gap between housing stock supply and demand is widening in all developing countries. (10)(11)

In some cases, the widening gap between supply and demand for housing can be attributed to inadequacies in development process. For example poor resources planning may lead to insufficient investment to develop employment opportunities in rural areas. Also, most of the available and acceptable building technologies are either too costly or consume too much energy. A combination of cost effective building techniques and employment generating development processes is essential if the housing shortage is to be alleviated. (12)

Earth is the most widely used construction material in Pakistan, especially among the underprivileged. Earth offers tremendous cost advantages, but has a number of drawbacks. It provides adequate strength when dry, but water absorbed when raining causes significant depletion of both tensile and compressive strength. Thus it is common to see mud walls eroding due to the impact of raindrops.

Some earths such as black cotton earth tend to crack extensively on drying and cannot be used in the construction of walls. Termite infestations in mud walls are also a common drawback in tropical regions. However, mud is the only basic construction material available to villagers for free. More advanced and expensive materials are usually untenable.

It is apparent that bricks and stones will be beyond the reach of the poor in the immediate future. Hence, it is essential to explore ways and means of increasing the reliability of mud housing, without involving significant additional expenditure for villagers. The use of mud as a basic construction material in rural areas is described in section 3.3. There are several ways to improve the behaviour of earth as a construction material:

a) Compaction

Compaction increases the dry density of the earth and involves either the pressing of earth blocks by machine (e.g. BREPAK) or the ramming of earth directly into a mould for wall construction. The density is significantly increased when the moisture content of the earth approaches as optimum value. This value varies depending on the composition of the earth. (13)(14)

b) Stabilisation

Earth can be stabilised by mixing with various materials, such as cement, lime and bitumen, in specific proportions. Stabilisation provides a marked increase in the strength and durability of earth.

As described in Chapter 4, there are three modes of stabilisation: mechanical, physical and chemical. These three modes are based on the modification of earth properties by the following six methods: (6)

1. Densification of earth (mechanical stabilisation)

There are two different ways to increase the earth's density:

a. Use mechanical apparatus to compress the earth and remove air voids. Grain size is not changed but the earth's structure may be modified due to redistribution of grain size. (15)
b. Directly modify the grain size distribution by filling voids with other grains. For this method to be used, grain size distribution must be perfect, i.e. the void left between each group of grains should be filled by another group of grain. (16)

2. Reinforcing earth with inert stabiliser (physical stabilisation)

An armature can be created by wide variety of animal, vegetable, mineral and synthetic fibres. The fibre armature reinforces the material at the macroscopic level, i.e. at the level of grain aggregation rather than individual grains. The armature also helps to reduce the movement of particles relative to each other, which may be caused by compression, tension, water action, thermal expansion and so on. (1) (16)

3. Binding earth particles with stabiliser (physico-chemical stabilisation)

The addition of cement to earth creates a three dimensional matrix structure. This matrix is strong, inert and resists the relative movement of particles in the earth. The cement acts through phsyical means, by filling voids with an insoluble binder that coats the grains and holds them in place. Portland cement is most commonly used for this method of stabilisation.

Certain resins, adhesives and an electrolytic solution of sodium silicate salts can each be used to bind earth particles. (17) They undergo chemical reaction to form an inert matrix, although clay particles do not play a significant role in the reaction. (6) The main consolidating reaction takes place between the stabiliser and the sandy fraction of the earth.

4. Creating links between earth particles (physico-chemical stabilisation)

This method of stabilisation comprises two mechanisms: (6)

c. The matrix is created by stabiliser physically binding the clays.
d. The matrix is created by chemical reaction between stabiliser and clays. Chemical stabilisers acting in this way include certain acids, polymers, flocculates, and so on. (17)

5. Reducing permeability of earth (physico-chemical stabilisation)

This method of stabilisation reduces water permeability, swelling and shrinking when the material is subjected to repeated wetting and drying cycles. There are two mechanisms for water proofing: (16)(18)

a. A stabiliser unaffected by water, such as bitumen, is used to fill micro cracks, voids and pores in the earth. This mechanism is particularly suitable for sandy earth because the stabiliser improves volume stability and reduces water permeability. In silty and clayey earth, the particles have a greater surface area and so more stabilisers needs to be added.

b. An expandable stabiliser, such as Bentonite, is mixed with earth and swells in the presence of water to block the pores.

6. Water repulsion treatment (chemical stabilisation)

The movement of water and water vapour through earth is modified either by changing the nature of the water or by reducing the sensitivity of the clay to water. The three mechanisms for modifying the movement of water and water vapour are: (18)

a. Modification 1: Drying the earth by adding calcium chloride stabiliser to modify the state of the pore water. This stabiliser raises surface tension, reduces the vapour pressure and evaporation rate of the water and also reduces variation in moisture content.
b. Modification 2: The addition of certain acids promotes ion exchange or replacement in the earth. Ions from these acids bond to the surface of the clay plates and so a film of adsorbed water does not form around the clay particles. (6)(17)
c. Modification 3: The addition of quaternary amines and resins promotes molecular exchange or replacement. These additives, surrounded by compact aggregates in the earth, become fixed only to the edge of clay plates. The outward-facing surface of the additive has an ionic charge that repels water molecules. (16)

There is a direct relationship between dry density and compressive strength for all types of earth; the more compact the material, the higher its dry density. In the compaction process, strain always takes the path of least resistance, which means that the largest pores usually broken down before smaller ones. Thus, it is easier to compact a well-graded material with small, evenly distributed pores than a poorly-graded material, where additional energy is required to break down large pores.

It is rare to find a naturally compact earth that can be cut directly into blocks for construction purposes - some degree of compaction is normally required. Pore size and distribution clearly influences the behaviour of the material. (19)

c) **Stabilisation and compaction**

A satisfactory wall construction material can be produced using a combination of compaction, to increase earth density, and by improving earth properties, through the addition of cement or lime. Although the cost of stabilised and compacted earth blocks is high, they require approximately 75% less inputs to produce the fired clay bricks. (1)

d) **Partial stabilisation and compaction**

Stabilised earth offers increased strength under wet conditions and resistance to rain erosion. Under certain circumstances, it is sufficient to reduce water absorption and increase the erosion resistance without substantially altering the wet strength. Such an improvement in the behaviour of is referred to as partial stabilisation. This type of earth processing involves the addition of small quantities of adhesive material such as syrup made from waste Jaggery (non-refined sugar commonly consumed) or boiled starch solution. A Research using small amount of calcium sulphate and some other materials improve earth stabilisation and compaction properties. (10) Improvements to the physical properties of earth stabilisation blocks produced by NBRI are possible. Investigation of the composition of earth would enable blocks with greater stability to be made.

3.5.1 Earth block as a building material

Comparison between stabilised blocks and other masonry materials should not be restricted solely to their compressive strengths and production costs. (19) Any comparison should be based on wide range of parameters, such as the shape and dimensions of the material, its appearance (colour, texture) and performance measures (wet and dry compressive strength, thermal insulation, apparent density, and durability).

However, factors other than those linked to production and use of the material have to be considered. Comparison between stabilised blocks and other masonry materials must also take into account the nature of earth deposits supplying the raw material, the means by which the raw material is processed into a building material, the energy involved in this processing or production, the properties of the material when used as a building material and its condition in the finished building. (13)

Table 3.13 shows the results of comparative study, undertaken by CRATerre-Eag, masonry material. (13)

Characteristics	Unit	Earth Stabilised Blocks	Fired bricks	Adobes	Concrete blocks
Shape and Size Type IXWXH	cm	29.5x14x9	22x10.5x6.5	40x20x10	40x20x15
Appearance of masonry		Smooth medium to good	Rough to smooth good to excellent	Irregular poor	Rough average
Performance of masonry	MPa % (strength) w/m°c (conductivity) Kg/m3 (bulk density)	1 to 4 0.02 to .2 0.81 to 1.04 (low to very good)	0.5 to 6 0 to 0.02 0.7 to 1.3 1 400 to 2 400 (low to excellent)	0 to 5 0.4 to 0.8 1 200 to 1 700 (poor)	0.7 to 5 0.2 to 0.05 1.0 to 1.7 1 700 to 2 200 (low to very good)
Use in masonry		Load bearing without render	Load bearing without rendering	load bearing with render	In fill

Source from CRATerre-Eag Video Film (Earth Construction course)

3.5.2 The steps for development of earth stabilised block as building material

Following the development of a new building material, its durability, availability of its raw ingredients, and its economic viability, must be investigated prior to use. (20)

The development of any material is generally based on the following criteria:

(i) Economics

One should consider the effect of the new material on the local economy. Improvements to the housing stock, based on use of a new, an affordable building material, will result in a spiral of increased usage and marketing of the material. Increased use of the material will lead to a reduction of imported materials and the establishment of small, local businesses, resulting in the creation of jobs and an increased skill base. In more global terms, energy consumption will be reduced and a contemporary approach to construction, based on traditional ways, well evolves. (21)(22)

(ii) Specification and Marketing

The performance standards earth stabilised blocks are usually based on specifications for concrete or other materials. (22) Clearly this is unsatisfactory for measuring functionality and durability of earth stabilised blocks. Therefore it is important to develop dedicated specifications for earth stabilised blocks according to its characteristics. The promotion of quality standards in this way will provide additional credibility to support the use of earth stabilised blocks.

(iii) Ease of adoption

One of the characteristics for producing earth-stabilised block is the degree of adoption, in conditions for creating production units. The possibility of investing in production stages, both in terms of equipment and technical capacity (training, skills) makes it very easy to adopt to a given context by modifying the approach selected in the light of market needs and constraints. (12)

(iv) Partnership

It is easier to obtain funding to establish small-scale production units than large scale ones, especially where national development strategies have been implemented. Funding agencies provide not only financial assistance for establishing production facilities but also with preparatory studies, marketing and technical support. (12)

(v) Obtaining information

It is important to study the performance of materials and their utilisation in order to promote more effective use. The materials must be described and cost estimate determined. Performance information must be endorsed by the relevant technical organisation, i.e. in the case of earth stabilised blocks; the demonstration building must be examined. (1)

(vi) Diversification

New products and process utilising a given material should be considered. For example, the design requirements of earth stabilised blocks should be assessed. It is also necessary to maintain is contacting with users and partners so that information about the latest needs and techniques are collected. (15)

3.6 Choice of Stabilisers for Stabilisation Process in this Study

The following materials have been selected for use in this study. The parameters of selection of these materials are described in chapter six.

3.6.1 Portland cement

Portland cement is defined by the British Standards Institution in BS12: 1978 as

> 'A product consisting mostly of calcium silicate, obtained by heating to partial fusion, which is a pre-determined and homogenous mixture of materials containing principally lime (CaO) and silica (SiO_2) with small proportion of alumina (Al_2O_3) and iron oxide (Fe_2O_3)'. (23)

In the presence of water, the calcium silicates and aluminates in Portland cement form hydrated compounds that, in time, produce a strong, hard matrix. The material with which the cement has been mixed is embedded in this matrix. The hydration reaction is slow and commences at the surface of the cement grains; the centre of the grains may remain unhydrated. Thus, as the cement cures, the rate of hydration decreases with time, as does the rate of gain of strength of the cement stabilised material. (23)

3.6.2 Lime

Lime is the generic term for calcium oxide, calcium hydroxide and calcium carbonate. Calcium oxide (CaO) is more commonly termed quicklime, calcium hydroxide $Ca(OH)_2$ is known as hydrated or slaked lime, whilst calcium carbonate ($CaCo_3$) is often called carbonate of lime and is the main constituent of chalk and limestone. (24) The relation between the above types of lime can be represented by the following equations:(24)

1. $CaCo_3$ + Heat =CaO +Co_2
2. CaO +H_2O = Ca $(OH)_2$ +Heat
3. $Ca(OH)_2$+ CO_2 = $CaCo_3$ + H_2O

Heating chalk or limestone to temperatures in excess of 500^{O}C produces quicklime (equation 1). Hydrated lime is produced as a result of the reaction of quicklime with water (equation 2). Quicklime (by the reversal of equation 1) and hydrated lime (equation 3) can both be used as raw materials for the production of carbonate of lime. This form of lime serves no value to earth stabilisation for civil engineering purposes, although it is used as an additive to adjust soil pH for agricultural purposes. (24) Consequently, in the context of earth stabilisation, the term lime refers to hydrated lime and, very occasionally, quicklime. Hydrated lime is used for earth stabilisation purposes in Sindh because it is easy to handle and readily available. On the other hand, quicklime is difficult to use because of its caustic nature and is not widely available in Sindh.

Under the given compaction load, lime has the effect of reducing the ratio of voids in the specimen (vδ max.) and raises the optimum moisture content due to flocculation. (19) By adding 1-2% lime to an earth sample, a 10% linear shrinkage value can be reduced to approximately 1%. The lime also eliminates swelling of the earth. Lime affects the earth through five mechanisms: (25)

1. The presence of water or moisture in earth mixed with quicklime causes a hydration reaction to occur. This reaction is strongly exothermic and releases about 300Kcal for every kilogram of quicklime. (24)
2. When lime is added to moist earth, the latter becomes flooded with calcium ions. Cation exchange then takes places, with calcium ions replacing the exchangeable cations, such as magnesium, sodium, potassium, and hydrogen, of compounds in the earth. (25)
3. As a result of the above cationic exchanges, which increase the quantity of electrolytes in the pore water, the earth grains flocculate and tend to accrete. These accretions form more readily in clay-rich earth, altering both. They alter both the grain size distribution and structure of the earth. (24)
4. Lime reacts with carbon dioxide from the air to form weak carbonated cements. This reaction uses part of the lime available for pozzolanic reaction. (26)
5. The strength of the stabilised material results from the dissolution of clay minerals in the alkaline environment produced by lime. Silica and alumina from the clay minerals combines with calcium from the lime, forming complex aluminium and calcium silicates that cement earth grains together.

Lime is added to earth in order to maintain the high pH necessary for the dissolution of clay minerals. The high pH must be maintained for a sufficient length of time to allow an effective stabilisation reaction. The dissolution of clay minerals at high pH is the most important reaction involved in lime stabilisation. (25) It has been found lime stabilised material gains in strength when the curing period is extended. (25) This phenomenon persists for months and is more pronounced warm and humid environments. During the curing process, lime stabilised products can be exposed to high temperatures of up to 60°C. High temperatures and relative humidity may be attained by curing in the sun under plastic sheets, or in tunnels built of corrugated iron. Research carried out by the University of Denmark indicates that durable products can be made by drying for 24 hours in an autoclave at 60-97°C, with a relative humidity of 100%. (25)

3.6.3 Linseed oil

Linseed oil is a naturally occurring triglyceride vegetable oil derived from the seed of the flax plant 'Liniium Ustatissimum'. The oil is used in raw state as stabilising additive to earth. There are no critical hazards associated with the use of linseed oil and, importantly, it is not classed as a flammable liquid. It is a pale brown liquid with a viscosity of approximately 0.4poise@25°C and density of 0.99@15.5°C. Linseed oil is insoluble in water, a property that can be harnessed to reduce permeability of earth. From an ecological and health perspective, linseed oil is an appropriate stabilising additive because there is not any toxicity or bacteria associated with it.

3.6.4 Calcium Chloride

Calcium chloride exists as colourless crystals, with a specific gravity of 2.15, and is very soluble in water. The dissolving of the crystals results in the evolution of much heat and water. Calcium chloride modifies the properties of earth by means of Modification 1 of the water repulsion treatment, as discussed in Section 6.2. When used as a stabilising additive, calcium chloride provides good protection against fire hazards. It is better to use liquid calcium chloride for stabilisation so those gaps are not left in the specimens after compaction, as discussed in Section 6.3.1. Empirical data produced by the American Transport Board show that Liquido Calcium Chloride provides adequate compressive strength for ground improvements.

It is proposed in this study that liquid calcium chloride can be used to achieve Optimum Moisture Content without the need to add water to the earth. There are many advantages to using calcium chloride in liquid form. For example, its drying effect and reaction with clay particles acts to repel water after curing. (6) It should be noted that calcium chloride stabilised blocks require long periods of curing in order to attain an adequate compressive strength.

3.7 Summary

In this chapter the main parameters of technological improvements for mapping out a solution to the rural housing problem are discussed. The study of technological improvement concepts concludes that a combination of indigenous and modern technologies, such as energy saving, environmental harmony and ease of use, are optimised.

The concept of blending technology is also discussed, representing an additional traditional construction technology option. The study shows that earth is used as a basic construction material for walling, roofing, flooring and foundation. It is used in three main forms for walling; sun-dried bricks, wattle and daub, and puddle form. It is also used n slurry form for the plastering of walls. Thatch and bamboo are also used in the construction of traditional Sindhi housing.

One house with three residential units has been investigated in order to determine the causes of defects in earth buildings. The two main causes found were: (i) moisture migration and (ii) structural defects, e.g. construction on unstable ground, use of unsuitable earth that is weak under tensile/bending stresses, design of building with off-centre foundations, etc. Therefore, two types of improvement can be made in order to for the earth to act in accordance design guidelines and bear the structural stresses applied: (i) permeability of earth and (ii) stability of earth.

The literature survey into new research and innovation of construction technology in Pakistan has found that modern construction materials are suitable for use only when cost effective. However, most require high energy inputs and need to be imported.

NBRI has carried out extensive research into the use of modern materials but failed to fully evaluate their cost effectiveness. The earth-stabilised block is the only modern construction material evaluated by NBRI that is suitable for use in low-income housing. However this research has focused on only one approach to earth stabilisation (using cement). The characteristics of earth stabilised blocks has been analysed and compared with other masonry materials. It was found that earth stabilised is suitable for use as substitute masonry material. NBRI's research into earth stabilised block has not yet been commercialised and six steps to marketing the product are recommended.

The detail description has been made the nature of selected stabilisers and their physical and chemical properties. These properties will guide author to understand their suitability parameters with imported earth sample. The following chapter contains the details of the research methodology and design adopted to solve the above problems in earth buildings.

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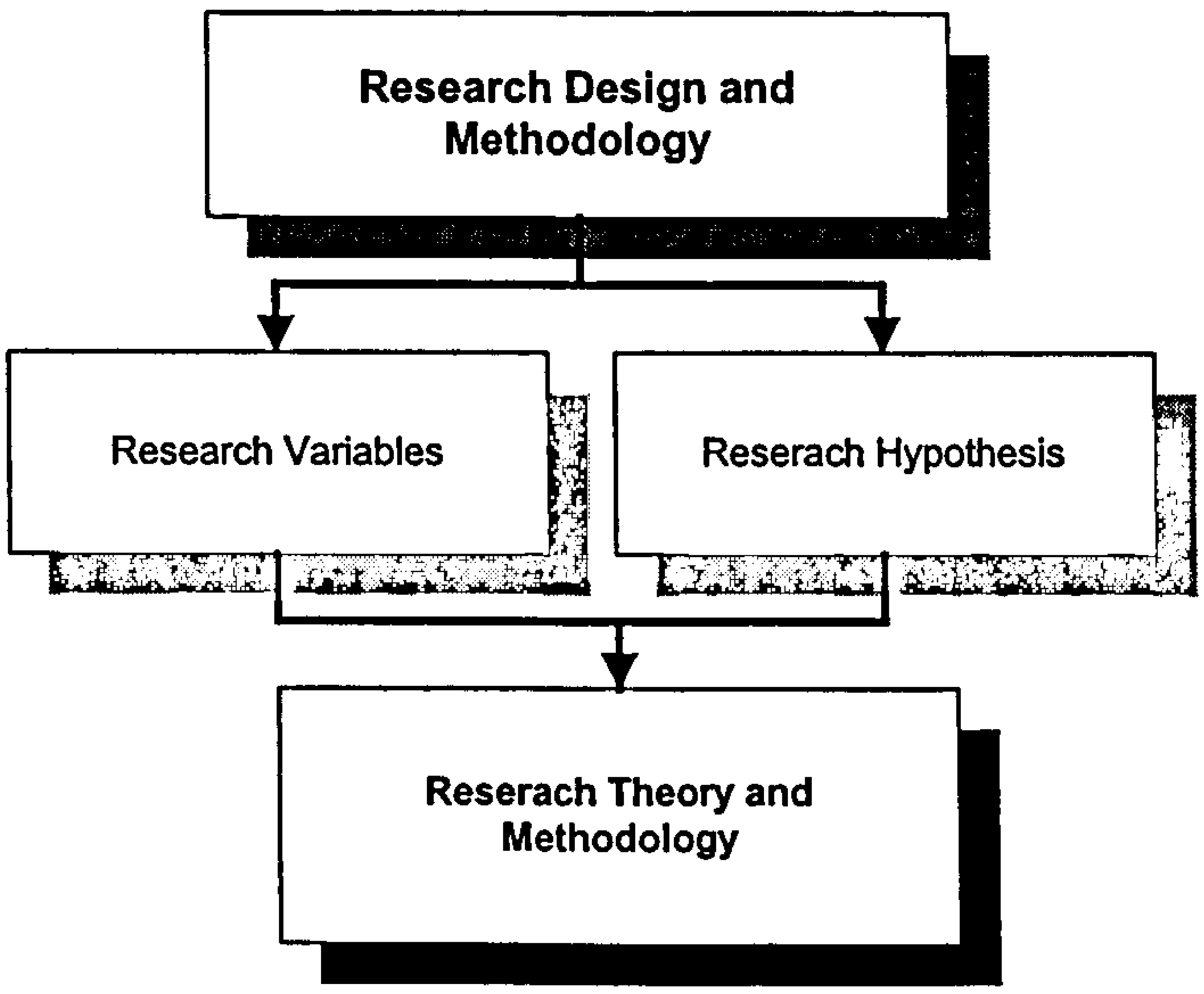

CHAPTER FOUR

Research Design and Methodology

Chapter Four

Research Design and Methodology

4.1 Introduction

This chapter contains a comprehensive description of research design and methods used in this study. It is important to define the basic elements of the research conducted on the stabilisation of earth samples imported from Sindh. A hypothesis has been formulated that clay-rich earth can be stabilised by mixing with certain additives to improve engineering properties.

In first part of this chapter, the problem, sub-problems and their cruces are identified. Research theory, including the need for stabilising earth and the processes used, is discussed. The scope of research is then defined in a statement of delimitation.

In the second part of the chapter, the research variables are identified and their types, relationships and position in the research are discussed. The formulation of null and target hypotheses is based on the relationship between these variables. Most data used in the study derives from laboratory testing of sample material from Sindh province, Pakistan. The laboratory testing, carried out to British Standards Institute specifications, took place in two stages: (i) analysis of earth and (ii) stabilisation of earth.

4.2 The Problem Statement

This study investigates ways to improve the engineering properties of earth originating from Sindh province. Houses built in rural Sindh from similar material are prone to severe cracking, erosion and exhibit problems of rendering lacking adhesion to walls and other surfaces. These building also suffer from premature disintegration.

It has been observed that earth in Sindh province has a propensity to swell and shrink with changing moisture content. When dry, the earth becomes hard and is characterised by deep cracks. When wet, it becomes plastic because of its high clay content. These properties are particularly relevant in Sindh, with its adverse climate poor drainage system. Sindh has a low annual rainfall, with marked wet and dry seasons, and high temperatures. As such, annual evaporation exceeds precipitation, leading to dehydration of earth and disintegration of earth buildings.

4.3 The Sub-Problems

The problem of unstable earth can be broken down as follows:

- Analysis of imported earth material
- Improving the engineering properties of earth
- Appraisal of engineering properties and cost effectiveness of the stabilised earth.

Figure 4.1define the relationship of the sub problem and their position in study

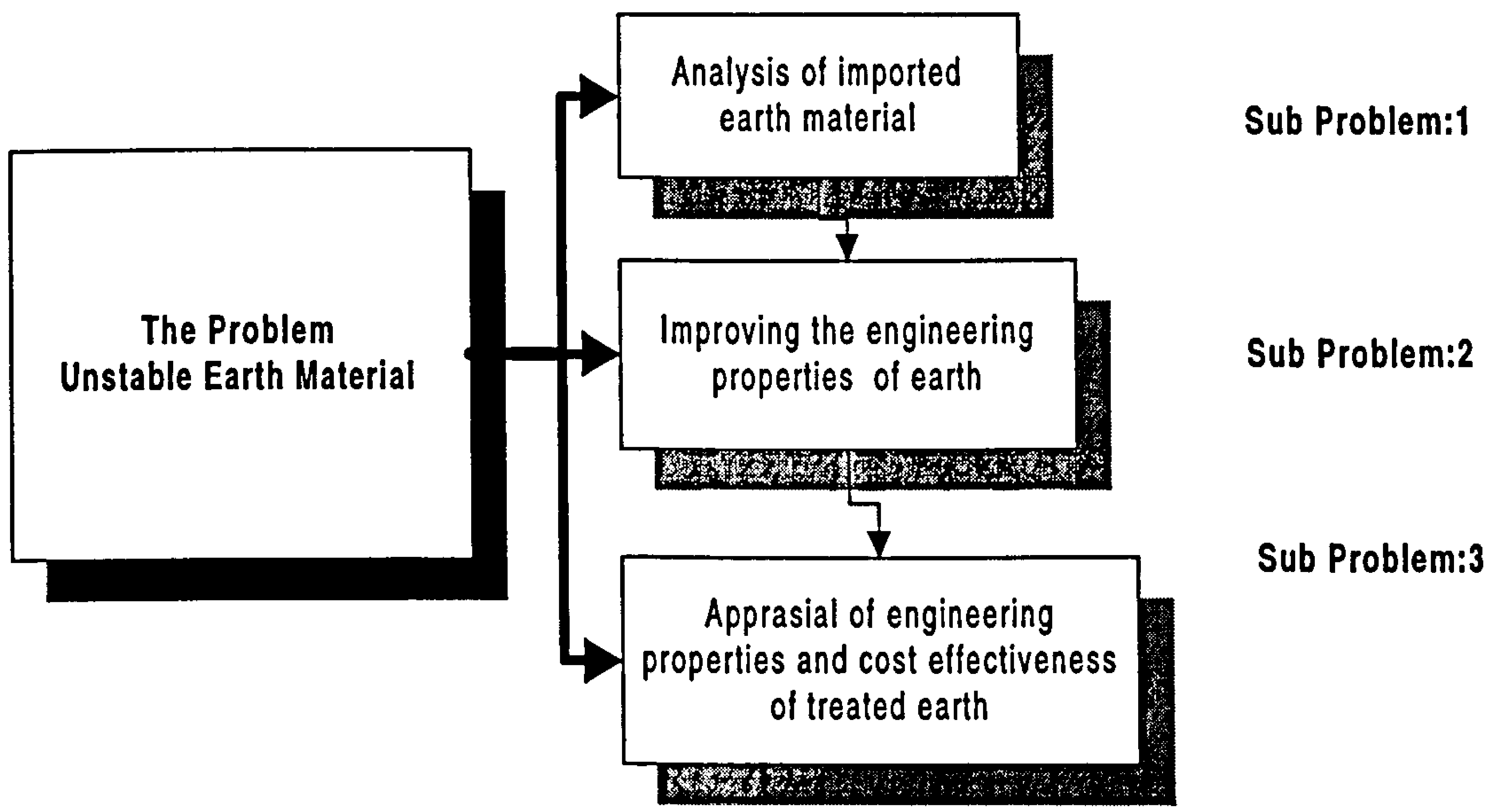

Figure 4.1 Representation of the problem and its sub-problems

4.3.1 Sub-problem 1: Analysis of Earth Samples

Earth comprises, in varying proportions, four types of material: gravel, sand, silt and clay. Gravel and sand impart strength to the earth and clay acts as a binding agent; silts fulfil a less clear intermediate function. Each size fraction has inherent characteristics and, if present in sufficient quantities, influences the overall characteristics of the earth. Thus, particle size distribution plays an important role in defining the properties of the earth.

All four types of material must be present if earth is to be stabilised. Over-abundance or lack of one of these types of material renders the earth unsuitable for stabilisation. (1) (2) In such cases, compensation for anomalous proportions of a given size fraction is necessary. This is achieved by either adding or eliminating material.

Laboratory and on-site tests have been conducted to analyse earth samples. A template chart, produced by the British Standards Institution (BSI), was used to plot the test data. Using a BSI standard curve, reference was made to a comparative analysis of earth to evaluate the results. By plotting particle size distribution in this way, the grading characteristics of an earth can be recognised. (1)

Figure 4.2 summarises the analytical procedures used in this study, together with the processes adopted to improve particle size distribution.

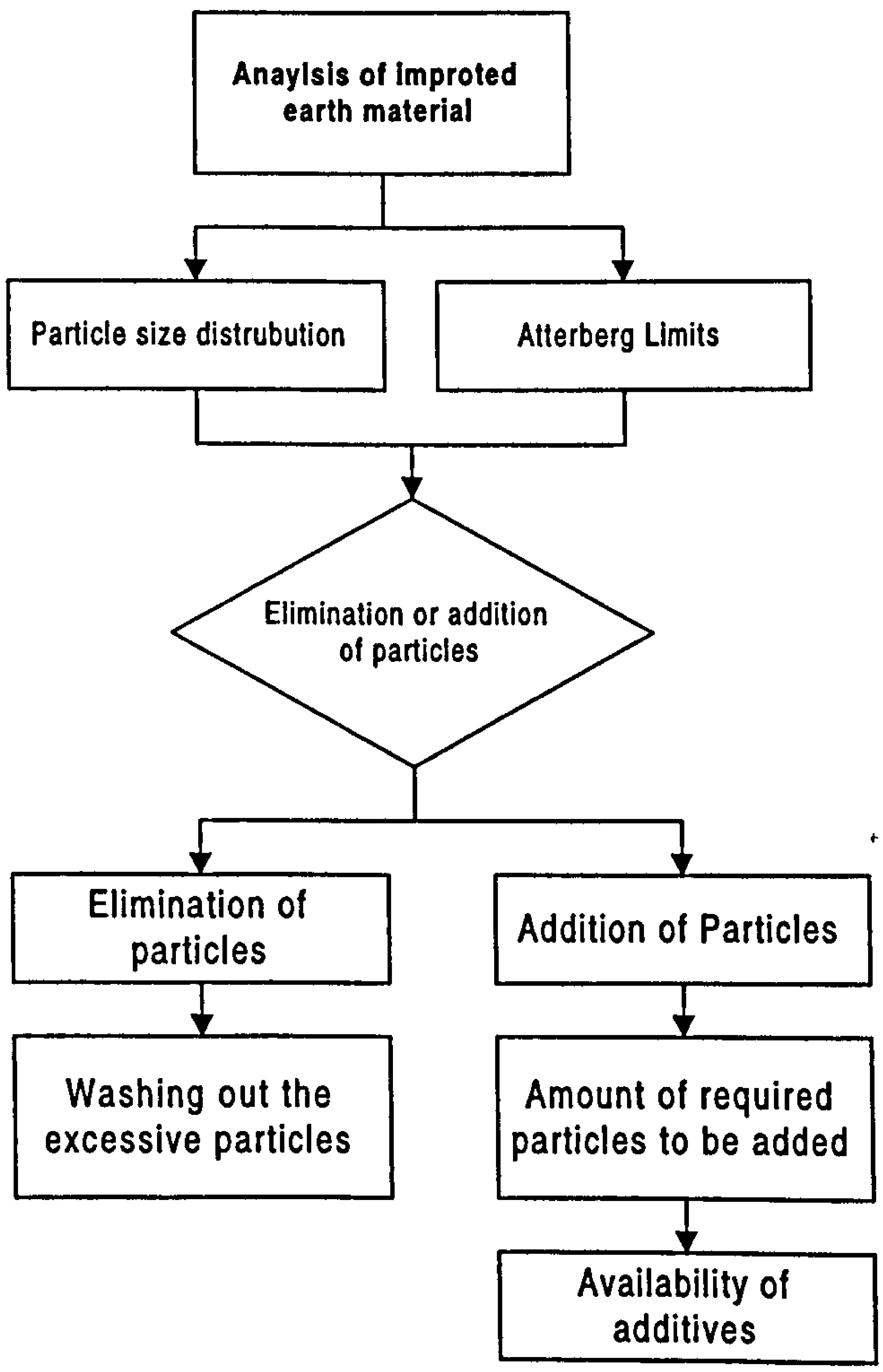

Figure 4.2. Sub-problem 1 and its crux

4.3.2 The Sub-problem 2: Improving Engineering Properties of Earth

The following three approaches are discussed in the context of improving the engineering properties of earth:

- Reducing shrinkage.
- Increasing compressive strength.
- Reducing water permeability.

The above can be achieved through the process of earth stabilisation. This involves mixing earth with stabilising additives and then compacting the mix. The choice of stabilising additive and compaction load used is dependent on the quality and properties of the earth. Many additives have been suggested for use in the stabilising process, but experimental data and conclusive analysis is available for relatively few of them. In practice, choice of stabiliser is dependent on availability, cost and the raw material being used. (3)(4) See Figure 4.3.

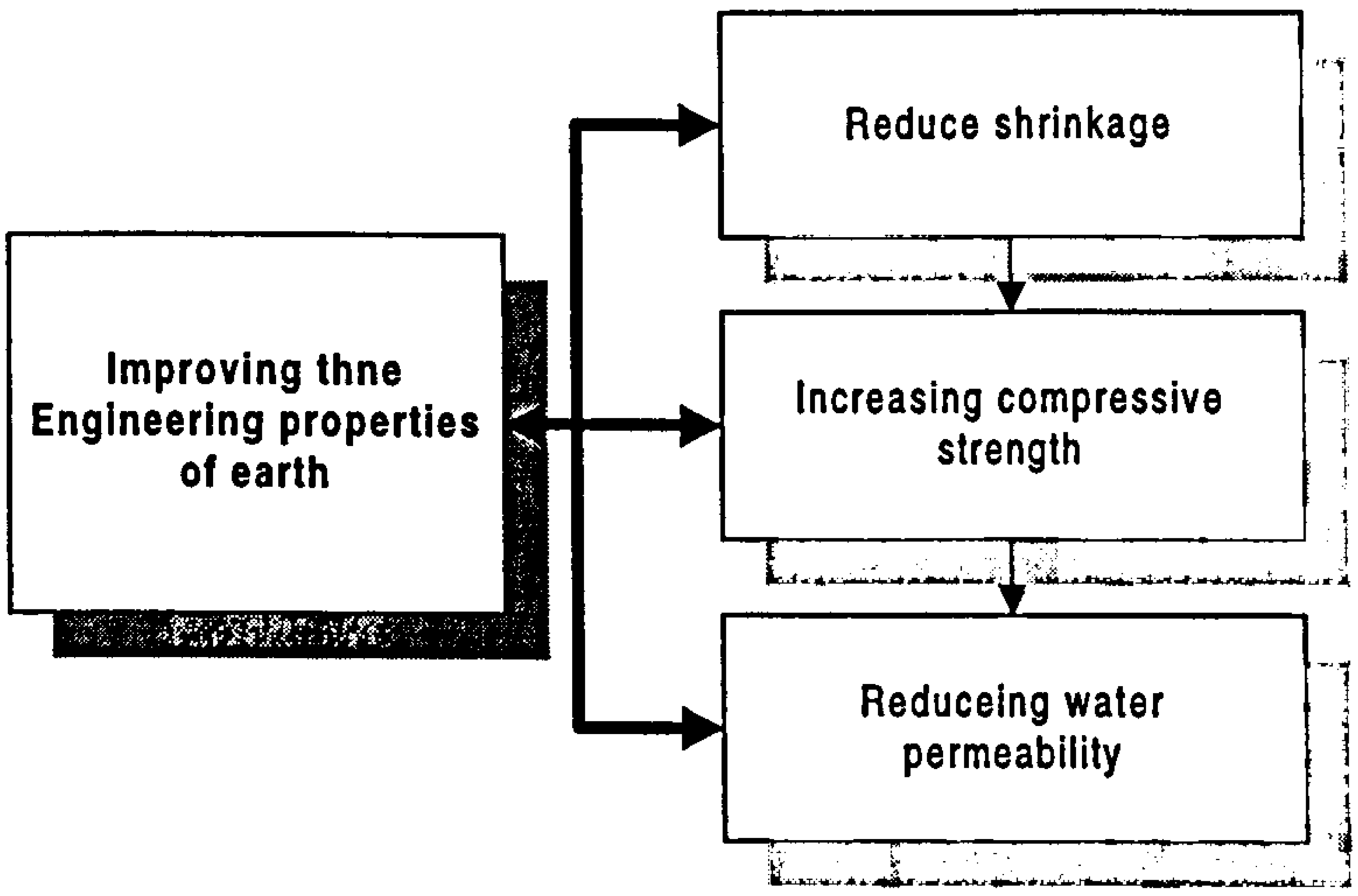

Figure 4.3The sub-problems 2 and its crux

4.3.3 Sub-problem 3: The Appraisal of *Engineering Properties* and *Cost Effectiveness* of Stabiliser

Both laboratory and on-site tests can be used to appraise the engineering properties of stabilised earth blocks. The purpose of these tests is to determine the engineering properties under simulated conditions of use or in actual structural systems.

The following parameters are considered in the evaluation of engineering properties of stabilised earth:

- Compressive strength.
- Water resistance.

For the evaluation of cost effectiveness, the following parameters are examined:

- Ease of use for labourer or user.
- Local production of block.
- Low-cost maintenance.

Sub-problem 3 is summarised in Figure 4.4

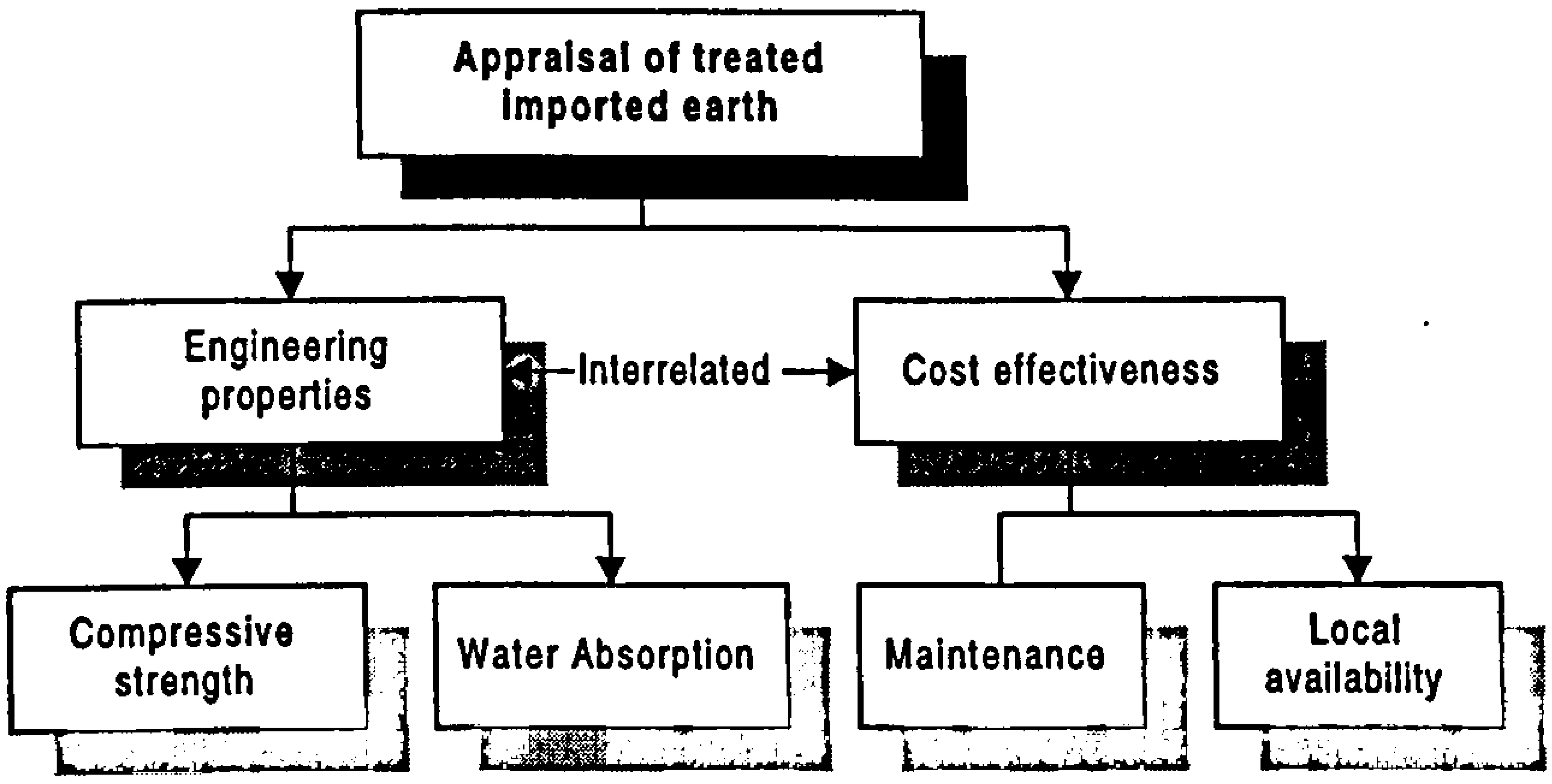

Figure 4.4 sub - problem 3 and its crux

4.4 Research Theory

Earth is the most commonly used building material in the world; its use is particularly prevalent in ancient traditional communities. Earth architecture in Sindh province is enriched by the diversity of expression, due to the use of various indigenous techniques. Earth is both the most widely used building materials in Pakistan. However, its importance is overlooked in terms of research into innovative new ways to use the material. The insulating properties of earth make it a suitable construction material for dealing with the temperature variations found in Sindh. Most houses built in the local traditional manner are 'naturally conditioned'. This means that the design of the buildings has evolved through repeated cycles of trial and error, embodying the experience of generations of builders. However, some problems arise from the use of earth as a building material, such as water erosion, its low tensile strength and low adhesion to wood.

In some parts of the country, earth is used predominantly in the form of sun-dried bricks or blocks, whilst in other parts it is used mainly in the form of burnt clay bricks and tiles. The use of sun-dried bricks is most prevalent in rural communities where people have low income. Most sun-dried bricks/blocks and burnt clay bricks/tiles are produced in cottage industries established by farmers. The farmers make these products during their spare time, when not working in the paddy fields. The raw material is obtained by peeling away topsoil from the fields and then extracting earth from 50 cm to few meters deep.

The extracted raw material is moulded into the required shape and then the green bricks/blocks/tiles are stacked in the paddy fields to be sun-dried. Where burnt products are to be made, the sun-dried bricks and tiles are then placed into wood-burning kilns for firing. The quality of both sun-dried and burnt product is low in terms of engineering properties and shape. Better quality burnt products are produced in large-scale factories, but are normally more expensive than those made by the farmers. However, these factories produced burnt bricks and tiles often lack uniformity of size.

Literature on low-cost housing reveals that the costs of material supply, including material and transportation, accounts for 50-60% of the overall building cost. (2) Therefore, the use of locally produced material plays an important role in reducing the construction cost of houses for low-income groups.

Indigenous building technologies take account of regional needs, availability of material and regional labour expertise which is based upon the cumulative experience of many generations. However, it is possible to make significant improvements to indigenous building technologies by 'blending' with imported, modern technologies. For example, the engineering properties of earth, a traditional construction material can be improved by stabilising with additives, a modern innovation.

The use of stabilised earth blocks satisfies demands for high quality living within a built environment that maintains harmony with the natural surroundings. The production of earth stabilised blocks offers the most favourable socio-economic solution to housing needs. Notably in countries that depend on the importation of materials, earth stabilised blocks gives access to high quality housing at affordable cost. (6)(7)

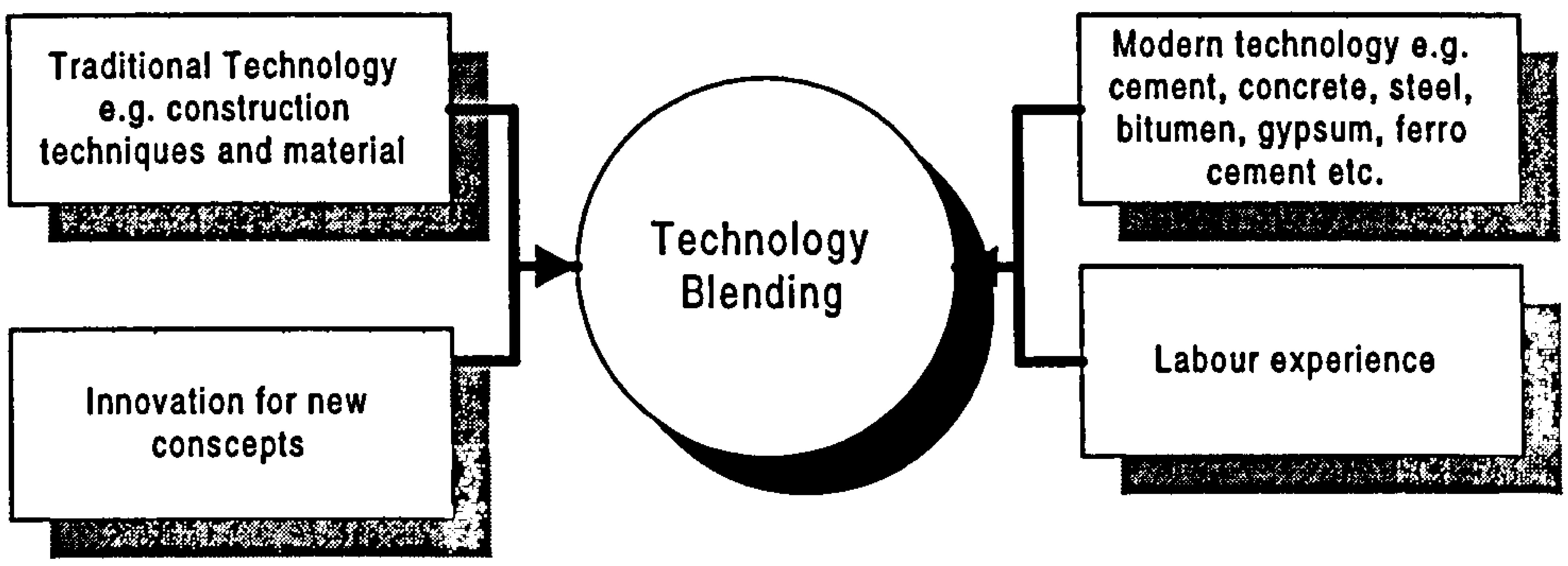

Figure 4.5 Effect of various factors on the promotion of blending technology

Currently, more than 100 additives are used to stabilise earth. These stabilisers can be used in the bulk of earth walls or can be applied to the surface of walls to provide protection. The term "earth stabilisation" is defined in this study as the alteration of the properties of earth to meet specified engineering requirements, such as compressive strength, volume stability, and water permeability. (2)(4)

There are three basic modes of stabilisation: (2)

- Mechanical stabilisation (via compression): Various properties of earth, such as density, mechanical strength, compressibility, water permeability and porosity are improved through compaction using mechanical presses.

- Physical stabilisation (via mixing): Changing texture through the controlled mixing of different grain fractions can modify various properties of earth.

- Chemical stabilisation (via chemical agents): In this procedure, materials and chemicals are added to the earth to modify its properties. The modification occurs either through physico-chemical reactions, which lead to the formation of a new material, or through creating a matrix, which binds or coats the grains and improves their properties.

For optimum results, usually two procedures are combined. Typically, mechanical stabilisation is undertaken together with physical or chemical stabilisation. The selection of procedures for stabilisation depends on the properties of the earth. (3)

4.5 Statement of Delimitation

In this study, earth stabilisation is investigated in the context of clay-rich earth imported from Sindh province, Pakistan. The following aspects of earth stabilisation are investigated:

- Enhancement of durability (modification of compressive strength and reduction water absorption properties).
- Reduction of shrinkage and expansion (alteration of linear shrinkage, correction of the particle size distribution and the addition of stabilising material).
- Reduction of water permeability (addition of water proofing, compaction effect).
- Cost considerations (availability, easy of use, local production of the stabiliser).

4.6 Research Variables

'A variable is the concept which can differ in its essence' (8)

It could be argued that there are three main variables which researchers usually encounter: (9)(10)

- Independent variable: A variable that is manipulated to examine its impact on a dependent variable.
- Dependent variable: A variable that indicates whether the treatment or manipulation of the independent variable had an effect.
- Control variable: A variable that is related to the dependent variable; the influence of the control variable needs to be removed. It takes different forms depending on the experimental research design used.

In this study, the following variables have been identified:

4.6.1 Independent Variable (IV): Earth Stabiliser

Earth stabiliser is taken to be the independent variable in this research. It varies in terms of type of stabilising material and the percentage added to the earth samples:

- Type of stabiliser used (IV_1): Portland Cement, hydrated lime, linseed oil, and calcium chloride.
- Percentage of stabiliser added (IV_2): The percentage of stabiliser added to the earth samples is based on the results of analytical testing of the earth and linear shrinkage tests.

There are two dependent variables:

4.6.2 Dependent Variable (DV_1): Engineering Properties of Stabilised Earth Blocks

The type of stabiliser used affects the physical, chemical and mechanical characteristics of the earth and determines the engineering properties of earth stabilised blocks. The term "engineering properties" relates to two parameters: compressive strength and water absorption of the test specimens. Thus, in this study, compressive strength and water absorption tests are used to measure the extent of change in DV_1 resulting from change in IV. The change is measured by the difference in compressive strength and water permeability values between earth and earth stabilised block.

4.6.3 Dependent Variable (DV_2): Production Cost of Stabilised Block

The production cost of stabilised block is dependent upon on the costs of the additive and labour. This variable is measured by calculating the overall cost with the respect to IV.

4.6.4 Relationship between Variables

All three of the above variables are interrelated. Additive material directly improves the engineering properties of earth. Production cost varies according to the type and amount of stabilising additive used.

The following equation summarises the relationship between independent and dependent variables:

$DV = f\ (IV_1, IV_2 \ldots IV_k)$

Where DV = The dependent variable

f = Function of

IV = The independent variable

This equation can be applied to investigate the effect of using different types and amounts of additive on the engineering properties and the cost of the stabilised block. (10)(11) See Figure 4.6.

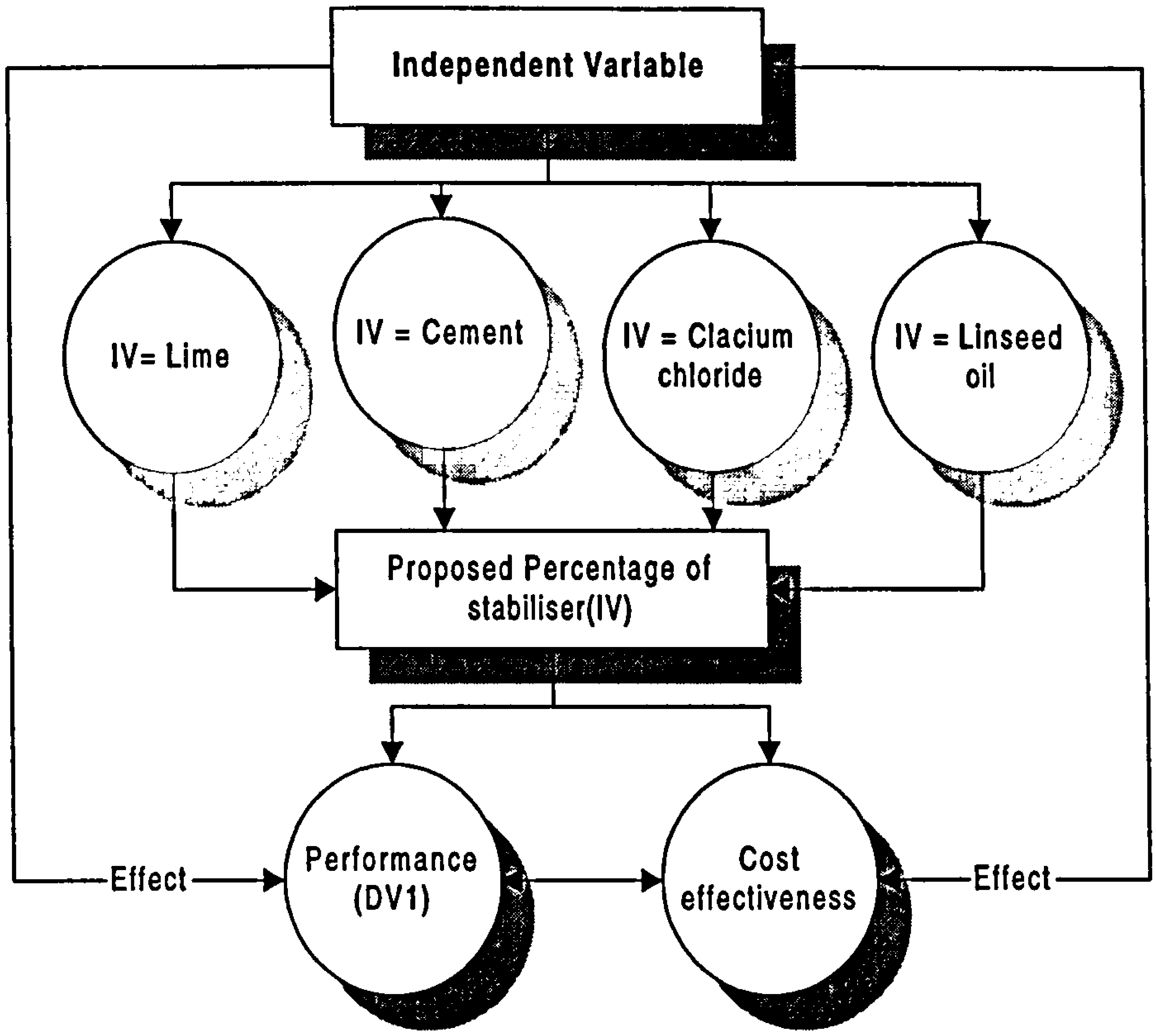

Figure 4.6. Relationship between Variables

4.7 Null Hypothesis

"The null hypothesis is always a statement of equality" (10)

The null hypothesis is usually the starting point and benchmark against which the outcomes of a study are measured. The bench marks for this research are as follows:

- Clay-rich earth cannot be stabilised by correction of particle size distribution alone.
- Changing the type and amount of additive used cannot affect the engineering properties of earth.
- There is no relationship between the production cost and engineering properties of the stabilised block.

4.8 The Target Hypothesis

Hypotheses are substitute answers to research problems and are expressed in the form of a relationship between independent and dependent variables. (10)(12) The following target hypothesis, based on 4 propositions, has been designed for this study:

Proposition 1: Clay-rich earth mixed with well-graded sand produces a cost-effective material with adequate engineering properties for construction purposes.

It has be argued that, in order to produce stabilised blocks, earth must contain silt and clay to provide cohesion. (1)(3) Earth is a variable and complex material and is not always suitable for use in construction. However, its engineering properties can be improved for construction purposes by the addition of various types of stabilising material. The earth samples used in this study contain a high percentage of clay, which means that the material is not well graded and lacks coarse grains in its composition. The proposition has been formulated that the engineering properties of the earth samples can be improved by modifying the particle size distribution through the addition of sand. In other words, by mixing well-graded sand with imported earth at its OMC (Optimum Moisture Content) and then compacting the specimens, stabilisation can provide a cost-effective means of improving the raw material's engineering properties.

Proposition 2: The type of stabiliser used affects the degree of improvement in engineering properties.

The stabilisers selected for use in this study each have different physical and chemical properties and affect clay-rich earth in different ways. For example, the strength of lime stabilised blocks increases over time, whilst cement stabilised blocks reach maximum strength within a specific time limit. It is also important to note that the stabilising materials act in different ways. For example, cement works as cementatous material between earth grains, whereas lime reacts chemically with the earth and creates a matrix. (2) Chemical stabilisers, such as calcium chloride, react with clay in the earth to create a water proofing membrane. (2) Based on these observations, it was envisaged that there would be a difference in the engineering properties of specimens stabilised with different stabilising additives.

Propositions 3: The type and amount of stabiliser used affects the cost of production.

It is argued that both the type of stabilising material used and the amount added to the earth directly affect the production cost of the stabilised block. Therefore, it is postulated that the relationship between both these variables is linear. The amount of stabiliser used in this study was based upon the recommendations of experts and the manual for the earth compressed block. (4) However, the effect of varying the amount of stabilising material on engineering properties of earth samples was tested in order to produce a predictive guide. Once the relationship between type of stabiliser, amount used and cost of production has been identified, it is possible to determine the type of relationship existing between all dependent and independent variables.

Propositions 4: The type of stabiliser used and the cost of stabilised blocks are directly proportional to each other.

The stabilised specimens were prepared using 4 different types of stabilising material: cement, lime, linseed oil, and liquid calcium chloride. Costs of production were estimated for all specimens being analysed. It is recognised that the addition of any other material to earth samples will result in increased production costs. The different types and amounts of stabiliser, together with labour costs, will affect the overall cost of producing stabilised blocks. Therefore it is envisaged that the type of stabiliser used and the cost of producing stabilised blocks are directly proportional to each other.

4.9 Research Methodology

The methodology for research depends upon the type of data being recorded and analysed. (9)(13) Usually, by identifying the type of data to be used, the most appropriate research methodology can be applied to the problem. An experimental methodology is the most suitable approach for quantitative research. (9) In this study, the independent variable consists of two main essences as previously described in 4.5.1. IV_1 comprises four different types of stabiliser, whilst IV_2 comprises four different amounts of stabiliser. In order to measure the affect and relationship of these variables, five experimental groups were established. This enabled the target hypothesis to be analysed and tested.

The five experimental groups were set up using different types and amounts of stabiliser mixed with the earth samples.

- Experimental group 1 was treated using the recommended amount of type 1 of the independent variable (IV_1), i.e. the recommended percentage of cement.
- Experimental group 2 was treated using the recommended amount of type 2 of the independent variable (IV_1), i.e. the recommended percentage of linseed oil.
- Experimental group 3 was treated using the recommended amount of type 3 of the independent variable (IV_1), i.e. the recommended percentage of lime.
- Experimental group 4 was treated using the recommended amount of type 4 of the independent variable (IV_1), i.e. the recommended percentage of calcium chloride.
- Experimental group 5 was treated using the recommended amount of type 5 of the independent variable (IV_1), i.e. the recommended percentage of well-graded sand.

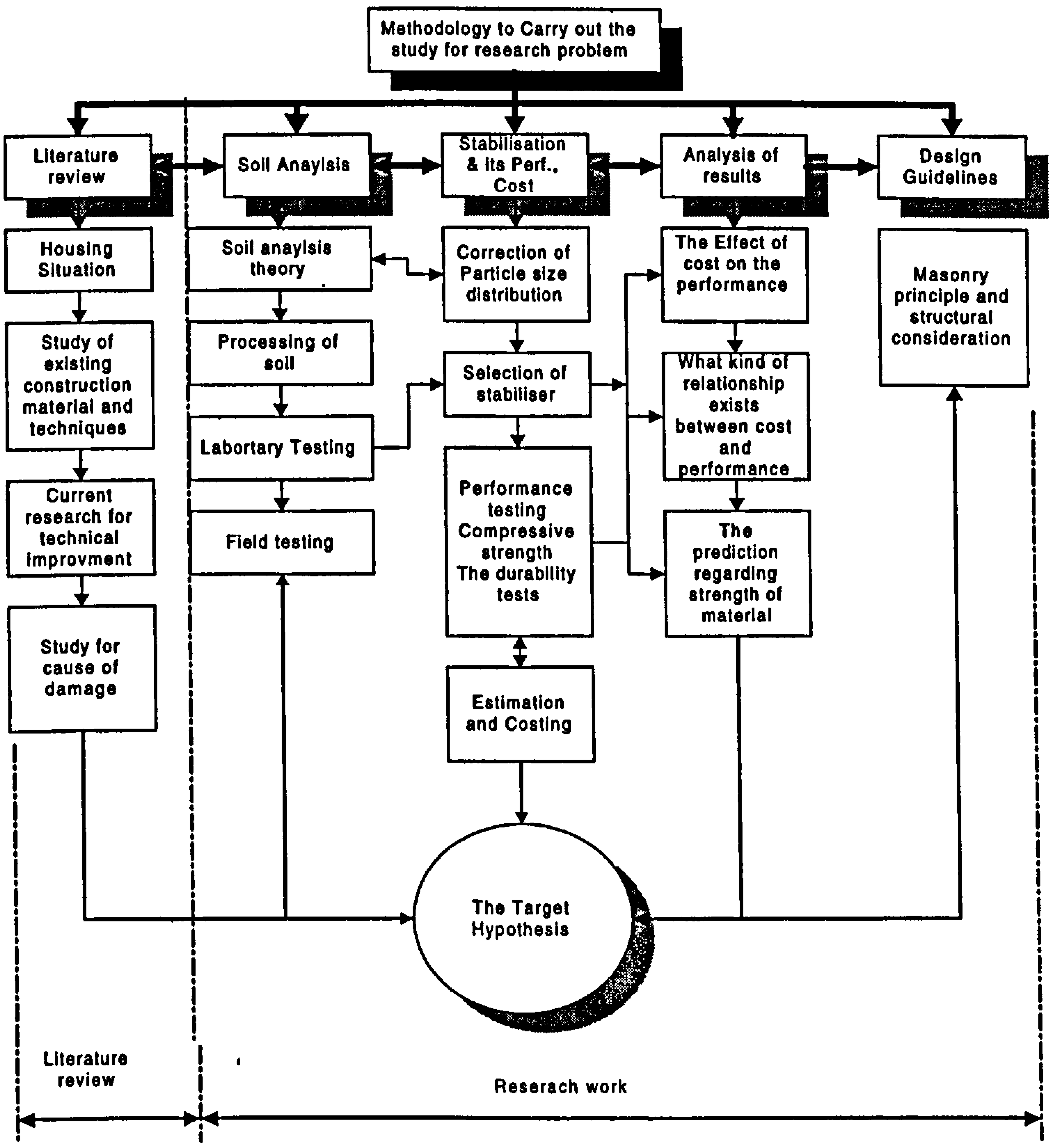

Figure 4.7 Representation of research stages and methodology

4.10 Stages of the Research Study

4.10.1Stage 1

Problem description

This study aims to identify the problems associated with escalating demand for housing and the lack of appropriate construction materials for use in rural Sindh. It consists of two phases:

Phase 1

The following issues are examined in Phase I:

- The housing situation in Sindh.
- Government housing policy.
- Use of traditional construction materials and techniques.
- Current research into modern construction materials and techniques.

The sources of literature used are: annual Sindh survey reports, Statistical Department of Sindh, Sindh gazetteers, books, appropriate technology journals, conference papers, manual for low-cost housing in Karachi by Building Research Department of Karachi, Pakistan, 1996. Furthermore, reference is made to supplementary literature about appropriate technical solutions for developing world countries, with particular emphasis on Pakistan. The results are presented in Chapter3.

Phase 2

In this phase, a case study approach is adopted to investigate the causes of damage in rural housing. The case study comprises an examination of three houses in the village of Shikarpur, Sindh province. It focuses on the causes of damage arising from the instability of construction materials used. A rough sketch of the houses is attached in Appendix A. In addition, a rough sketch of the village plan, based on observations made during the field work, is included in Appendix B. Village plans are never officially recorded by the Government of Pakistan. The results of the fieldwork are presented in Chapter 3. The terminology definitions and theoretical information can be seen form Appendices B(I) used during the investigation of causes of damages in earth building.

Problem Investigation

4.10.2 Stage 2

This stage of research contains two phases:

Phase I: Earth Analysis Theory

In this phase, experimental methods for earth analysis are reviewed in terms of evaluating the engineering properties and characteristics of the imported earth samples. Theories relating to the use of earth as a raw material in construction are also examined. The following organisations acted as sources of literature for the review of experimental methodologies and study of theories.

- British Standard Institution, 1990.
- American Society for Testing Material (ASTM).
- UN Technical Assistance Programme, New York.
- CRATerre- EAG, Paris.
- Building Research Establishment, UK.
- Intermediate Technology Group, London.

In addition, books, journals and conference papers presenting research on earth mechanics and use of earth as a construction material were used.

Phase II

As a part of the research programme, laboratory and on-site tests were undertaken on earth samples from Shikarpur. These samples were taken from the same source as those used to determine causes of damage to three houses. Permission was obtained from UK authorities, with the assistance of the Mackintosh School of Architecture, to import the earth samples from Pakistan.

It is important that, prior to the stabilisation process, the earth is analysed to determine its suitability for stabilisation. The earth samples were, therefore, analysed to assess suitability for stabilisation and then dried and sieved through a 5mm mesh. The analytical testing of the earth also helps to predict the engineering properties of the stabilised earth block.

Laboratory tests

The following tests were carried out:

a) Particle size distribution

The particle size distribution, or grading, of a earth determines how effectively it can be compacted and stabilised. Well-graded earth contains a wide range of particle sizes in the correct proportions for stabilisation, with all voids between larger particles being filled by smaller particles. A combination of tests was adopted to determine particle size distribution, with sedimentation being used for finer particles, and wet sieve analysis being used for coarse ones.

b) Atterberg limits

Earth can have different consistencies depending upon the moisture content. The consistencies range from liquid to plastic and solid. Atterberg limits define these consistencies as a percentage of moisture content by weight. The following limits were measured:

- Liquid Limit (LL): If sufficient water is mixed with clay, it can be made into slurry and it then behaves like a viscous liquid. This is known as the 'liquid limit'. (14) The penetrometer test was used to determine the liquid limits of the earth samples.

- Plastic limit (PL): If the moisture content is gradually reduced from the liquid limit by allowing the earth to dry out slowly, the 'plastic limit' is eventually reached. At this point, clay minerals begin to adhere to each other and start to resist deformation. The same samples tested to determine liquid limit must be used in the thread test to ascertain the plastic limit. The tests to determine liquid and plastic limits are considered important because they provide a direct indication of the behaviour of earth with varying moisture content. (14)(15)

- Plasticity Index (PI): The plasticity index is calculated as the numerical difference between the liquid and plastic limits. (15) It represents the upper limit of optimum moisture content by weight for use in the stabilisation process.
- Linear shrinkage (LS): Earth samples at around their liquid limit were formed into bars and then oven dried. The change of length of the bars was measured using

semi-cylindrical bar apparatus. (14)(15) Linear shrinkage is used to predict the amount of additive required to stabilising the earth samples.

c) Activity coefficient (Ca).

This coefficient indicates the swelling and shrinkage properties of an earth sample. It is the ratio between PI and the percentage of grains smaller than 2µm, i.e. the percentage of clay. (14)

d) Dry Density/Optimum Moisture Content.

This is the moisture content at which the maximum dry density of earth can be obtained. It can be determined by the 'Proctor tests'. The results are recorded on a graph where the Y- axis represents the dry density and the X-axis represents the moisture content as a percentage by weight. (14)(15)(16)

All laboratory tests were carried out in accordance to the specifications laid down by the British Standards Institute. These standards are discussed in detail in Chapter 5. The laboratory equipment and machinery used during the testing and analyses are illustrated in photographs in Chapter 5 and Appendix C.

On- site tests

Laboratory testing, usually carried out by skilled technicians, often requires the use of sensitive and highly calibrated equipment that can not be easily transported. Therefore, sometimes it is not feasible to set up a laboratory at a project site. In such cases, on-site testing can be carried out using portable equipment to provide an approximate analysis of the earth. On-site tests have the added benefit of providing quick results and may utilise unskilled labour. CRATerre-Eag and other authoritative organisations in earth stabilisation recommend specific on-site tests to predict the type and properties of earth.

In this study, the following tests were carried out to identify the characteristics and properties of earth samples: drop test, sedimentation, or bottle, test and linear shrinkage test. Further details of these tests are provided in the earth analysis section of the Chapter 5.

The above mentioned tests resolve sub-problem 1.

4.10.3 Stage 3

Earth stabilisation: Theory and Results

This stage again consists of two phases:

Phase I

The earth samples used in this study were analysed in accordance with the tests prescribed in Phase 2 of Stage 2. These samples are clay-rich, with more than 45 % of the material comprising particles smaller than 0.002mm. Thus, first of all, the particle size distribution of the samples was corrected and then, secondly, a suitable stabilising additive was selected. As previously noted, the choice of stabilising additive depends on the properties and type of earth used.

The particle size distribution of the earth samples was corrected by adding well-graded sand in various proportions. The dry densities and optimum moisture contents of the samples were recorded and plotted on graphs before adding the sand. Further details are discussed in Chapter 5.

A plotting chart produced by BSI was used to determine, on the basis of the results from the particle size analyses, the amount of sand needed to be added. According to this chart, at least 50% sand was necessary. However, trials were undertaken with 10%, 30% and 50% added sand to find out, on the basis of required dry density and optimum moisture content, whether less sand could be added. If it is possible to add less sand than recommended by the BSI chart in order to provide a stabilised material, there are clearly cost benefits in doing so.

Next, appropriate additives were selected for the production of stabilised blocks. The earth samples were mixed with various stabilisers, including cement, lime, linseed oil and calcium chloride. The mixing was carried out using a kitchen blender. The criteria for selecting the stabiliser depended on the composition of the earth samples and their linear shrinkage. Also, recommendations by the Building Research Establishment for selection of stabilising additives were considered.

Phase II

In Phase II, the samples prepared in Phase I were used to produce stabilised blocks that were then analysed to determine their engineering properties. An assessment of the cost effectiveness of using various stabilising additives was also undertaken.

The stabilised specimens were made into 50mm diameter cylinders and then compacted under a load of 2-10MPa. The samples were cured, dried and then tested for their engineering properties. The tests were carried to the specification of BS1377: 1990 (British Standard Institution). The presses conformed to CINVA and BREPAK standards.

The compaction of each stabilised earth cylinder, usually undertaken at the material's optimum moisture content, utilised a mechanical press capable of applying a wide range of loads. Each cylindrical earth specimen was carefully demoulded, weighed, measured for size and then sealed in an airtight, labelled plastic bag at 32-36^{o}C for 28 days. After 7, 14, 27 and 28 days, the specimens were weighed and measured. Further details of these experiments are included in Chapter 6.

The following tests were carried out on cured stabilised specimens:

a) Compressive strength
b) Water Absorption
c) Porosity & Durability

a) Compressive strength

After curing for 1 month, the recommended minimum compressive strength value of earth for use in construction is 15kgs/cm^2, and ideally 20 kg/cm^2 or more. (1) Compressive strength values are given for cured stabilised earth. Wet compressive strength is taken to be half of the dry strength value. (2) (16)

b) Water absorption

Water absorption tests were also carried out on the earth stabilised specimens. The specimens were measured in terms of weight and size and then immersed in water for 24 hours. After this period, the specimens were removed form the water and measured for weight and size. From these results, the water absorption of the specimens was calculated. The results of both the compressive strength and water absorption tests were used to analyse the engineering properties and cost effectiveness of the stabilised earth specimens.

c) Porosity and Durability test

These both tests were carried out on the earth stabilised specimens. The specimens were processed under required temperature and soaking for 24 hrs. These tests were conducted according to British Standards Institution. The results were analysed to evaluate the performance of the stabilisers with imported earth material. The choice of methodology to conduct the tests were severe comparing the earth's engineering properties. However these test provided a significant results which can be referred.

A 'model house', as proposed by the Government of Pakistan for a "low-income communities shelter project" in Sindh, was used to estimate the cost of using various stabilising additives in the construction. (17)

The proposal for the model house was prepared in November 1995 by the Building Research Institute, Karachi, Sindh. Cost estimations for constructing the model house using earth blocks stabilised with various additives were compared to actual costs. The cost estimations also included the provision of other construction materials. A plan of the model house is shown in Chapter 7.

The costing information is intended to assist entrepreneurs, staff of financial institutions, business practitioners and government officials to estimate production costs of stabilised earth blocks. In this way, the least-cost technology is identified, which will encourage investment in the technology and provide a boost to production.

A methodological framework for the estimation of production costs is described in Chapter 7. The production costs will vary according to the time scale of the construction project and local circumstances, such as:

- Availability of earth : whether it is present on-site or has to be transported to the site.
- Suitability of the earth for stabilisation, the type, quality and quantity of stabiliser required. It may be necessary to buy sand if the earth has a high linear shrinkage.
- Current prices for commodities, especially stabilising agents.
- Current wage rates, and productivity of the labour force.
- The building owner's contribution in construction.

It should be noted that stabilised blocks can be made on a 'self -help' basis to eliminate labour costs. Furthermore, earth is often available at no cost.

4.10.4 Stage 4

Analysis of the data

At this stage, four scenarios are discussed in order to evaluate the relationship between the independent variable (stabiliser) and the two dependent ones (engineering properties and cost).

1) Stabiliser imparting adequate engineering properties for construction purposes at high cost
2) Stabiliser imparting adequate engineering properties for construction purposes at low cost
3) Stabiliser imparting inadequate engineering properties for construction purposes at high cost
4) Stabiliser imparting inadequate engineering properties for construction purposes at low cost

The above scenarios are used to determine the kind of relationship existing between engineering properties and cost.

4.10.5 Stage 5

Choice of structural system

At this stage, structural specifications for using earth stabilised blocks are reviewed, together with design guidelines. This involves an examination of masonry principles, masonry bonding patterns and systems.

Precautions for using earth as a filling material in foundations and footings are investigated, as are different techniques for the construction of roofs and walls. In addition, many different additives are considered to waterproof plastering and rendering.

4.11 Summary

The research problem is identified and divided into three sub-problems. The sub-problems are further divided into cruxes. Examination of these issues enables an appropriate solution to the research problem to recommended. The research theory provides conceptual frameworks for the earth stabilisation process and proposal for blending technology.

Three main variables have been identified. The stabiliser is the independent variable, the engineering properties and production cost of blocks are the dependent variables. The effect of changing the independent variable on the dependent variables is recorded.

A target hypothesis has been formulated to define the relationship between the variables. The statement of delimitation defines the scope of research undertaken.. The following two aspects of earth stabilisation are considered in this study:

(i) Engineering properties of the product.

(ii) Cost of the product.

This study comprises five stages:

<u>Stage 1</u> contains a literature review of the housing situation in Sindh and the causes of damage to houses constructed of earth. Policies of the Pakistan Government and current research work are also examined.

Stage 2 contains a review of the theories of earth analysis that underpin the research carried out. Preparation of earth samples imported from Sindh (Pakistan) is discussed. This stage also provides details of all the laboratory and on-site earth analysis tests conducted.

Stage 3 contains details of all the laboratory tests conducted on the earth stabilised specimens. Eighteen specimens were prepared in order to test the engineering properties of earth samples stabilised with different additives. This stage also contains estimates of production costs and examines the effect of various factors on production of stabilised blocks. A model house proposed by the Building Research Institute, Karachi, Sindh, is used to estimate the production costs.

Stage 4 contains details of the experimental methodology used to test the target hypothesis. A simple Microsoft Excel graphical formula is used to analysis test data.

Stage 5 contains a review of the general design and maintenance guidelines covering the use of stabilised blocks in construction. Figure 4.8 is a process flow chart showing the research design and the sequence of research activities. This Figure provides guidelines for action where the null hypothesis is rejected or the target hypothesis is accepted.

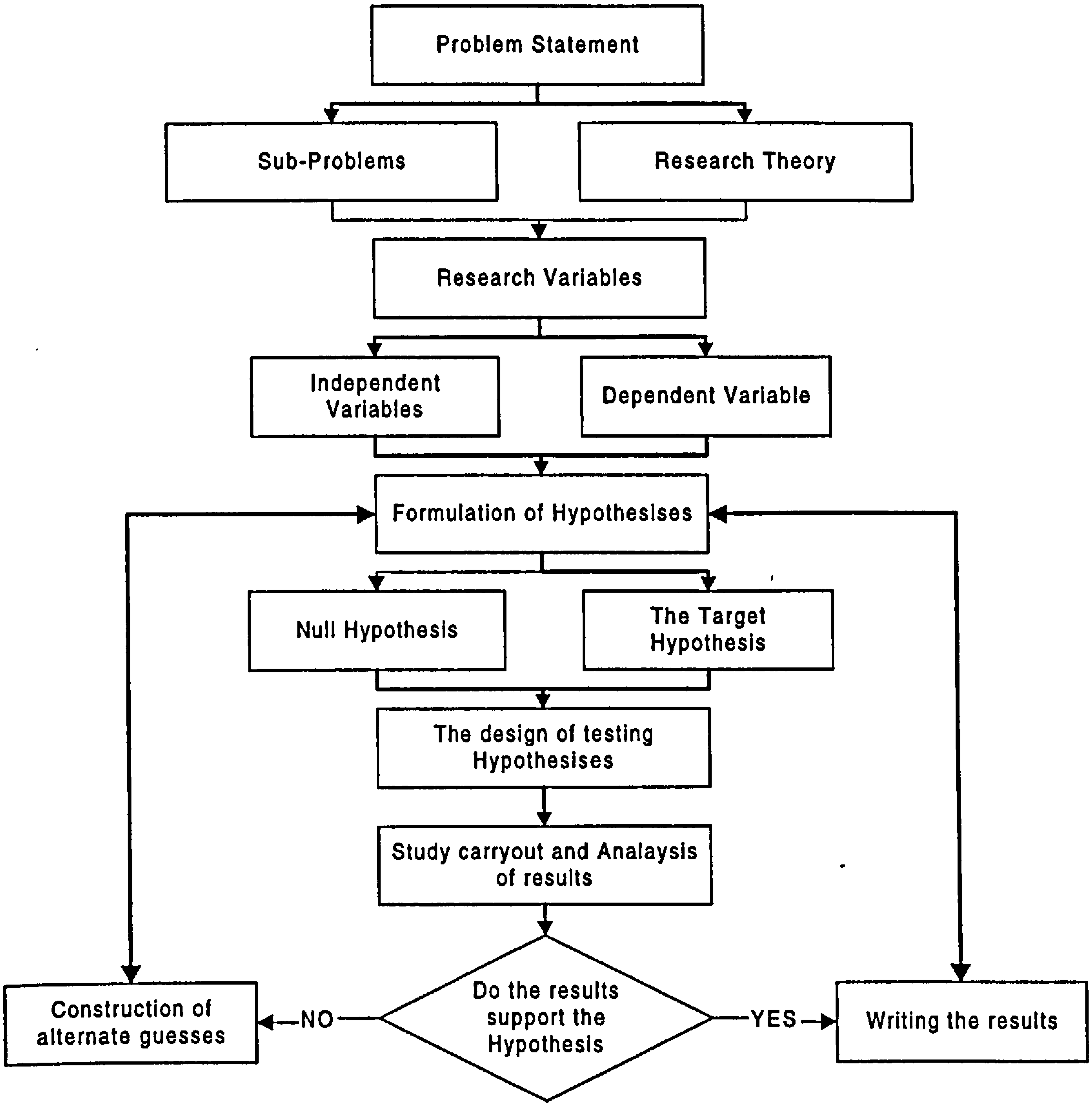

Figure 4.8 Diagram of the research elements and their conceptual location in the sequence of study.

4.12 Reference

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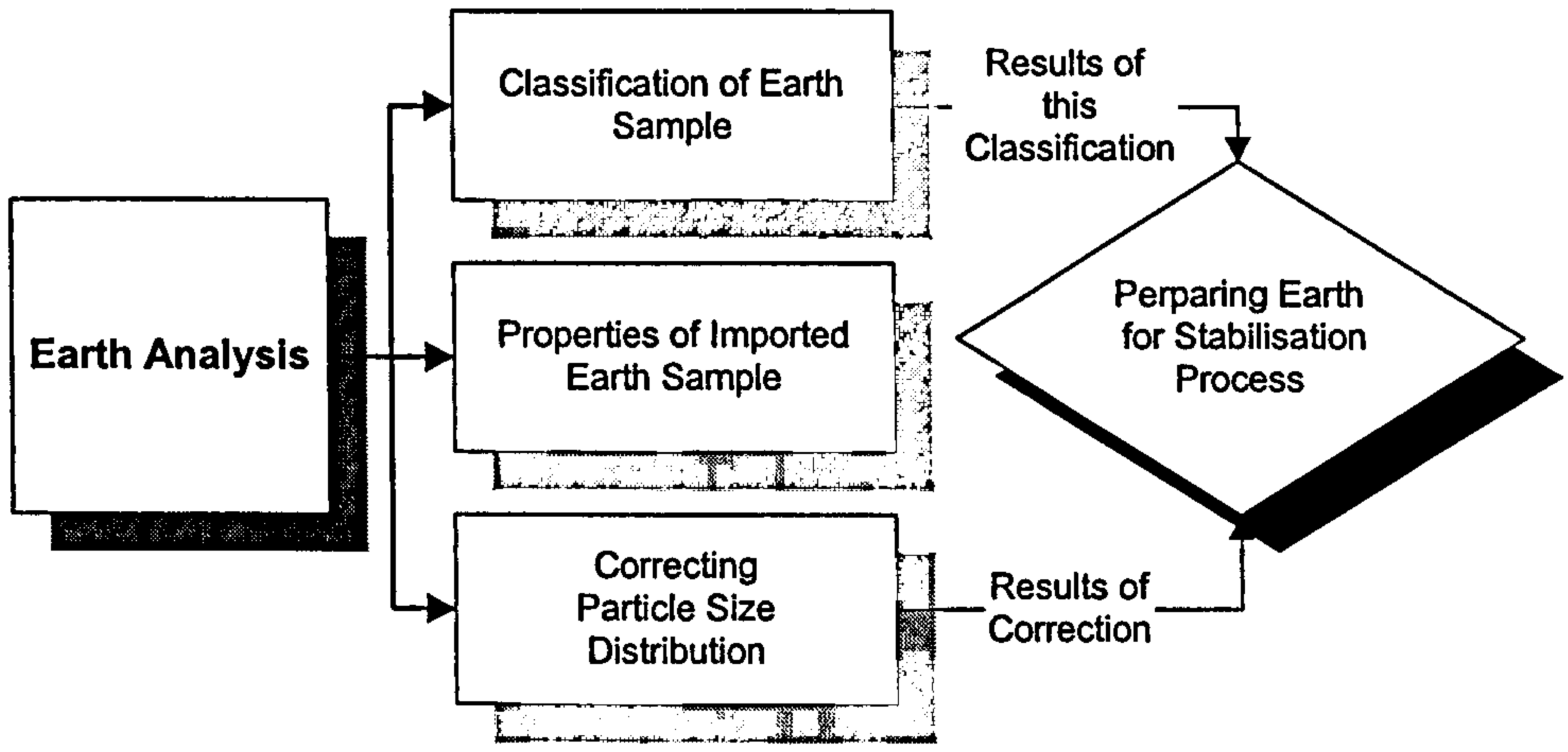

CHAPTER FIVE

Earth Analysis: Theory and Results

Chapter Five

Earth Analysis: Theory and Results

5.1 Introduction

This Chapter comprises two parts. The first part attempts to provide an understanding of the theory behind the experimental tests conducted by this research. The second part reports on the experiments carried out by the author using imported soil from Pakistan. It describes the results yielded by the experiments and highlights the difficulties and procedural problems encountered by the researcher during the experiments.

Earth, in the geotechnical sense, can be regarded as an engineering material. Its physical characteristics can be determined by analytical testing in order to predict its likely behaviour under defined working conditions. In contrast to other engineering materials, such as metals and concrete, over which control can be exercised during manufacture, earth is a naturally occurring material that is normally used in its natural condition.

The composition and characteristics of earth vary from site to site and, therefore, many of the procedures used to determine its characteristics consist of empirical methods derived from practical experience. The physical properties of earth are usually determined by laboratory testing of samples. The British Standards Institution divide these tests into two main categories:

- Classification tests, which indicate the general type of the earth and the engineering categories to which it belongs.
- Assessment of engineering properties, such as shear strength, compressibility and permeability.

In this chapter, tests are studied which relate to the classification and properties of earth. The results of these tests are discussed in order to consider improvements that can be made to earth and the suitability of the material for stabilisation. Most tests for analysing earth were undertaken in accordance with specifications laid down by the British Standards Institution. Also, specifications for on-site testing of earth were carried out according to specifications set by CRATerre.

5.2 Earth Analysis for Stabilisation Purposes

In Chapter 2, the different ways to improve earth as a construction material, especially in terms of engineering properties and efficiency in relation to economic and climatic considerations, are discussed. The properties of earth and choice of stabiliser to improve its functionality as a building material are also investigated.

Before assessing ways to stabilise earth for construction purposes, the material must undergo a series of tests to determine its engineering properties. Since the composition and characteristics of earth can vary considerably over a small area, it is important to analyse earth samples taken from different sites. Analysis of earth can be categorised according to the location of the testing: (i) field, or on-site, tests and (ii) laboratory tests.

Field, or indicator, tests are relatively simple and quick to carry out. They do not require specialised machinery and may be undertaken on-site during sample collection or construction. If used by experienced people, they can provide a direct and quantitative indication of the type of earth being examined and its potential for application as a building material. Although indicator tests are normally required, some workers argue that, in certain cases, earth identification on the basis of experience is sufficient for small operations. However, field tests provide valuable information about the need for laboratory tests, especially when contradictory field results are obtained. (1) It should be noted that laboratory tests are more sophisticated and time consuming than field tests, but provide more accurate results.

It is not always necessary that the complete suite of tests are carried out on a sample, but sufficient tests must be carried out to provide adequate information about its suitability for building and characteristics for stabilisation. Completing all engineering tests can be a lengthy and expensive process. It is not always necessary to achieve accurate information about the quality of the material; the whole evaluation process can be optimised for cost, material, stabiliser, human power and energy input. (2)

5.3 Taking Earth Samples for Tests

It is recognised that, ideally, earth used for construction purposes should contain four materials: coarse sand or aggregate, fine sand, silt, and clay. It is most cost effective to excavate earth on-site, with and several holes being dug to supply all the required earth. (2)(3) Samples must be taken from homogeneous layers; depending on the scale of the project, these can be chosen visually or by using a statistical sampling system. (4) The sample size and weight depend on the number of tests to be carried out. In principle, a sample weight of 1-2 Kg is sufficient for field-testing. The Proctor Test for compressive strength requires a sample weighting 6-10 Kg. A standard block, measuring 29.5cm x 14cm x 9cm, requires approximately 10Kg of material. (5)

Samples should be collected at least 300mm below surface in order to avoid organic matter, which renders earth unsuitable for stabilisation. However, in practice, the depth of topsoil, which contains the organic matter, can vary considerably. (6) A special device, called an auger, is used to extract samples from various depths. Each different sample is collected and stored separately. The thickness of each layer of earth, its type and colour are recorded. In addition, an accurate description of the location of the hole is recorded on labels attached to the bags of earth taken for testing. (1) (6)

For the earth analyses undertaken as part of this study, a 30Kg earth sample was imported from the Sindh province of Pakistan (See Appendix D). In Chapter 3, the causes of damage to a earth-built house in Sindh are discussed. The earth sample was collected from the source of the material used to construct this. The importance of identification of the characteristics and properties of earth prior to commencement of construction is well established. It is, therefore, a worthwhile investment of time and money to ensure that accurate results are obtained.

CRATerre specifies quality control in terms of earth sampling procedures. This organisation states that the sample must be representative of the quality of the earth under test. In order to obtain a representative sample, the following principles should be adopted:

- Avoid earth contamination due to the mixing of different sampling horizons.
- Take nothing from and add nothing to the sample. Do not modify its natural state.
- Collect samples from restricted areas.
- Do not try to take an average sample if the earth is heterogeneous, but take more samples from different spots.
- Reduce the size of a sample by piling it into a conical shape on a clean surface, flattening the pile and then separating into four sectors. Discard two opposing sectors of material and then repeat the process until the desired sample size is obtained.

As already noted, two types of earth analysis may be conducted: (1)(2)

- Laboratory tests
- Field tests
-

5.4 Laboratory Tests for Earth Analysis

5.4.1 Particle size distribution

Earth comprises discrete particles of various shapes and sizes. Particle size analysis separates these particles (gravel, sand, silt and clay) into their constituent fractions, so that the relative proportions, by dry weight, of each fraction can be determined. (7)(8) Gravel and sands provide earth with its compressive strength, whilst clays bind the material; silts fulfil a less well-defined, intermediate function. (9)(10)

Particle size analysis, also known as mechanical analysis (MA), comprises two separate procedures for analysing particle size distribution: sieving and sedimentation. Sieves, with meshes of standard apertures, are used to separate the coarse fractions, such as gravel, sand and silt, whilst sedimentation is used to separate the fine fraction (clay). (11)(12)

Since particles of each fraction have their own characteristics, particle size distribution has a significant influence upon the properties of the earth as a whole. Particle size analysis determines the proportions of the various fractions and the influence on the properties of the earth of the presence or lack of a particular fraction. A number of methods have been proposed for classifying the earth for different purposes, including:

(a) Particle Size Distribution Chart

This chart is recommended by the British Standards Institution for presenting the results of particle size analysis. The advantage of plotting particle size data on a standard chart of this kind, rather than using tabulations, is that the grading characteristics of the material can be recognised instantly. The curve that is plotted can also be used to classify the earth. Moreover, the position of a curve on the chart indicates the fineness or coarseness of the grains; the higher and further to the left the curve lies, the finer the grains, and vices versa. (This can bè seen in results of particles size distribution tests) shown in further part of the chapter with. The slope and shape of the curve indicate the particle size distribution of the earth. (2)(11)

(b) Triangular Classification Chart

The Triangular Classification Chart, introduced by the US Bureau of Reclamation, uses the term 'loam' to classify earth. This chart is not recognised in the British Standards Institution classification system. However, it is useful and convenient for comparing clay-silt-sand mixtures on the basis of the proportions of each constituent. The sides of the triangle represent clay, silt and sand and comprise 100 divisions so that the percentage of each constituent fraction can be recorded. A point within the triangle indicates the amount of these three fractions within the sample and totals 100%. (3)(13)

As clay-rich earth is not suitable for stabilisation, appropriate raw materials for mixing with stabilising additives are found in the bottom half of the chart. The bottom corners contain uniform-sized material, with the most appropriate earth for stabilisation being found towards the bottom left-hand corner. (This can be seen in results of particles size distribution tests)

(c) A-Line Chart

The third method of classification is based on the A-line Chart, also known as the Plasticity Chart. This chart plots the liquid limit (LL) as ordinate against the plasticity index (PI) as abscissa. This chart is normally used for the fine fraction of an earth, since the coarse material is usually removed prior to performing the Atterberg limits tests. A liquid limit below 50% indicates low plasticity, whilst a liquid limit above this value indicates high plasticity; material classified as silt and organic earth plot below the line A (This can be seen in results of particles size distribution tests) whilst material classified as clay earth plots above this line. (3)(14) The dark colour and smell of organic earth distinguishes this material from silt. The most suitable types of earth for stabilisation have a liquid limit of less than 40%, a plasticity index of between 2.5-22%. (3)(13)

Earth classification is less appropriate for the tropical earths, particularly laterites, where the process of formation and the chemical and mineralogical composition are of equal significance. (15) The American Society for Testing Materials (ASTM) has established a convenient classification of different earth according to the nature and the proportions of the gravel, coarse sand, fine sand, silt and clay fractions (see Table 5.1). In this approach, standard ASTM sieves are used to determine the proportion of particles larger than 0.074mm, whilst hydrometers and sedimentation is used to determine the proportion of smaller particles.

Table 5.1 Earth classification according to the American Society for Testing Material.

Sieve Size/ Number	Fraction Contained	Fraction Passed through	Remarks
20mm (No. 3/4)	Stones		
2 mm (No. 10)	Gravel		
O.25 mm (No. 200)	Coarse sand		
0.075 mm(No. 200)	Fine sand		
0.075 mm(No. 200)		silt	Settled by sedimentation
0.0750mm(No.200)		clay	Stays in suspension during sedimentation

Source ASTM quoted in LNTPB (1971), p 3

Sedimentation Test

The sedimentation test is based on the observation that large particles suspended in a liquid settle more quickly than small particles, assuming that all particles have similar densities and shapes. The velocity eventually attained by a falling particle 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 **Stokes' law**, named after Sir George Stokes (1891). This law states that the terminal velocity is proportional to the square of the particle diameter:

$$V \propto D^{2\#}$$

Although clay particles are not spherical in shape, the application of Stokes' law, based on the diameter of equivalent spheres, enables particle size distribution for fine fractions to be determined. This approach is sufficiently accurate for most practical purposes. (16)(17)

Particle size Analysis of Earth Samples

This analysis provides a quantitative measure of particle size distribution. Detailed descriptions of the different methodologies for performing this analysis are included in British Standard Institution specifications BS1377: 1990. A combination of tests was used to determine particle size distribution of the imported earth sample. The sedimentation test, using the standard method of hydrometer analysis, was performed on the finer fraction, whilst wet sieve analysis was carried out on the coarser fraction.

Results from the sedimentation test show that 46-49% of the samples are finer than 0.002mm (see Table 5.2). The particles smaller than 0.002mm consist predominantly of clay minerals. Thus, the sedimentation test shows that the **imported earth comprises 49% clay.** The data were evaluated using a Nomographic chart to solve Stokes's equation (see Appendix D).

Table 5.2 Fine particle size distribution by sedimentation tests (imported earth sample from Pakistan)

Silt	*43%*
Clay	49%-50%

Clay minerals are characterised by their small size, plate-like or rod-like shape and by having surface electrostatic charges that attract a layer of water. The thickness of the water layer depends on the normal pressure to which the earth mass is subjected. Thus, clay-rich earth tends to have a low dry density and a high water content. If the water content increases, the compaction curve rises and then falls, eventually approaching the line of zero voids. Tables 5.3 and 5.4 show the results of wet sieve analysis on a 708g.

Table 5.3 Wet sieve analysis of imported earth sample

Sieve Size mm	Mass retaining (g)	Percentage retained	Retained amount of earth/Initial amount of earth = R
2 mm	0.308	P1 = 100-R1	R1 = .435
600μm	1.468	P2 = P1- R2	R2 = .207
212μm	6.22	P3 = P2-R3	R3 = .878
63μm	39.36	P4 = P3- R4	R4 = 5.559

Table 5.4 Particle size distribution by wet sieve method (Imported earth sample)

Particle	Percentage Passing	Particle percentage
Gravel	99.956%	.088%
Medium Sand	99.956%	1.131%
Fine Sand	98.869%	6.691%
Silt and Clay	93.309%	92.09%

5.4.2 The Atterberg Limits

The degree to which addition and removal of water causes clay to expand and contract is expressed by the plasticity index. Depending upon its water content, a earth may be liquid, plastic or solid. The Atterberg limits define the boundaries between these states. A Swedish researcher named Atterberg defined various hydrous states and boundaries, separating them as limits and indices, expressed as percentages by weight of the moisture content. Five limits can be measured: liquid limit, plastic limit, shrinkage limit, absorption limit, and adhesion limit. The liquid and plastic limits are important measures in earth analysis, whilst the other three, although of interest, are rarely used. Atterberg limits are determined using the 'fine mortar' fraction of the earth, i.e. the material that passes through a 0.4mm mesh sieve. The consistency of the 'fine mortar' fraction is modified by the amount of water present.

(a) Liquid Limit (LL)

This is the transition from the plastic state to the liquid state. LL is measured in the plastic state. The Cone Penetrometer Test, developed in Sweden in 1915, can be used to determine the liquid limit. For this test, the liquid limit is defined as the water content that allows a 76g cone, with 30° apex, to penetrate 10mm. The penetration must be checked within 5 seconds of dropping the cone from a fixed height. (18) A full description of the Cone Penetrometer Test is given in British Standard Institution (BSI) specifications BS1377:1990. BSI defines the liquid limit as the water content that allows an 80g cone, with 30° apex, to penetrate a sample to a depth of 20mm. The imported earth samples, tested in accordance with BS 1377:1990, have a **liquid limit of 52.7% (see Figure5.1).** Owing to the lack of sample material, the results of the liquid limit test were not confirmed by other methods, e.g. the Casagrande test.

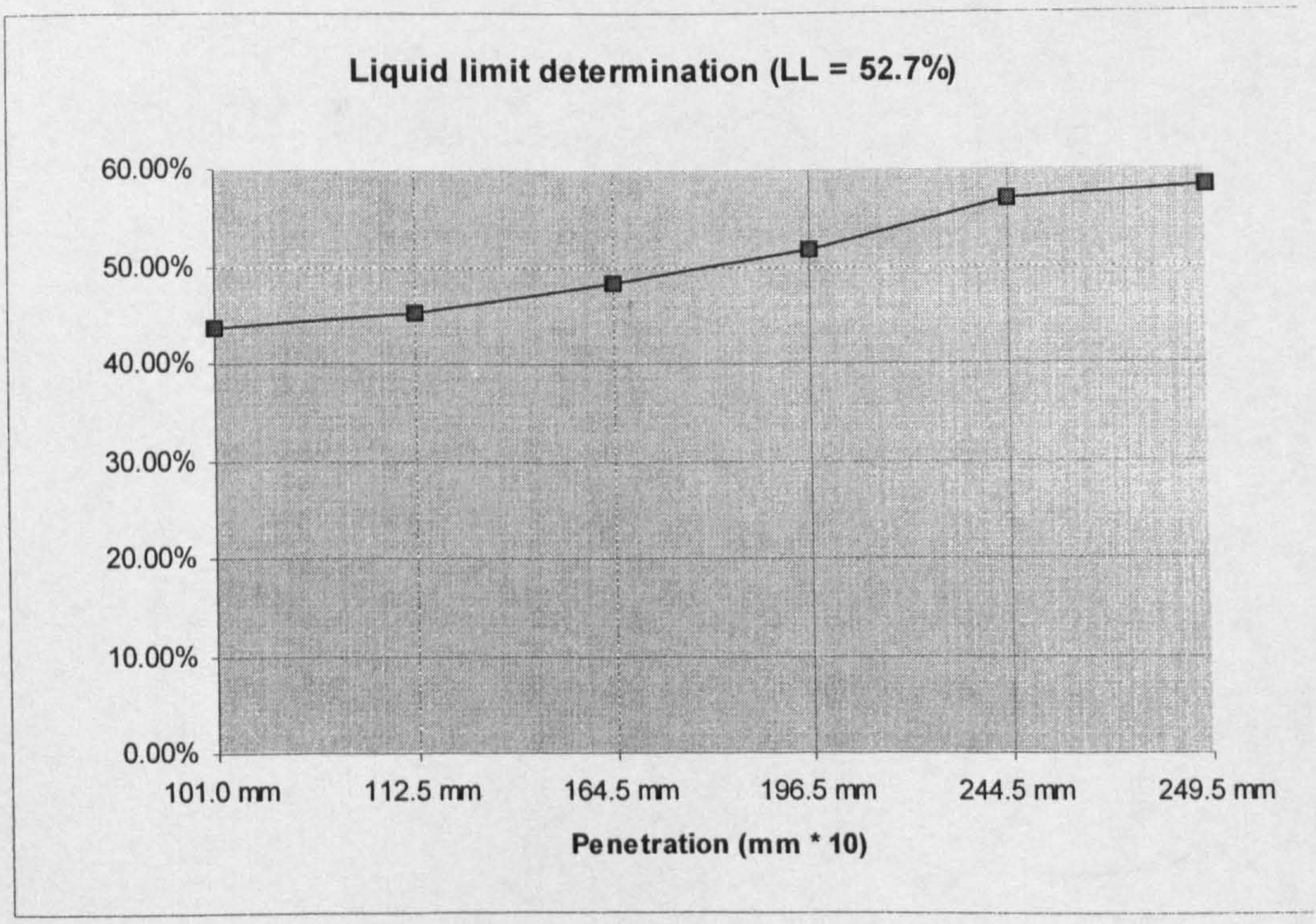

Figure 5.1 the liquid limit of imported earth from Sindh (Pakistan)

(b) Plastic limit (PL)

This is the transition from the plastic state to the solid state. The material tested in the Cone Penetrometer test is rolled to a 3mm thread. It is then rolled into a ball and the process repeated - each subsequent thread having a slightly lower moisture content than the last because of the work done on it. Eventually, when rolled to a 3mm-diameter thread, the sample breaks into pieces. The moisture content is then measured to determine the plastic limit. Full details of the procedures are given in BS1377: 1990. It should be noted that subjective influences by the technician carrying out the test can cause variations in the results of 0.2-0.3%. (9)(10) The imported earth samples, tested in accordance with BS 1377:1990, have a **plastic limit of 25.0%** (see Table 5.5).

Table 5.5 Presentation of the data for Average of Plastic limit

Tray No.	Tray wt. (g)	Tray + wet earth wt. (g)	Tray + dry earth wt. (g)	wet earth wt. (g)	Dry earth wt. (g)	Moisture content (%)
36	15.6	50.7	43.4	35.1	27.8	26.3
58	17.4	65.6	55.7	48.2	38.3	25.8
61	15.8	46.6	40.7	30.8	24.9	23.7

(c) Plasticity Index (PI)

The liquid limit and plastic limit are used to determine the plasticity index of a material. The plasticity index is calculated by the formula. PI = LL - PL, and is the range of moisture content over which a material exhibits plastic properties. Both the liquid limit and plasticity index are affected by the amount, and type, of clay minerals present in the material.

A high liquid limit and plasticity index indicates that the material has a high water absorption value, and will therefore be more susceptible to movement of moisture. The imported earth samples have a **plasticity index of 28%** (PI = 53-25).

From previous studies, a PI of 5-10% corresponds to low plasticity, a PI of 10-20% corresponds to medium plasticity, and a PI greater than 20% corresponds to high plasticity (9)(16)(14). Thus, it can be seen from these figures that, with a plasticity index of 28%, the imported earth samples have high plasticity.

(d) Linear Shrinkage (LS)

Linear shrinkage is defined as the percentage change of length of a bar of material when dried from approximately its liquid limit. The laboratory test to determine linear shrinkage is described in BS1377: 1990. Using this standard test methodology, the imported earth sample exhibited a **linear shrinkage of 11%.** Using the wooden box method for determining linear shrinkage, as recommended by Webb (1994) (see the Appendix G), the imported earth sample exhibited a **linear shrinkage of 65mm.** An understanding of the linear shrinkage properties of the earth will help to determine the best type, and amount, of stabiliser required.

5.4.3 Activity Coefficient (Ca)

The Atterberg limits are influenced by the combined effect of two important properties of clay: particle size distribution and mineral composition. The plasticity index is dependent on the amount of clay in the sample, i.e. the percentage of particles finer than 0.002mm. The activity of clay, i.e. the ratio between the plasticity index and amount of clay, is more or less constant regardless of clay type. (17) Clay activity is sometimes termed colloidal activity. Clays can be classified according to their activity as shown in Table 5.6.

Table 5.6 Classification of the clay. (11)

Description	Activity
Inactive clays	< 0.75
Normal clay	0.75 - 1.25
Active clays	1.25 - 2
Highly active clays e.g. bentonite	6 or more

Clay activity can be calculated using the following equation:

$$Activity = \frac{PI}{\%Clayfraction(D < 2\mu m)}$$

The imported earth sample has a **clay activity of 0.5714,** calculated as follows:

$$\frac{28\%}{49\%} = 0.5714$$

The observed value for Ca of 0.5714 indicates that the earth sample contains inactive clays. See Table 5.7 for typical values of commonly occurring clay minerals.

Table 5.7 Typical properties of common clay minerals (11)

Clay minerals	Liquid Limit	PI range	Activity (approx.)
Kaolinite	40-60	10-25	0.4
Illite	80-120	20-70	0.9
Sodium Montmorillonite	700	650	7
Other Montmorillites	300-650	200-550	1.5
Granular Earth	20 or less	0	0

From Table 5.7, it can be seen that the clay mineral composition of earth can be determined by measuring the liquid limit and plasticity index. Based on Table 5.7, the imported earth sample **contains Kaolinite** clay minerals.

During investigation of the house in Sindh, it was found that the earth is sensitive to weathering and is insufficiently strong to support the roof loading. In this context, the suitability for stabilisation of clay-rich earth requires further investigation. It was found in this study that clay-rich earth requires the addition of sand to correct particle size distribution as well as stabiliser to improve engineering properties.

Further analysis of the earth's capacity for compaction can be carried out to determine its potential for improved engineering properties. This involves an assessment of the relationship between dry density and optimum moisture content.

5.5 The Classification of the Imported Earth Sample

A particle size distribution curve was plotted for the imported earth sample. From this analysis, it was decided to correct the particle size distribution through the addition of sand. The effect of mixing sand, in various percentages, with the earth sample is shown in Figure 5.2. The sand was mixed following the completion of the Atterberg tests.

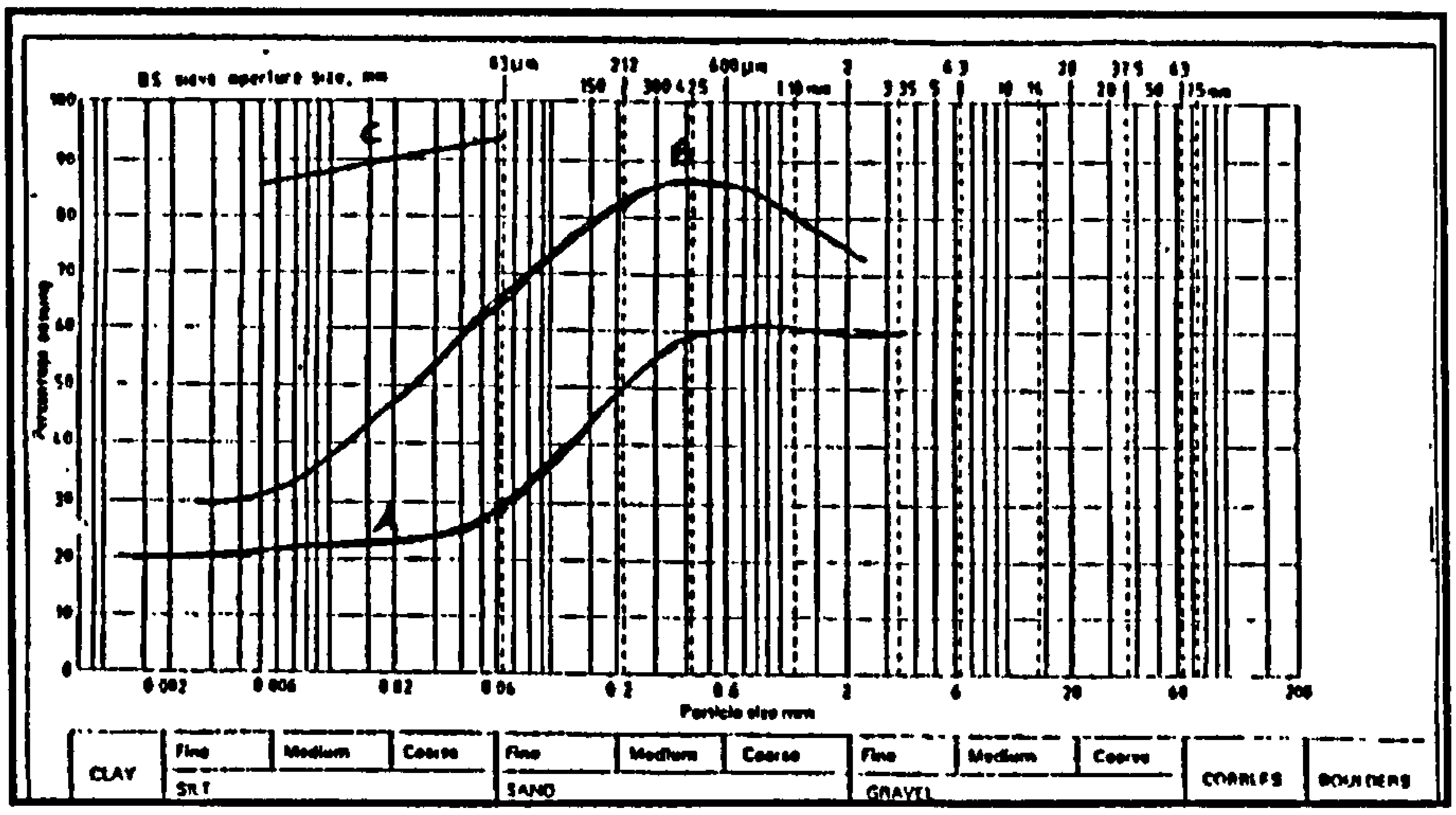

Figure 5.2 The Particle size distribution chart. Line A - earth mixed with 50 % sand; Line B - earth mixed with 30% sand; Line C - raw earth.

The data for the imported raw earth sample, based on the values of liquid limit and plasticity index, are plotted on the A - Line chart (see Figure 5.3). As can be seen from the chart, the sample falls outside the shaded area that is considered suitable for stabilisation.

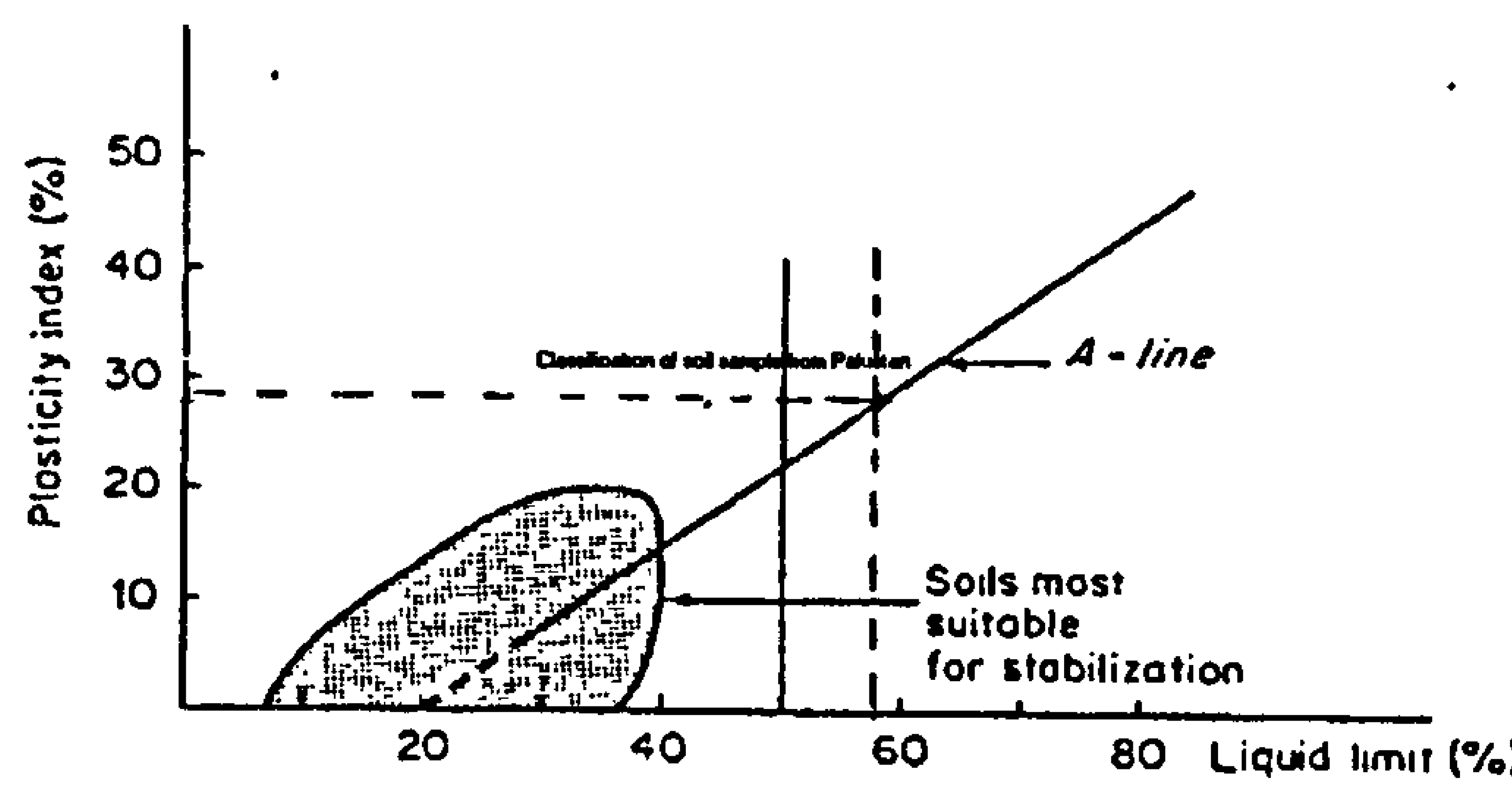

Figure 5.3 The A-Line chart. The dotted line represents the classification of the imported raw earth sample.

The composition of the imported raw earth sample, based on results of the particle size analysis, is plotted on the Triangular Chart shown in Figure 5.4.

The triangle outlined by the thick black line represents the classification of the earth sample according to this methodology. It can be seen that this chart also indicates that the imported raw earth sample is unsuitable for stabilisation as it falls outside the shaded area. The sample is classified as silty clay loam by this chart.

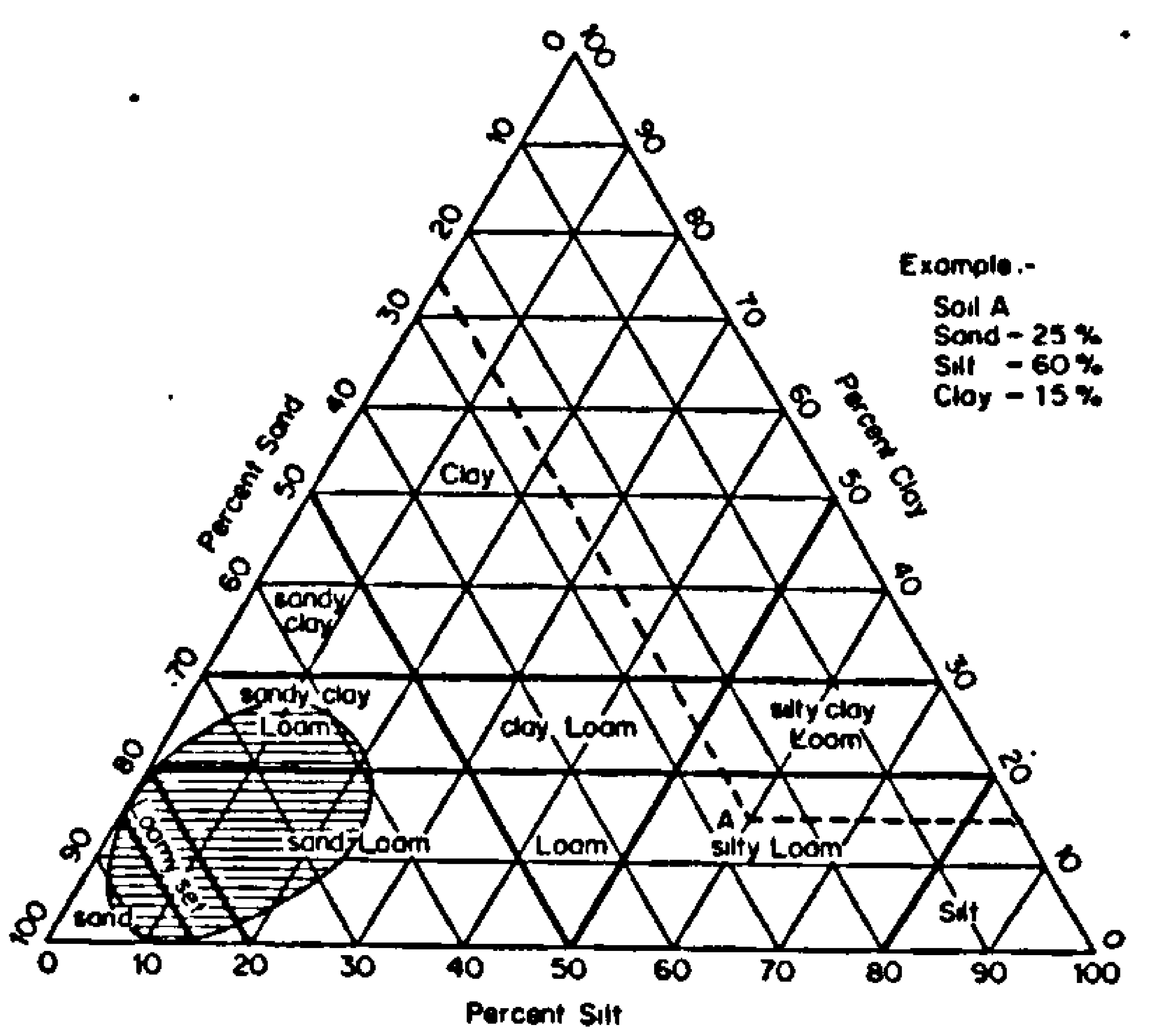

Figure 5.4 The triangular chart with the shaded are representing suitability for stabilisation.

The suitability for stabilisation of the imported raw earth sample is also shown plotted on the Liquid Limit and Plasticity Chart shown in Figure 5.5. According to this chart, the imported raw earth sample, plotted at Point A, is unusable for stabilisation.

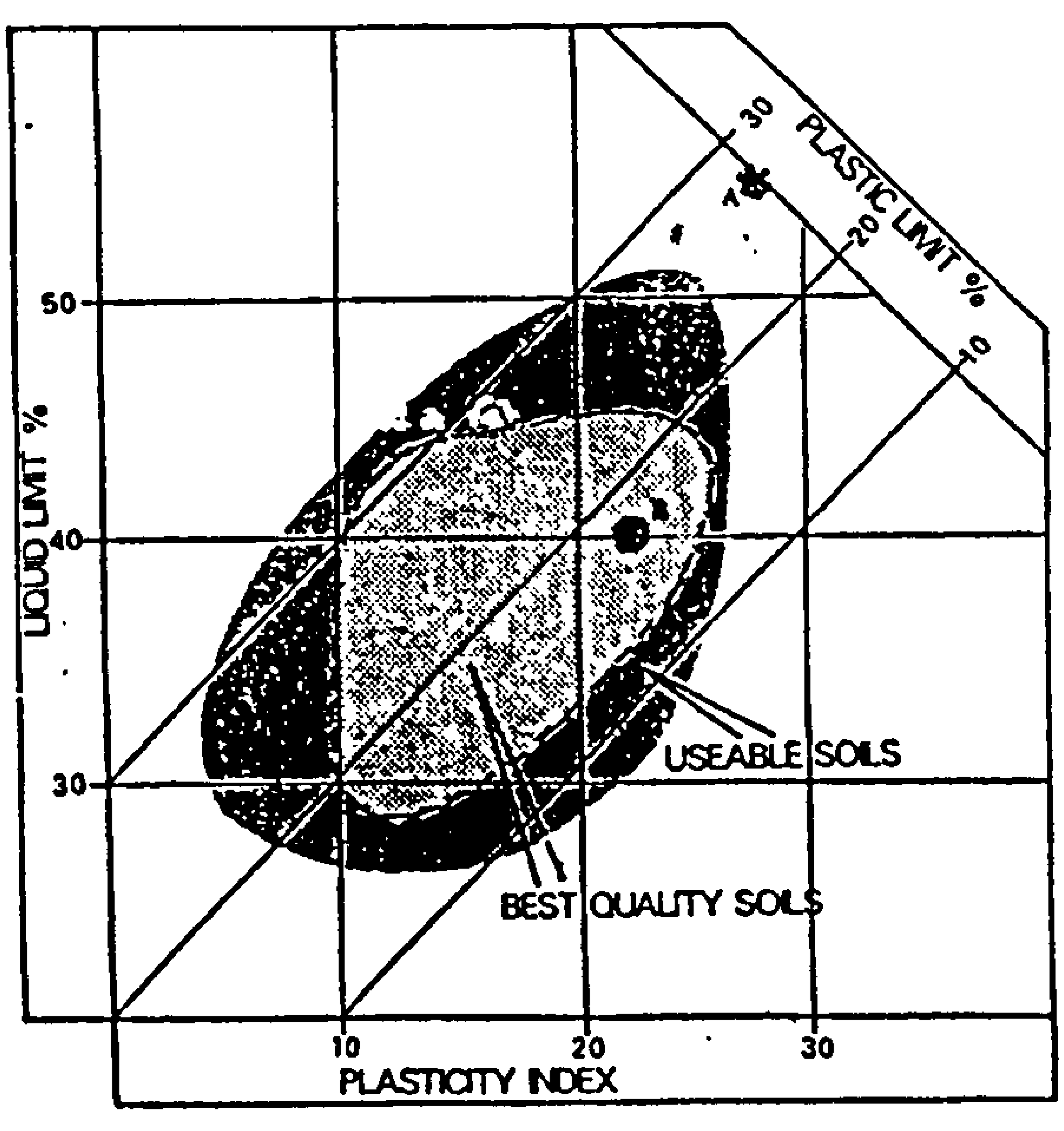

Figure 5.5 Liquid Limit and Plasticity Chart.

5.6 The Relationship between Optimum Moisture Content (OMC) and Dry Density (DD)

The relationship between Optimum Moisture Content and Dry density can be determined by measuring the compressibility of the earth. The compressibility of earth is defined as its capacity to be compressed for a given amount of compaction energy at a given moisture content. Maximum compressibility will be achieved at the optimum moisture content. When forces are applied to a quantity of earth, the material is compressed and the number of voids decreases. The higher the density of the earth, the lower will be its porosity and permeability. Increased density results from tighter packing of particles, reducing the risk of the structure being modified in the presence of water. (11)

The presence of water has a significant influence on dry density. There must be sufficient moisture present to lubricate the particles and enable them to move around so that they pack as tight as possible. However, if the moisture content is too high, water begins to push the particles apart and reduces the dry density. On increasing moisture content, voids fill with water and so little or no air is displaced by compaction and the dry density continues to decrease.

Water is added in incremental amounts to the sample and, at each stage, the material is compacted and the dry density is measured. The compacted dry density is calculated and plotted against moisture content. The highest value for dry density plotted on the graph, i.e. the maximum dry density, is obtained at the optimum moisture content. At this moisture content, the earth particles are packed as efficiently as possible for the given compaction load. (11)(12)

The Proctor test is used to determine the OMC at which the maximum dry density is obtained for a given compaction load. The results are recorded on a chart that plots dry density (ρ_d), expressed in Mg/m^3, on the ordinate and moisture content, expressed as percentage by weight, on the abscissa. The three principal variables that affect the maximum dry density are: the texture of the material, its hydrous state and the compaction energy used. (7) For the standard compaction test used in this study, a succession of blows, of controlled force, from a 2.5Kg weight rammed the imported earth sample into a small cylindrical mould. The sample was then removed from the mould, weighed and the test repeated for different moisture contents (see Figure 5.6). Behaviour under compaction is the most important engineering property of earth for building purposes. The dry density of an earth sample, for a given compaction load, is dependent on its moisture content. The imported earth sample has an **OMC of 16% and a dry density of 1.8076 Mg/m^3** for a compaction load of 2.5Kg.

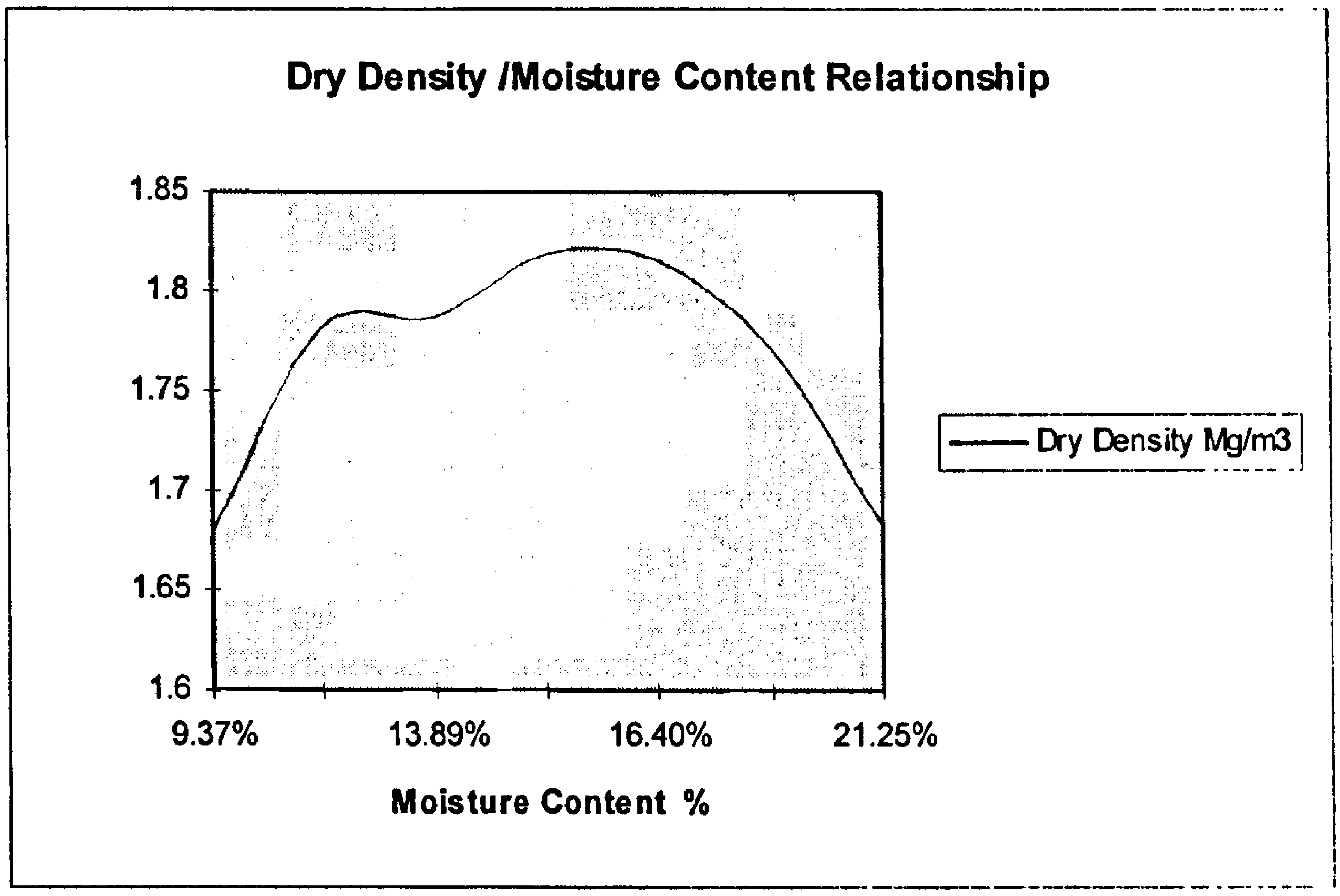

Figure 5.6 the relationship of dry density and optimum moisture content of the imported earth sample.

5.7 Correction of Particle Size Distribution

The earth analysis results show that the imported earth sample is clay-rich, with high swelling and shrinkage values. The Proctor test was performed in order to determine the relationship between the dry density and moisture content of the imported raw earth sample. After conducting this test, the particle size distribution of the earth sample was then corrected by the addition of 10%, 30%, and 50% well-graded sand (see Figure 5.2). The particle size distribution of this sand is shown in Table 5.9.

Table 5.8 Particle size distribution of the well-graded sand added to the imported earth

Sieve (mm)	Wt. Material Retained	Percentage retained	Percentage passing
10			100
5	21	2.2	97.8
2.36	118	12.3	85.6
1.18	119	12.3	73.3
0.6	257	26.6	46.7
0.3	311	32.2	14.5
0.15	119	12.3	2.2
Tray	20	2.2	0

The Proctor test was repeated on the samples with added sand to determine maximum dry density and optimum moisture contents (see Figures 5.7, 5.8 and 5.9). Different proportions of sand were blended with the earth samples to determine the mix that provides optimum combination of compressive strength and water permeability.

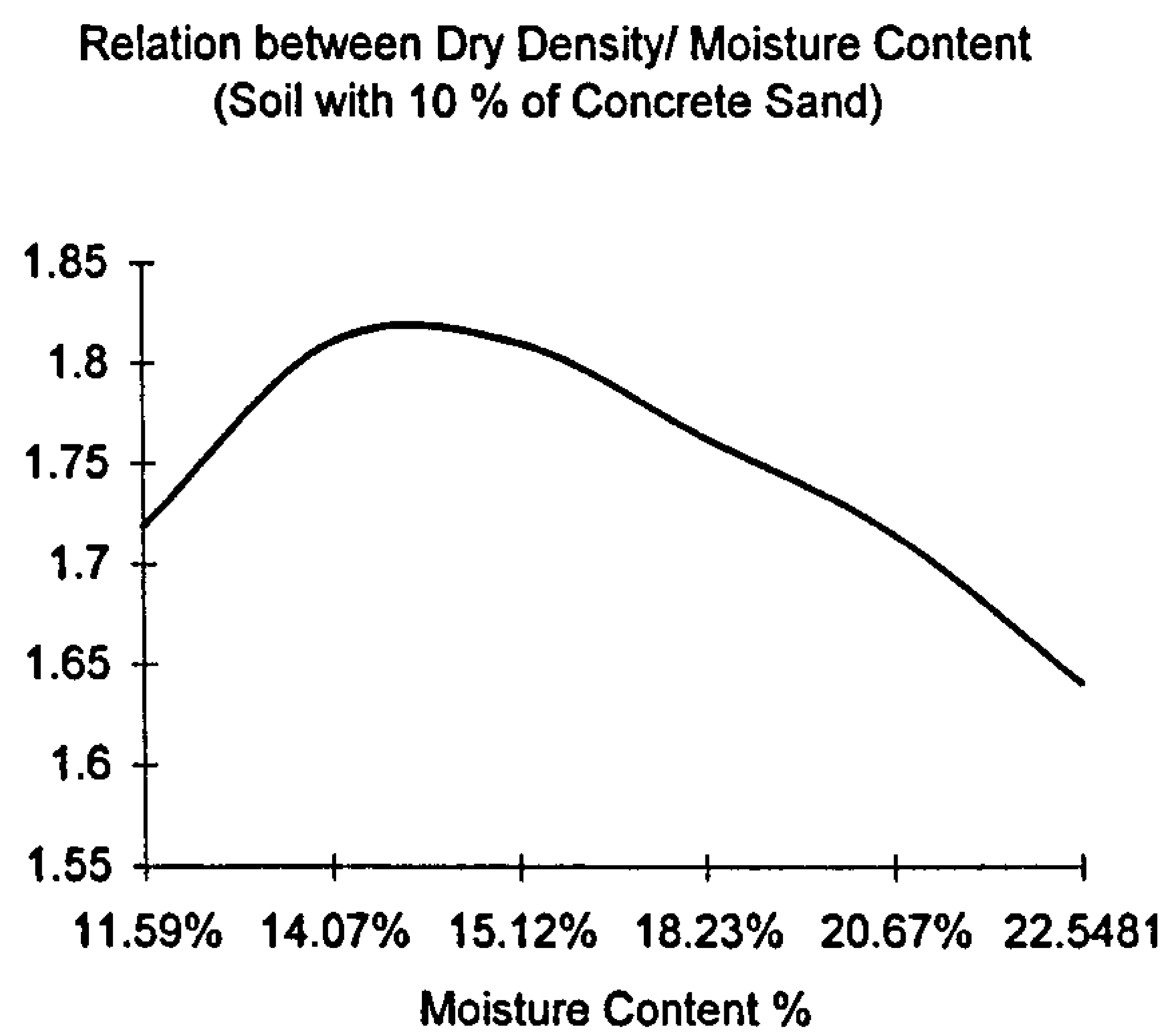

Figure 5.7 Maximum dry density and optimum moisture content of the imported earth sample blended with 10% well-graded sand

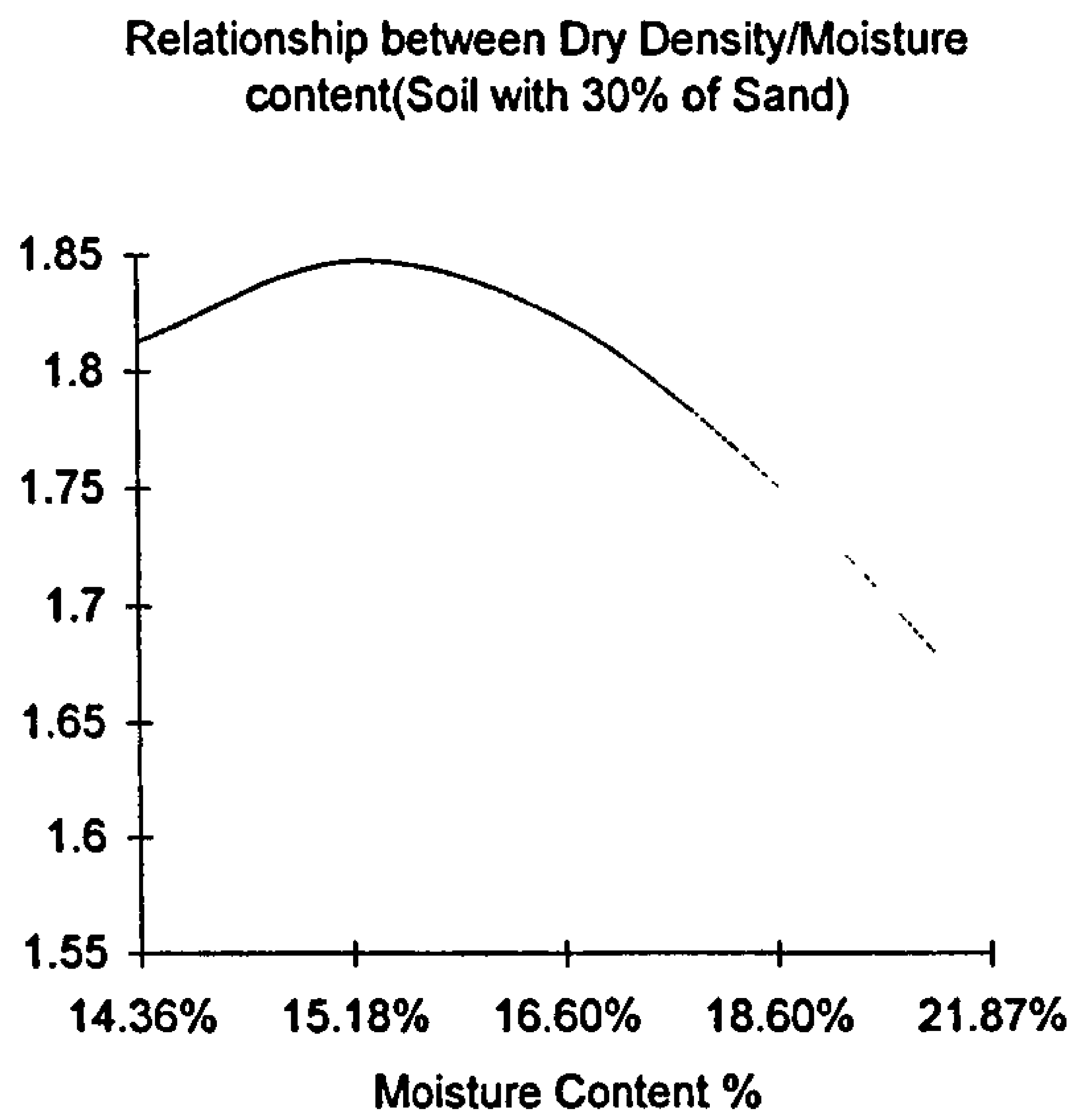

Figure 5.8 Maximum dry density and optimum moisture content of the imported earth sample blended with 30% well-graded sand.

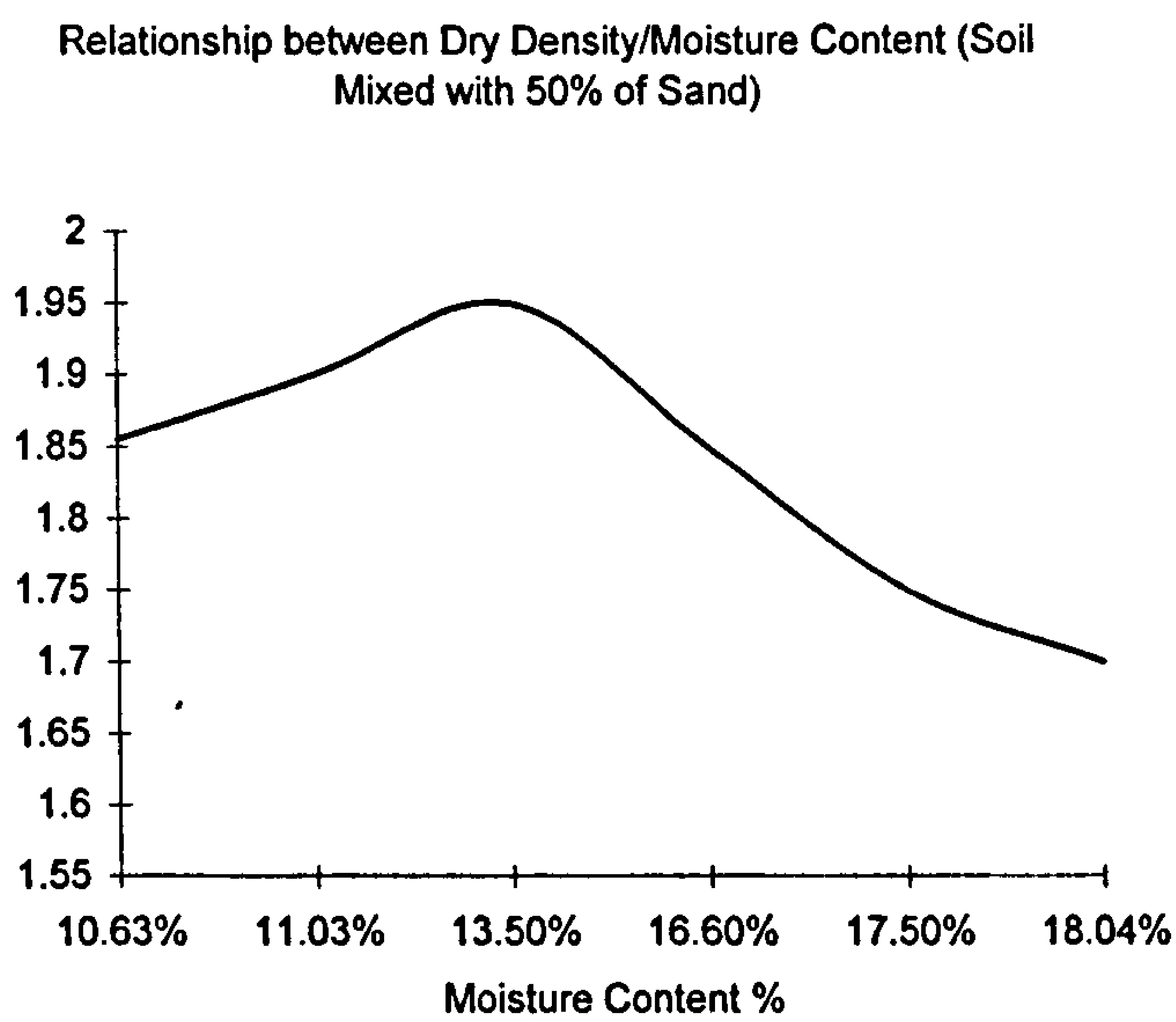

Figure 5.9 Maximum dry density and optimum moisture content of the earth sample blended with 50% well-graded sand.

If the maximum dry density falls within the range 1650-1760Kg/m^3, the engineering properties of the material are inadequate for construction purposes. In the range 1760-

2100Kg/m^3, the material is satisfactory for construction purposes. If the maximum dry density is between 2100 and 2200Kg/m^3, the earth makes an excellent construction material because it contains abundant coarse particles that contribute to high compressive strength. If the maximum dry density is between 2200 and 2400Kg/m^3, the material is considered to have exceptional engineering properties. (6) Using the above criteria, it can be seen that the imported earth sample with a maximum dry density of 1808Kg/m^3 has **satisfactory engineering properties** for use in construction. This finding is contrary to the results of the particle size analysis, Atterberg tests and classification of earth according to Triangular Chart, A-Line Chart and Liquid Limit and Plasticity Chart. These results indicate that the earth is not suitable for use in construction due to its high clay content. For example, the particle size analysis shows that the imported earth contains almost 50% particles smaller than 0.002mm.

This high clay content enables the imported earth sample to absorb large amounts of water, resulting in excessive swelling and shrinkage. Thus, shrinkage cracks were observed in the house described in Chapter 3. Investigation of this house, constructed of earth from the same source as that sampled, shows that the earth is sensitive to the presence of water and that it has inadequate engineering properties for use as a construction material. Therefore, the particle size analysis, Atterberg tests and earth classification are considered more appropriate than the Proctor test for determining the suitability of the imported earth as a construction material.

5.8 Reduction in Shrinkage

The shrinkage limit is another valuable index property for evaluating engineering properties. It is the water content below which no further shrinkage occurs. The shrinkage limit is a useful aid for predicting the percentage of additive material needed to stabilise the earth. The wooden box test was undertaken to determine the shrinkage characteristics for the imported raw earth samples blended with various percentages of well-graded sand (Figures 5.10a and 5.10b). From this experimental data, the high linear shrinkage (65mm) of the imported raw earth sample is evident. Clearly, with such high shrinkage values, it requires the addition of stabiliser to make it suitable for use in construction.

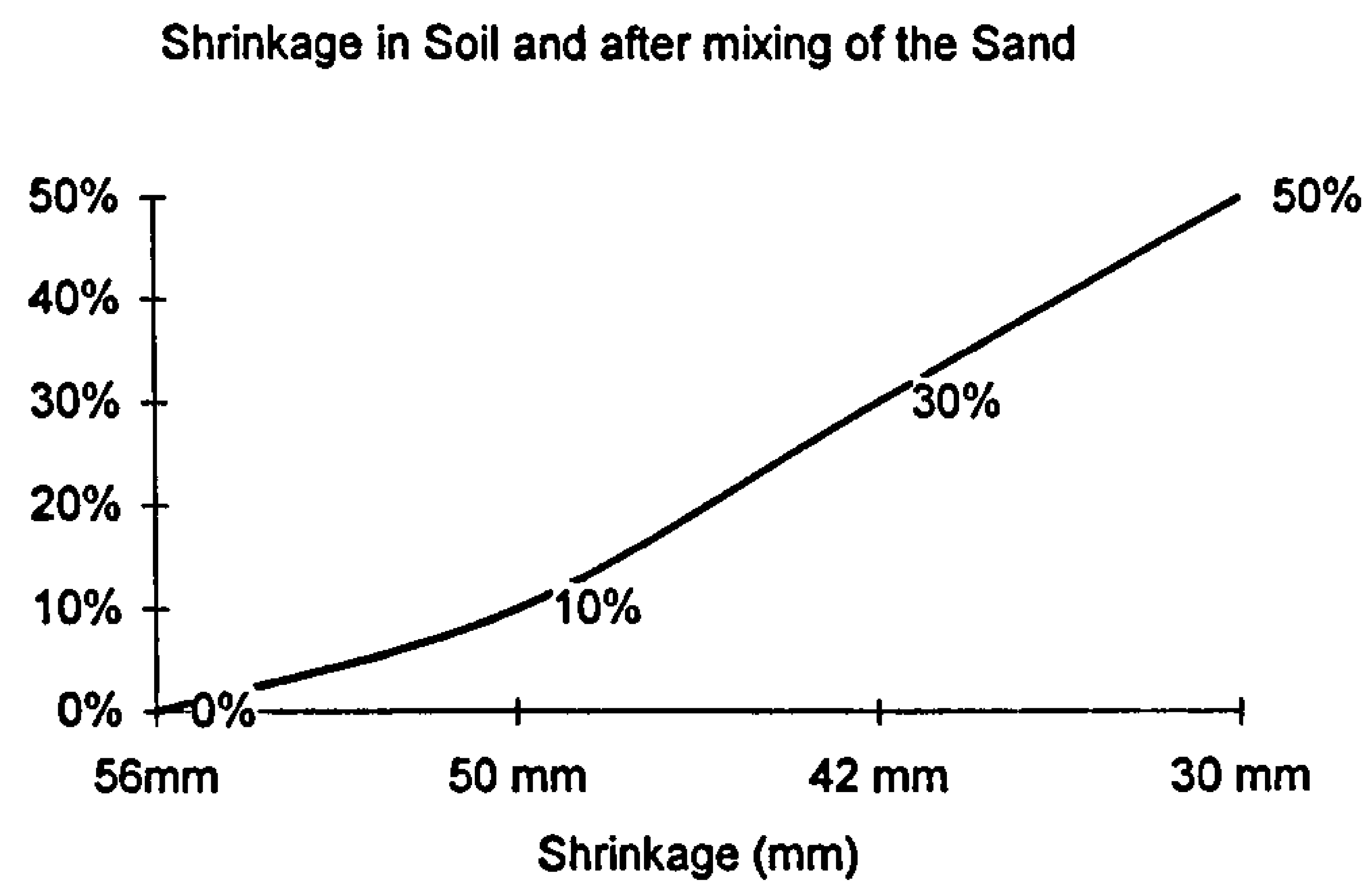

Figure 5.10 (a) Shrinkage characteristics of the earth sample after mixing with well-graded sand after 3 days.

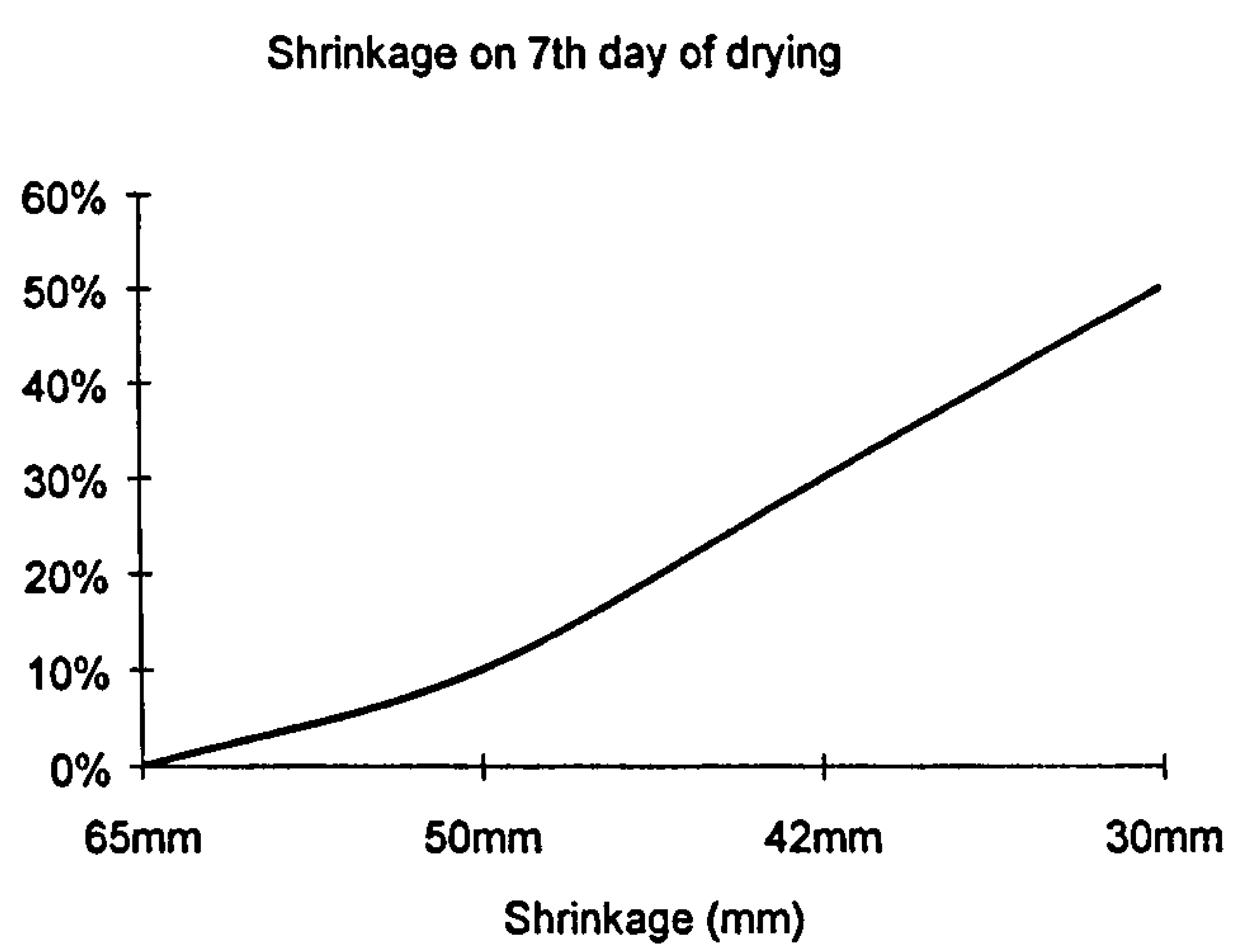

Figure 5.10 (b) Shrinkage characteristics of the earth sample after mixing with well-graded sand after 7 days.

Three guidelines for stabilising earth using the CINVA- RAM compaction machine are shown in Tables 5.9, 5.10 and 5.11. These guidelines provide recommendations for the amounts of cement and lime to be added to stabilise earth, based upon the linear shrinkage of the raw material. Further research is needed to establish guidelines for other stabilisers although, in this investigation, the above guidelines formed the basis for deciding the amount of linseed oil and calcium chloride to add.

Table 5.9 Guidelines for using stabiliser. (13)

Specimen Shrinkage (mm)	Cement : earth ratio
Less than 12 mm	1 : 18 parts (5.56 %)
12mm - 24mm	1 : 16 parts (6.25%)
25mm - 39mm	1 : 14 parts(7.14 %)
40mm - 50 mm	1 : 12 parts (8.33%)

Table 5.10 Recommended percentage of stabilisers according to earth shrinkage. (5)

Specimen Shrinkage (mm)	Cement: earth ratio
less than 12 mm	1 : 18 parts (5.56 %)
12mm - 24mm	1 : 16 parts (6.25%)
25mm - 39mm	1 : 14 parts(7.14 %)
40mm - 50mm	1 : 12 parts (8.33%)
Shrinkage more than 60 mm	Earth is not suitable for stabilisation or may be need to add sand

Table 5.11 Recommended percentage of stabilisers according to earth shrinkage. (9)

Specimen Shrinkage (mm)	Cement : Earth Ratio
Less than 15 mm	Probably in sufficient clay
15 mm - 30mm	1 part cement to 20 parts of earth
30 mm - 45 mm	1part cement to 15 parts earth , or 1 part of lime to 7 parts of earth
45mm - 60 mm	1 part cement 12 parts of earth, or 1 part of lime to 6 parts of earth
more than 60 mm shrinkage	In sufficient sand - earth is not recommended for block making unless more sand is added

According to these guidelines, the shrinkage of 65mm for the imported raw earth sample is outside the recommended range for stabilisation. It can be seen that sand must be mixed with the earth to bring the shrinkage into the recommended range. The compaction tests and other measures indicate that 20-30% sand must be added to the imported raw earth sample to give reasonable results for stabilisation. The addition of 30% sand resulted in linear shrinkage of 42mm by the 4^{th} day of the wooden box test. It was observed on the 7^{th} day of the test that no further shrinkage had occurred.

5.9 Field Test

On-site investigation of earth for use in construction can be supported by carrying out a small number of quick tests. These simple tests make it possible to evaluate the more important characteristics and engineering properties of the earth and provide a preliminary indication of its suitability for construction purposes. The tests are somewhat empirical and should be repeated several times in order to obtain representative values. (4) The following tests are considered appropriate for field investigations of earth:

a) *Odour test*

The imported earth sample smelt clayey and like mud so was considered worthy of further investigation. This test is based on the look and smell of the earth. After extraction, earth is smelt in order to detect organic matter (a musty smell, which becomes stronger on moistening or heating). Earth that contains organic matter should not be tested further or used as a construction material.

b) *Touch test*

This test is carried out on earth sample, following the removal of coarse gravel particles, by holding a sample of earth between the fingers and palm of the hand. A sandy earth feels rough and has no cohesion when moist. A silty earth still feels slightly rough, but has moderate cohesion when moist. Hard lumps that resist crushing when dry, but become plastic and sticky when moistened, indicate a high percentage of clay. Coarse particles were not evident on visual examination of the imported earth sample and so it was sieved to remove any unseen gravel. The touch test was then carried out on the imported earth sample, with medium hard lumps indicating a high clay content.

c) Lustre test

A slightly moist ball of earth, freshly cut with a knife, reveals either a dull surface (indicating the predominance of silt) or a shiny surface (indicating a higher proportion of clay). When cut, the balls of imported earth exhibited a shiny surface, indicating a high clay content.

d) Adhesion test

Once the lustre test is completed, the same moistened ball was used for the adhesion test. The balls of imported earth resist the cutting effect of a knife, which indicates that the clay content is high. If the ball of earth is penetrated easily by knife, the clay content is assumed to be low. Clayey earth tends to resist penetration and sticks to the knife when it is pulled out.

e) Washing test

The way earth washes off the hands gives further indication of its composition; sand and silt are easy to remove, whilst clay needs to be rubbed off. The imported earth is not removed easily from the hands, suggesting that it contains a high percentage of clay.

f) Visual test

After sieving, dry gravel and sand particles are separated into two piles on a clean surface. Crushing any lumps of clay may be necessary beforehand. By comparing the sizes of the two piles, a rough classification of the earth is possible.

The imported earth was sieved through 1.18mm mesh, with all material passing through the screen. This suggests that the earth contains a negligible amount of coarse particles.

g) Water retention test

A little water is added to a small amount of earth, which is then moulded into an shape-shaped ball. The amount of water added should be sufficient to bind the earth, but not so much that it becomes sticky. The ball is gently pressed into the curved palm of the hand, which is vigorously tapped by the other hand, shaking the ball horizontally. The composition of the earth can be gauged as follows:

- A fine sand or course silt is characterised by a rapid reaction in which it takes 5-10 taps to bring the water to the surface (a smooth, 'livery' appearance). When pressed, the water disappears and the ball crumbles.
- A silty clay is characterised by a slow reaction in which the same result is achieved within 20-30 taps. The ball flattens, rather than crumbles, on being pressed.

- A high clay content is characterised by very slow or no reaction. There is no change of appearance when the ball is pressed.

The imported earth sample does not react when tapped, indicating a high clay content.

h) Dry strength test

Two or three samples used in the water retention test are flattened to a thickness of 1cm and a diameter of 5cm and then either air- or oven-dried. The relative hardness of the dried sample is assessed by squeezing it between the thumb and index finger. This enables the sample to be classified as follows:

- Silt/fine sand, with low clay content, is pulverised without effort.
- Silty or sandy clay can be crushed to a powder with little effort.
- Pure clay can not be crushed, or breaks only with great effort.

It took great effort to break the imported earth sample by hand, indicating a high clay content.

i) Thread test

A small ball of earth, approximately the size of an olive, is rolled into a thread on a board. If the thread breaks before its diameter is reduced to 3mm, the material is too dry and so it is remoulded into a ball with more water added. If the thread breaks at a thickness of less than 3mm, the material is rubbed in the hand to reduce moisture content The process of rolling the thread is repeated until the it breaks at a thickness of 3mm, indicating the desired moisture content. The thread is then re-moulded into a ball and squeezed between thumb and forefinger. At this stage, the earth is classified as follows:

- An organic earth feels soft and spongy.
- Low clay content is characterised by incipient cracks and crumbling.
- High silt or sand content is characterised by the material breaking up before forming a ball.

- High clay content is characterised by the ball being hard to crush and not cracking or crumbling.

Small balls of imported earth, prepared to the desired moisture content, are very hard to break. This indicates high clay content.

j) Ribbon Test

Once the 'desired' moisture content has been established in the thread test, a further sample is prepared with approximately the same amount of moisture. This sample is moulded into a 12-15mm thick cigar-shape. It is then progressively flattened between thumb and forefinger to form a 3-6mm thick ribbon of material, which is allowed to grow as long as possible. The earth is classified as follows:

- Negligible clay content: a ribbon can not be formed.
- Low clay content: a short ribbon (5-10cm) is formed.
- High clay content: a long ribbon (25-30cm) is formed.

The imported earth sample formed a ribbon in excess of 30cm long, indicating high clay content.

k) Sedimentation test

This test was conducted on the imported earth sample. A glass jar is quarter filled with earth and then filled almost to the top with clean water. The earth is allowed to soak for one hour and then, after firmly sealing the top aperture, the jar is shaken vigorously and placed on a horizontal surface. This step is repeated again after another hour and then left undisturbed for at least 45 minutes. Coarse, heavy particles settle first and form layers at the bottom of the jar, with progressively finer particles settling later. Layers of fine silt and clay form the upper layers. The various layers can be distinguished with the naked eye due to their different textures. It should be noted that inaccuracies in establishing relative proportions of particles occur because silt and clay expand in the presence of water.

l) Linear shrinkage test

This test takes 3-7 days to complete. A 600mm x 40mm x 40mm wooden mould, open at the top, is used. Water is added to the earth to create a paste with optimum moisture content. The optimum moisture content is determined by slowly adding water to the earth, which is then mould by hand into a ball and dropped onto the floor from a height of 1.1m. The following observations can be used to establish optimum moisture content:

- If the earth ball stays in one piece it is too dry. Add water and try again;
- If the earth breaks into many pieces, it is too wet. Leave it to dry for a while and then try again;
- If the earth ball breaks into only a few pieces, it is close to the optimum water content and suitable for use.

The earth paste is pressed into the corners of the mould with a small spatula, which is also used to smooth the surface. The mould can be left exposed to the sun for three days, or left in the shade for seven days. After the chosen drying period, the hardened mass of earth is pushed to one end of the box and the total linear shrinkage is measured.

This test was carried out on the imported raw earth sample, which exhibited a linear shrinkage of 65mm. On adding 30% sand to correct the particle size distribution, the linear shrinkage reduced to 43mm. The results of these tests enabled the required amounts of stabilising additives to be established. In accordance with the guidelines described in section 5.8, additions of 5-7% cement and 7-8% lime were made to stabilise imported earth samples blended with 30% sand. The amounts of linseed oil and calcium chloride stabiliser were based on the additives' chemical and environmental characteristics.

5.10 Summary

As there are a wide variety of earth types, it is necessary to describe and classify them in terms that convey their characteristics in a clear and concise manner. The descriptions and classification systems adopted must be generally accepted and understood. Various tests, used to obtain the physical and index properties of earth, are discussed in this chapter. These properties define the suitability of earth for use in construction and in the stabilisation process.

The data obtained in these tests are used to:

a) Classify the earth and determine its suitability for construction purposes in the raw state.

b) Establish engineering properties of the raw earth and/or earth corrected for particle size distribution. Based on these results, recommendations can be made in the site and the material investigation report to add stabiliser in order to improve engineering properties.

Earth contains four main fractions: gravel, sand, silt and clay. Each of these fractions has an important effect on the stability of the earth. In particular, the activity and amount of clay affects the stabilisation process. Therefore, the thorough investigation of the earth must be undertaken prior to stabilising the material.

The imported earth sample from Sindh falls into the category of fine earth, i.e. silts and clay. It contains 49% clay and 43% silt, with the remaining part comprising fine sand and negligible amounts of gravel. In order to stabilise this earth, a higher proportion of coarse particles is required. Gravel and sand impart strength during the compaction of the stabilised block, but reduce the plasticity in earth. Plasticity defines the extent to which earth can change its state from solid to liquid phase without any elastic reaction and distortion.

The engineering properties of earth are governed to a large extent by physical properties and behaviour. Therefore, careful visual inspection supported by a few simple on-site tests can provide a valuable first appraisal of the earth. The imported earth sample was subjected to both visual inspection and a suite of on-site. All tests indicate that the imported earth has a high clay content.

Particle size distribution was corrected by blending the earth with 10%, 30% and 50% well-graded sand. For the purposes of stabilisation, the optimum blend is considered to be 20-30% sand added to the imported earth.

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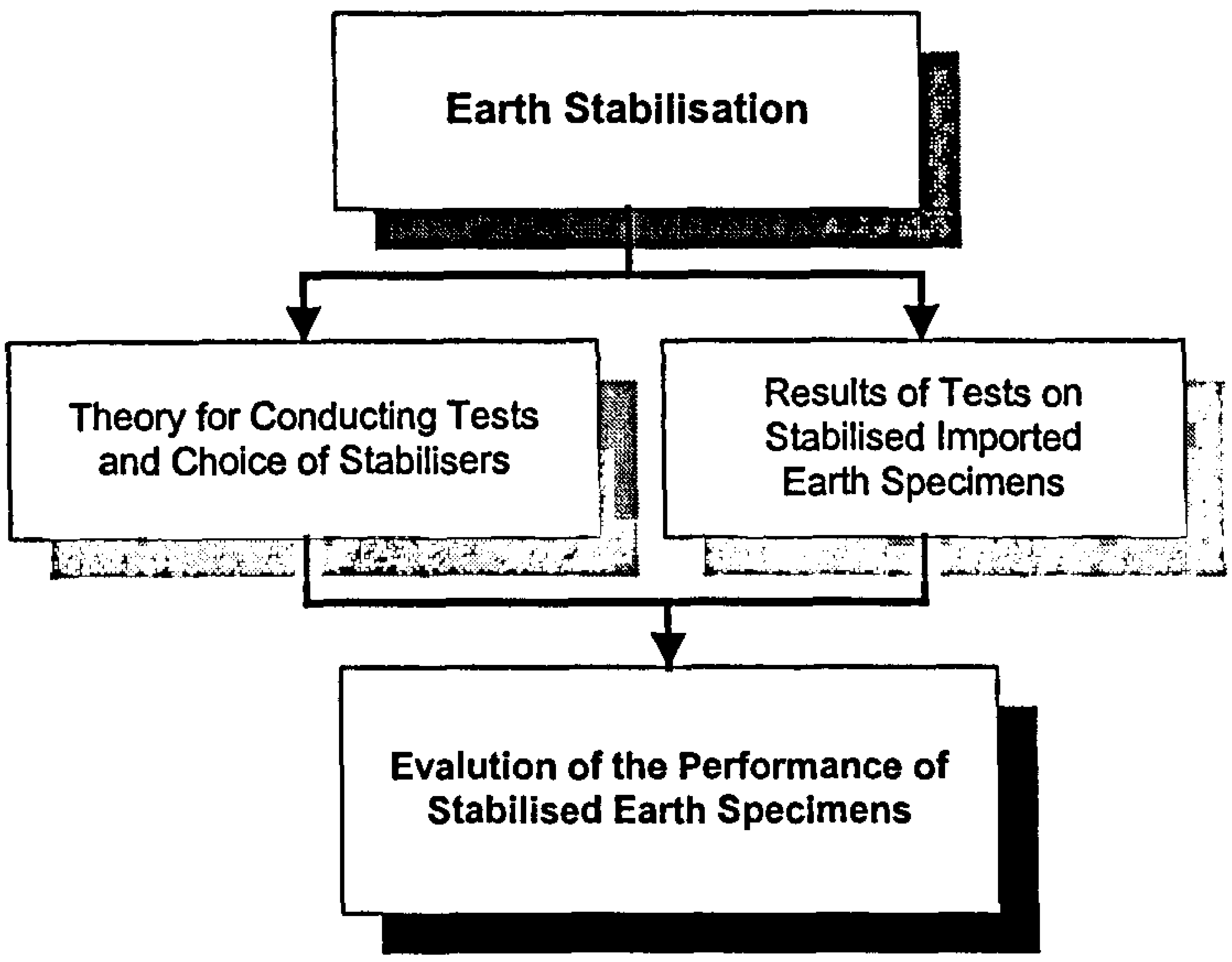

CHAPTER SIX

Earth Stabilisation: Theory and Results

Chapter Six

Earth Stabilisation: Theory and Results

6.1 Introduction

In this Chapter earth stabilisation using a combination of modes is investigated. The selection of cement and lime as stabilisers was based on the results of the literature review, whilst the selection of linseed oil and calcium chloride was based on cost and local availability. For further study see Chapter 3.

The imported earth sample was stabilised with cement and lime by consulting the guidelines described in Section 5.8. The amount of linseed oil and calcium chloride used for stabilisation was based on the extrapolation of data in existing literature for other materials.

At the present time, there are no internationally accepted standards for using earth as a construction material. Nonetheless, many countries have developed their own guidelines and specifications for stabilised earth blocks. The engineering properties of the stabilised imported earth specimens are evaluated with reference to the well-established Kenya specification for stabilised earth blocks. However, the validity of the evaluation is debatable, given the variations in conditions of use and requirements.

Specific performance tests, including compressive strength and water absorption, durability, and porosity tests were conducted on the stabilised earth specimen to determine engineering properties. The tests were performed in accordance with the specifications laid down by the British Standard Institution.

6.2 The Method Adopted for Stabilising the Imported Earth Sample

The laboratory tests conducted to determine the engineering properties of the imported earth sample are discussed in Chapter 5. The imported earth comprises 90-96% of fine particles and so requires particle size correction prior to stabilisation. The correction was carried out by adding 30% well-graded sand to the earth. The imported earth sample, corrected for particle size distribution, was stabilised using a combination of stabilisation modes, i.e. physical-mechanical and chemical-mechanical.

These modes involved the modification of earth properties by the following methods: binding earth particles with stabiliser, creating links between earth particles and water repulsion treatment of grains (modification 1). All of these methods also involved densification of the earth, by means of compaction, to remove air voids. Two aspects of compaction were relevant considered relevant at this stage:

a. As the *compaction load* is increased, *optimum moisture content* falls and *dry density* rises. Greater compaction may cause layering to occur in the block. (6)
b. It is difficult to compact poorly-graded material to achieve a high dry density. In contrast, a well-graded material can be compacted to achieve a high dry density. (6)(10)

A load of $10N/mm^2$ was applied in order to compact the imported earth specimens. This loading was considered suitable for the type of press being used, i.e. a CINVA-RAM machine, to produce the blocks in the field. The suitability of this loading was also confirmed by recommendations found in the literature review.

6.2.1 The Parameters of Effectiveness

Earth must contain significant amounts of clay in order to be suitable for stabilisation. The nature of the clay minerals influences the properties of the stabilised material. Earth containing almina silicates, silica and ferrous hydroxide is considered to be the best material for use in stabilisation. (6)(11) As discussed in Section 3.5, cement, lime, linseed oil and calcium chloride were used as stabilisers to improve the engineering properties of the imported earth sample.

Cement

Portland cement stabilises material by binding grains, with additional compaction being applied. The guidelines in Section 5.8 specify the amount of cement required. By adding cement, three types of structure form within the earth-cement mix (6):

- An inert sandy matrix bound with cement.
- A matrix of stabilised clay.
- A matrix of unstabilised earth.

All types of earth can be stabilised by cement, with sandy earth providing the best results. The presence of organic material in earth is considered harmful, particularly if nucleic acid, tartaric acid or glucose is present. Organic material slows the setting of the cement and reduces the strength of the stabilised material. Generally, an organic matter content greater than 1% is considered to be hazardous to the stabilisation process, whilst earth containing more than 2% organic matter must not be used. (12)(13)

Lime

Hydrated lime stabilises material by creating links between particles, with additional compaction being applied. The guidelines in Section 5.8 specify the amount of lime required. Naturally hydrated lime is considered to be a more effective stabiliser than artificially hydrated lime. (6). The presence of organic matter can block ionic exchange in clayey earth without blocking the pozzolanic reactions. Earth containing up to 20% of organic matter can be stabilised with lime, but care is essential. (14)

Calcium Chloride

Calcium chloride acts as a stabiliser by creating water repulsion forces within the material. Again, compaction is applied as a supplementary method of stabilisation. Calcium chloride can be added in liquid, powder or granular form. . However, care has to be taken when using calcium chloride in powder or granular form. During compaction, water and clay particles in the earth cause the calcium chloride grains to dissolve. The dissolved grains leave gaps in the compressed specimens. This makes it difficult for them to achieve maximum dry density because the moisture content increases above the optimum value. Specimens prepared with liquid calcium chloride takes longer to cure compared to those prepared with other stabilisers. Therefore, care must be taken that sufficient time is allowed for the curing process. It should be noted that the American Transport Board use liquido calcium chloride widely for ground improvement.

Linseed Oil

Linseed oil acts as a stabiliser by creating water repulsion forces within the material, with compaction being applied as a supplementary method of stabilisation. Two types of linseed oil are available in the market:

a. Raw linseed oil: dries slowly.
b. Boiled linseed oil: dries quickly as soon as it is exposed to air.

6.3 Producing the Earth Samples to test their Engineering Properties

Earth samples were produced using a triaxial compaction machine (see Figure 6.1). A compaction load of 2-10MPa was applied to earth specimens mixed with various stabilisers. This load was chosen in accordance with specifications for the CINVA-RAM machine, which is used to produce compressed earth blocks on site. A 50mm diameter x 100mm long cylindrical mould was used to produce the stabilised earth specimens (see Figure 6.2).

The results are recorded in terms of cylindrical sample size. See Appendix E.

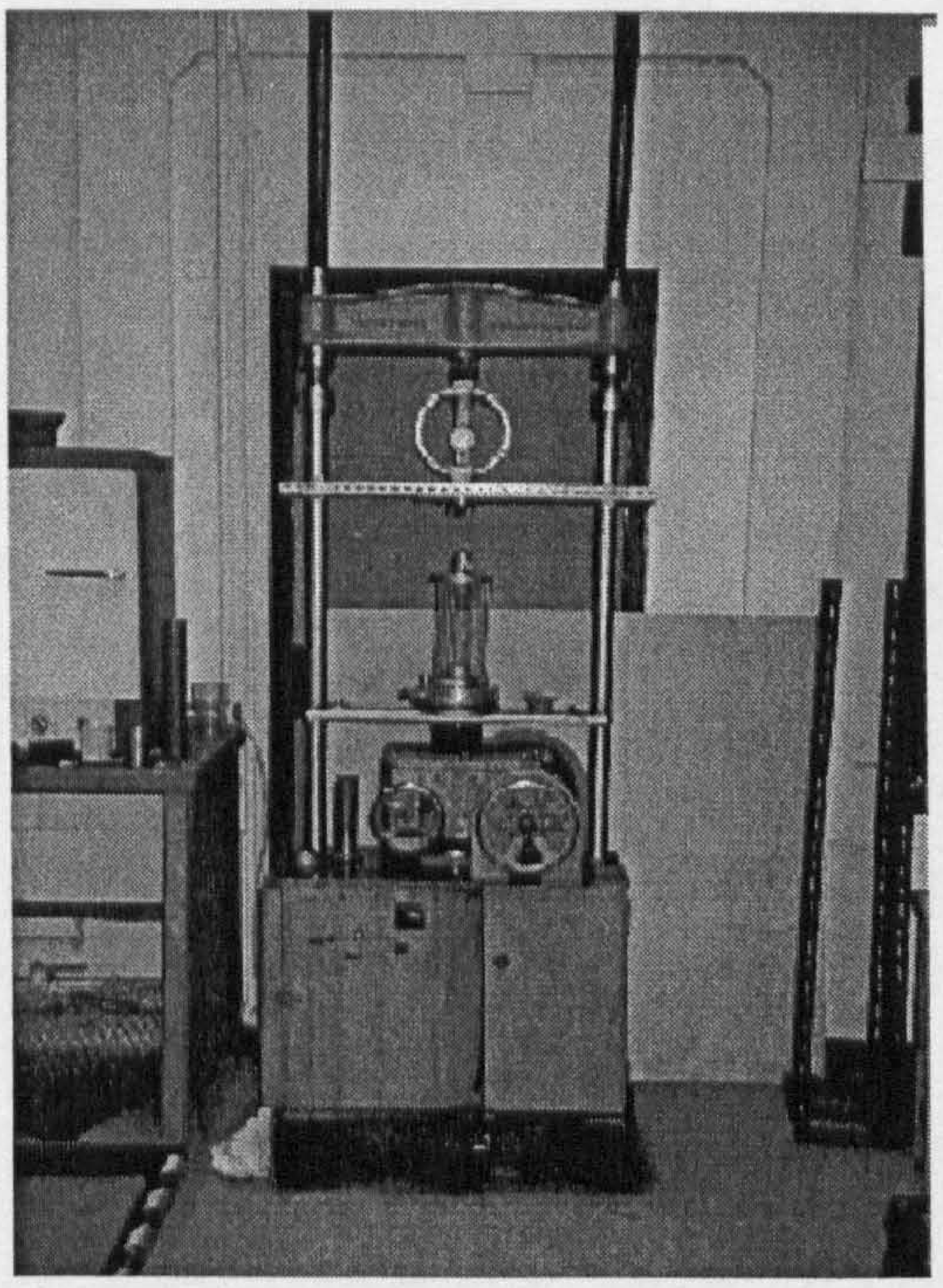

Figure 6.1 The triaxial machine used to compress specimens

Figure 6.2 The mould used to produce the test specimens

6.3.1 Sample Preparation

The proportions of cement and lime used to stabilise the imported earth depended upon the percentage of linear shrinkage in the earth, as specified by Building Research Establishment guidelines. Figure 6.3 shows the stages gone through to produce the stabilised earth specimens.

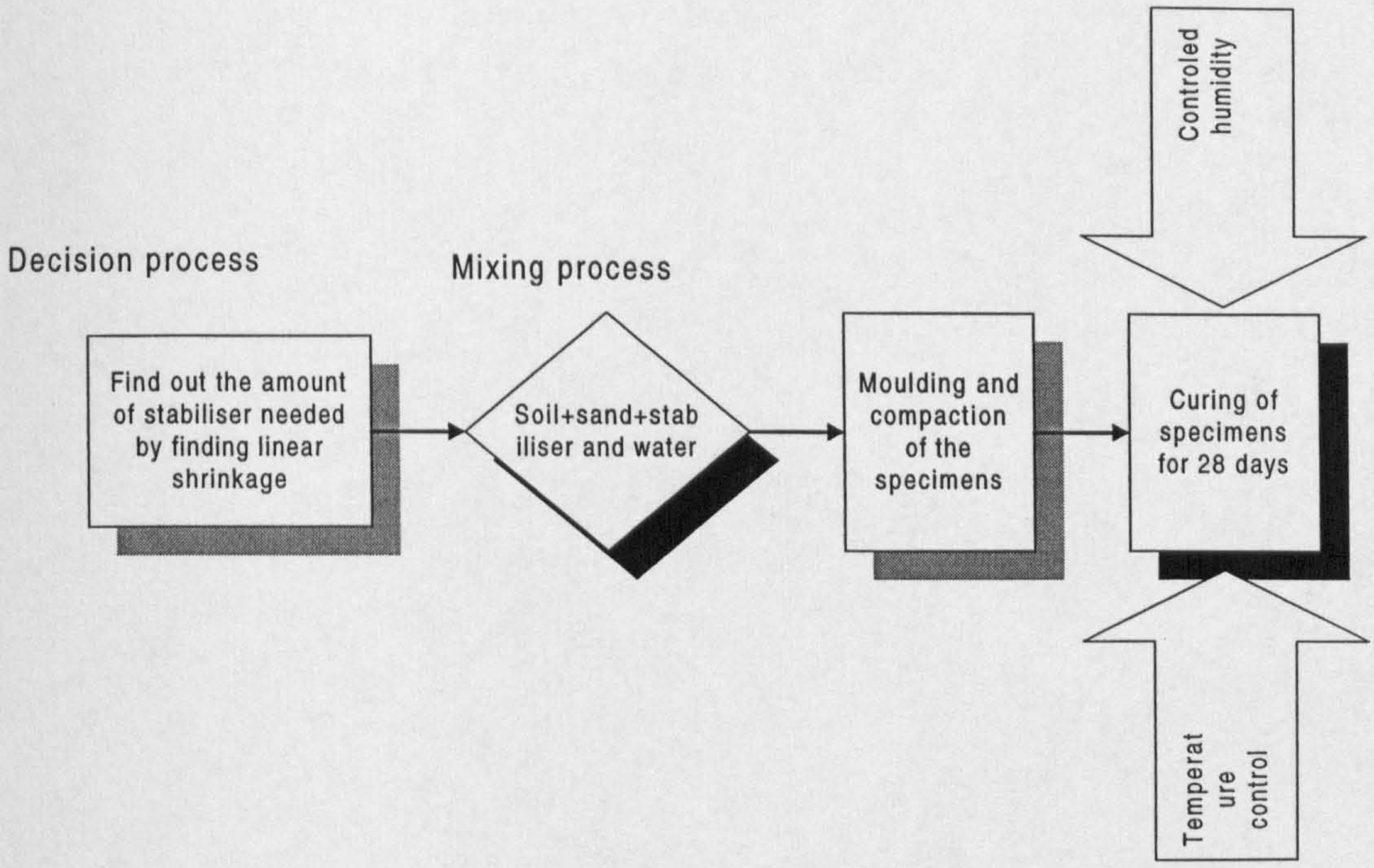

Figure 6.3 The process of sample preparation for performance testing

All measurements during the specimen preparation were made in terms of volume, rather than weight, using a small cup. The dimensions of this cup were 65mm in diameter by 100mm in length. Five cups of earth were corrected for particle size distribution with 1½ cups of well-graded sand, with ½ cup of cement, or $^{1}/_{3}$ cup of lime, then being added. The dry mixture of sand, earth and stabiliser was mixed using a kitchen blender (see Figure 6.4). Water was added periodically during the mixing process to obtain the optimum moisture content. The OMC was determined by field tests for each of the specimens.

A similar procedure was used for calcium chloride and linseed oil. One third of a cup of calcium chloride powder was dissolved in water, and then added to 6½ cups of corrected earth. The optimum moisture content was obtained in this case by adding the calcium chloride solution rather than pure water. In the case of linseed oil, ½ cup of linseed oil was mixed with 6½ cups of corrected earth. Half of the water needed to obtain optimum moisture content was added to prevent an excessive build up of moisture.

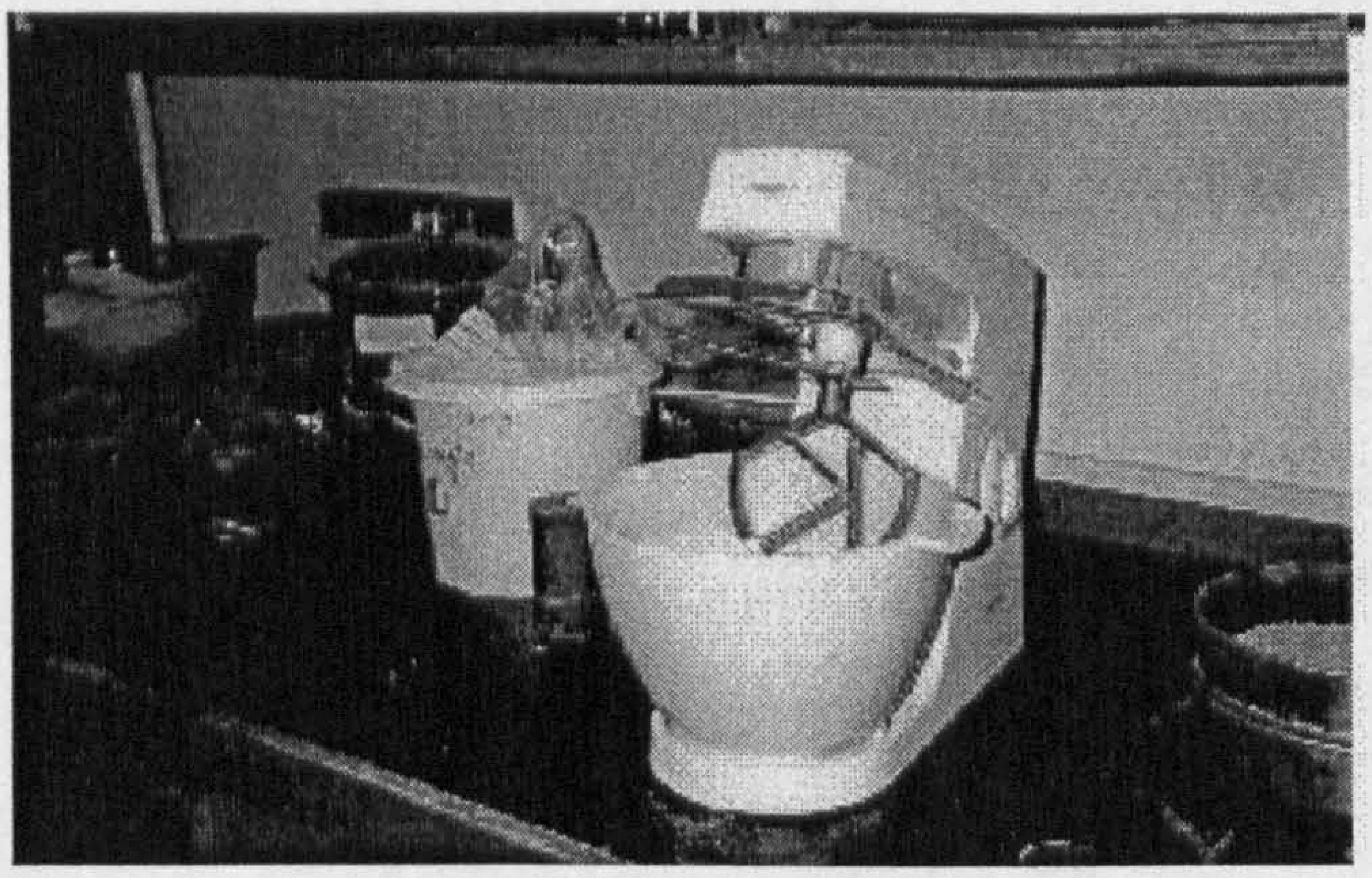

Figure 6.4 The kitchen blender used to mix the specimens

6.3.2 Curing of sample

After demoulding, the specimens were measured for weight and dimension, placed in plastic bags to prevent moisture loss and then cured in an oven for 28 days (Figure 7.5). The presence of moisture is important during curing period to facilitate maturation of specimens, i.e. gaining of strength through physico-chemical reaction. Temperature control in the oven was regulated in order to replicate the temperature conditions of Sindh. Thus, the oven was kept at 35- 40 ^{O}C during the curing process.

Figure 6.5 Specimens during the curing process.

The weight and dimensions of the specimens were measured on the fourth and seventh days of the curing period. On the twenty-eighth day, the curing process was terminated and the final weight and dimensions of the specimens were measured. The specimens were then ready to undergo tests to evaluate their engineering properties. See the Appendix F.

The importance of retaining moisture content within stabilised earth blocks during the curing process is well recognised in the field as an essential part in the manufacturing process. The curing period needed is dependent on the type of earth and, more importantly, the type of stabilising agent employed. (24) For example, when cement is used as a stabiliser, a minimum of 2 weeks curing is recommend (24). In addition, it is recommended that cement stabilised specimens should be cured in humid conditions to ensure complete hydration of the cement. When using lime, a curing period of at least 4 weeks is recommended. (25).

6.4 Testing the Engineering Properties of Specimens

6.4.1 Compressive strength tests

The standard method of measuring compressive strength was adopted, which involves the use of a compressive strength machine (see Figures 6.6a, 6.6b, 6.6c and 6.6d). For further details about this standard method, refer to British Standards Institution specification BS1377: 1990.

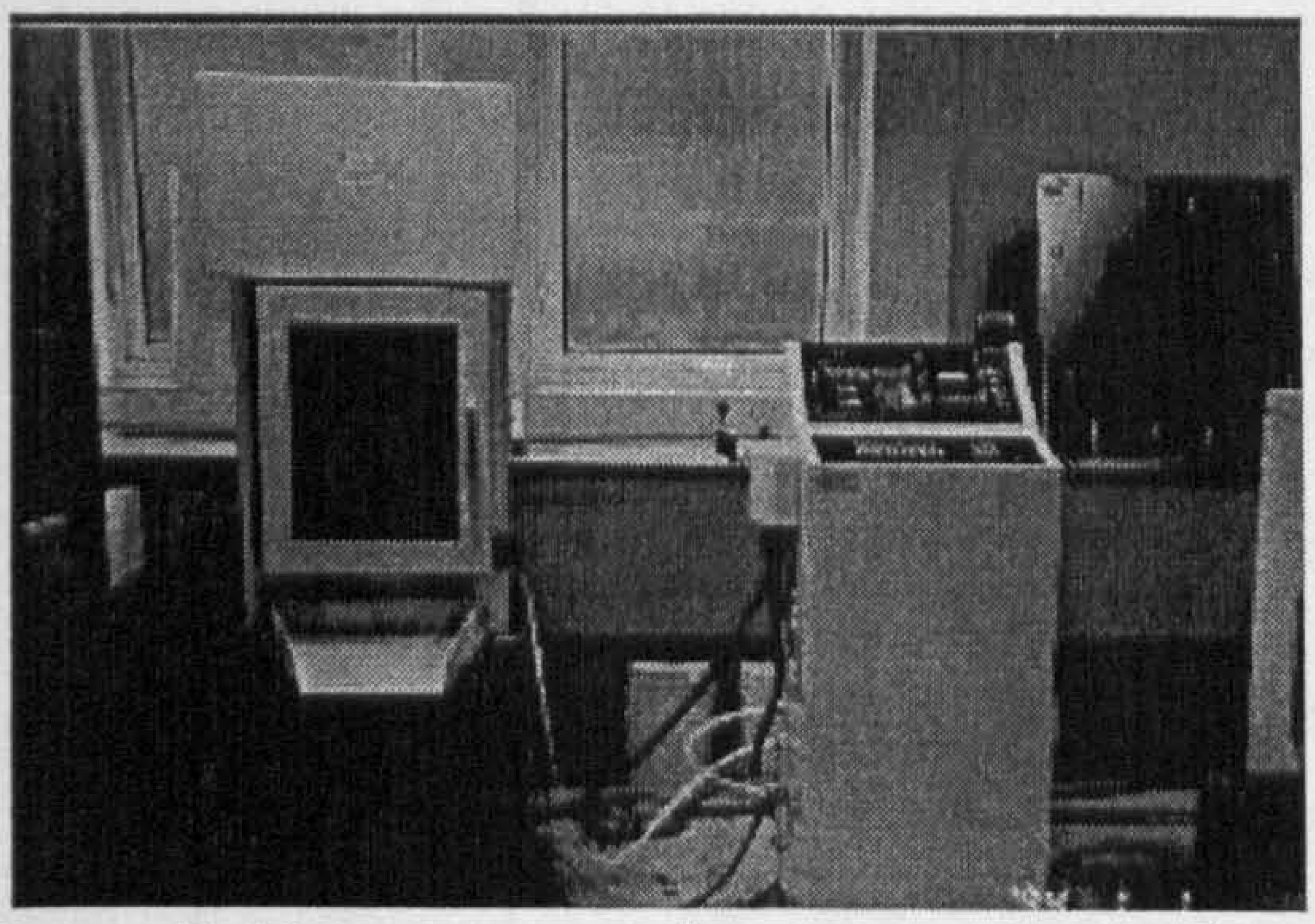

Figure 6.6(a) compressive strength machine

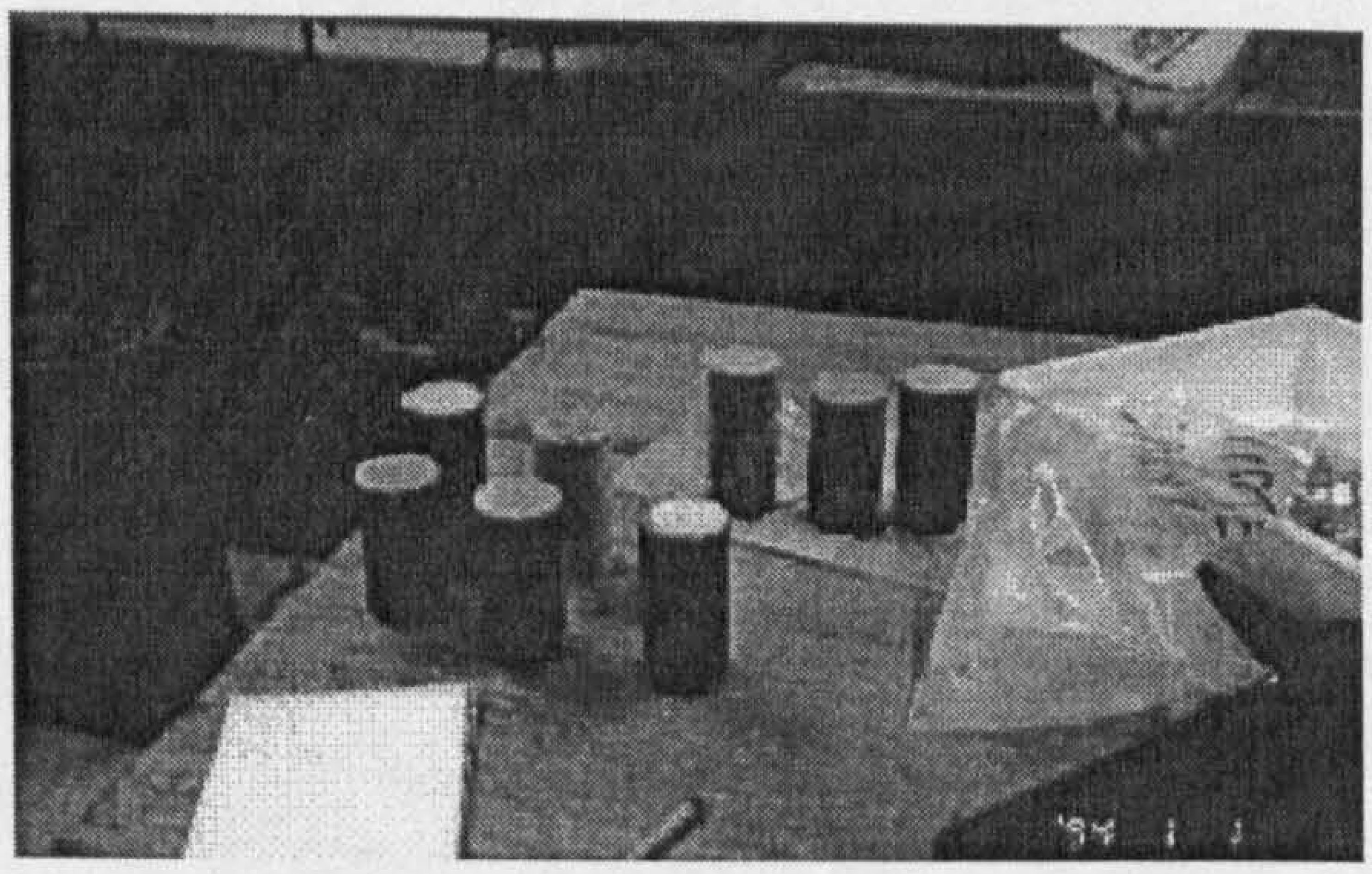

Figure 6.6(b) Cured specimens prior to crushing

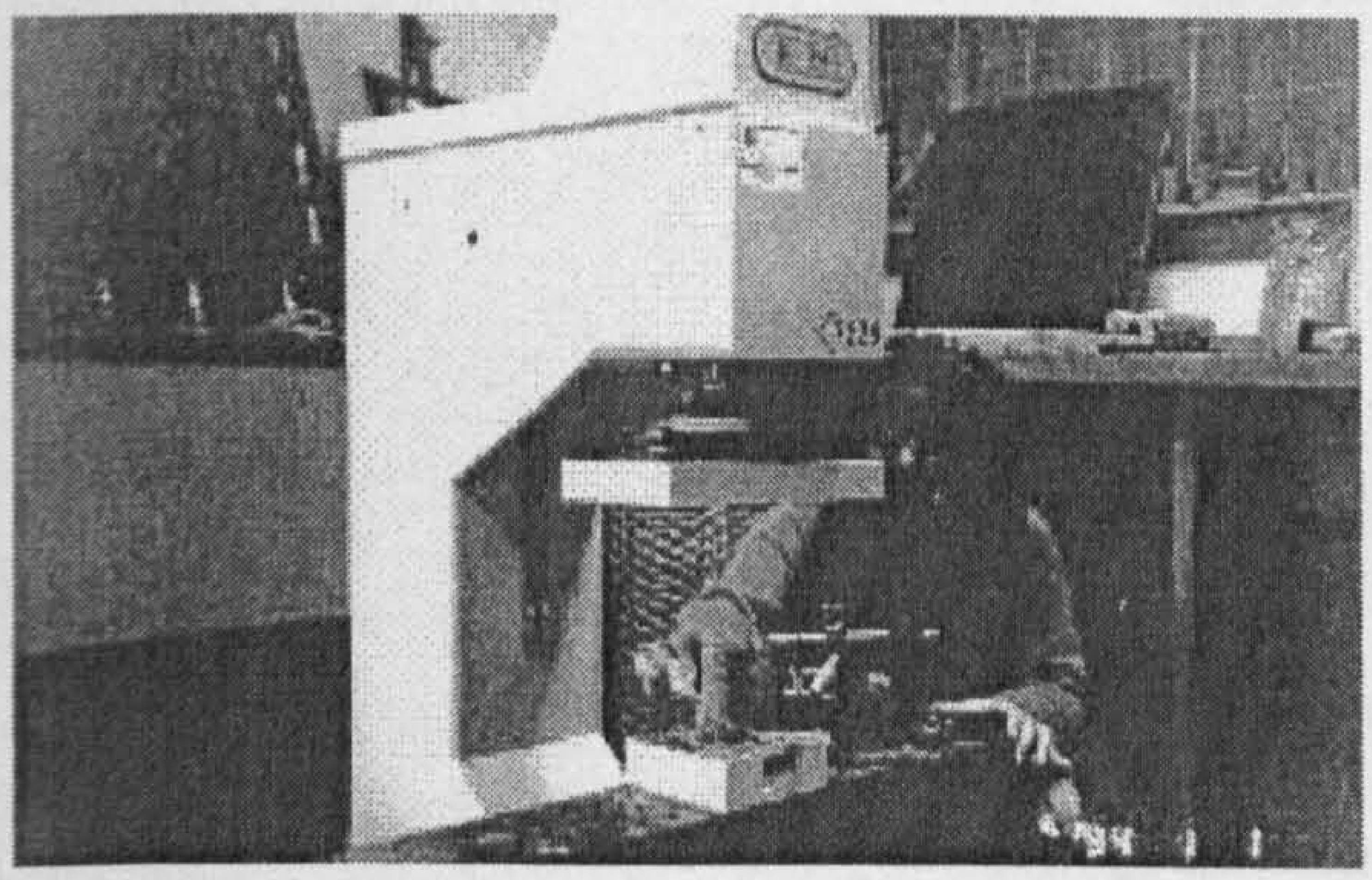

Figure 6.6(c) Specimen after crushing

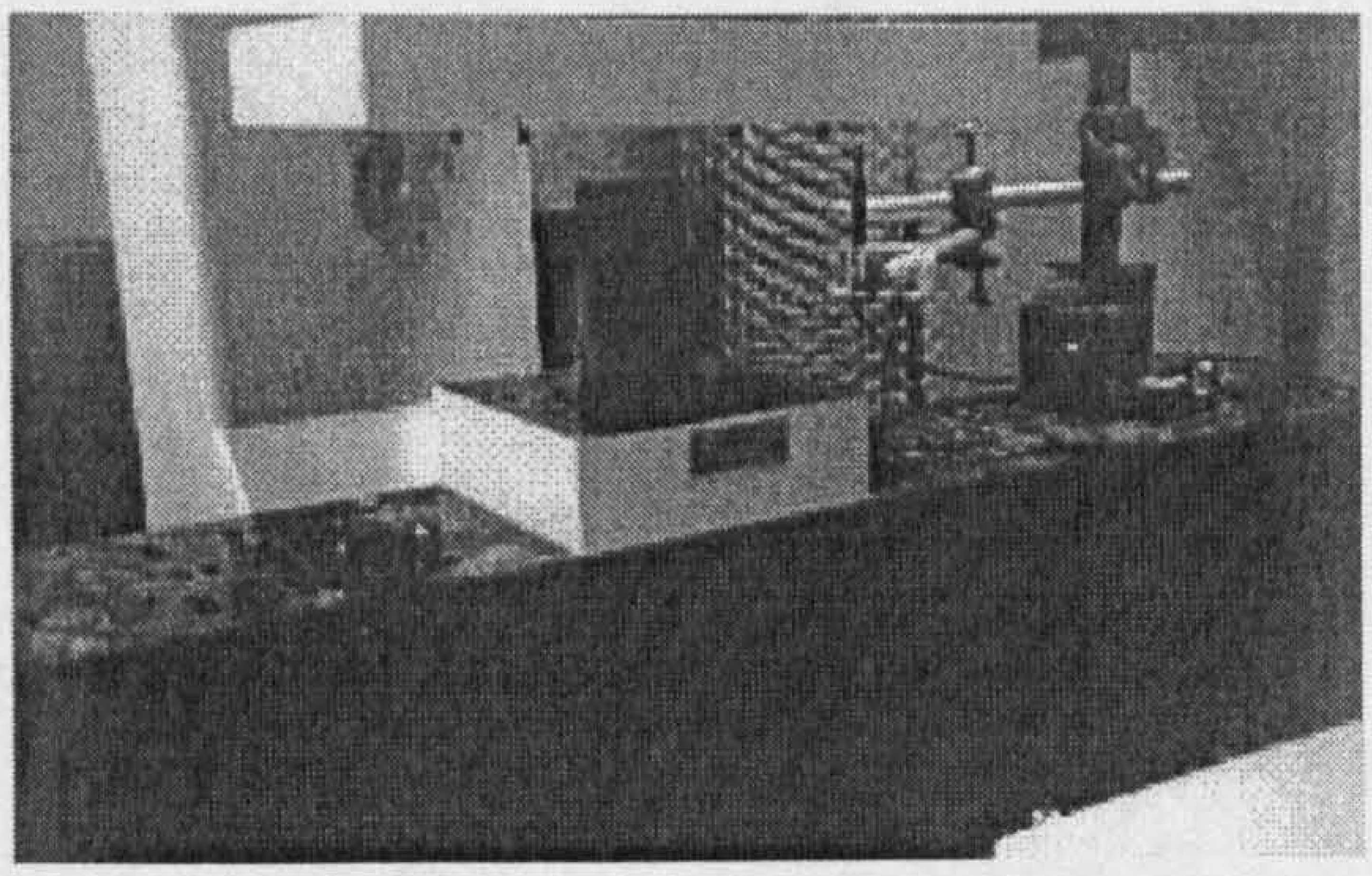

Figure 6.6(d) Specimen after crushing on the transverse testing side of the machine.

The compressive strength machine shown in Figures 6.6a, 6.6c and 6.6d has two loading ranges: a 300KN range with 1KN increments and a 750KN range with 0.1KN increments. The upper platen of the machine was attached to a double ball sheet mounting so that cylindrical specimen could be tested. In Figure 6.6a, the unit on the left is the main compression frame, whilst the unit on the right is used for transverse testing and the application of small loads. See the Appendix G for displacement rate under the applied load.

Two corrected earth specimens were tested for compressive strength by applying a load to each at the rate of lKN per minute. The resulting displacements in the specimens were recorded (see Figures 6.7 and 6.8).

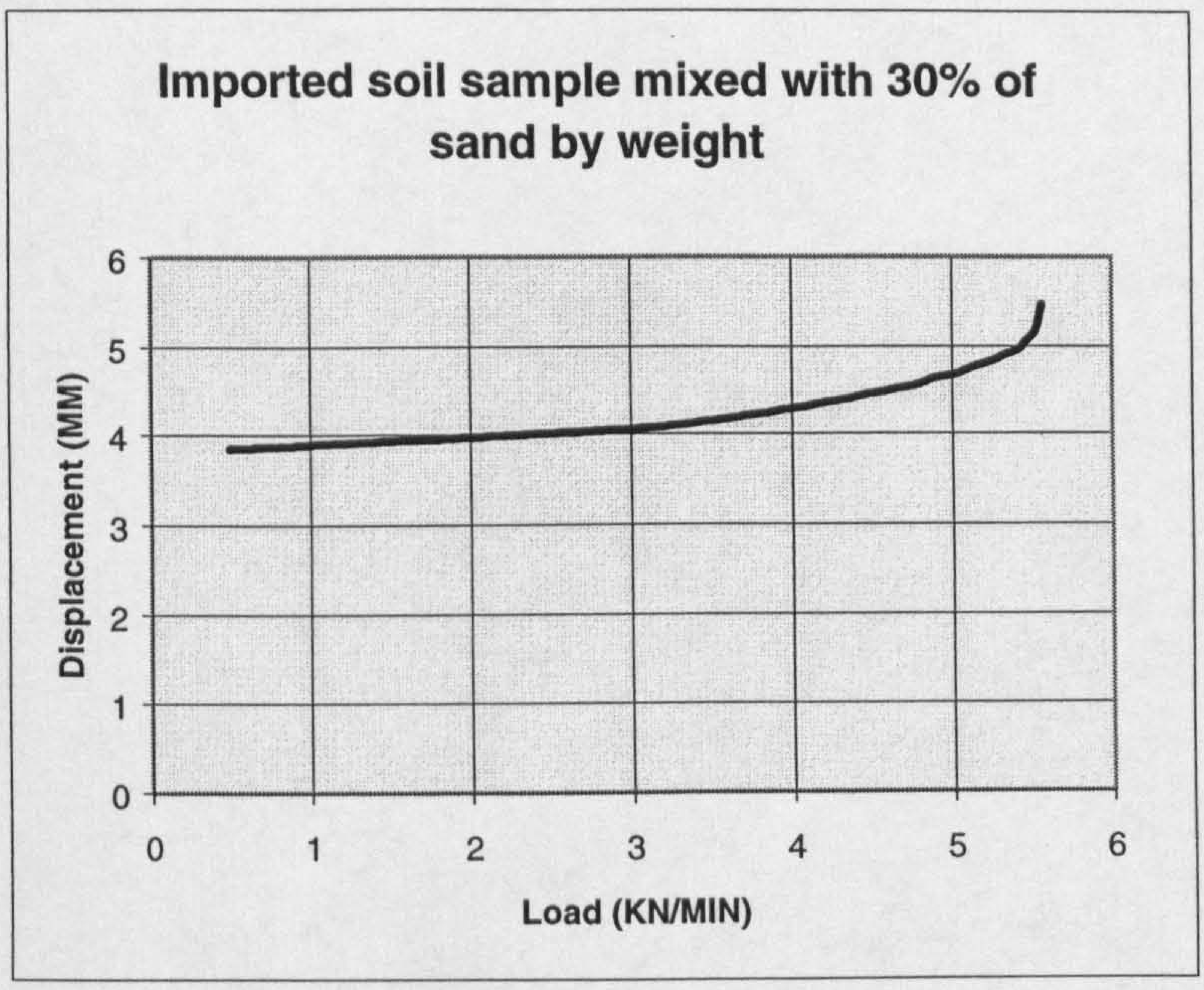

Figure 6.7 Displacement rate in corrected earth specimen 1

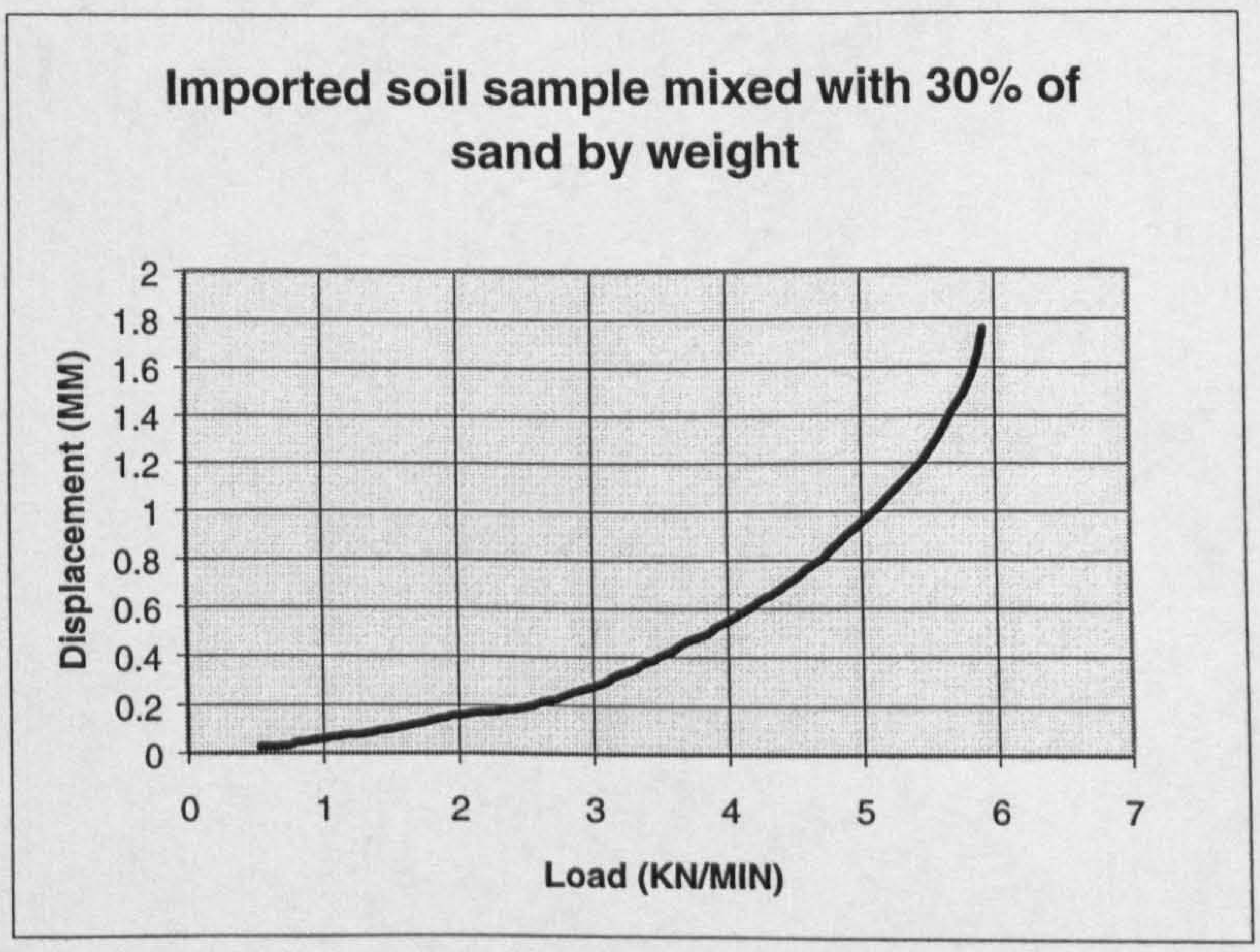

Figure 6.8 Displacement rate in corrected earth Specimen 2

A crushing load of 5.66KN, at the rate of 1KN per minute, was recorded for both corrected earth specimens. Based on the equation shown below, the unconfined compressive strength of the specimens was found to be 2.8 MPa. Use of this equation is recommended by the British Standards Institution.

Compressive Strength = Maximum load / Area

The linseed oil stabilised specimens were also tested in the compressive strength machine. Again, two specimens were tested for compressive strength by applying a load to each at the rate of lKN per minute. The displacement rates under this load are shown in Figures 6.9 and 6.10. The mean crushing load for both the linseed oil stabilised earth specimens was 1.65KN at a rate of 1KN per minute. Their mean compressive strength was calculated to be 0.0845 MPa.

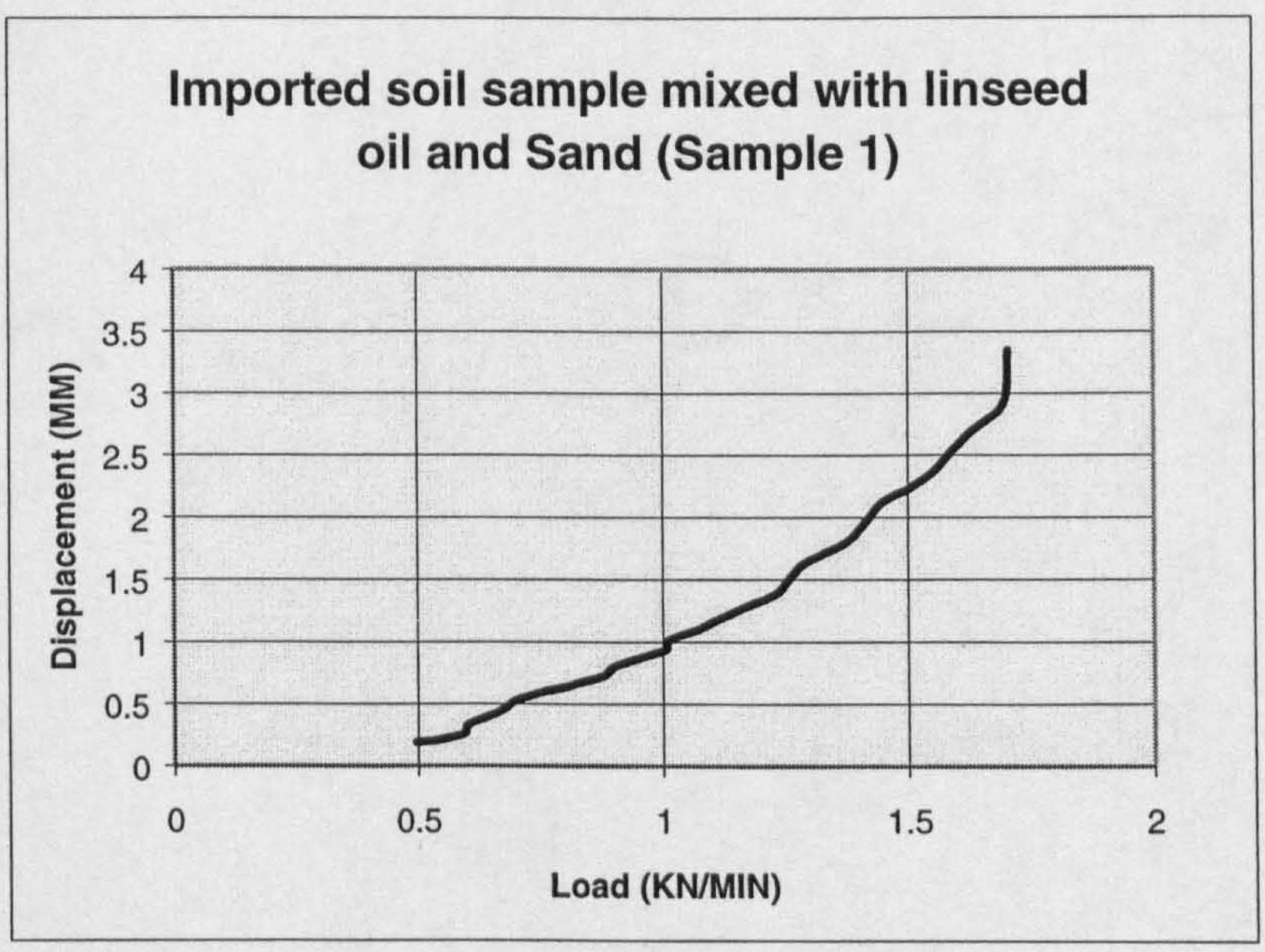

Figure 6.9 Displacement rate in linseed oil stabilised earth Specimen 1

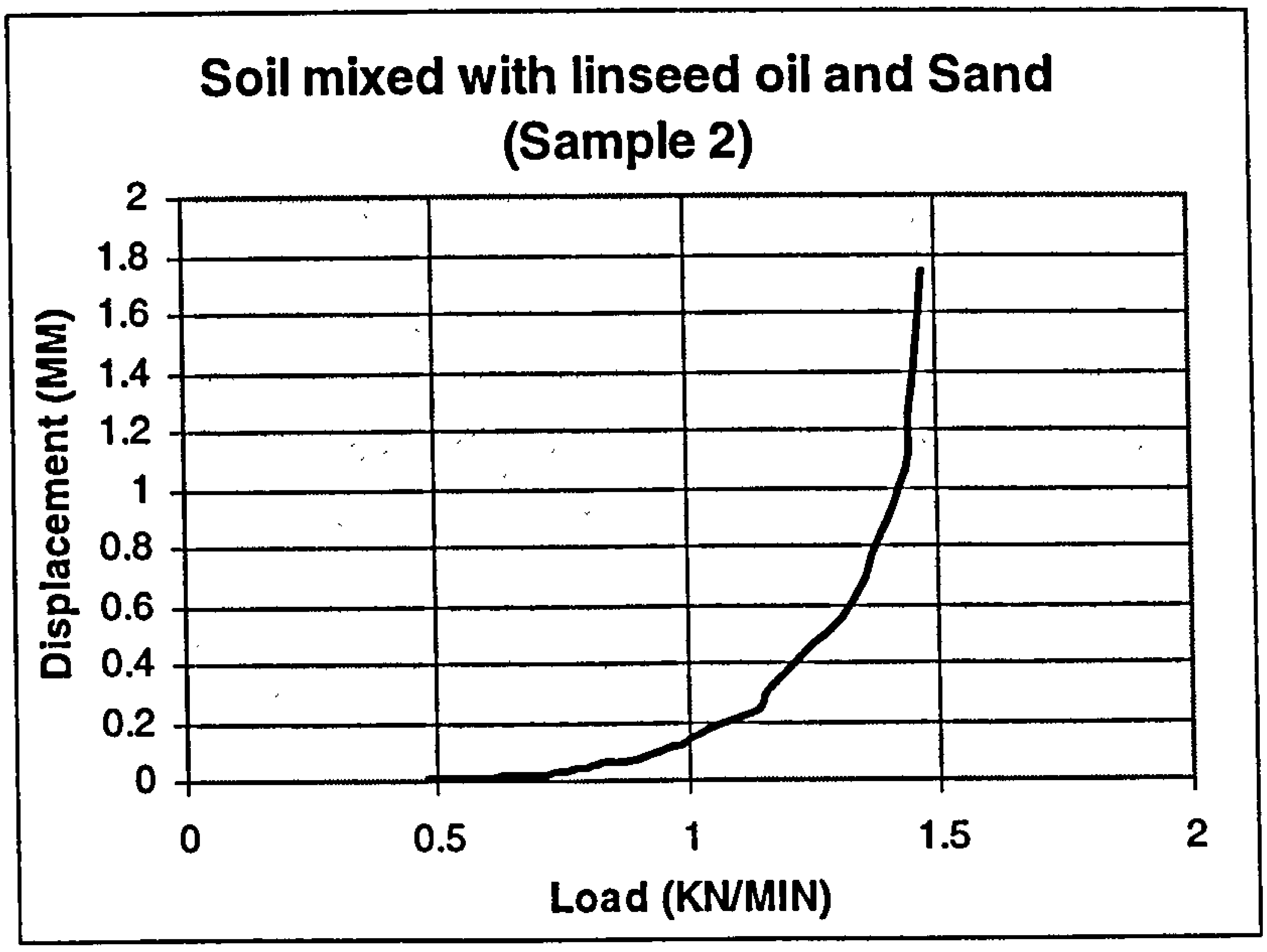

Figure 6.10 Displacement rate in linseed oil stabilised earth Specimen 2

Two specimens of calcium chloride stabilised earth were prepared for the compressive strength test. The deformation of these specimens under a load of 1KN per minute differed greatly from the displacement characteristics exhibited by the previous specimens. The specimens deformed quickly as the loading was increased (see Figures 6.11 and 6.12). Their mean crushing load was calculated to be 2.3KN at a rate of 1KN per minute. The mean compressive strength was calculated to be 1.17 MPa.

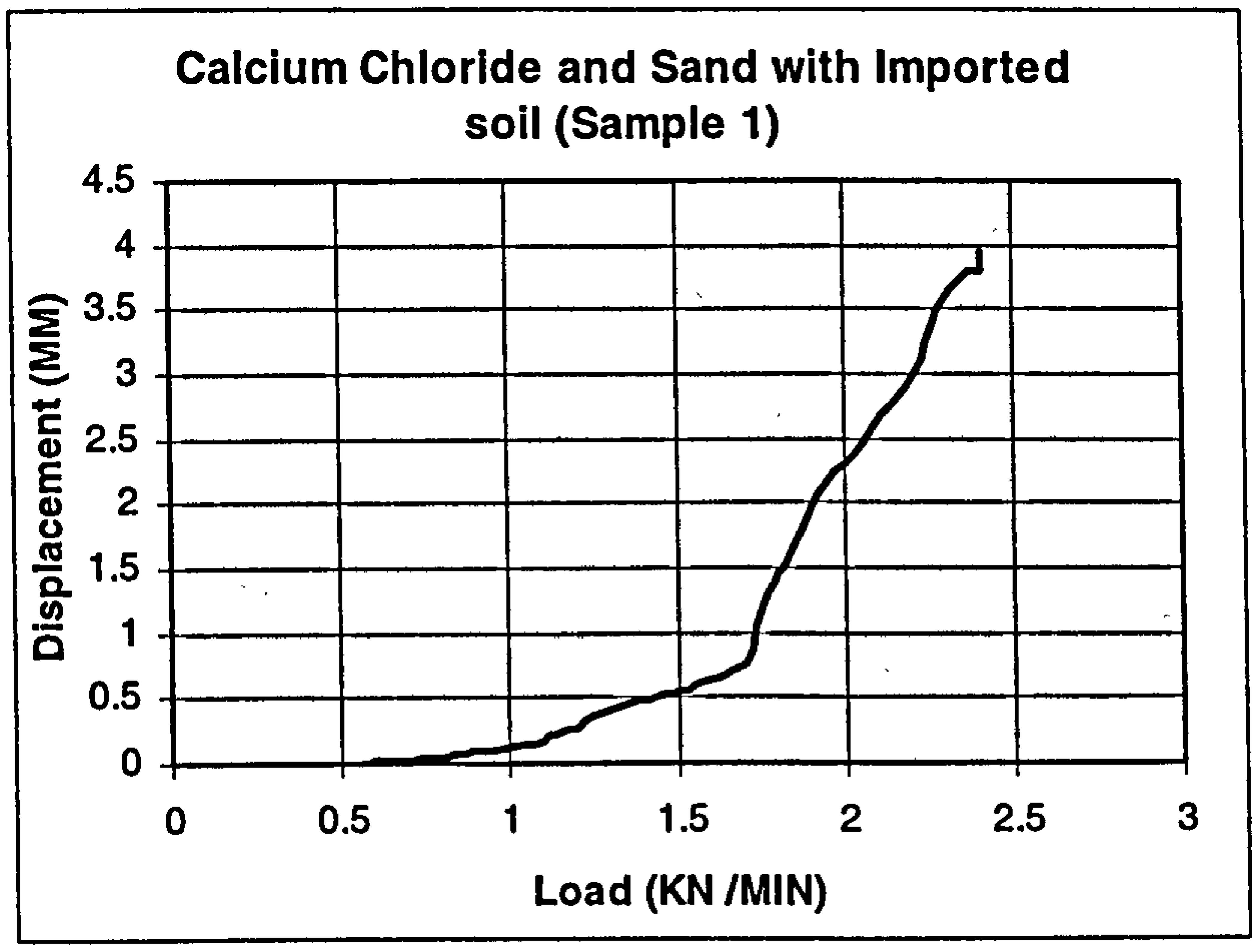

Figure 6.11 Displacement rate in calcium chloride stabilised earth Specimen 1

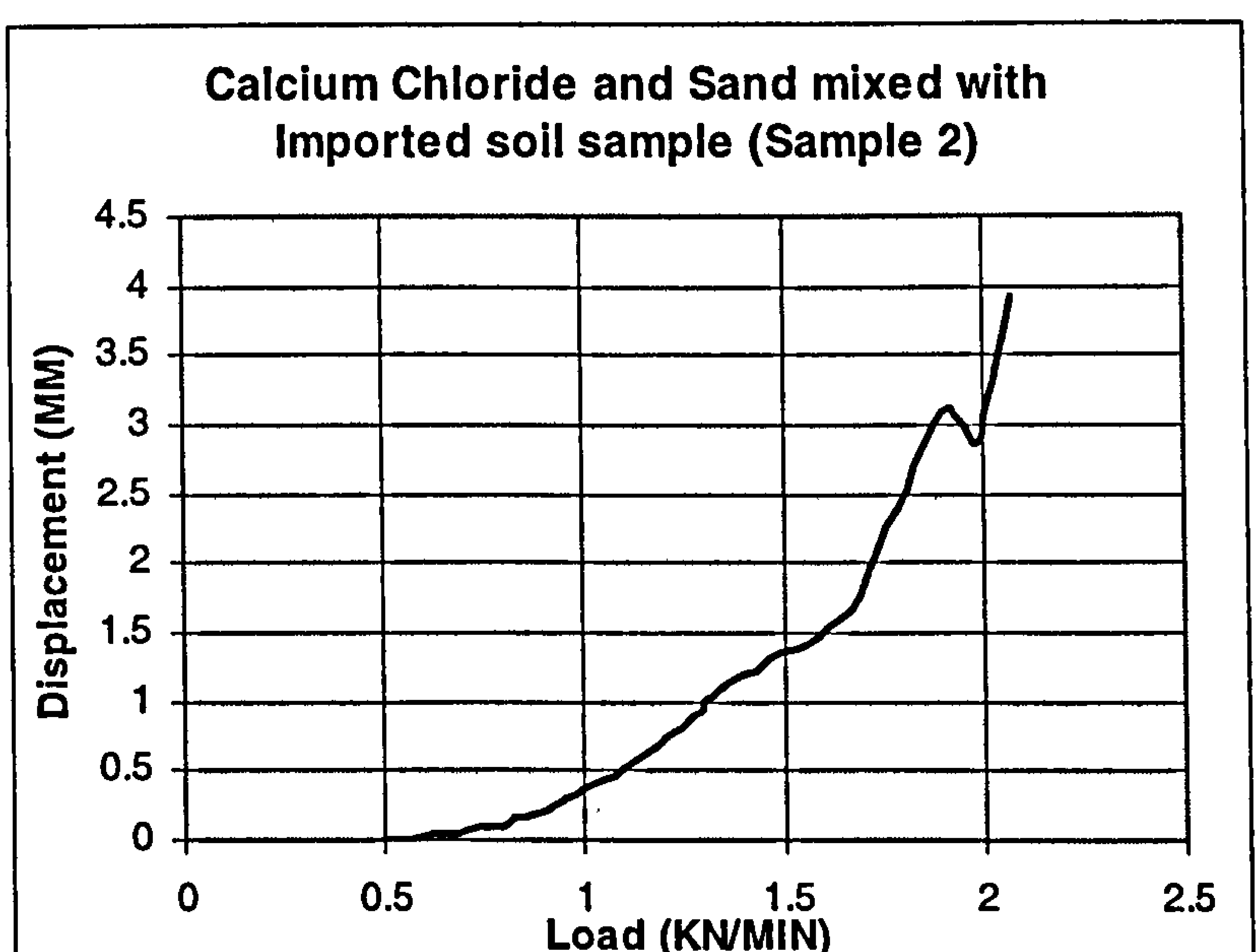

Figure 6.12 Displacement rate in calcium chloride stabilised earth Specimen 2

The calcium chloride stabilised earth specimens demonstrate variant curves of displacement. This shows that the specimen exhibited some resistance to application of the load.

The mean crushing load of two cement stabilised earth specimens was 8.5KN at a rate of 1KN per minute. Their mean compressive strength was calculated to be 4.33MPa. The cement stabilised earth specimens demonstrated significant resistance to deformation due to their high compressive strengths (see Figures 6.13 and 6.14).

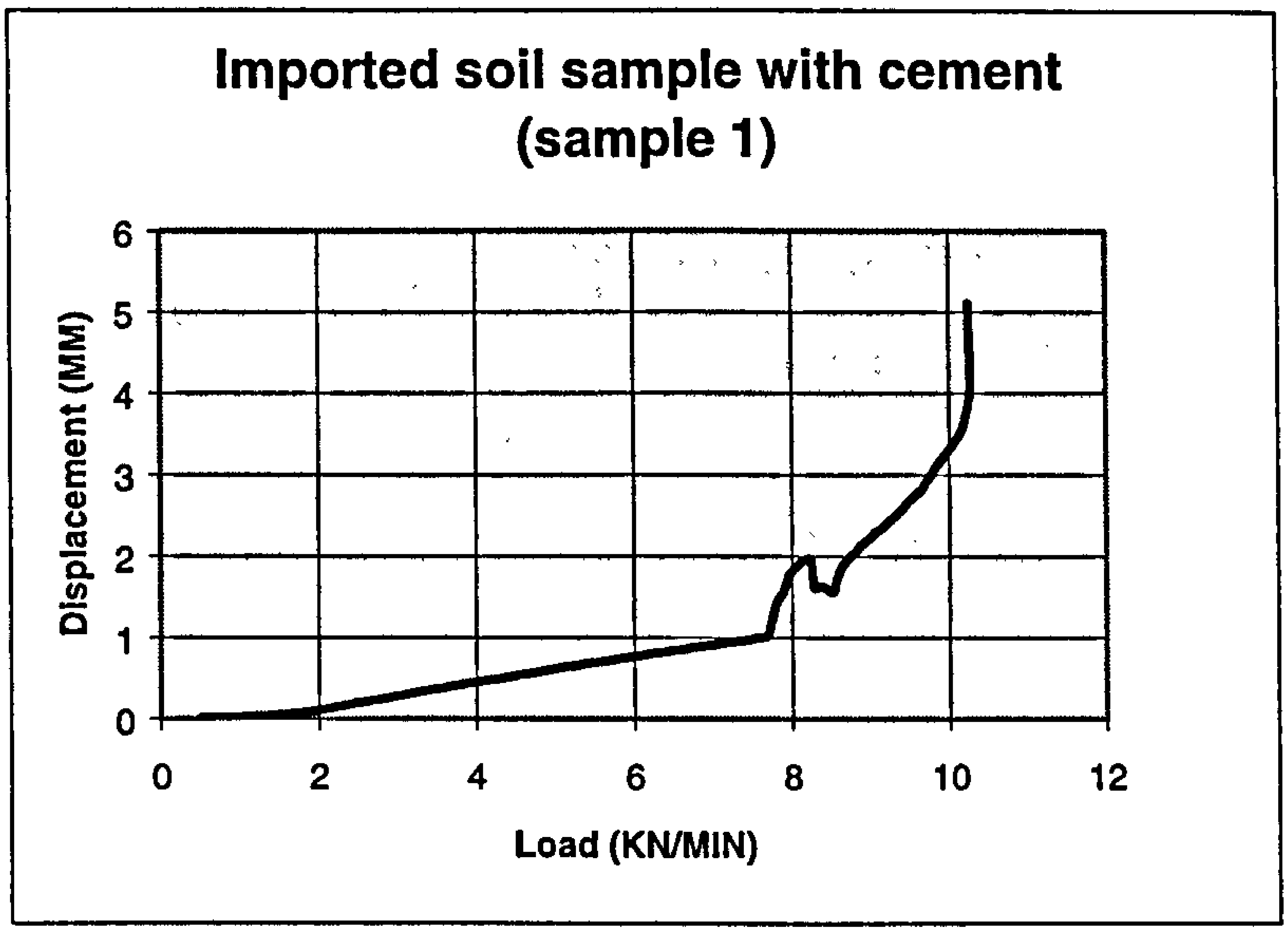

Figure 6.13 Displacement rate in cement stabilised earth Specimen 1

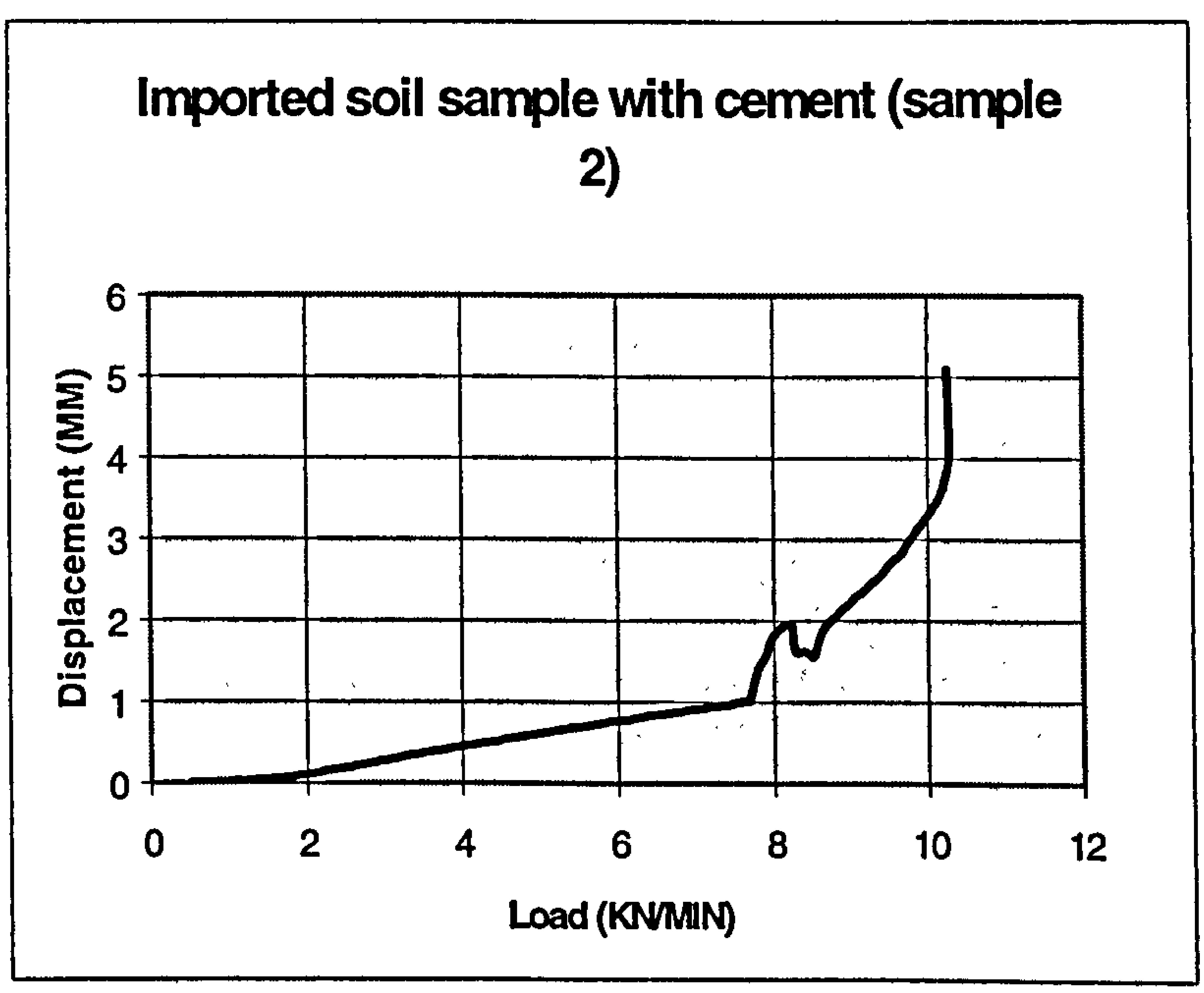

Figure 6.14 Displacement rate in cement stabilised earth Specimen 2

Literature studies suggest that lime is more suitable for clayey earth than the other stabilisers used in this study. The mean crushing load of two lime stabilised earth specimens was 5.99KN at a rate of 1KN per minute. Their mean compressive strength was calculated to be 3.05MPa. The displacement curves in Figure 6.15 and 6.16 shows the effect of the loading on the two specimens. Previous research has demonstrated that lime stabilised earth achieves a higher compressive strength when cured at higher temperatures. Therefore, lime stabilised earth is likely to have increased compressive strength in regions with hot climates. (27)

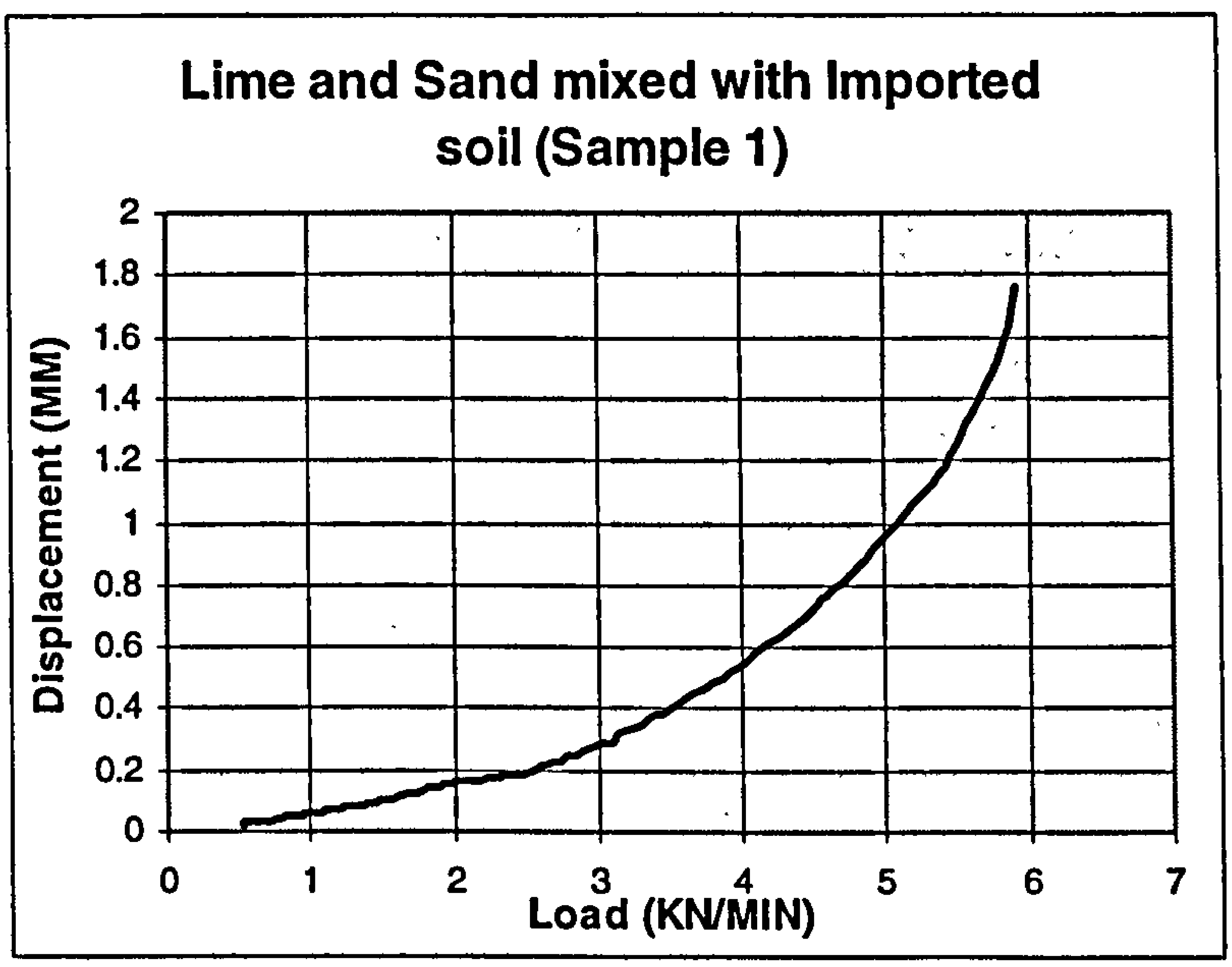

Figure 6.15 Displacement rate in lime stabilised earth Specimen 1

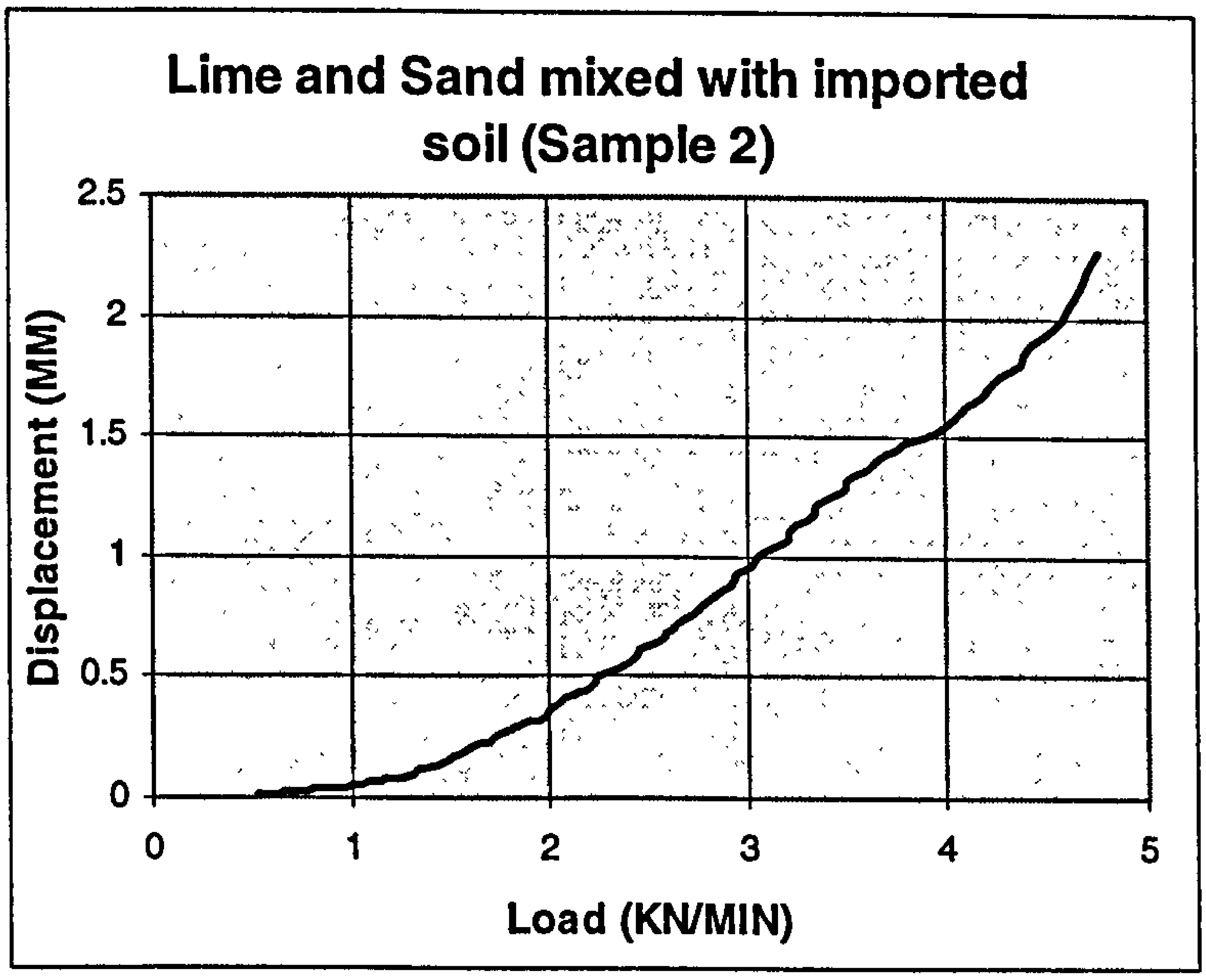

Figure 6.16 Displacement rate in lime stabilised earth Specimen 2

Lime stabilised earth gains not only compressive strength during the curing period but also durability. For example, dry clay earth has a considerable capacity for moisture uptake, which can lead to substantial swelling. The swelling results from moisture being either adsorbed onto clay particle surfaces (illite and kaolinite) or absorbed between the alumino-silicate layers of the clay structure. (26) The addition of lime reduces swelling in the earth by causing ion exchange to occur, which modifies the alumino-silicate layers and reduces the thickness of the adsorbed water film. In addition, a slow chemical reaction occurs between the lime and the clay, resulting in cementation of particles. The principal product of the cementation reaction is C-S-H gel or C-A-S-H. (27) This gel bonds clay particles together, which restrains expansion and increases strength.

Figure 6.17 summarises the results of the compressive tests conducted on the specimens in this study. It shows that cement stabilised earth is capable of withstanding the highest compaction loads.

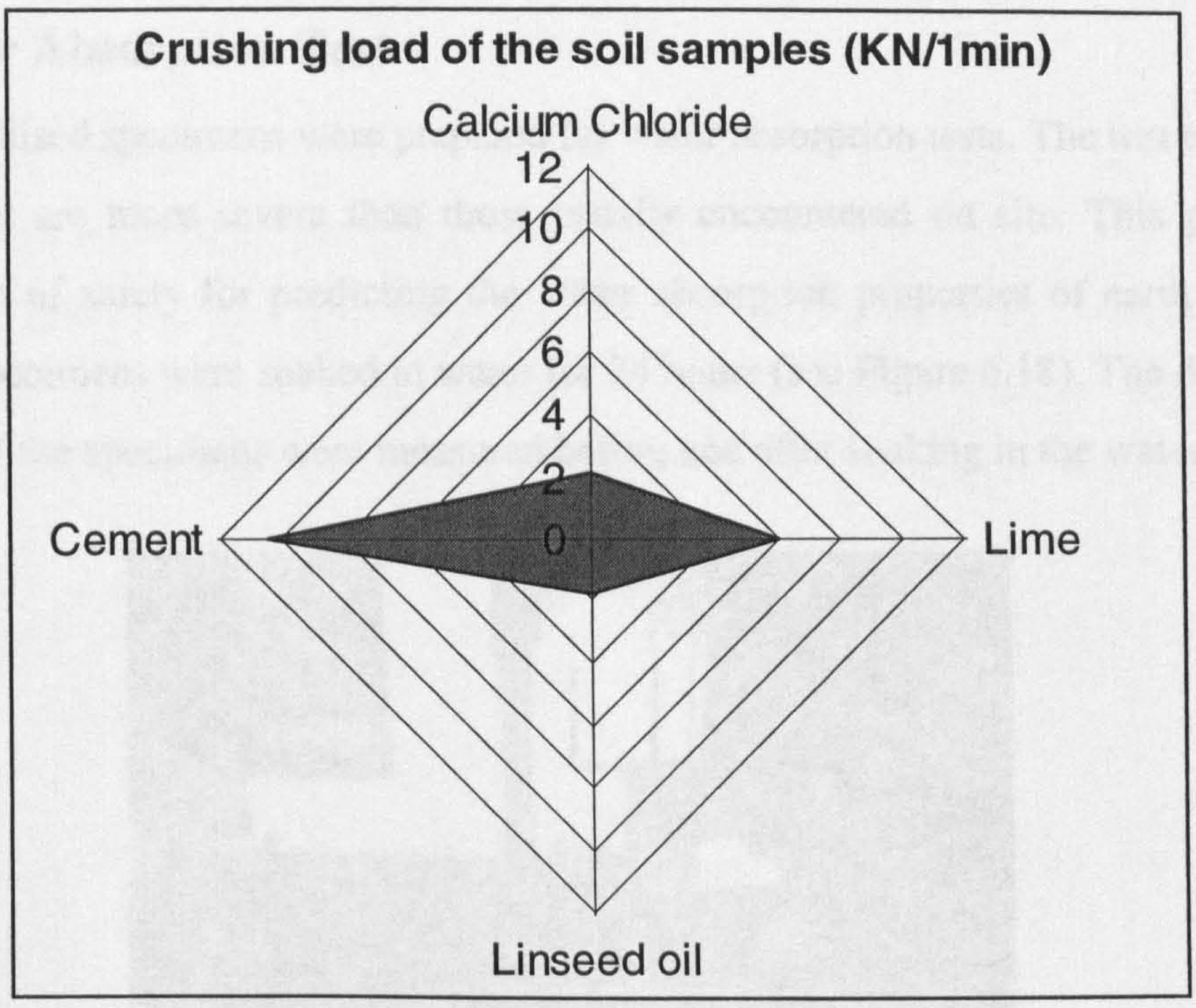

Figure 6.17 Summary of compressive test results

It is stipulated in the Kenyan Standard that the minimum mean compressive strength for an earth stabilised block should be at least 1.5 N/mm^2 after curing for 28 days and then immersing in water for a further 24 hours. Also, the dry strength of the block should be at least 50% higher than its wet compressive strength, i.e.

$$f\text{dry} = \text{Twice x } f\text{wet}$$

The Kenyan Standard also specifies that an earth stabilised block should not have more than three shrinkage cracks, measuring no more than 3mm wide and 75 mm in length. Ideally, block should be free from every kind of cracking, honeycombing and other visual defects that reduce strength. Following visual inspection of the test specimens, it was found that they were free of obvious cracks, broken edges and honeycombing (see Figure 6.2). However, the calcium chloride stabilised specimens exhibited slight rust on their surface.

6.4.2 Water Absorption Test

The earth stabilised specimens were prepared for water absorption tests. The test reproduces conditions that are more severe than those usually encountered on site. This provides a greater margin of safety for predicting the water absorption properties of earth stabilised blocks. The specimens were soaked in water for 24 hours (see Figure 6.18). The dimensions and weights of the specimens were measured before and after soaking in the water.

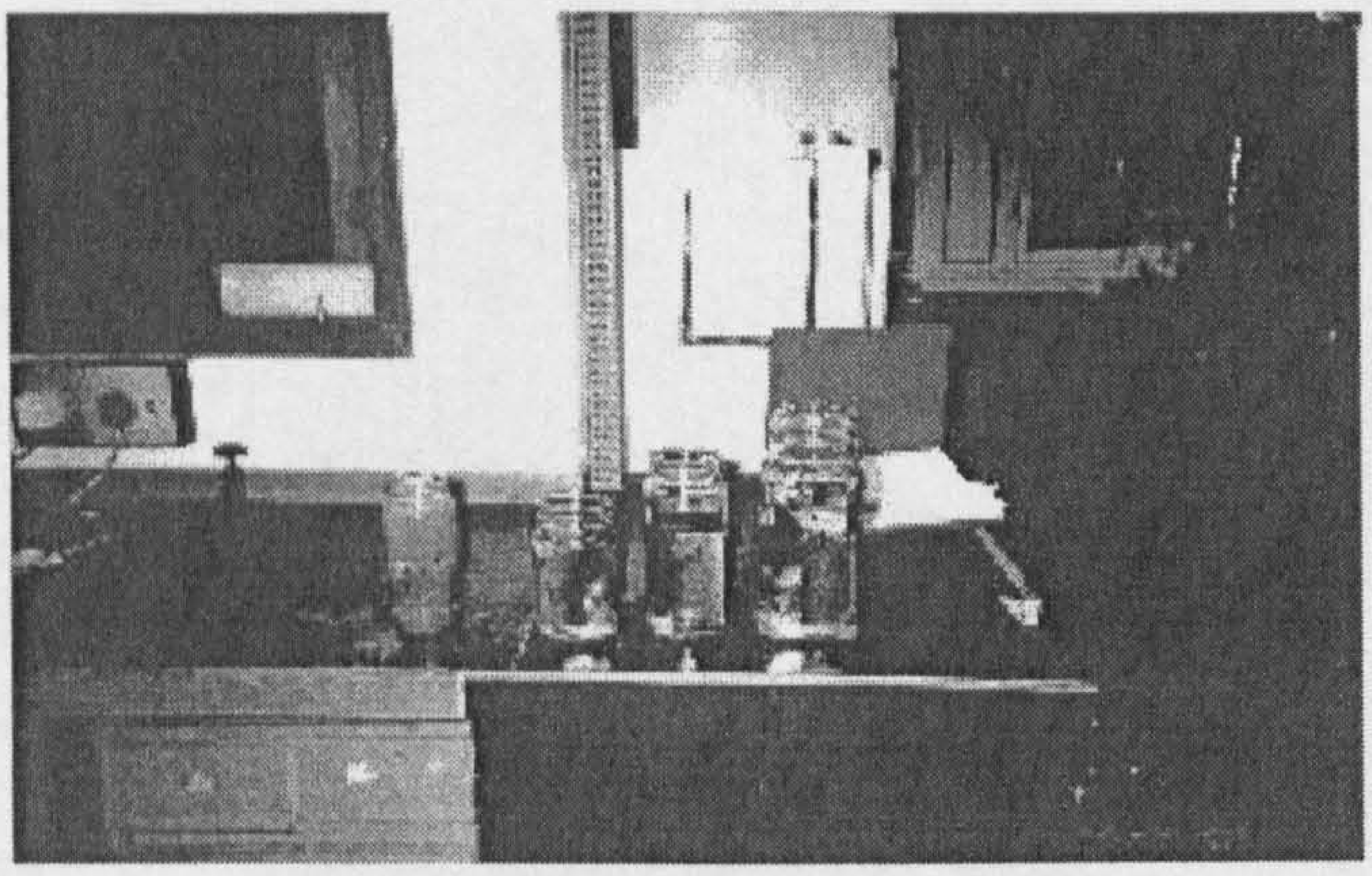

Figure 6.18 Specimens immersed in water bottles

The water absorption test determines the extent to which an increase by weight of stabiliser results in a reduction of water absorbed. The test is necessary because any large uptake of water leads to cracking of the wall, failure of rendering and penetration by rain. There are various water absorption tests, but these are often difficult for inexperienced technicians to carry out in the field. The test methodology adopted for this study is based on the earth construction practices.

The following equation can be applied in order to determine the percentage of moisture absorption by weight (Mc):

$$Mc(\%) = \frac{M2 - M1}{M1} x100$$

M1 = Mass of dry specimen

M2= Mass of specimen after 24 hours in water (g)

A Kenyan workshop report recommends that, after immersing an earth stabilised block in water for 24 hours, its water absorption should not exceed 15% of the original mass. (23)(24) Other literature supports this recommendation, stating that an earth stabilised block with less than about 15% moisture absorption is likely to have good long-term engineering properties. This figure compares favourably with the water absorbency of burnt, flattened clay brick, which is about 22%. (28)

Water absorption tests were carried out on one of each of the stabilised specimens. The results are shown in Table 6.1 and Figure 6.19.

Table 6.1 Results of the water absorption tests on earth stabilised specimens

Earth Sample	Wt. of dry sample	Wt. after 24 in water	Water absorption
Earth with Lime	335 grams	390 grams	16.417%
Earth with Cement	340 grams	390 grams	14.705%
Earth Linseed earth	351 grams	388 grams	10.54%
Earth $CaCl_2$	330 grams	Melted (completely)	----

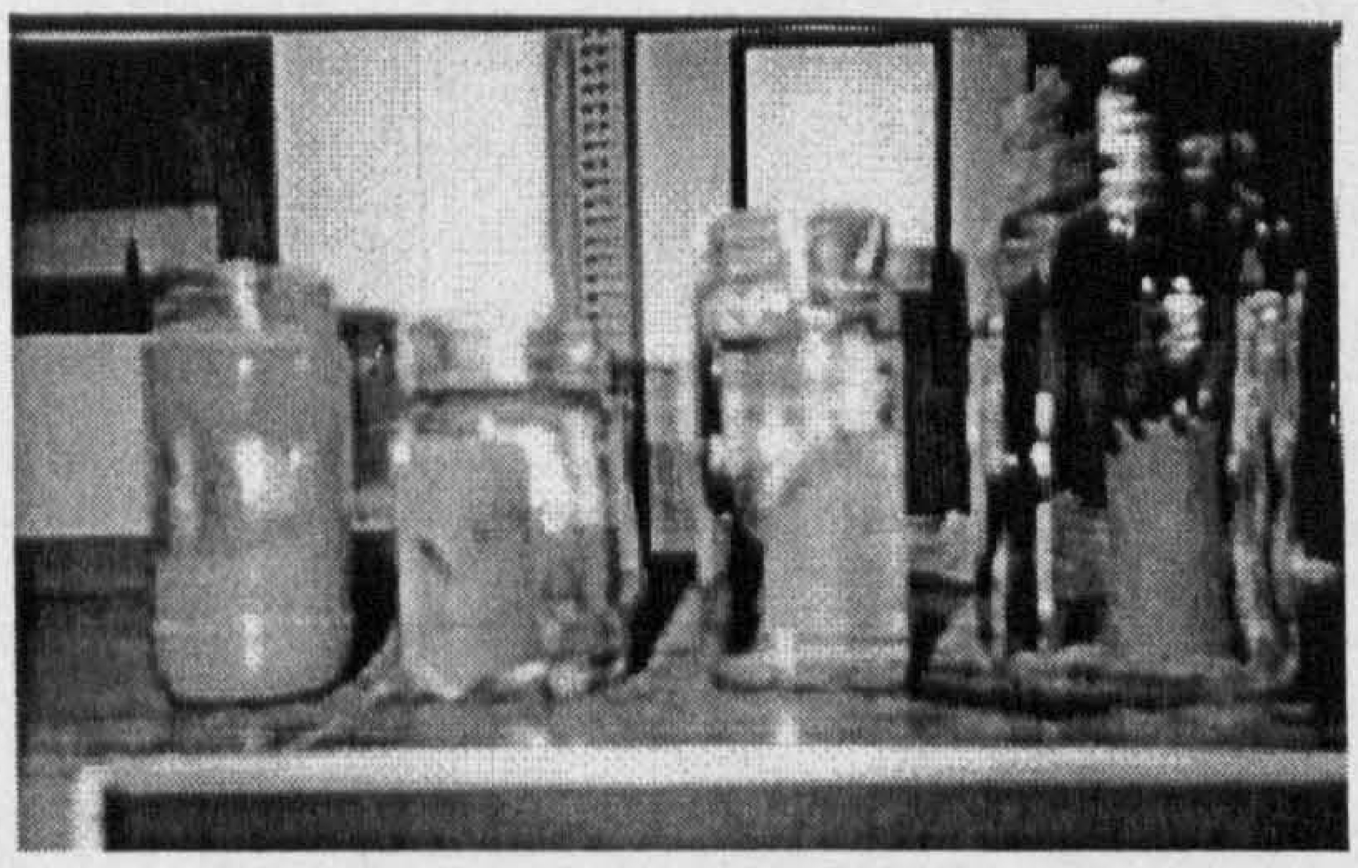

Figure 6.19 Earth stabilised specimens after immersion in water for 24 hours

The results shown in Table 6.1 indicate that, based on the recommendation of the Kenyan workshop report, only two of the earth stabilised specimens can be considered for use in building construction.

The specimens stabilised with linseed oil and cement demonstrated water absorption of less than 15% and can be considered suitable for use in construction. It has been suggested, as previously discussed, that lime is a suitable stabiliser for clay-rich earth. The addition of lime to the imported earth resulted in high compressive strength, although not as high as when cement was used as the stabiliser. However, the lime has a high water absorption value of 16.417%, which lies outside the range specified by the Kenya Standard. Considering the high margin of safety inherent in the water absorption test used, it is recommended that lime could be used as a stabilising additive in dry climates such as Sindh.

The water absorption values of cement and linseed oil stabilised earth specimens met the specifications of the Kenyan Standard. These specimens have water absorption values of 14.705% and 10.54% respectively. Therefore, the water absorption characteristics of cement and linseed oil stabilised blocks can be considered acceptable for relatively dry climates such as Sindh. However, calcium chloride stabilised specimen dissolved completely after immersion in water for 24 hours. Clearly, calcium chloride does not warrant further consideration for use as a stabiliser for clay-rich earth.

6.4.3 Durability Test

Durability tests are usually carried out on earth samples with a California Bearing Ratio (CBR) in excess of 80%. Although CBR tests were not performed, durability tests were undertaken on the earth stabilised specimens in order to evaluate general performance under controlled laboratory conditions. The specimens were compacted at optimum moisture content in a standard mould and stored for 7 days. They were then submerged for 5 hours in tap water at room temperature. Thereafter, the specimens were removed and placed in an oven at a regulated temperature of 71°C for 42 hours. On removal from the oven, the specimens were given two firm stokes all over with a wire brush and weighed again. This process was repeated until all the specimens had gone through 12 cycles of wetting and drying. After this, samples were dried to a temperature of 110°C and the oven-dried weights measured. The final results obtained for the test are shown in Table 6.2.

Table 6.2 Durability test on stabilised earth samples

Stabiliser Type	Weight lost at failure (%)
Cement	27.3 % on 12 cycle
Lime	38.9% on 12 cycle
Calcium chloride	70.0% on 1st cycle and Failure on 2nd cycle
Linseed oil	51.2% on 12th cycle

From Table 6.2 it can be seen that the cement stabilised earth sample survived 12 wet-dry cycles and suffered the lowest loss of weight - indicating that it is the most durable of the test sample. Both lime and linseed oil stabilised samples survived 12 cycles and lost 39% and 51% of their weight respectively. The calcium chloride stabilised sample exhibited low durability and failed after two cycles.

Although lime stabilised earth has low water absorption properties, it is not as durable as cement stabilised earth. It is, therefore, more advantageous to use cement if financial constraints allow. The decision about whether to use earth stabilised blocks with adequate compressive strength but high water absorption ultimately depends on factors such as the cost of the stabiliser and the average rainfall in the region. For further discussion about the cost variable, see Chapter 7.

6.4.4 Porosity Testing

Porosity is defined as the volume of pore space expressed as a percentage of a block's total volume. (This definition is produced by author's understanding of literature) The degree of porosity depends on the amount and type of clay used, as well as the duration of the curing process.

The British Standards Institution test procedure for determining the porosity of a material was adopted. (28) However, the test was slightly modified by the author due to a lack of material available on-site. Each earth-stabilised specimen was broken down into small pieces, with fines smaller than 14mm being removed. A 100g representative sample of each crushed specimen was dried in an oven to $105^{\circ}C$ for 24 hours. The samples were then removed from the oven and placed in a desiccator for 30 minutes to cool down. Finally, each representative sample was weighed and the mass recorded (Mass C).

The representative sample of the cement stabilised specimen weighed **91.45g** after drying, whilst for lime the dried weight was **93.78g**, for calcium chloride **92.05g** and for linseed oil **94.86g**. Each representative sample was placed in a glass beaker that was, in turn, placed inside a bell jar. The bell jar was sealed with silicon to ensure that it was totally airtight. All air was evacuated from the bell jar using a vacuum pump operating at a pressure of 0.07bar. After 30minutes, the beaker was filled with water via a hose in the neck of the bell jar.

The vacuum pump was switched off and air was allowed to re-enter the system. The lumps of sample in the beaker were then left in the water for over 16 hours to ensure that all the pores became filled with water. After this period, the lumps were placed on a dry cloth and their surface was gently dried until no further moisture could be removed. They were then transferred to a second dry cloth and their weight recorded (Mass D). The cement stabilised lumps weighed **71.34 g,** whilst for lime the dried weight was **76.35 g**, for linseed oil the weight was **68.7 g**. The calcium chloride dissolved in the water.

The weight of the surface dried aggregates in water was also recorded (Mass E). The cement sample aggregate weighed **1.45g,** whilst the lime sample aggregate weighed **1.98g,** and the linseed sample aggregate weighed **2.34g.**

The porosity of the stabilised specimen (P) can be calculated, as a percentage of volume, from following equation:

$$P = \frac{MassD - MassC}{MassD - MassE} x100\%$$

According to above equation, the cement stabilised earth has porosity of **24.6%,** the lime stabilised earth specimen **22.3%** porosity and the linseed oil stabilised earth **26.27 %** porosity. Comparing this data to the porosity of other conventional construction materials, it can be stated that earth stabilised blocks exhibit adequate porosity for construction purposes.

It should be noted that the porosity test adopted is designed for use with fired bricks and concrete blocks, and different results might be obtained in tests specifically designed for earth stabilised blocks. Nonetheless, the test methodology adopted gives an indication of relative porosity using different additives. A more accurate test procedure is desirable because porosity can influence how water is transported through the structure of the brick/block unit. The structure of the pores dictates the movement of water through the material, hence affecting the material's resistance to freezing and thawing and the movement of harmful chemicals contained within absorbed water.

Porosity affects compressive strength, water absorption and permeability. (28) This is confirmed by the experimental results undertaken by the author, which show that porosity in earth stabilised specimens is correlated to water absorption and permeability and has an inverse relationship with compressive strength (see Figure 6.20).

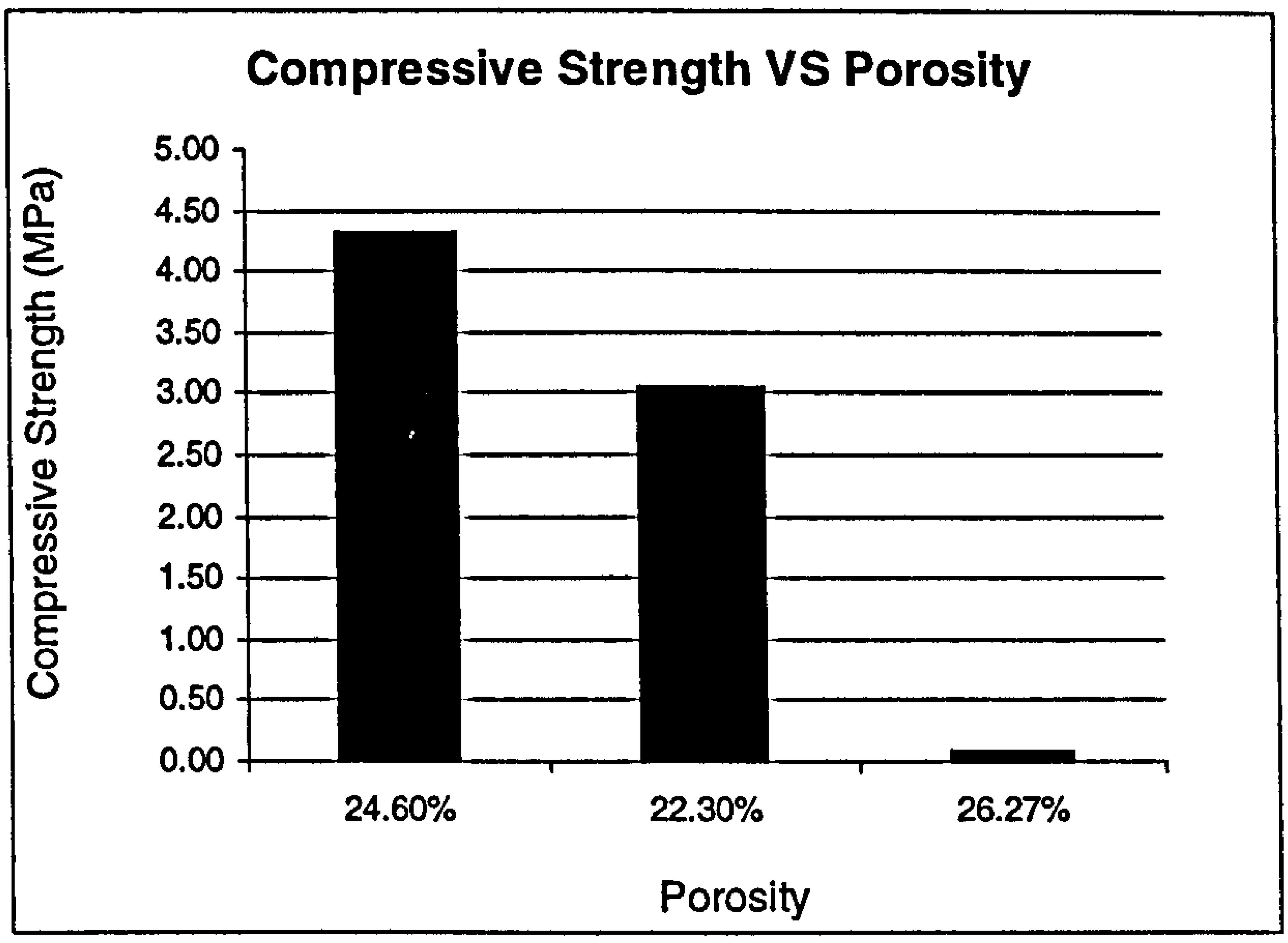

Figure 6.20 Compressive strength vs. porosity

Figure 6.21 shows that the durability and porosity of the stabilised earth vary according to the type of additive. The different ways in which the additives react with clay particles leads to distinctive improvements to engineering properties of the raw material. It was not possible from the test results to identify a correlation between durability and porosity.

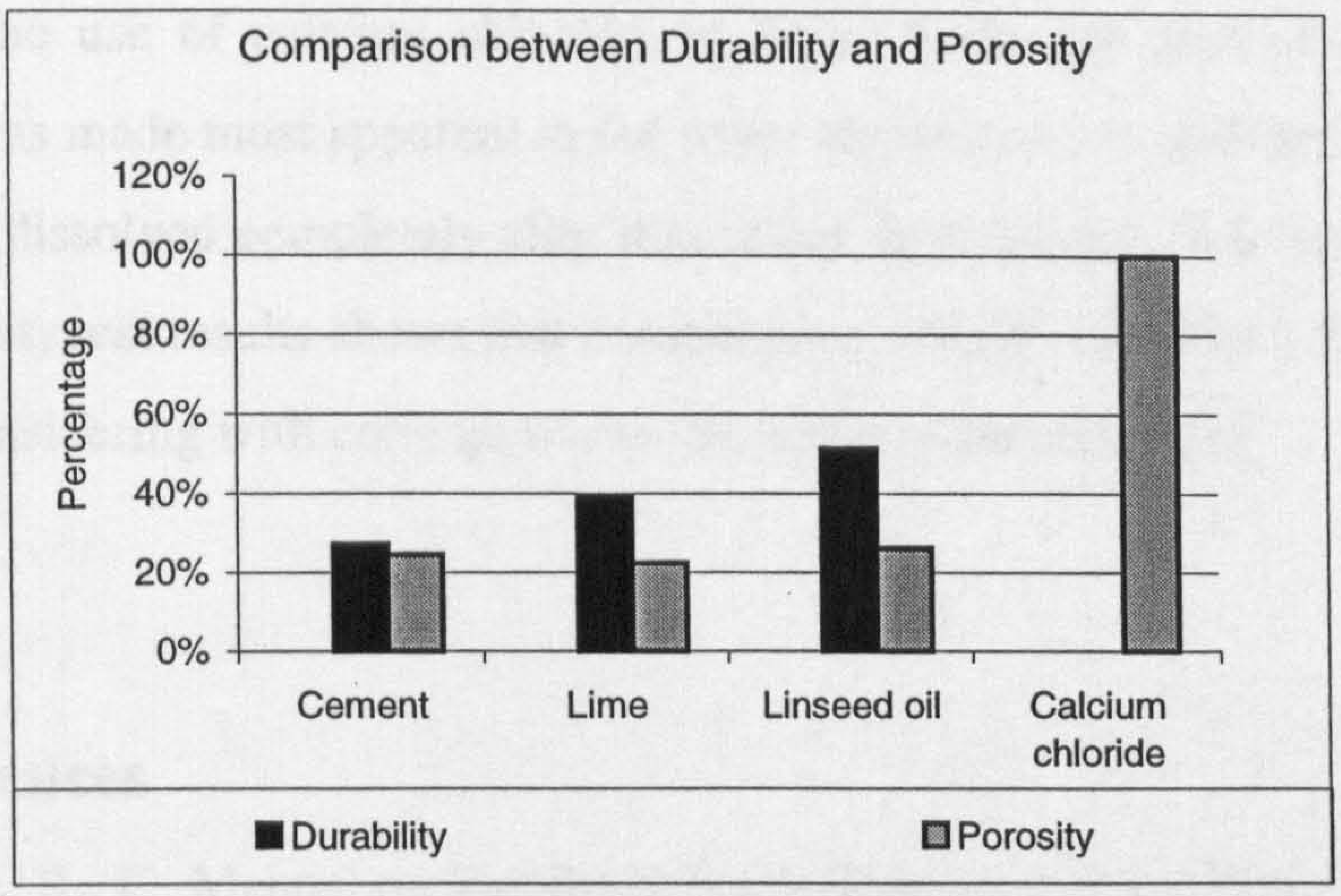

Figure 6.21 Comparison between durability and porosity

6.5 Summary

The imported earth was corrected for particles size distribution using 30% well-graded sand and then stabilised with the following: cement, lime, linseed oil or calcium chloride. The choice of stabiliser was made according to local availability, low cost and suitability of the stabiliser for use with the raw material. The amount of stabiliser added was based on the linear shrinkage tests, with reference to BRE and Kenya guidelines.

The earth stabilised specimens were cured at temperatures that reflect the climate in Sindh. The specimens were tested for compressive strength and water absorption characteristics. In the compressive strength test, a loading at the rate of 1 KN per minute was applied All specimens showed adequate strength with reference to Kenya specifications. Cement and lime gave the highest readings. The compressive strengths of the linseed oil stabilised earth specimens were also considered satisfactory for practical application of this stabiliser. It should also be noted that the corrected raw earth specimen showed adequate compressive strength for construction purposes.

Calcium chloride is not considered suitable for use as a stabiliser with clay-rich earth, although its use is strongly recommended in literature. The American Transport Board recommends the use of calcium chloride, in liquid form, for ground improvement. Its unsuitability was made most apparent in the water absorption test and durability test, where the specimens dissolved completely after immersion in water for 24 hours and 2nd cycle of test. The porosity test results shows that compressive strength between 2.5 MPa to 3 MPa is adequate to considering with corresponds to the porosity percentage of

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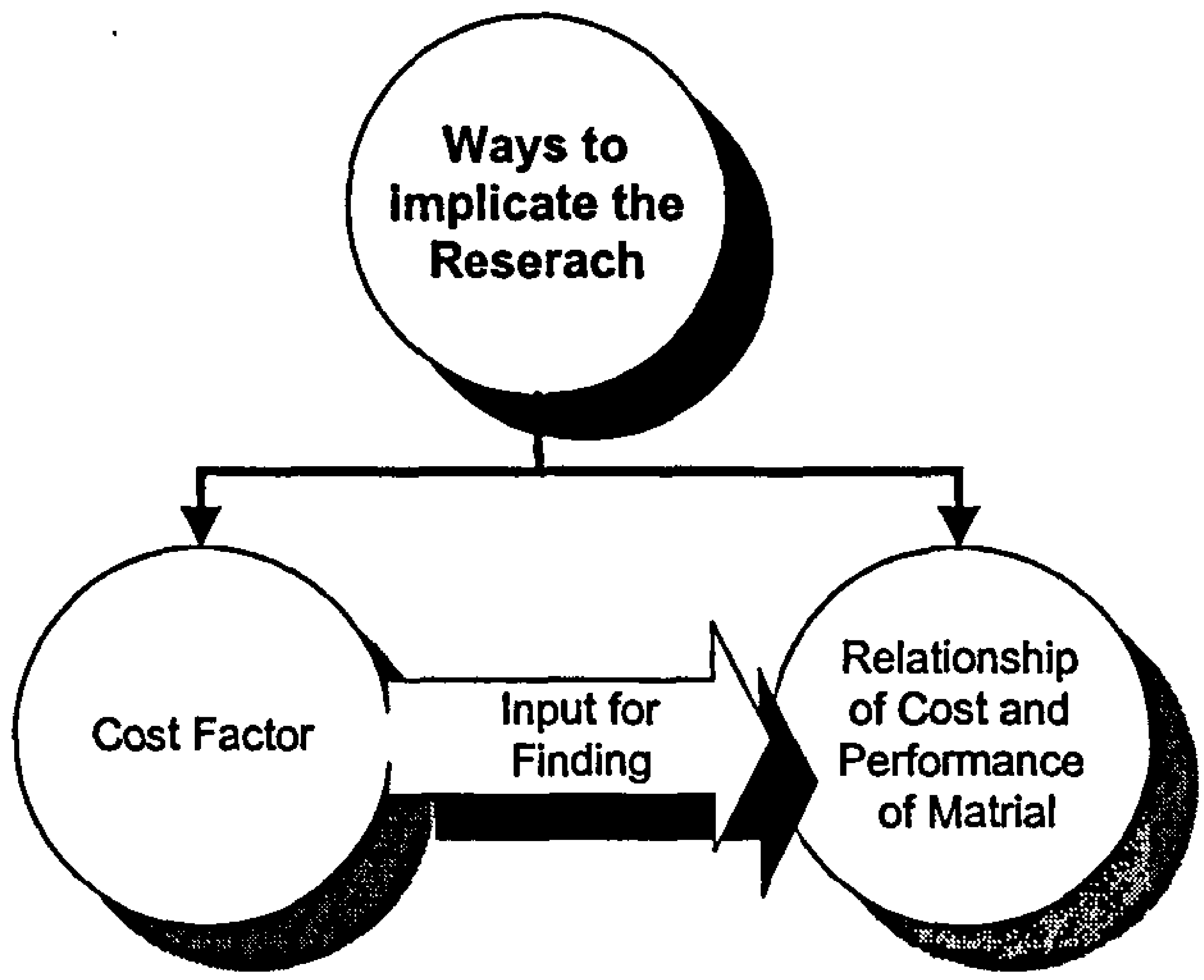

CHAPTER SEVEN

Cost Evaluation and Analysis of Results

Chapter Seven

Cost Evaluation and Analysis

7.1 Introduction

Of the four stabilisers investigated in this study, cement, lime and linseed oil provided significant improvements to the engineering properties of earth and were further evaluated. In this Chapter, the cost evaluation of these three stabilisers is discussed in the context of producing stabilised blocks for use in construction.

It is essential to cost the different options for construction materials before deciding which to use. It is good practice when undertaking construction projects to plan all aspects of the work in advance, including cost of materials, timely provision of funds and the necessary financial controls. This helps to ensure that projects are completed not on time and within budget.

A budget is a financial plan for a given period of time in which money is allocated for specific purposes, such as purchase of construction materials. All activities that are affected by resource supply, whether they are developmental, operational or maintenance require the allocation of a budget. Thus, budgets are set in all types of organisation, including government, and at all levels. Preparation of budgets within government departments, such as those responsible for housing, requires particular care. This is because the resources being allocated have a direct bearing not only on the provision of services, but also on people's overall quality of life.

In this chapter, the costs of cement, lime and linseed oil stabilisers are evaluated for the construction of a single 'model' house. Details of the full materials requirements for the house are also provided. An analysis of cost and performance of the stabilisers forms the basis for assessing the target hypothesis developed in Chapter 4. In other words, the suitability of the stabilisers for use in low-income housing in rural/urban Sindh is established.

7.2 Cost Evaluation

The cost of building materials and labour varies widely across Sindh province. Therefore, as this cost evaluation exercise is based on a 'model' house, it can be used as a template for materials costing in rural areas of Sindh, as well as for low cost housing in urban areas of the province. Cost calculations are based on the rates of materials and labour prevailing at Sindh in April 1998.

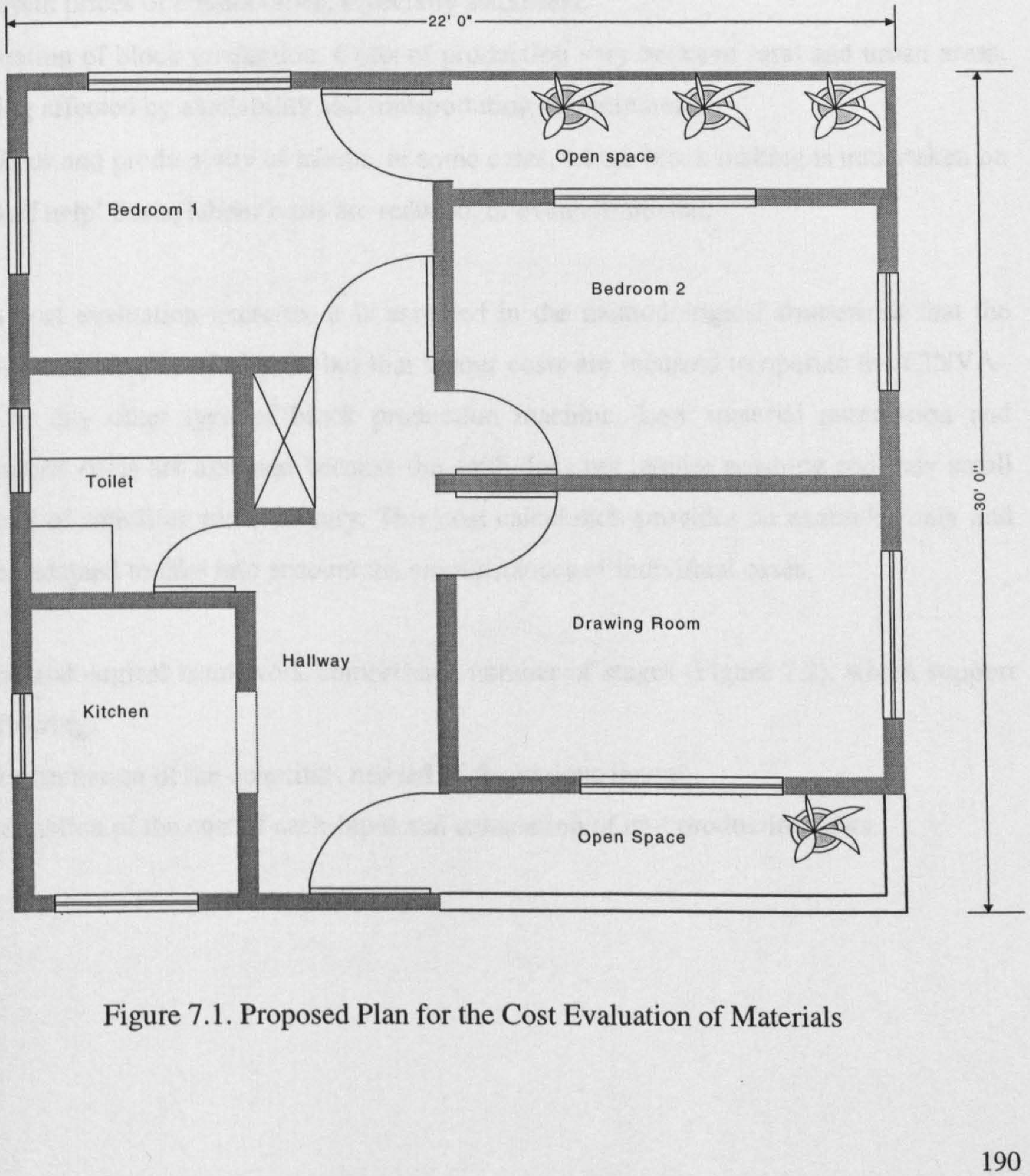

Figure 7.1. Proposed Plan for the Cost Evaluation of Materials

The specification of the model house, which includes a plinth area of 80 yds^2, is shown in Figure 7.1. This specification that will provides the basis for costing comparable buildings proposed for rural Sindh, where the earth samples used in this study originated.

The cost of earth stabilised blocks varies according to local circumstances, such as:

- Availability of earth.
- Suitability of the earth for stabilisation. This determines the type, quality and quantity of stabiliser required. It may also be necessary to buy sand to correct particle size distribution.
- Current prices of commodities, especially stabilisers.
- Location of block production. Costs of production vary between rural and urban areas, being affected by availability and transportation of equipment.
- Labour and productivity of labour. In some cases, where block making is undertaken on a 'self help' basis, labour costs are reduced, or even eliminated.

In this cost evaluation exercise, it is assumed in the methodological framework that the earth is available free of charge, but that labour costs are incurred to operate the CINVA–RAM or any other type of block production machine. Low material preparation and stabilisation costs are assumed because the earth does not require crushing and only small additions of stabiliser are necessary. This cost calculation provides an examplar only and must be adapted to take into account the circumstances of individual cases.

The methodological framework comprises a number of stages (Figure 7.2), which support the following:

(a) Determination of the quantities needed of the various inputs.

(b) Estimation of the cost of each-input and calculation of unit production costs.

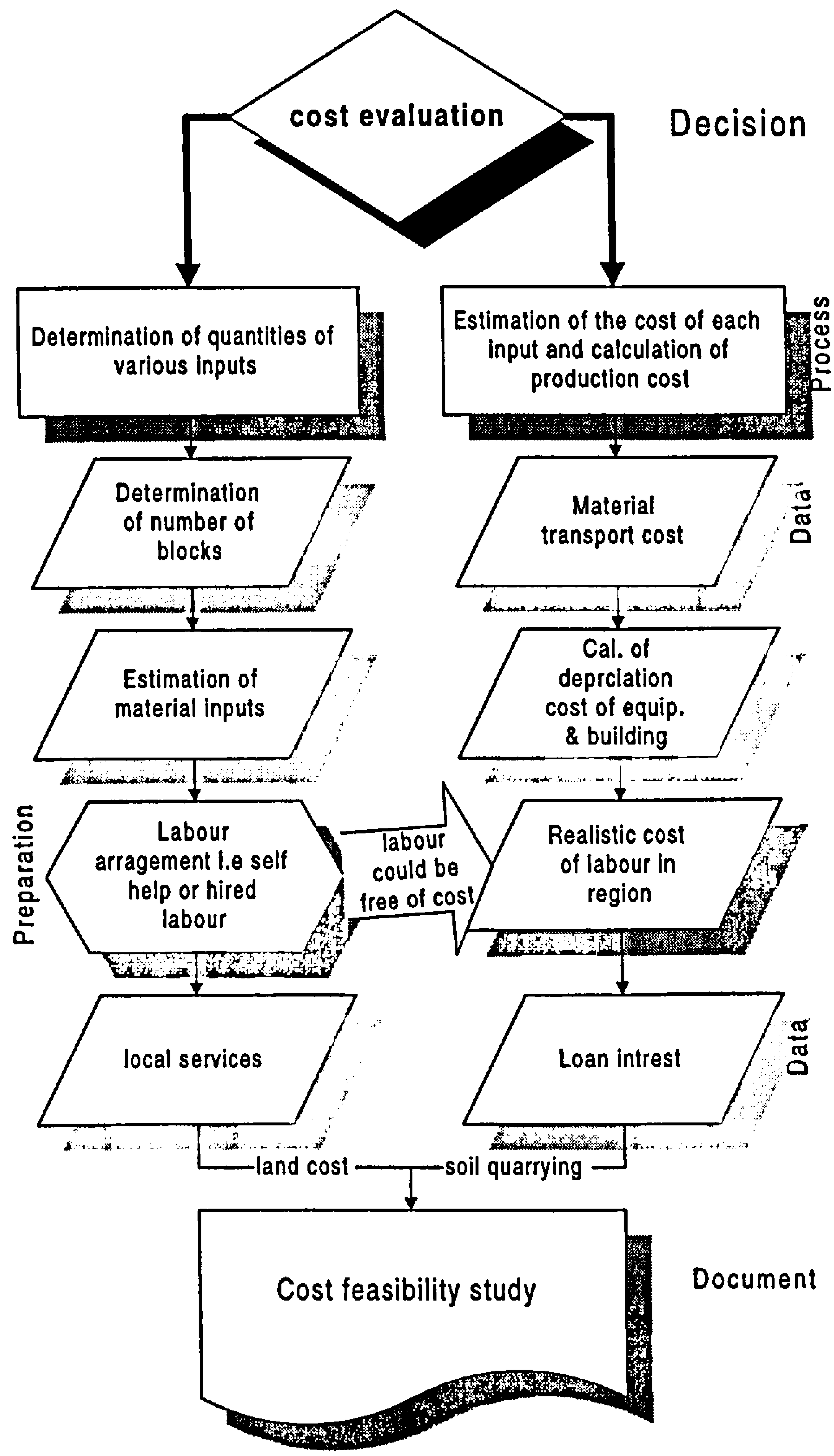

Figure 7.2. The Stages of the Cost Evaluation Process.

The activities carried out at the various stages of the cost evaluation process are described below:

(i) Determination of the quantity of materials needed.

(ii) Estimation of the number of earth stabilised blocks needed.

The number of blocks required to construct the building is established. In this study, the number of blocks needed for a two-bedroom house covering an area of 80yds^2 was determined in Table 7.1., based on the plan shown in Figure 7.1.

Table 7.1 Quantities of materials proposed for 80-sq. yard plan

S. No.	Item	Description	Unit	Quantity	Cement/Lime/Linseed oil (Bag)	Sand Cft.
1	Excavation	1.5' x 2'	Cuft.	590.00	-	-
2	Foundation	3% cement soil Mix	Cuft.	590.00	19.25	-
3	Plinth	a.6%Blocks b.1:8 mortar	No. Cuft	2360.00 119.00	16.00 11.00	- 106.00
4	D.P.C.	1:2:3concrete	Sft	197.00	5.60	14.00
5	Super Structure.	a.5% Cement soil block/6%Lime/7% Linseed oil b.1:8 Cement soil mortar	No Cuft	5523.00 212.40	37/44/ 51.8 19.50/26.50/	188.00
6	Roof Slab	a.Rectangular beams b. RBC tiles (39"x20") c. Roof screed	Rft No Sft	111.00 91.00 510.00	3.00/4/5 2.71/3.712.70/13 .70 3.8/4.8	13.43 10.84 91.00 6.96
7	Lintel	a. Precast-RCC-frame b. Ferro-cement lintel and sun shade	Rft No	174.00 6.00	3.48 2.16	6.96 8.16
8	Doors & windows shutter	a. Ferro-cement b. C.C Jali c. Ferro cement o/h d. U/G block masonry tank	Sft Sft Lit Lit	149.0 - 450.00 5000.00	3.50 - 1.00 13.50	8.70 - 2.90 112.00
10	Flooring	i. Soil layer 1.5ft ii. 3%CSI 4" thick 1:8 cs2 2"thick	Sft Sft. Sft	436.00 436.00 440.00	- 4.73 10.60	- - 103.00
11	Plaster	i. 5%CSI Mortar ii. 1:5CS2 Mortar on	Sft.	2968.00	8.80	-

		ceiling	Sft.	436.00	3.80	23.00
12	Painting	i. Lime wash ii. Enamel Paint on Door & window	Sft. Sft.	3400.00 480.00		
13	Manhole Cover	Ferro cement	No.	1.00	.08	.35

Soil (C.ft.)	Gravel C.ft.	Wire Mesh(s.ft)	Steel(kg)	Bindingwire(kg)	Polythene sheet	Roofing blocks
-	-	-	-	-	-	-
1100.0	-	-	-	-	-	-
544.00						
	21.00				266.00	
935.00						
	13.43		51.00 44.70	1.11		444.00
		106.02 341.00	21.72 53.00	0.12 -		
	- - - 16.00	341.00 - 104.00 -	53.00 - 8.25 17.00	- - 0.04 0.05		
1200.0 197.00 -						
181.00 -						
	-	.64	1.00	0.01		

This plan was developed in accordance with the standard requirements of low cost housing schemes in Sindh. The needs of local people, particularly in terms of adequate ventilation and privacy, are met by this house design. However, it is recognised that, in practice, it may not be possible to build houses to this specification initially. Therefore an 'incremental approach' to construction is recommended to solve shelter problems as rapidly as possible.

(iii) Estimation of the quantity of material inputs needed

The quantity of material inputs required for the selected scale of production is estimated. The estimations for the 'model' house are shown in Table 7.2. The principle materials considered were earth, sand (to correct particle size distribution) in earth with high linear shrinkage), stabiliser, water and oil. In this example, engine oil is used as a mould release agent.

Table 7.2. The Recommended Percentages of Stabiliser and Other Materials.

Foundation	Earth stabilised with 3 % cement or 4% lime.
Plinth	Earth stabilised block masonry with 6% cement, 7% lime or 3% linseed oil.
Super structure	Earth stabilised block masonry with 6% cement, 7% lime or 3% linseed oil.
Plaster on the wall	It is recommended that the same percentage of stabiliser used for block production is mixed in the plaster.
Plaster on the ceiling	1 part cement: 5 parts sand.
Roofing	Pre cast beams/battens and earth stabilised blocks in the case of flat roofing.
Door and Windows	R.C.C frames, wooden shutters, ferro-cement sunshades and lintels.
Manhole Cover	Ferro-cement.
Overhead water tank	Ferro-cement.
Underground water tank	Ferro-cement.

(IV) List of equipment required

The list of requirements includes equipment for digging, moving earth, crushing or sieving earth, mixing, moulding blocks and, possibly, facilities to cover blocks whilst curing. Facilities should also be available for earth testing and investigation. The equipment requirements for construction of the 'model' house are shown in Table 7.3.

Table 7.3 Equipment Required for Earth Block Production and Other Aspects of Construction

Earth stabilised foundation.	Manual/Mechanical Compactor.
Earth stabilised blocks.	CINVA-RAM or other type of block production machine.
R.C.C door and window frame work.	Manual wooden/steel mould.
R.C.C. battens.	Nil.
Ferro-cement sunshade/lintel.	Nil.
Overhead water tank.	Tools of the trade for masons carpenter workers etc.
Others.	

(iv) List of labour requirements

The productivity of the labour force may vary not only from one country to other, but also from one site to another site within the same country. Therefore, it is necessary to specify the length of the working day, the number of days worked per week and the number of working weeks per year. These specifications must always take into account projections for leave of absence, such as sick leave, and must also comply with conditions agreed between unions and employers etc. The level of skill requirement should also be specified.

(v) Local services

Other local services and facilities may be required, such as:

- Land for quarrying earth;
- Land for storing raw materials;
- Land for block production;
- Land for curing of blocks;
- Provision of access to working area for delivery of materials and dispatch of products.

(vi) Estimation of capital requirement

The funds required for the purchase of equipment and land must be itemised. It is essential that sufficient financial resources are available for purchase of raw materials and payment of wages in the first month of the project, since there will be no income from the sale of blocks until they have been made and cured. If difficulties are anticipated in the procurement of any particular materials, it is recommended that sufficient stocks of those materials be maintained to meet more than one month's demand.

The cost of the materials identified in stage (ii) - clay, sand and water - must be calculated. Clay, sand and water are low cost commodity materials and, often, extraction and transport costs are the largest components of their total cost. The mould release agent is not needed in large quantities and so is relatively inexpensive. Used engine oil can be purchased at a low price, or even obtained free of charge, because it is a waste product. In the latter case, costs will be limited to the transportation of the oil to the project site.

Annual depreciation costs for equipment and buildings must be calculated. All equipment, of whatever type and application, has a limited useful life and will depreciate in value.

7.3 Space Requirements

In terms of the planning, design, lighting and ventilation systems, the design specifications of the model house meet the stipulations of the governing authorities in Pakistan. The design specifications adopted are shown in Table 7.4

Table 7.4 Design Specifications for the Model House

Plot Area	**24' x 30' (Code requirement)**	**80 yds^2 (proposed house)**
Covered area	540 sq. ft.	510 sq. ft.
Open area	180 sq. ft.	210 sq. ft.
Width of room	8.2 ft.	9.00 ft
Kitchen width	4.92 ft.	5.00 ft
Combined WC & bathroom	-	-
Latrine & WC width	3.28 ft.	3.50 ft
Bath room width	3.28	3.50 ft
Latrine & WC. Area	12.91	17.81 ft
Bath room	15.06	17.81 ft
Clear Height	9.18	10.00 ft
Lightning &Ventilation All rooms	10 % of floor area	10 %

In order to solve the immediate problem of a lack of shelter in Sindh, an incremental approach to the construction of houses is recommended. By designing houses suitable for construction on a modular basis, building work can proceed at a rate compatible with the amount of funds available. Thus, funding for full construction of a house does not need to be in place before building work can commence.

The incremental approach facilitates rapid owner occupation, with construction being completed whilst the owner is already living in part of the house. This approach is adopted by dividing the proposed house plinth in the following ways:

Incremental approach: Stage I Activities

1. Excavation	6. Roof Slab or Vault, Dome
2. Foundation	7. Lintel
3. Plinth	8. Door and window, Shutter
4. Damp proof course	9. Underground Tank
5. Super structure (I)	10. Boundary wall
a. Room	
b. Toilet	
c. Kitchen	
d. Living	

Incremental Approach: Stage II Activities

1. Super structure (II)	5. Overhead Tank
a. Room 2	6. Flooring
b. Drawing Room	7. Plaster and painting
2. Roof slab	8. Sanitary and water supply
3. Lintel	9. Electrification
4. Door and windows, shutters	10. Main gate

7.4 Specification of the Stabiliser and Construction

7.4.1 Earth stabilisation

As discussed in Section 7.2, the addition of water and 5-6% cement, 6-7% lime or 6-7% linseed oil provides satisfactorily results for stabilisation of the imported earth. The following procedure was adopted to calculate cost of materials for the model house:

A. Specification of materials

- Cement

  Portland Cement
- Lime

  Hydrated or locally available lime may be used to stabilise clay-rich earth.
- Raw linseed oil

  Locally available linseed oil.
- Sand

  Use is optional, based on the need for correction of the earth's particle size distribution. This can be analysed using the field tests described in Chapter 5.
- Water

  Must be portable.

B. Calculating the amount of materials

- Sand (by volume of earth): 20% to 30%
- Cement (by volume of earth)/Lime: 5% / 6%
- Optimum Moisture (by volume of earth+sand+cement): 10%
- Linseed oil: 50% of the OMC

N.B. The earth classification chart described in Chapter 5 can be used to determine the percentage of stabiliser to be added.

C. The proposed dimensions of the stabilised blocks

The proposed dimensions for the blocks (Figure 7.4) of the model house are:

- Length: 11½ inches
- Width: 5½ inches
- Height: 3 inches

Figure 7.3. The Proposed Block Size for the Model House

Based on the specifications of the plinth and superstructure of the model house, it was estimated that the compacted volume of the materials would be $1105ft^3$. The CINVA-RAM and other similar compaction machines compress earth to between 50% and 60% of original volume. The quantity and cost of materials required for a plinth area of $80yds^2$ are shown in Table 7.5.

Table 7.5. The Costs of the Proposed Earth Stabilised Blocks

Material	Quantity	Cost per Total Requirement of Blocks
Cement(stabiliser)	58 bags	250 Rs./bag =14500Rs.= £207.50
Lime(stabiliser)	68 bags	111Rs./bag = 7548 Rs.=£107.80
Linseed oil (stab.)	859.25 litres	11Rs./Litre= 4296 Rs.=£61.37
Sand (optional)	120 bags(approx.)	Could be available free of charge
Water	3437 litres	Available free of charge, excl. transport costs.

D. The block production process

A measured volume of earth is spread onto the 'mixing base' in a layer not deeper than 4 inches thick. (1) Sand is sprinkled uniformly over this layer and then mixed thoroughly with the earth. Next, measured amounts of water and stabiliser are blended with the earth-sand mixture until a uniform distribution is achieved. The mould or 'CINVA-RAM machine box is then filled to the top with stabilised earth and the material is compacted. The process of block production (Figure 7.5) is completed by demoulding the block and taking it to a drying area, where it is cured for at least 14-28 days. (1) In the case of lime stabilised blocks, the recommended curing period is longer. In this study it can be assumed the lime stabilised earth can be preparatory cured for 28 days but as this material gains strength in months or may be years. So material is ready for use after preliminarily curing period.

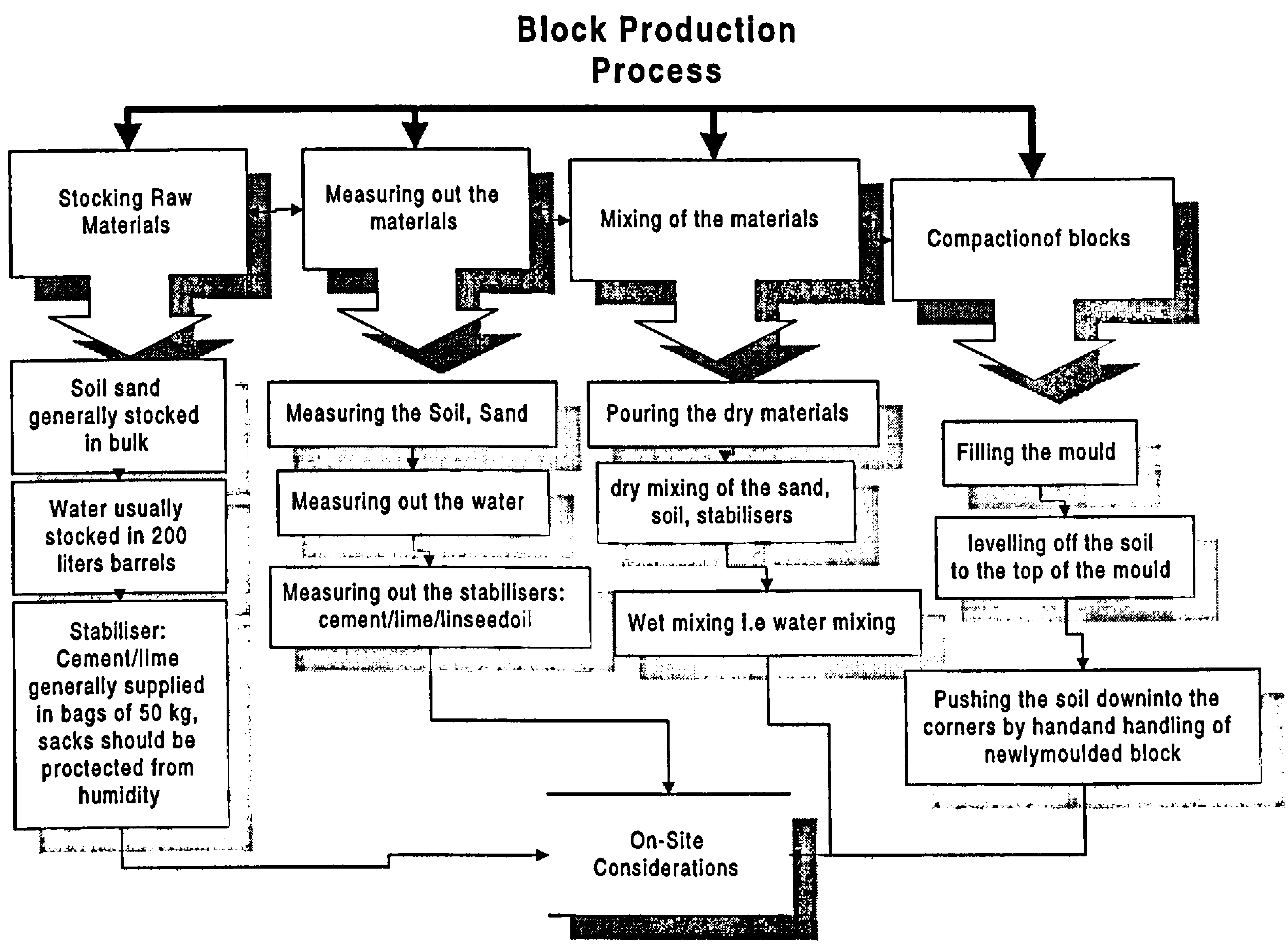

Figure 7.4. Block Production Process

Linseed oil stabilised blocks also require an extended curing period and may, in fact, gain in strength when in place as part of a building's infrastructure. Tests on linseed oil stabilised blocks demonstrate that this stabiliser is a good waterproof agent, but is unsuitable for roofing purposes or for using in underground water tanks.

E. Calculating how much stabiliser to use

Stabilisation calculation always refers to the weight of dry materials. The proportion of stabiliser used corresponds to the percentage by weight of the stabiliser compared with weight of the earth. For this purposes the density of material, which is being used in mix, should be know. (2)

F. Overall House Cost of the Proposed House

In this study, the target investigation is conducted to determine the cost effectiveness of earth stabilised blocks. The overall cost of the proposed house, using appropriate construction materials, has been calculated in order to establish the overall cost implications of using a particular additive to stabilise the earth. The cost of materials used in the calculations is based on 1998 prices.

Types of Blocks used	Overall Cost of the proposed House
Cement Stabilised Blocks	80000 Rs. £1000
Linseed Oil Stabilised Blocks	65000 Rs £812
Lime Stabilised Blocks	70000 Rs 875

It should be noted the cost of proposed house with conventional material would cost more than £2000 or 160000 Thousand Rupees.

7.5 Relationship Between the Cost and Performance of Stabilisers

It ca be seen from Table 7.5 that cement is the most expensive stabilising option considered for use in low-income housing in this study. The other three stabilisers investigated are lower cost options, and are deemed more cost effective in terms of regional requirements.

Figure 7.6 provides a graphical comparison of the cost and performance characteristics of the proposed stabilisers relative to each other.

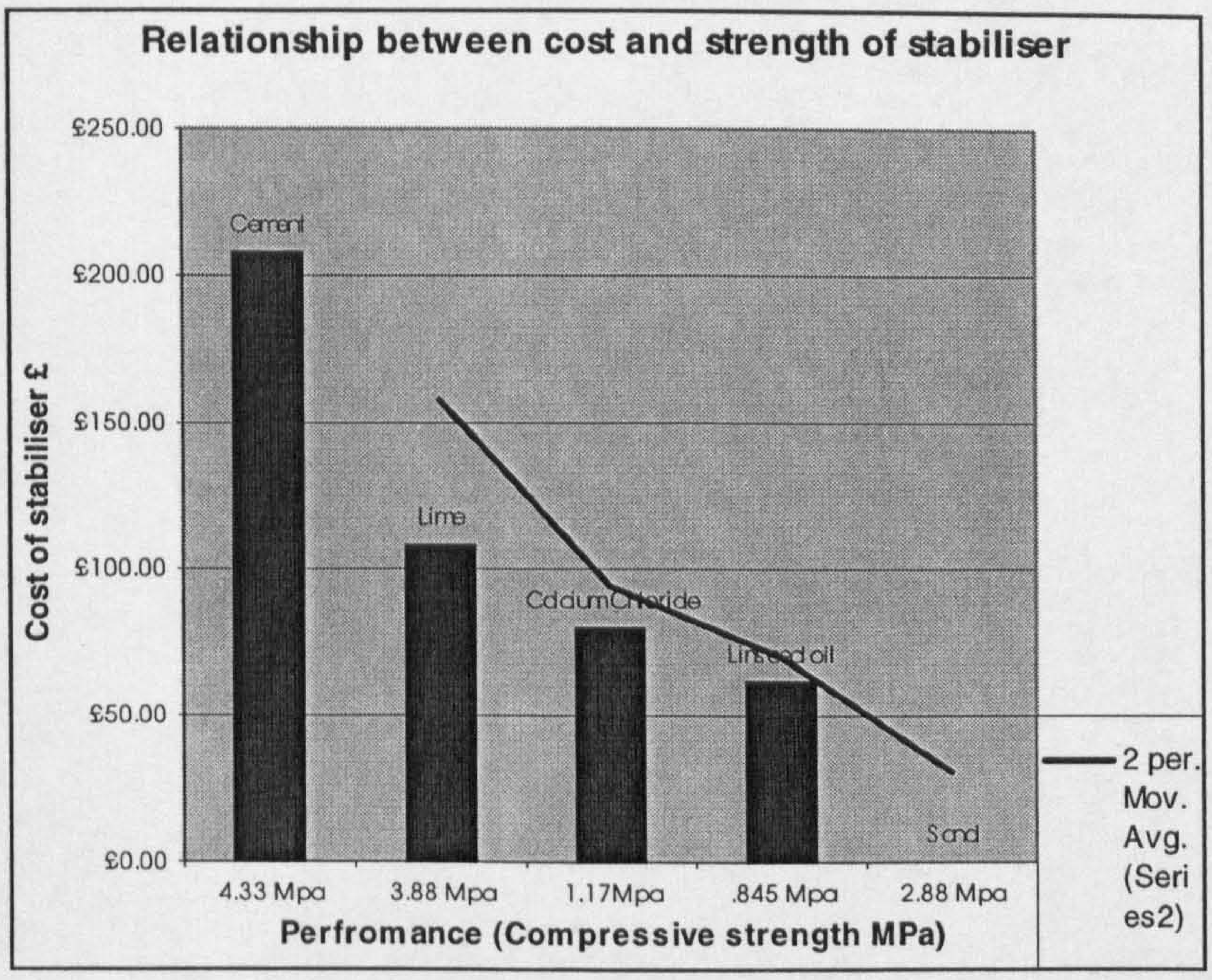

Figure 7.5. Cost and Performance Characteristics of Stabilised Earth

In Figure 7.5, the performance of the stabilisers was measured in terms of the compressive strengths of the test specimens. Water absorption values of the test specimens were also considered important indicators of performance (Figure 7.6). During the water absorption tests, it was found that calcium chloride, although a low cost additive is unsuitable for use in wet regions. Linseed oil performed well in the water absorption test, but was found to have low compressive strength relative to the other stabilisers under investigation. Figure 7.7 shows the porosity of stabilisers and their comparative cost. In this analysis of porosity and cost, lime shows to impart adequate requirements of material. Figure 7.8 shows the durability verses cost of stabilisers. This analysis guides that durability and cost is directly proportional to each other in this case of study.

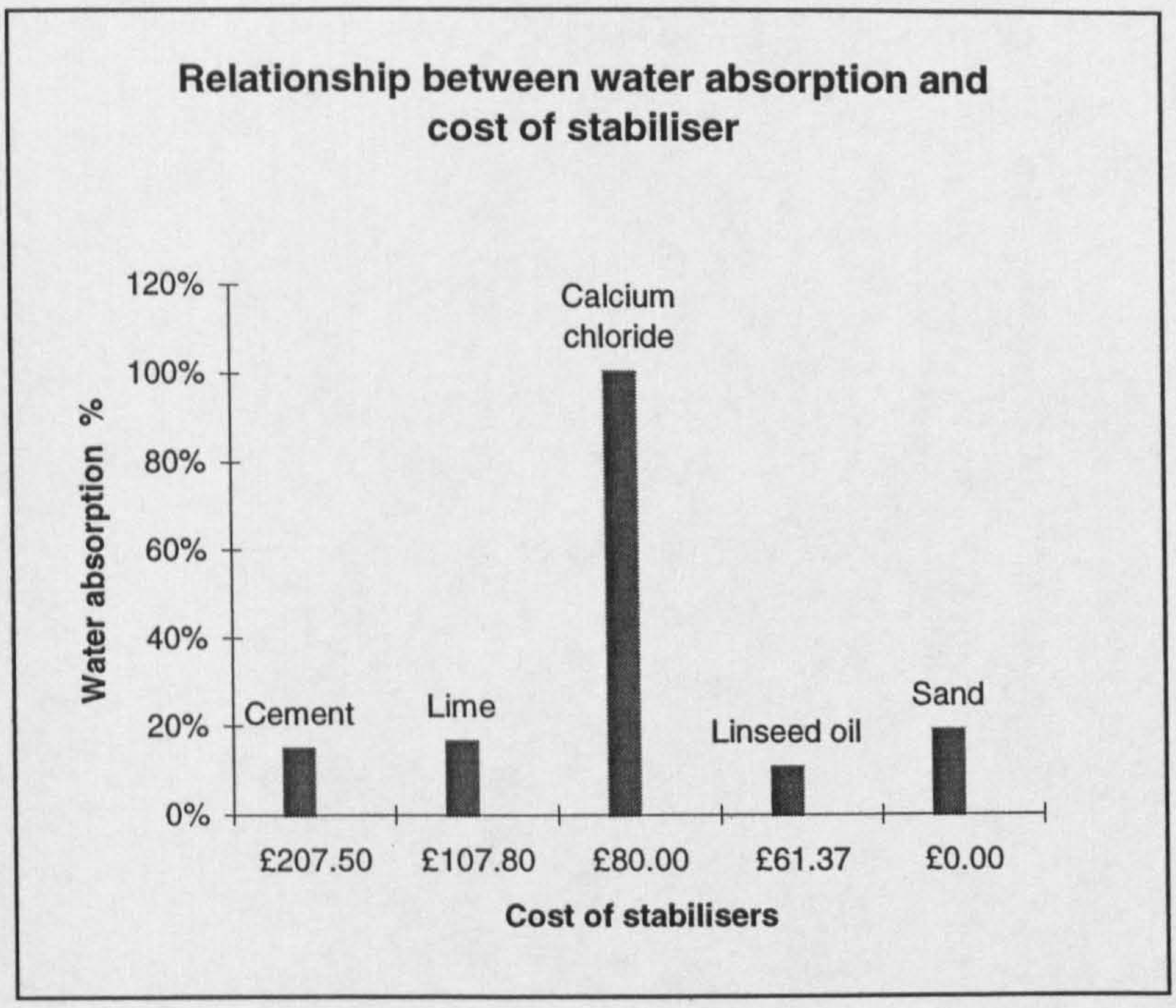

Figure 7.6. Relationship between Cost and Water Absorption for the Test Specimens

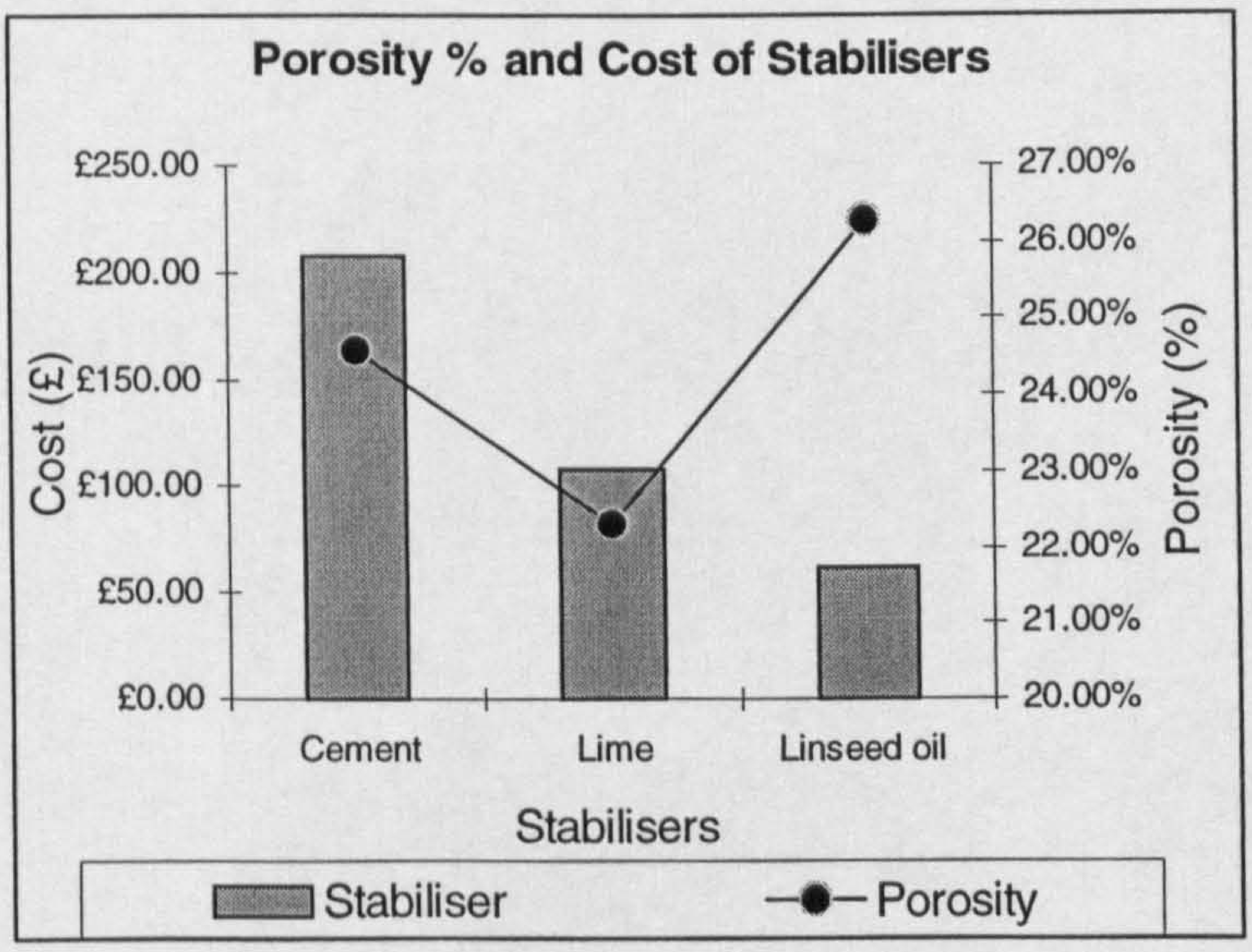

Figure 7.7 Porosity and cost of stabilisers

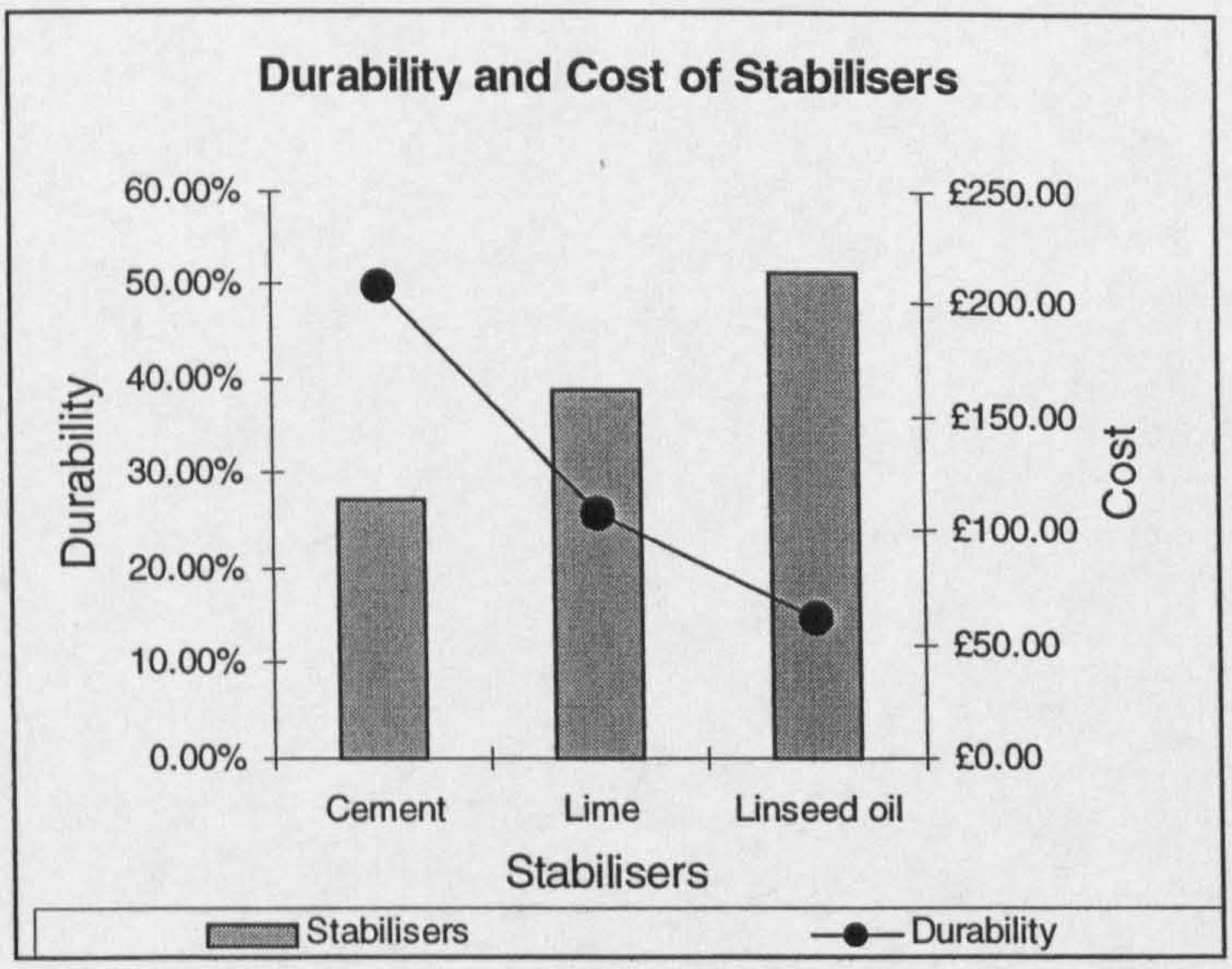

Figure 7.8 Durability and cost of stabilisers

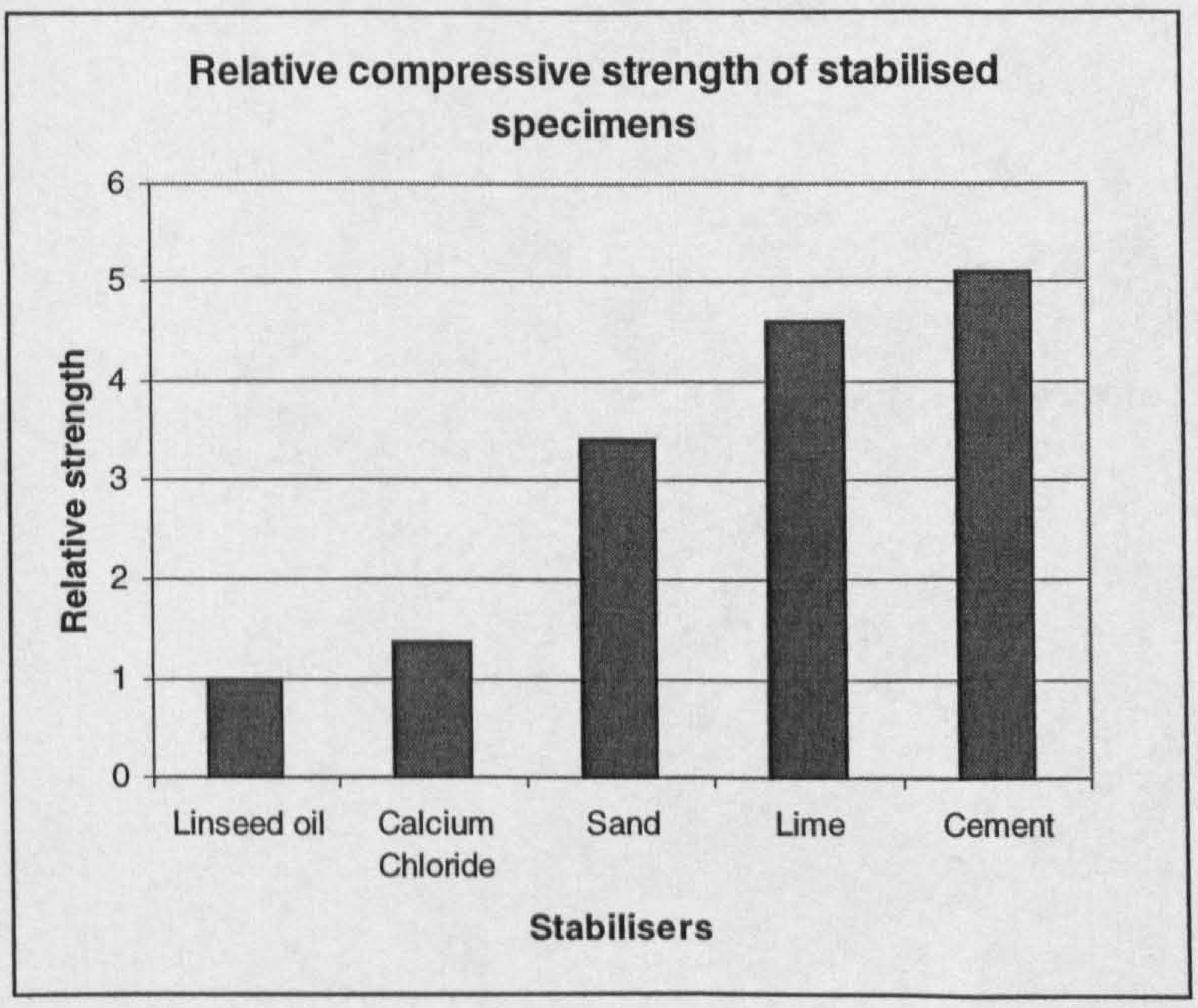

Figure 7.9. Relative Compressive Strengths of the Stabilised Earth Specimens

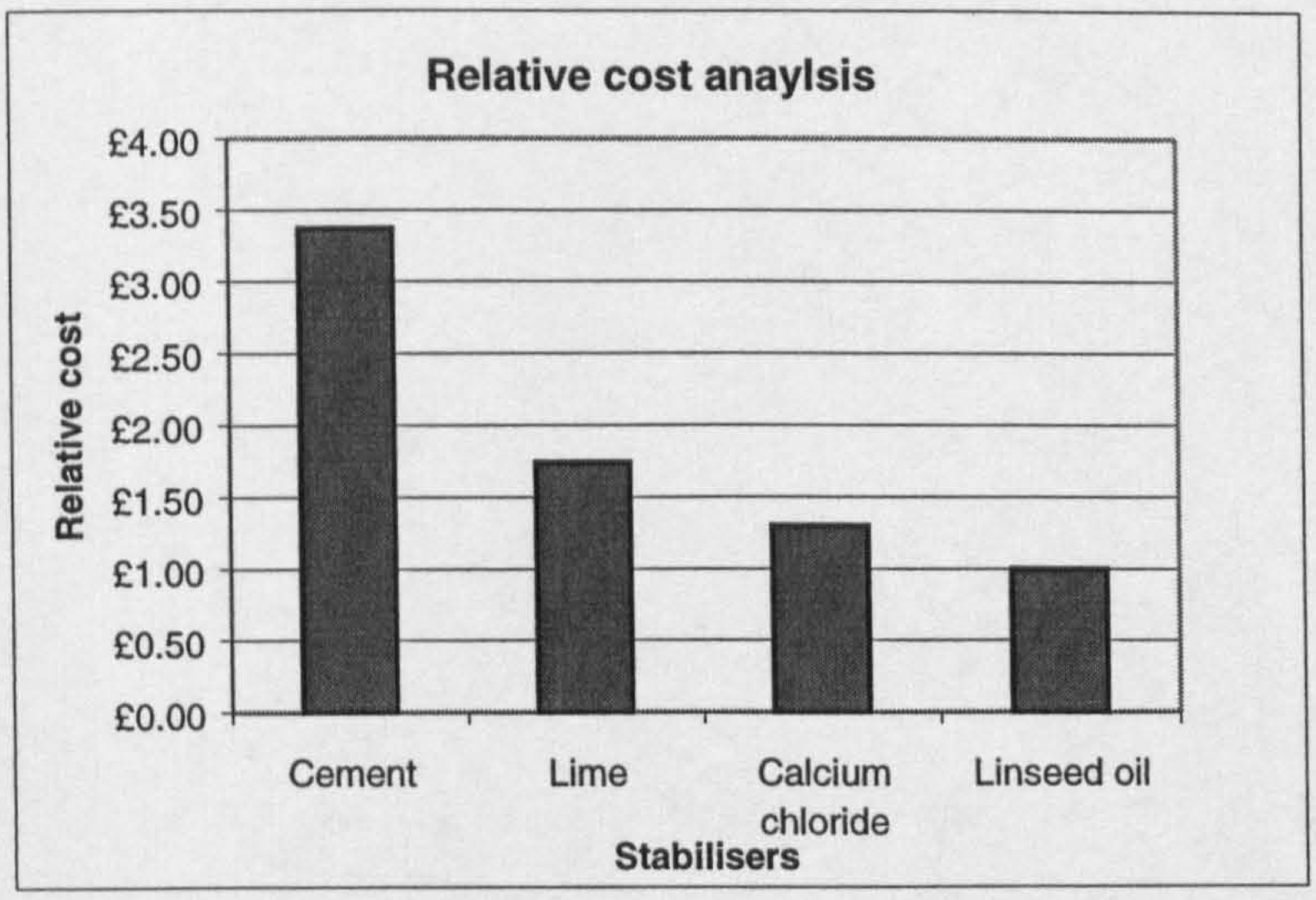

Figure 7.10. Relative Costs of the Proposed Stabilisers for the 80yds^2 Plot.

Figures 7.9 and 7.10 show relative performance of the proposed stabilisers in terms of compressive strength and cost respectively. It can be seen that, for the stabilisers under investigation, higher compressive strengths are imparted by the more expensive additives.

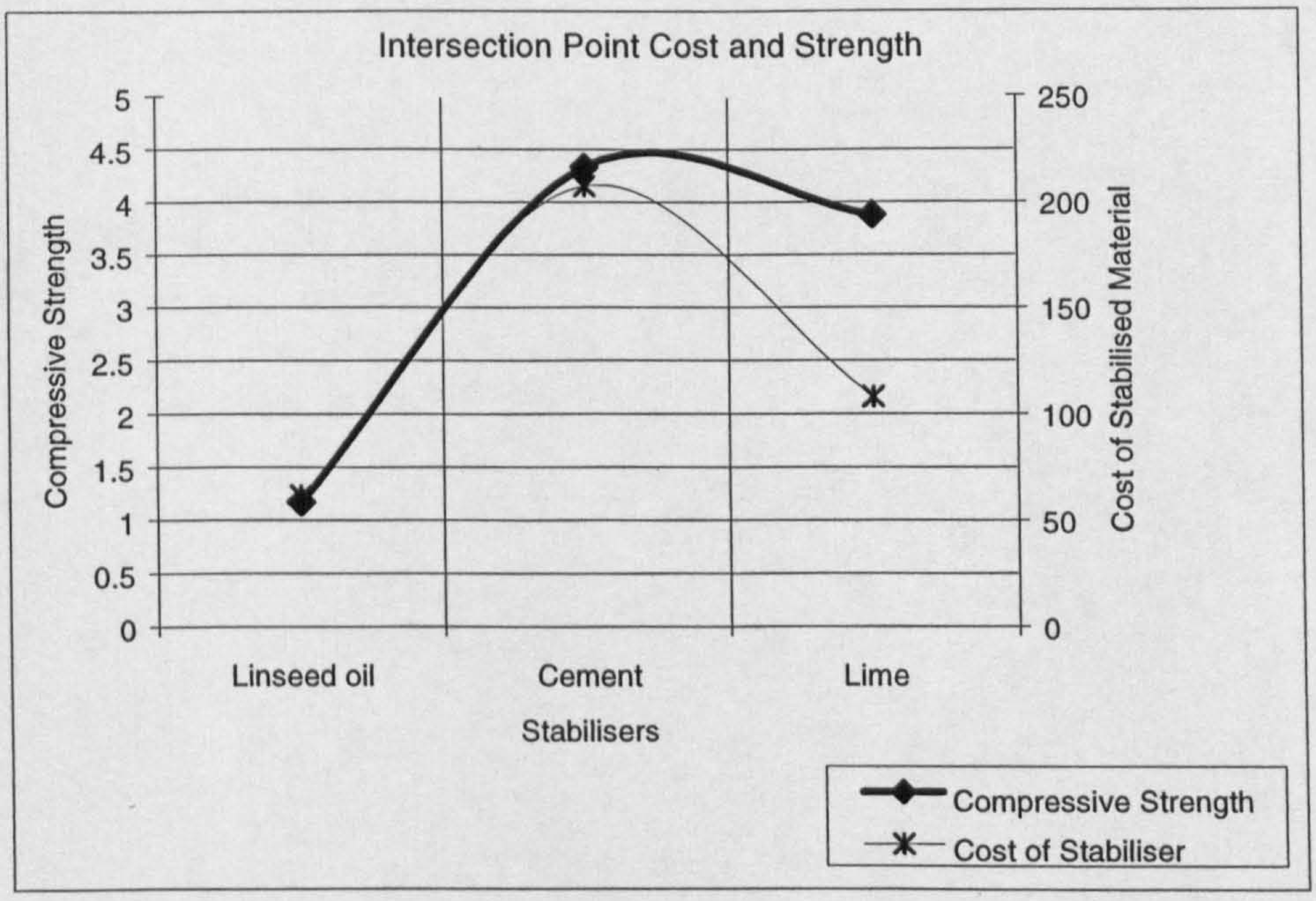

Figure 7.11 Optimum intersection point between cost and strength of material

It can be observed from Figure 7.11. a intersection point can be considered a guidelines for cost and strength. This optimum intersection point will helps researcher to choose the optimum strength on the required optimum cost and vice versa.

7.6 Life Cycle Estimation

As it can be observed from above discussion that is analysing the practice of cost for earth stabilised masonry including the initial material and energy content. But its is also necessary to investigate the process of estimating the life cycle costs of building. Various researchers have described that life cycle of building is considered under three factors: (5)

- **Primarily cost of building:** material cost and energy consumption cost which includes such as transport, design cost, assembly cost, speed of construction, waste, liability costs. This factor has been tried to analyse previously in this chapter.
- **Design life of building:** Design life of different applications, assessing the service life of a masonry building, obsolescence, appearance, cost of building over time.
- **Maintenance:** Appearance and durability, structural integrity, alteration and change of use, extensions, and internal appearance.

Some these factors are discussed as below:

7.6.1 Design Life

Design life for different applications

It is hard to find codes of practice for an explicit reference to the design life of any resultant structure. In the context of earth stabilised building still code of practice is under consideration by various experts. For reinforced concrete buildings a design life of 50y before major maintenance is required has been claimed when design is carried out to BS8110. (6) For Major highway structures a design life of 120 years is expected. In the case of masonry the historic design life for dwellings was 60 years but this was primarily derived from public sector funding requirements. Nevertheless the rates of new dwelling construction in many countries have meant that the effective life of a dwelling has to be 120years or more but not without major maintenance taking place there are some applications where the inherent robustness of masonry is not necessarily advantageous. For example, the average life of a manufacturing process may be 7 years after which major redesign or change is necessary and this tends to mitigate against masonry and in favour of lightweight short life building solutions.

Assessing the service life of a masonry building

An approach for forecasting the service life of a building has been developed by WG9 of ISO/TC59/SC3. (7) The objective of forecasting the service life of a building is to determine whether it is sufficient given the required design life. The same approach is equally applicable to components. The method suggested by the committee makes use of a variety of sources of data including recorded performance, measurement of degradation over time, comparison, feed back from practice and expert estimation. In addition test data may be used to derive a predication of service life.

It would be worth to mention here that author found that there is lack of many required data for assessing service life of earth stabilised building but effort can be made to understanding various other materials assessment process.

A factor method has been developed which includes factors, which allow for the following: material and components; design; site work; indoor environment; outdoor environment; operating characteristics; maintenance level.

The following example is taken from ISO/CD 15686 1 (7) to demonstrate how the approach is meant to work.

Example – Pressed steel lintel

The example concerns a typical lintel installed into a block cavity wall in a UK industrial environment. In addition to the external environment there is the risk of degradation/deterioration internally caused by condensation. Standards of workmanship, while not in accordance with best practice recommendations, are considered typical. The applicable features for the worked example are shown below. Detailed factors for steel lintels as described by ISO/TC59/SC3/WG9.

Estimated service life of steel lintel (ESLC) is given by:

ESLC = RSLCxAxBxCxDxFxG

Where

RSLC: The reference service life: Structural components, not accessible: value 60years.

A: Quality of the component: as lower qualities within BS 5977: Value 1.

B: Design of the structure: installed in block cavity wall with toe exposed and browning plaster and risk of condensation: value 0.8.

C: Workmanship: no repair of damaged coatings: value 1.

D: Internal environment: browning plaster and risk of condensation: value 0.8.

E: External environment: industrial pollution: value

F: In use condition: appropriate use only: value 1

G: Maintenance: none: value I

Thus: ESLC = 60 x 1 x 1 x 1 x 0.8 x 0.8 x 1 x 1 = 38.4 years.

Nothing in the specification provides a counterbalancing positive figure to the negative external and internal environment factor and therefore the predicted service life falls below the requirements, which is to match the RSLC, that is 60 years. Selection of an enhanced specification or closer control over site repairs may be required.

From above example it can be assumed that it is possible for earth stabilised masonry to predict its service life if once complete specification of this material will be developed.

Obsolescence

Earth's inherent good life span of masonry structure does lead to the need to recognise that during the life of the building obsolescence of a functional, economic or technical kind will occur. This inability to satisfy changing requirements may have more than one solution. For example, the requirement to save more energy could be achieved by changing to a more efficient boiler or heating system, enhancing the thermal resistively of the building fabric or by a more sophisticated control strategy.

Appearance

In earth building, there are number of situation in which the appearance of building is more effected then structural integrity. In Sindh facing, masonry units rarely deteriorate with age unless, for example, inappropriate selection leads to the weather damage in an exposed location. Where masonry is rendered or painted then regular maintenance will be required at around 10 years intervals depending of the building protects the finishes and prevents discoloration.

Cost of a building over time

As there is not any information available in the context of Sindh on cost of an earth stabilised masonry building over time. But some UK information is available on various masonry buildings. These figures suggest that in developed countries maintenance and refurbishment account for about 50% of spending on construction. This may amount to 3% of initial capital cost of the building.

7.6.2 Maintenance

Durability

In terms of earth stabilised masonry construction maintenance should be minimal. As this is one of the reason to undertake research to improve the durability of material used in construction. Most of the time maintenance required where selection of mortar is not used according to the requirement of material. Due to extreme weather, which is may not be possible to appear in the meteorological reports may also require maintenance. It can be assumed that maintenance is required in the interval of 7years to 20years. This is assumed on the basis of other masonry limitation of maintenance considering the earth stabilised material properties.

Structural Soundness

Structural failures are common in earth construction when material is not choosing carefully for construction. According the recent reporting form Indian earth construction society at Aurvilla, Rookree, and CRATerre-Eag, France that the most recent concern are have centred on components such as wall ties, lintels etc. It is important that the components that are to be used in earth construction are properly assessed for the impact of failure, ease of replacement etc.

Alteration, change of use and extension

Any kind of alteration and change in building which contains earth stabilised material as masonry is hard to alter or bring any major changes in building. But in acute need time the any removal of structural elements need to reassess the structural design, the removals of non load bearing elements, the enlargement of openings, change of floors and other loading.

Extension is easy to achieve in earth masonry buildings and this is one of the good examples of its sustainable properties. These extensions usually taken by occupiers own need during the building service life.

7.7 Summary

The cost evaluation of the stabilisers under investigation was discussed in this chapter. For the purposes of making a comparative assessment of the stabiliser, a model house with a plinth area of 80yds^2 was used as the basis for estimating material requirements. The quantities of material and stabilisers required for block production were also calculated. The material requirements are listed in Table 7.1. The costs of labour, water, earth and sand for block production were not included in the calculations because they vary between projects, i.e. some or all of these materials might be available free of charge.

The most appropriate specifications for stabilisers and earth stabilised blocks were established. The Kenyan earth stabilised block specification provided the basis for investigation. The block production process was described and a block size of 11½" x 5½" x 3" was proposed.

A comparative study of the relationship between cost and engineering properties was undertaken for the stabilisers. Cement showed good performance characteristics in terms of compressive strength and water absorption, but was the most expensive stabiliser under investigation. On the other hand, lime imparted reasonable compressive strength characteristics at lower cost than cement. These results must also be considered in the light of previous research findings, where lime has gained strength over time periods outside the scope of this study. Linseed oil provided the best waterproofing characteristics but imparts low compressive strength. However, it is a low cost additive. Calcium chloride is not considered suitable for the stabilisation of clay-rich earth because of its sensitivity to solubility in water. However, it is a low cost stabiliser that might have applications in arid regions.

In this chapter the author identified the means and ways to assess the life cycle of earth stabilised masonry building by discussing the examplar. Many aspects to developing a comprehensive approach to life cycle cost of earth stabilised masonry building are currently under investigation by various institutes e.g. South Wales University at Australia and Building Research Establishment, UK. The approaches being adopted need to be informed by the extensive base of research, testing and experience relating to the masonry which should be made readily available. Government policy and indeed international policy require a coherent response from the industry as a whole. It is important that all the very positive aspects that earth masonry construction offers are properly articulated and gaps in our knowledge filled.

7.8 References

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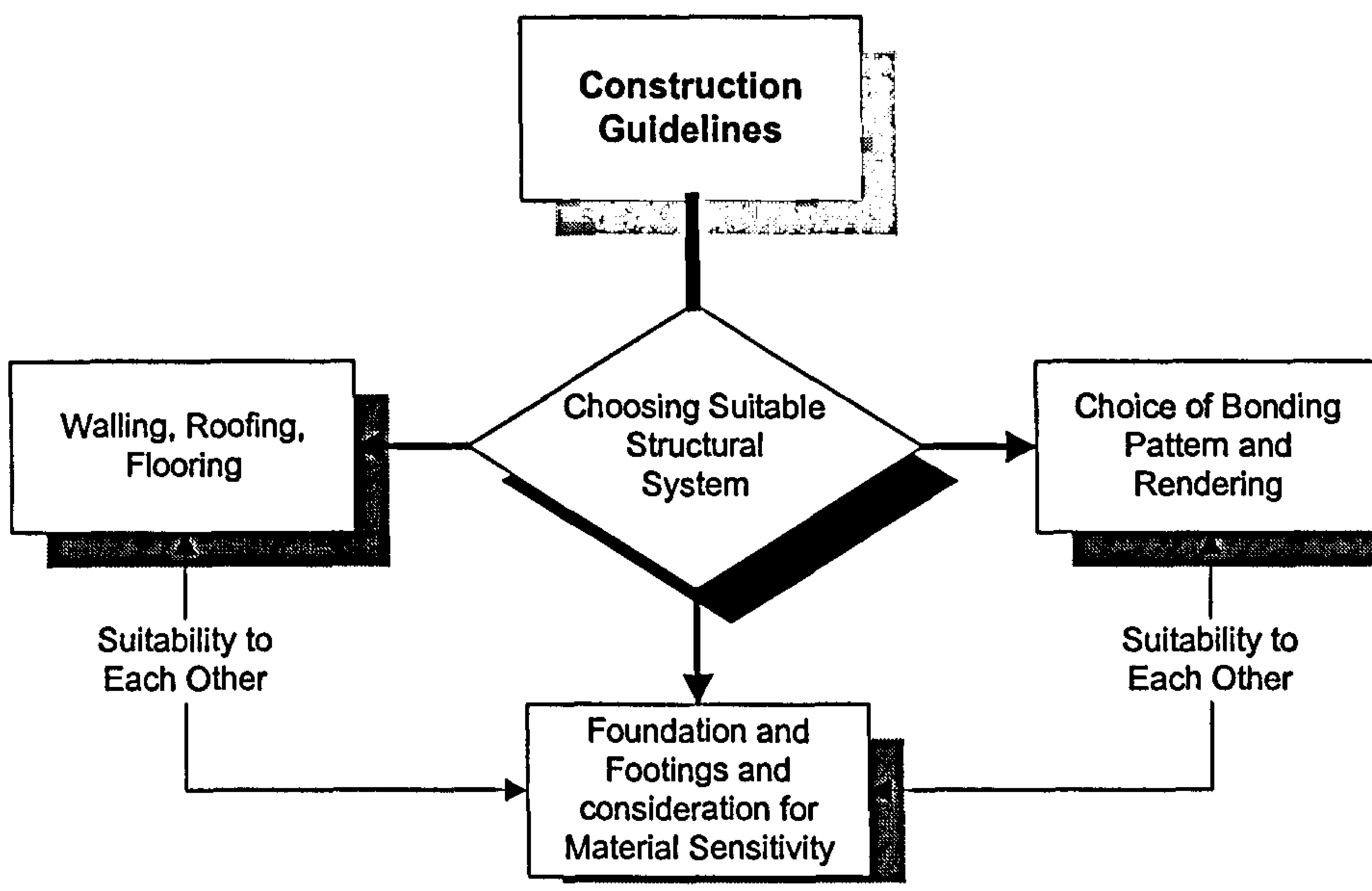


CHAPTER EIGHT

Construction Guidelines for Proposed Plan

Chapter Eight

Construction Guidelines for Proposed House

8.1 Introduction

It is important to select an appropriate structural design when using earth stabilised blocks as the construction material. For example, a well-designed building does not need external rendering and so money, time and energy expenditure can be reduced. For this study a proposed house plan was considered to choose the structural system and its design guidelines. Problems related to earth buildings, such as structural integrity and the effects of humidity, and precautions necessary to counter them are discussed in this chapter.

In order to develop an appropriate structural design using earth stabilised blocks, the relationship between the architectural techniques, structural principles and types of construction materials used are investigated. It should be noted that less expensive, non-stabilised blocks can be used in protected parts of the building. One of the major challenges of earth construction is to limit the damaging action of water.

8.2 Choice of Structural System for Proposed House

This study proposes a structural system that is suitable for earth stabilised blocks, and accommodates its good compressive strength and poor tensile, bending and shearing strengths. The load bearing frame and arches system is adopted. In foundation a reinforced concrete beams links the pillars together.

It is important to consider carefully the choice of structural system when using earth as the basic construction material. It is necessary to compile information about the material, its physical characteristics, properties and mechanical performances. Investigation of earth construction techniques that can be employed and determine whether any special equipment is required would be useful to initiate the construction process. (14)

Architectural techniques are also considered to protect from walls from direct contact of climate through designing projections and overhangs. To increase the thermal comfort of earth stabilised building wind catchers are proposed. Wind catchers are traditional method to catch the wind and light. The functionality of wind catchers can be increase by providing water container in the bottom of wind catchers. (See the Figure 8.1)

8.3 Foundations and Footings

In Chapter 7 the proposed plan of house was considered for calculation of materials requirement, same proposed plan is used in this chapter for constructing the theories or authors study for design guidelines and maintenance.

The site for proposed plan was largely comprised of alluvial soil. Alluvial soils in particular are very expansive. Problems with foundations on unstable ground in this case overcome by using concrete, which will also increase the design life of the superstructure. The choice of foundations and footings must, above all, be suited to the nature of the ground.

Alluvial earths are particularly susceptible to swelling because water reduces cohesion between particles in them. Thus, in these areas, precautions must be taken during construction of foundations and footings to ensure structural integrity of the building. (10)

It is previously proposed that soil used in foundation stabilised with 3% of cement or 4% of lime by its weight. The foundations of earth stabilised block walls are similar in nature to those of conventional masonry walls. However, the design specification must ensure that the foundations are strong enough to accommodate the heavier weight of the earth stabilised blocks. Climatic factors and sub-earth conditions are also evaluated as with any other foundations. To protect foundation and footings from structural damage and humidity the precautions should be taken.

As earth stabilised block buildings are susceptible to structural defects and the effects of high humidity, special care must be taken to follow the appropriate rules and codes of good practice. Problems do not occur solely as a result of the nature of the material; they can also be caused by external factors, such as differential settling, landslides, earthquakes and floods. However, these external causes are even more damaging when a building has been badly designed or built.

It is recommended that choice of system for foundations depends on the nature of the ground and the type of super-structure. (3) There is a danger of structural weakness when a building is constructed on unstable or soft ground. This danger is exacerbated by poor design, e.g. under-dimension or insufficient strength of the foundation. Inadequate provision of drainage at the site can cause high humidity to develop around the foundation. This reduces cohesion within the earth stabilised blocks and weakens the structural integrity of the foundation walls. (4)(5) To prevent structure from these damages following measures are designed:

a) Drainage

Adequate drainage on the periphery of the foundations has been designed in order to provide protection against water ingress. Drainage ditches must be dug during the excavation of foundation trenches and should be a distance of at least 1.5m from the foundations. (4) Sloping channels are also dug at the bottom of the foundation trenches in order to remove water that collects. The drainage ditch is filled with broken pieces of burnt bricks and gravel to create a filter system. (6)

b) Gutters and Gradients

Gutters must be provided around the foundation walls. It is recommended that, for every millimetre of surface water run-off, a gap of 2cm between the foundation wall and side of the trench be left. (7)

The ground surrounding the foundations should not be waterproofed, e.g. by applying impervious material, pavement etc., because evaporation of moisture will be inhibited. It is better to backfill the foundation trenches with layers of compacted gravel that slope away from the building. (8)

c) Moisture barriers

Vertical and horizontal screens placed on the outer surfaces of the foundations act as an anti-capillary barrier between the foundations and the base course. These screens run continuously along the length of the foundations and must not be cracked or defective in any way. This study proposed that these moisture barriers made of water repellent concrete ($500kg/m^3$).

The foundation trenches must be dug down to stable ground and compacted properly before being laid. (11) Drainage ditches at the periphery of the foundation protect it from water ingress. At the surface, ground should slope away from the foot of the foundation wall at a gradient of 1:20. In order to provide a rigid foundation, reinforced concrete should be used in foundation trenches. According to the availability of materials, these trenches should also be filled with broken pieces of fired brick, stone, etc.

It is essential that there is an adequate water drainage system when constructing foundations in ground with low cohesion. The ground must be compacted in order to pack the earth grains tightly together and increase its density. Floating structures, e.g. floating slabs and sole plates, are compatible for use in compacted ground of this type. Reinforced concrete can be also used where there are poor ground conditions (see Figure 8.1). (13)

The hot and humid climate of Sindh encourages termite infestation. To protect foundations from termite attack, a damp-proof course should be included during the lying of the foundation walls. In the case where wood is used as a structural element, it should be treated with oil to protect against infestation. Mixing crushed glass with broken fired bricks in the foundation trenches also provides protection against termite infestation.

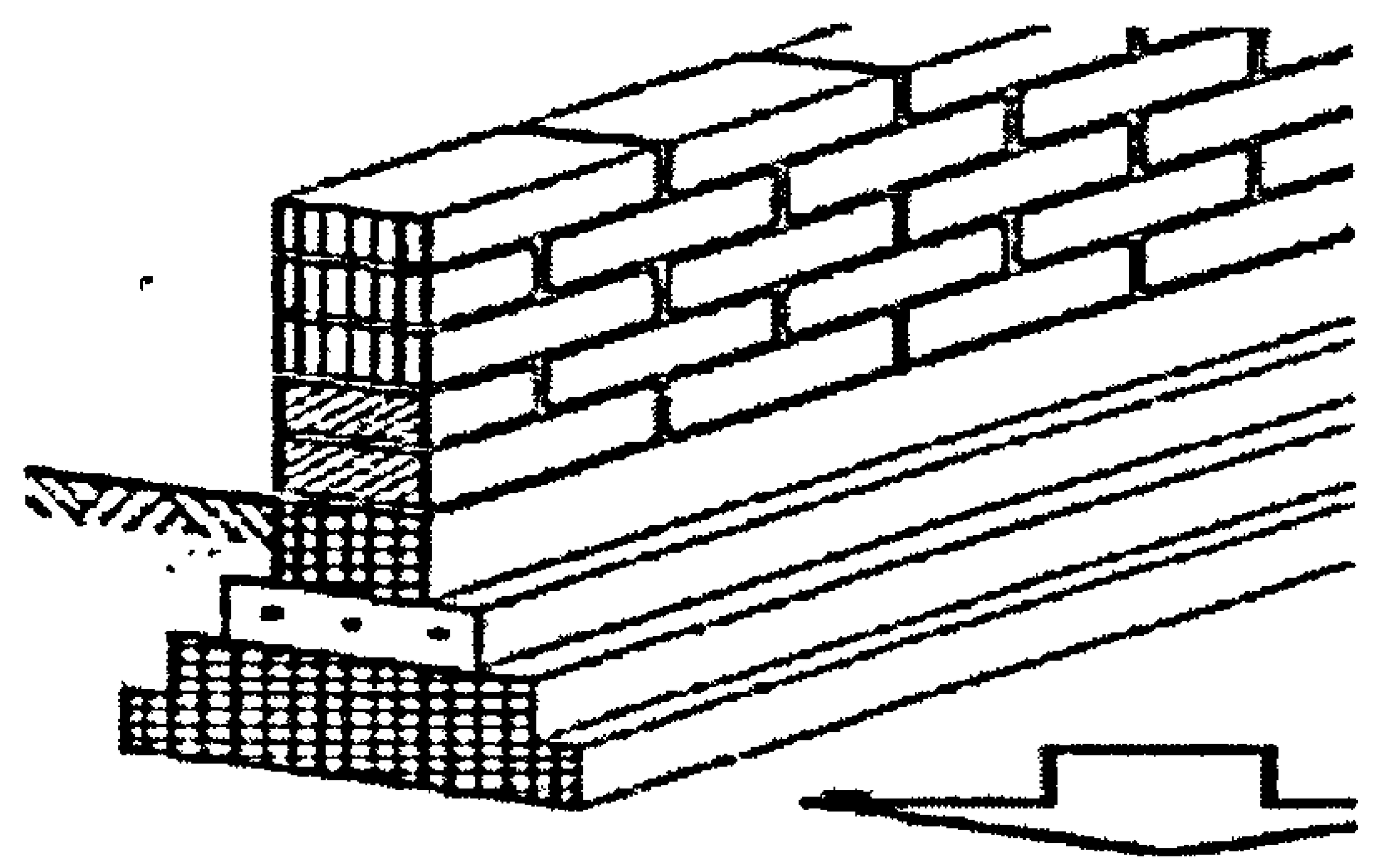


Figure 8.1 Poor foundation earth (reinforced concrete ground beam has been used) (15)

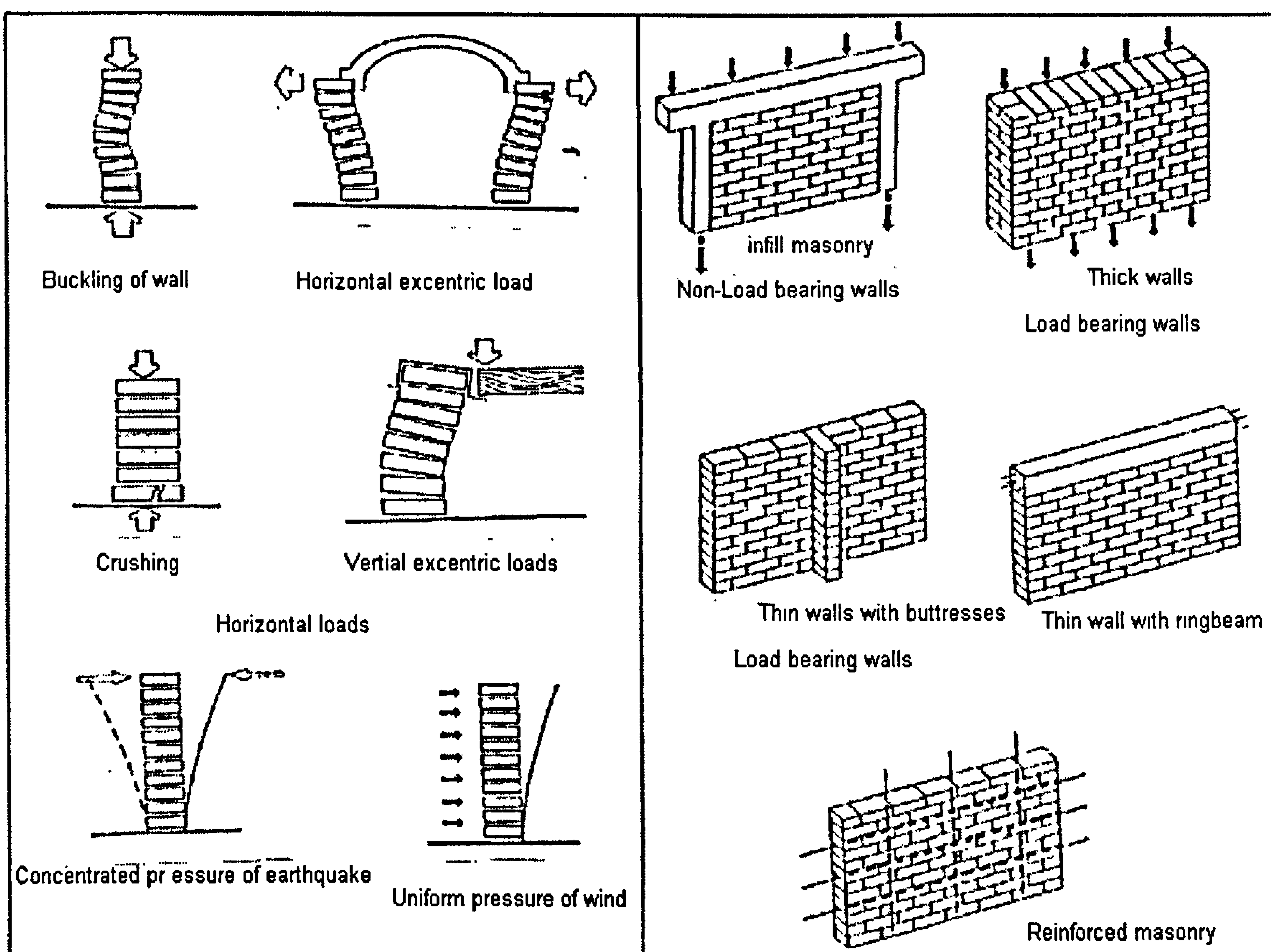
8.4 Walling Systems for Proposed House

In this study earth stabilised block masonry system is proposed to construct load-bearing walls, such as partitions for dividing the space within a building. The structural integrity of a masonry wall system is very much dependant on the types of stress to which it is subjected. So it is necessary to prevent the weight of wall itself or the application of concentrated vertical loads. These vertical eccentric loads can be resulting from the application of tensile forces (e.g. bending out at floor level). The use of vaults may also cause horizontal eccentric load and falling apart of walls.

Considering proposed site for house there will be less chance towards earthquake loads on the walls but horizontal wind load can cause the problem in walls in terms of erosion. It is observed in investigated house that most of erosion of material is occurred due to wind but not structural unstability. So simple thick walls with load bearing system would be suitable. As load bearing wall will not require any labour expertise and may cause less cost for construction. To prevent these loads the thick wall is used and in the case where thin walls are to be used the additional buttresses can also be built but the ring beam is recommended for thin walls.

Earth stabilised blocks walls, or those parts of the walls that are particularly exposed to erosion, must be protected by a rendering or 'hard masonry' work. The parts of a wall most likely need protecting are the bottoms, corners and tops of walls, parapets, reveals in openings, etc.

The mortar used for bonding masonry should have the same compressive strength and erosion resistance as the block. If the mortar is weaker than the blocks, it will become eroded and allow the water to penetrate. This will ultimately lead to the deterioration of the blocks. (15) However, if the mortar is stronger, then blocks will erode and water will stand on the exposed surface of the mortar. This will further aggravate the erosion of the blocks. (13)(15) The solutions shown in Figure 8.2 are recommended to counter the problems, as described above, which may occur in masonry walling systems: (15)



Common problems in walls	Suggested solutions for walling system

Figure 8.2 Commonly occurring problems and solutions in masonry wall systems. (15).

Infill masonry reduces the risk of blocks in the wall being crushed. Also, in the case of load-bearing walls, the risk of crushing can be mitigated by reducing the forces of eccentric, buckling or horizontal loads.

8.5 Bonding Patterns

This study proposed a bonding pattern which consists of courses being staggered and requires the insertion of a half-block at the end of the wall. It is recommended that the distance between the vertical edges of two blocks in adjacent courses should be at least a quarter of the length of a block.

A three-quarter bat is considered for the construction of right angles. Such blocks allows the construction of walls 45-cm thick, which offer the benefit of greater thermal inertia and of being able to assume the thrust due to arches, vaults or domes. The bonds in walls 45cm thick are as varied in walls which are not so thick. In the header and stretcher bond walling system, may be three-quarter and half bats are used for corners or in header and stretcher. (14)

Bonding pattern' refers to the arrangement, assembly and bonding of earth stabilised blocks in all three dimensions of a masonry structure, i.e. height, width and depth (thickness) of the wall. The bonding pattern determines the positions of earth blocks relative to each other from one course to another. Importantly, a planned bonding pattern prevents the vertical edge of one block from being aligned the vertical edge of the underlying block. This would create a vertical joint along which cracks could easily propagate.

Thus, it can be seen that bonding patterns play as essential role in ensuring the cohesion, stability and strength of masonry structures built from small elements bonded together with mortar. A good bonding pattern will ensure that no vertical joints exist in the masonry structure. In other words, the vertical edge of one block should never be flush with the vertical edge of the block on an adjacent course.

8.6 Bonding between Walls

In this study, the bonding type between walls is dependent upon the materials used to construct the walls, in particular whether the walls are constructed of the same material or not. As outlined in the proposed plan, most walls are to be constructed with identical material. A further consideration is that wall bonds between blocks should be positioned to ensure good toothing.

Wall bonds are designed in accordance with rules of the masonry bond so that, for example, there is an adequate overlap between courses to prevent vertical cracking through the perpends. (17)(18) The complexity of the bond between walls depends on their thickness, with the use of three-quarter bats and half bats being common practice. In the case of thick and thin walls are to be bonded together, a vertical groove is created in the thick wall into which the thin wall can slot. With this type of bond, horizontal reinforcement must also be inserted every 5 or 6 courses in order to strengthen the 'T' bond between the walls. (17) Ties also should be inserted to strengthen the bond at floor level. (14)

In the case of different materials used for walls the toothing bond can not be used where the walls are constructed of different materials because of differences in strength of the materials.

The recommended approach for masonry walling system or any other conventional wall is to create a groove in the thicker wall into which the thinner wall slots. In the case of bonding a light wooden framed dividing wall to a rammed earth wall, the recommended approach is to embed a wooden board within the rammed earth wall and then screw the dividing wall to the board. The end of wooden post of the partition wall can also be sunk into the rammed earth wall. (16)(18)

Block masonry corners are highly susceptible to damage and, because they have a significant impact on the stability of a structure, it is important that they are adequately protected. Structural cracks can often be observed in the corners of earth houses, jeopardising their overall structural stability. Where poor foundations have been laid, these cracks often result from differences in the rates of settlement of the ground and the structure. In such cases, the corners, as well as the other wall bonds, bear much of the resulting load. However, cracking in the corners of buildings may also be due to poor bonding between walls where, for example, bat size is too small. In the case of earth stabilised blocks, the three-quarter bat is the smallest element that should be used; a half-bat is too small. (14)(15)

8.7 Openings in Block Masonry

In the study's proposed plan all openings in a room were kept in same size. Locations of openings are provided in centre of the walls, corners of walls are avoided due to weak and eventually buckle. The close positioning of openings were avoided. Positioning of openings are dangerous where wall contains intermediate pier. The wooden jambs are considered and anchoring of the frame are also properly positioned.

During the use of earth stabilised block construction, careful attention should be paid to the structural bonding of frame openings in walls. This is necessary in order to mitigate the danger of cracking, which can lead to water infiltration and, thereafter, erosion of the blocks. It is important to compensate for shearing stress loads applied to the lower edge of the opening. These loads are transmitted directly down the jambs of the reveals from the lintels. Furthermore, openings are designed in the required specification. Too large openings are avoided.

In this proposed house structure, drips under lintels and sills, on outside walls are provided to prevent from water damages. Cracks in a building provide access routes for water penetration. The bonds between lintels and earth stabilised walls and between jambs and walls are highly susceptible to cracking and water penetration. Avoid unsuitable projections on lintels and jambs. Blocks, which are used under the sills should properly cured and stabilised. Reveals from both side i.e. outside and inside are rendered. Waterproofing is used underneath projecting sills.

Careful consideration must be given to the design of reveals and openings so that heavy lintels and sills are protected. Prevention from exertion of the point load. Openings can be dressed in wood or masonry, but care must be taken not to increase differential stresses between the frame and walls. It should be noted that the opening could be cut after the walls have been constructed and dried, but lintels must be fitted beforehand. (13)(16)

Lintels, Sills and Dimensions

In the proposed house plan reinforced concrete can be used as construction material for lintels. However, in order to preserve the structural homogeneity of the wall, various forms of earth block arches, such as Dutch and depressed arches, may be constructed in place of lintels.

In order to eliminate the danger of shearing, the length of the lintel embedded in the wall is recommended at least 20 cm for a small opening. Lintels are subjected to the high loads exerted by masonry they support. This load is transmitted through the frame jamb towards the sill or the threshold of the opening. Breast shearing is also a problem that needs to be addressed. It can be overcome by using dry joints between the breast and the wall. Thus, the window frame is built in the same way as a doorway, with the breast being added later. The dry joints can be filled in after the initial shrinkage and settlement of the masonry has taken place. (13)

Jambs need to have high compressive strength and earth blocks of equal strength should also be used. Sills are inserted most notably at windows, where they absorb loads transmitted by reveal jambs. Reinforcement can also be added below the sill.

The dimensions of openings must be carefully considered at the design stage. The proposed ratio of apertures to solid sections in a wall should not be greater than 1:3. The total lengths of the openings are not greater than 35% of the length of the wall. 1m of distance is kept between opening and corner of wall. Reveals can be strengthened by, for example, adding reinforcement underneath the sill.

Arches provide highly stable openings in earth stabilised walls because walls are kept under compression. The following types of arch can be constructed in earth stabilised walls (6):

i. Semi-circular and drop semi-circular.
ii. Basket handle (both full and drop).
iii. Ogee and drop ogee.
iv. Tudor, elliptical and flat.
v. Catenary and parabolic.

Normally, calculation, simulation or graphical methods can be used to evaluate an arch. However, in the case of load bearing masonry, it is not possible to simulate an arch. (6)(7) The shape of an arch should be determined in advance. By plotting thrust lines, the shape and thickness of the arch can be determined. The thrust lines should pass through the middle third of the arch or else cracking may occur. (8) However, thrust line calculations provide theoretical results because, in practice, masonry loading on an arch is not passive. The hypothetical nature of thrust line calculations means that a significant margin of error is required, especially for large spans, in order to avoid cracking and loosening of blocks.

Pier Design

Although in proposed house plan there is not any pier but it is necessary to understand the design process of arches in earth stabilised buildings. This understanding will facilitate the future consideration for arches in buildings. Arches transmit great thrusts onto their springing points and supporting piers. The piers, in particular, must be sufficiently robust to bear these thrusts. Graphical approaches, such as the Maxwell-Cremona polygon of the forces, can be used to calculate the scale of the thrusts involved. (8) (14)

The size of the piers needed to bear these thrusts can be determined by an empirical method. The prolongation of the first third of the arch should always fall within the pier. When two arches with identical thrust line profiles meet on the same pier, the thrust lines cancel each another out. In such cases, only the descending vertical load needs to be considered. (15)

8.8 Floor Systems for Proposed House

There are two options for floor construction can be considered: firstly floor construction consists of overlain by pre-cast beams covered with earth stabilised blocks, secondly use of Jack Arches acts like a lost formwork. The use of Jack Arches reduces the amount of sand, gravel, cement and reinforcements required compared with concrete floor systems. (8)

Vaulting floors have the advantage that compressive stresses are applied to the earth stabilised block work, whilst bending stresses are taken up by the wooden, concrete or steel beams or struts. The span for receiving the beams varies from 0.05m for small systems to 2m for the largest.

From structural point of view, a floor must be capable of withstanding static loads caused by use and concentrated loads caused by point loading. Earth stabilised blocks are normally used to support floors designed in accordance to a specific standard. The floors may also be overlain by wooden beams, or even load-bearing concrete floors that have been either shuttered in place or prefabricated and placed on reinforcements. (14)

The floor should spread the loads evenly and transmit them down to the load-bearing earth stabilised block walls that support it. The loads should be directed towards the centre of gravity of the load-bearing walls. (15)

Floors are often subjected to vibration; rotation, hydrous and thermal expansion and, in the case of a concrete floor fixed on its four sides, there is also the danger of lifting at the corners. Therefore, they must be designed with a significant degree of tolerance. In order to ensure this tolerance to applied loads, they must not be embedded in the walls in any way. This means that it is particularly important to ensure that the junctions between floor and wall are not out of true. (13)

Figure 8.3 shows a floor system recommended by CRATerre that utilises chamfered earth stabilised blocks.

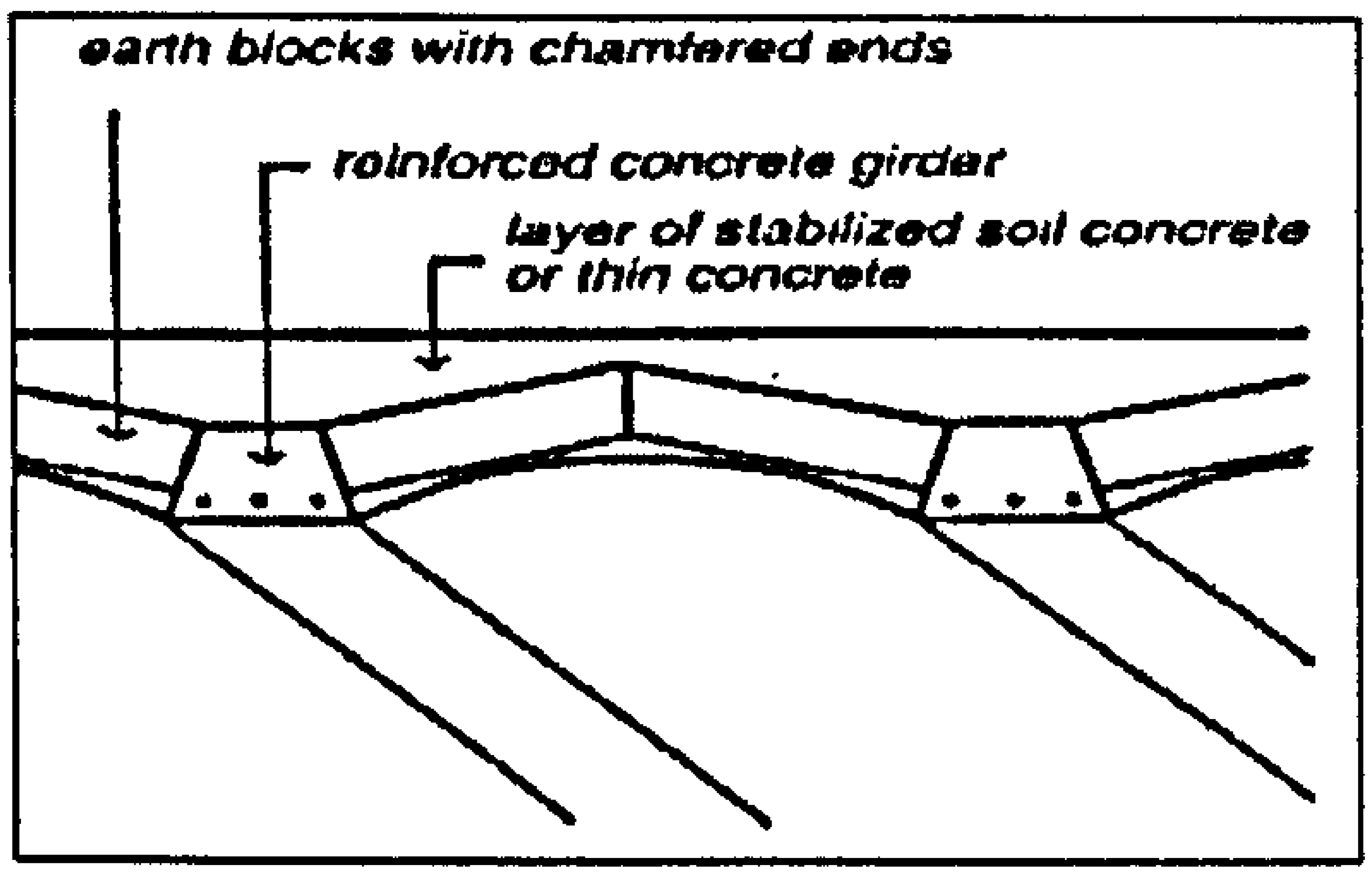


Figure 8.3 Floor utilising chamfered earth stabilised blocks. (14)

The best way to ensure that floors are laid carefully is to leave gaps in the wall to accommodate the beams or their bases. It is recommended that these gaps are drawn into the working plans of the structure. (2)(4) On site, the most important problem to resolve is that of protecting the floor structures from rain in order to avoid any water infiltration.

In the larger systems, metal tie-rods may be required, with the earth stabilised block vaulting resting on the lower wings of the IPNs or on the spines of the concrete struts. (4)(8) A small curve (10% of the span) enables the struts to take up the stresses better. (4) The floor may be finished by filling in with earth stabilised concrete or light concrete. (13) However, these floors are still heavy and so the load they exert must be evenly spread and transmitted to the base.

8.9 Roofing System

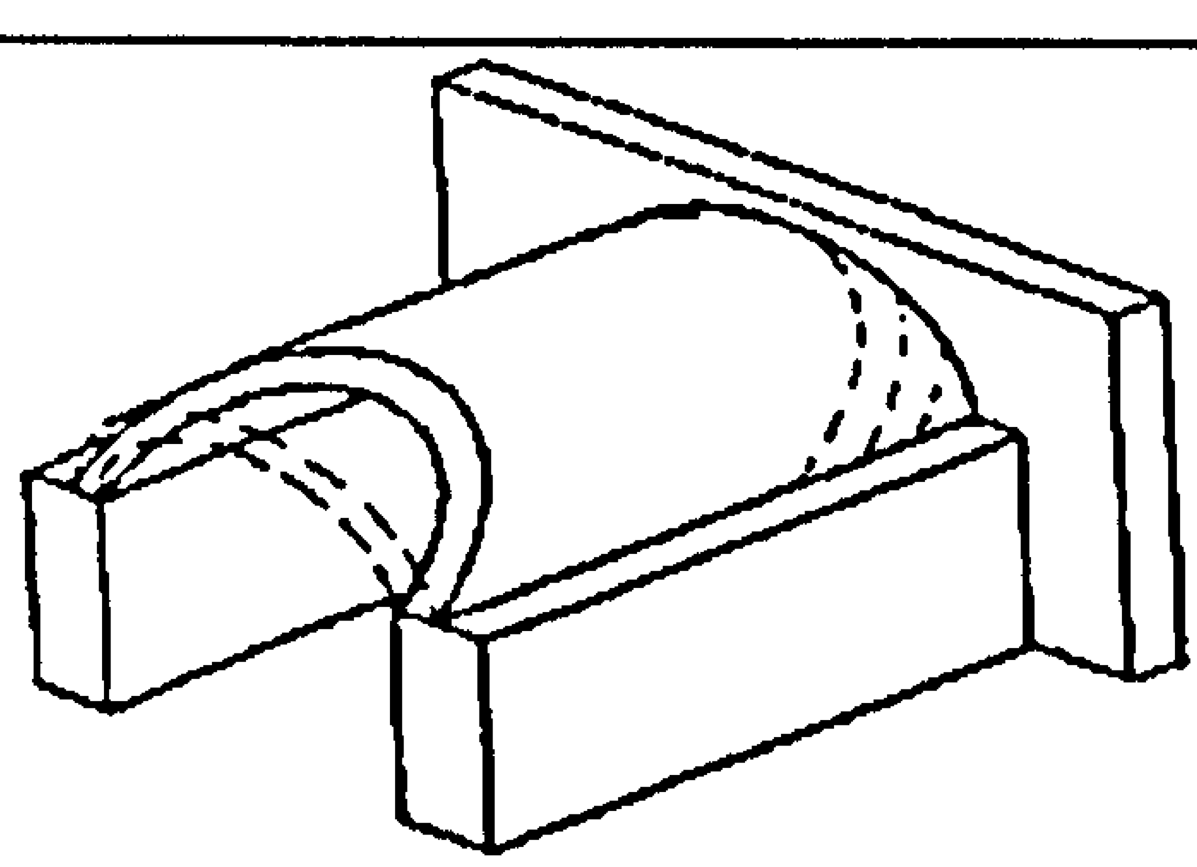
Earth stabilised block structures require the protection of a good roofing system from water and other climatic extremes. This is particularly important in regions with heavy rainfall. The use of earth stabilised blocks for roof construction is still at the experimental stage of development, but advanced studies indicate that the blocks are suitable for such purposes. It is estimated that use of earth stabilised blocks can save up 50% of the total cost of roofing. (14)

In this study flat roofs are used for proposed house plan. As flat roof fulfil the requirement of traditional architecture and functional requirement of the region. Flat roof sin villages is used for sleeping in summer and other household chores.

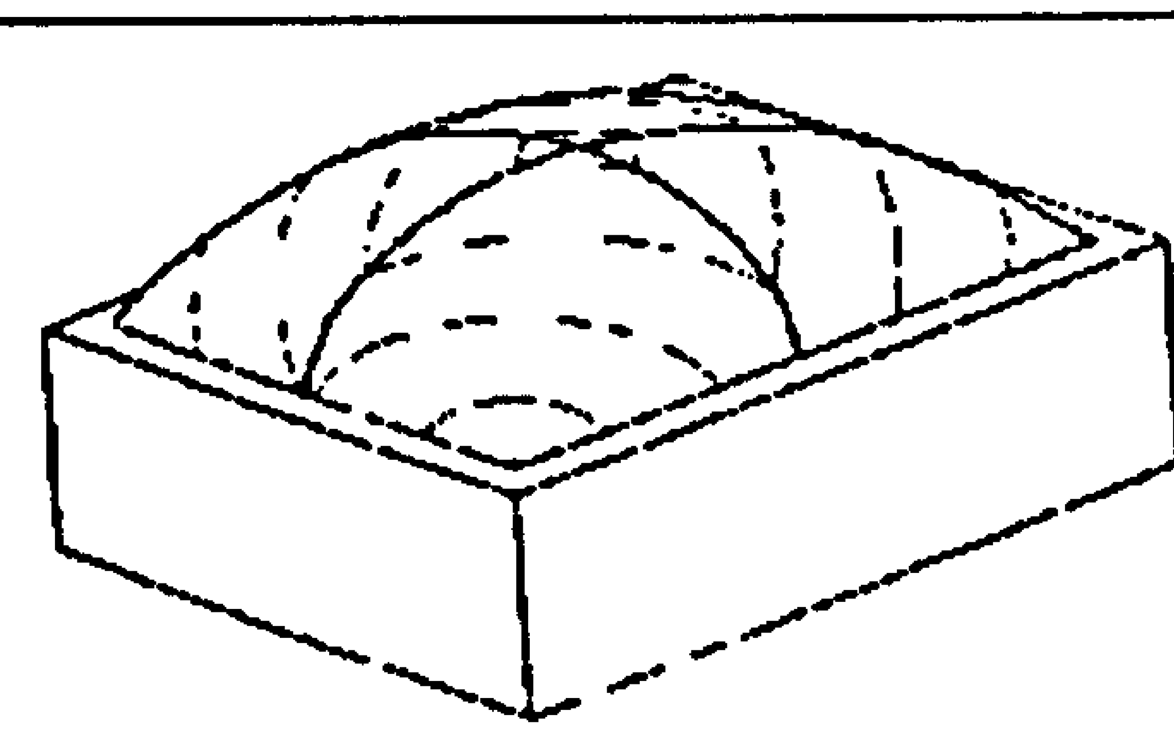
Flat roofs usually exert heavy loads on masonry load-bearing walls. Thus, the construction methods used to build floors are applied to the roofs, i.e. jack arch and vaults systems, with wooden beams and concrete or steel struts and stabilised vaulting. Key considerations include: waterproofing, thermal expansion (in hot climates) and water drainage off the flat roofs. (8) In order to eliminate the problems of standing water, a flat roof must be inclined at an angle of 1-2^{0}, with water being evacuated via a suitable system of spouts or channels. Care must also be taken to protect the edges of the roof with parapets. (8)

For further possibilities for roofing with earth, various types of roofing are investigated. Sloping roofs are built using conventional methods, with a timber frame being covered by tiles, felt or corrugated iron sheets. A sloping roof must be inclined sufficiently steeply, and have an overhang of at least 30cm, to ensure that rainwater is projected away from walls. (8)(13) Special; attention must be paid to ensure the stability of the gable–end walls (slenderness ratio) and the anchoring of the timber frame in load-bearing walls (use of ring beam). (14)

Figure 8.4 shows proposed earth stabilised block roofing systems that incorporate traditional Middle Eastern approaches to construction. (15)



Nubian vault with inclined courses



Course corner squinch vault

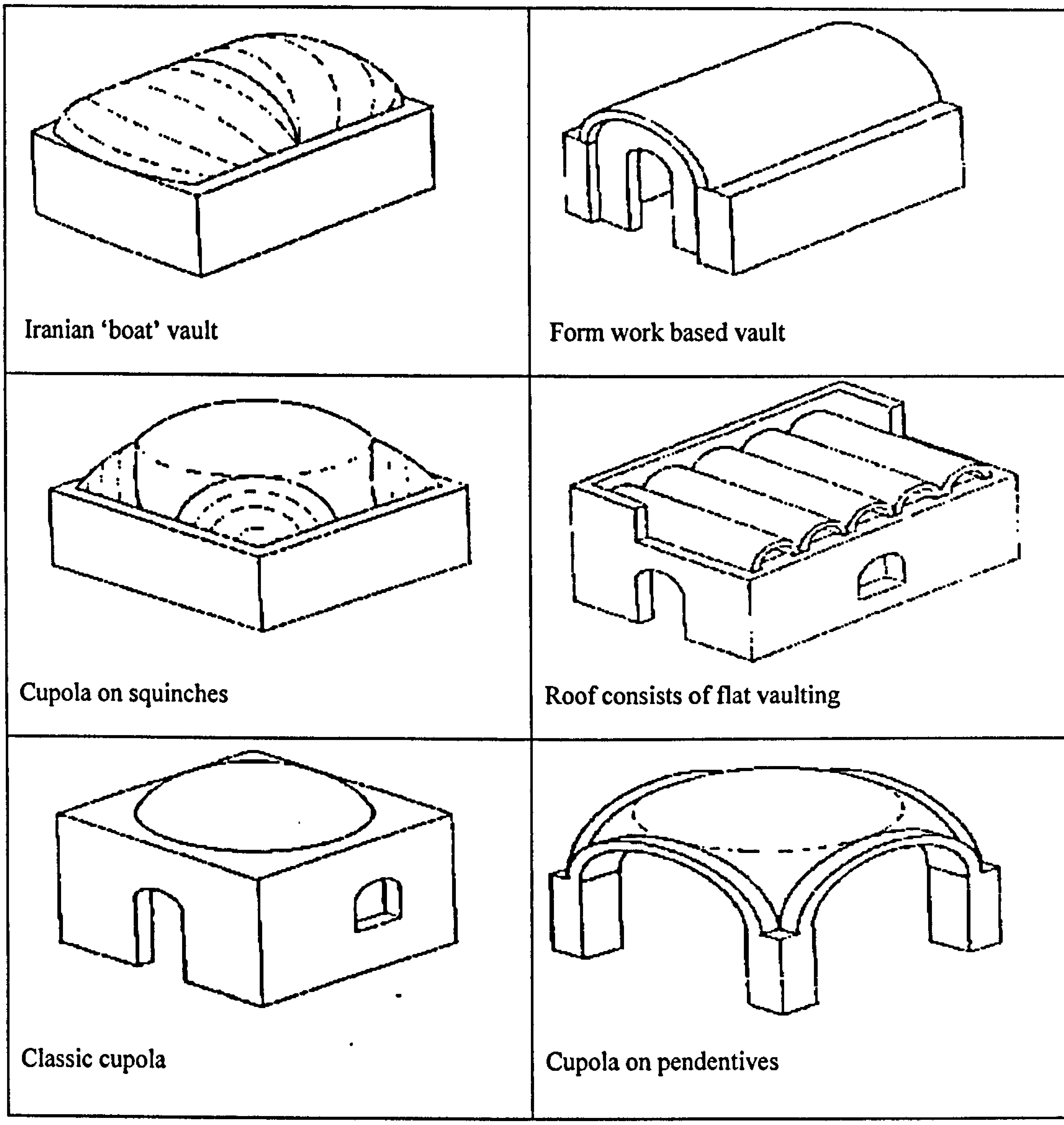


Figure 8.4 Traditional roofing systems (15)

(c) Curved roofs

These are built in the form of vaults or cupolas. These types of roofing systems suffer from the same kind of problems as flat roofs. In particular, waterproofing, thermal expansion and the removal of water away from walls are key considerations. Protection of peripheral areas is ensured by the construction of parapet walls.

(d) Traditional methods of roofing using earth as the raw material

The construction of earth stabilised block roofs has evolved from the tradition of adobe roofing developed in regions with dry climates and a scarcity of good roofing timber, e.g. Mesopotamia, Egypt and Iran. Builders who constructed earth vaults and copulas exploited the material's ability to work in compression. These types of roof also have an undoubted aesthetic appeal, both with regard to architectural design and the inner spaces that architects and their clients find attractive.

Earth stabilised block roofs are heavy and exert high lateral stresses on the walls, which must remain vertical. The use of ring beams, post compression loads (parapets), thick walls or buttresses, and sometimes tie-rods for wide span vaults, helps to dissipate the stresses and directs them towards the foundation. (8) Vaults with a span of up to 6m and 15cm thick have been built with earth stabilised compressed bricks, whereas the span of vaults built with rammed earth rarely exceed 2.5m. In Iran, spans are usually 4m, which is the maximum recommended for earthquake regions. It has been established that, in earthquake regions, the ratio of span to length should be 1.5x width (4)(9). Research conducted by the University of Baja, Mexico indicates that if the ratio exceeds 1.5x width, the vault could resonate and shatter. (4)

The rise of the arch is an important consideration when constructing a vault. Lateral thrust is proportional to the rise; the greater the rise, the lower the thrust, approaching a limit value of zero. (15) For catenary vaults, the rise should be half of the span plus 50cm. In earthquake zones, it is advisable to limit the rise to 20-30% of the span. (4)

Earth stabilised blocks may also be used in conjunction with the following construction systems:

1. Blocks without formwork

The Nubian style method, where courses are inclined at 10-15°, exploits the friction between blocks and the adhesion of earth mortar. (15) The blocks must be light, e.g. straw-rich adobe, and thin, i.e. 5-6cm thick. Thin earth stabilised blocks with grooves to enhance adhesion can also be used. The main challenge, arising from the curvature, is to confine thrust lines to the middle third of the arch.

The Auroville Building Centre (AV-BC) Earth Unit has gained experience of constructing domes using 'pointed cloister arches' (6m x 6m span and 2m rise) and surbased vaults (10.35m span and 2.25 m rise). Earth stabilised blocks has also been used to construct 'cloister arches'. These are built on 'angle squinches', covering an area of $6m^2$. All vaults and domes were built without forms, using a technique called 'Nubienne' that relies on the adhesion of the earth stabilised blocks and earth mortar (stabilised with 9 % of cement). (21)

<u>The historical evolution of dome construction with earth</u>

Egyptians were the first civilisation to adopt dome construction with mud bricks. This assertion is made by the author based on the existence of the Tomb of Seneb in the Cemetery at Giza. (7) It is a hemisphere that rises on pendentives set into the interstices of four arches set in a square at 90^o to one another. Fathy argued that the Byzantine dome, commonly considered in literature to be the first use of dome construction, is in fact an "ancient Egyptian dome" or Sassaid (a name derived from Persia). (6) He defines a dome as, "*. . . sitting on a square plan in Byzantine churches . . .(and) represents a microcosm*". The dome is built on pendentives and towers over the open space below.

In Islamic communities, the dome has a different symbolic meaning than in Byzantine architecture. Conceptually, the mosque is not an isolated microcosm. It is designed to be a quiet place for worship where the roof must protect worshippers from the elements but not cut them off from God. The dome is constructed on squinches in which the square plan is transformed firstly into an octagon and then into a circle. This transformation expresses movement upwards with eight sides of the octagon symbolising the eight angels carrying the throne of God. So, the construction process is pointing up towards the sky.

2. Blocks with formwork

Formwork makes it possible to work parallel to the walls. It can be heavy and fixed or light and sliding. In the latter case, the builder proceeds in successive layers of bonded bricks or even in rings. The setting of the keystone of the arch must be carried out with care. (7)

3. Rammed earth on formwork

This construction system is rarely used nowadays. Monolithic arches made of rammed earth on formwork are generally dropped into position and held by ties. The layer of earth above the extrados is inclined. The formwork is heavy, fixed by ramming stresses and cannot be used for several days. (15)(13)

4. Mud over the frame

An arched framework is prepared. It consists of interlaced branches and is covered with a mixture of mud and cow-dung. The rigidity and water-resistance of this system is poor. (13)

5. Prefabricated elements

This system is highly sophisticated and requires the use of concrete bars to provide the prefabricated vault with high degree of stability. (15)

The vault is built up from small half vaults assembled on a ring. (15)

<u>Construction Details of Arches, Vaults and Domes</u>

Most vaults and domes are based on a form of arch design, transferring roof loads to a vertical wall. Often the specific shapes and forms resulted from trial-and-error and evolved to yield traditional construction practices. Various geographic areas have traditional proven forms of vault and dome. Notable, in the Middle East, the construction of vaults and domes stretches back to ancient times when small masonry units were used to create structural roofing systems.

Earth stabilised blocks are strong in compression and relatively weak in bending or tension. For this reason, they are commonly used in the construction of load-bearing structures.

Traditional vaults and domes, which are similar to an inverted catenaries , also take advantage of the engineering properties inherent in earth stabilised blocks. (4) The shape of a catenary is similar to that of the tension curve taken by a chain when dangled freely by its ends. Thus, an inverted catenary-shaped vault or dome is always in compression and is a highly efficient structural form. (10)

Domes are usually semi-circular in shape. The geometry, slope and placement of bricks or blocks is determined by anchoring the end of a piece of string in the centre of the circle, with the other end being used to trace out the arc of the dome. (8) The dome, like the vault, is often built without any supporting formwork. However, in Europe, vaults and domes are traditionally constructed on formwork, which is removed once the vault or dome dries. (10)

Structural Behaviour of an Arch under Load using Castiglino's 'Energy' Model. (A Theoretical Study to using this Model in Earth Stabilised Construction)

Knowledge of the structural behaviour of masonry arches and vaults is particularly important in earth block construction. There have been many studies conducted to determine the structural behaviour of masonry vaults, domes and arches built of fired brick. In this study, the author presents findings from current research on this subject. The Energy Model is normally applied to concrete arches, but the author has found evidence of its application with fired bricks and so has used it for earth stabilised blocks.

This theoretical assessment was carried out to appraise the behaviour of a stabilised earth block arch under collapse load conditions. A practical assessment was not possible due to the lack of appropriate laboratory equipment and insufficient raw material. The assessment was based on work carried out by the University of Ancona, where a physical model of a 19th century polycentric fired brick barrel vault was constructed. (22)

Masonry arches have been studied for 300 years and a variety of approaches have been used to model this type of arch and vault. These approaches include plastic or mechanism analyses using the line of thrust concept, three-hinge analysis, finite-element models and small and full-scale tests. (22)

Heyman defined mechanism analysis as the basis for evaluation of safety and stated that, "If the thrust line can be found, for the complete arch, which is in equilibrium with external loading and which lies everywhere within the masonry of the arch ring, then the arch is safe". (22)

Crisfield and Packham used mechanism analysis of arches in their work, introducing procedures to allow for lateral resistance of the fill by using its passive resistance. (23)(24) Similar procedures have been adopted by Harvey and Smith (25). The mechanism method is not able to determine the stress state of masonry, which is assumed to have infinitive resistance. This hypothesis should not be adopted if the evolution of cracking up to failure needs to be predicted.

Castiglino's elastic method can be applied in order to determine the stresses at sections along an arch ring under a given load configuration. (26) The finite element procedure may be used to examine in detail cracking in the arch ring and to describe the evolution of behaviour up to compression crush in masonry. (27) All theoretical procedures have to be validated by experimental results. However, the behaviour of a masonry arch may be influenced by different mechanical and geometrical parameters and it is onerous to consider them completely in the theoretical model.

During experimental tests, the collapse load condition can be represented by a non-symmetrical concentrated, or almost non-concentrated, load at a quarter of the span of the thinner arch. The line thrust of dead loads can be modified by the collapse load or by a relatively low live load.

It has been shown by Bridle and Hughes that it is possible to use Castigliano's method for arch analysis. (27) This method is used to evaluate the elastic behaviour of masonry arches under load conditions. It can also be used to analyse arches or vaults built of earth stabilised blocks. Castigliano's method attributes imperfectly elastic behaviour to all bodies, such as masonry arches. Thus, when they are compressed they do not return to exactly their original form when the external forces are removed. In the energy method the calculations are, however, somewhat more complex with respect to a perfectly elastic body, because the effective dimensions of the resistant sections are not known. The effective dimensions of resistant sections can be obtained using a repetitive procedure of loading and unloading.

During the theoretical assessment using this method, masonry and earth stabilised blocks were considered to be an imperfectly elastic bodies with adequate compressive strength, whilst the mortar was considered to have low tensile strength.

The compression elastic modulus can be calculated before applying the load and theoretical assessment. This is done using ANSYS 5.2, a non-linear finite element programme, to determine the response of the arch under collapse conditions. (28) The material of the arch is assumed to be elastic up to failure. The strain energy expression is based on the effects of bending normal forces:

$$L_{Strain} = 1/2 \int \left[M^2(s) / EI(s) \right] ds + 1/2 \int \left[N^2(s) / EA(s) \right] ds$$

Eq(1)

In Figure 8.5, the circular curve between points A and B represents the centre line of the arch model. The edges AA_1 and BB_1 represent the zones with the greater thickness S_2. Section E represents the loaded area of the arch.

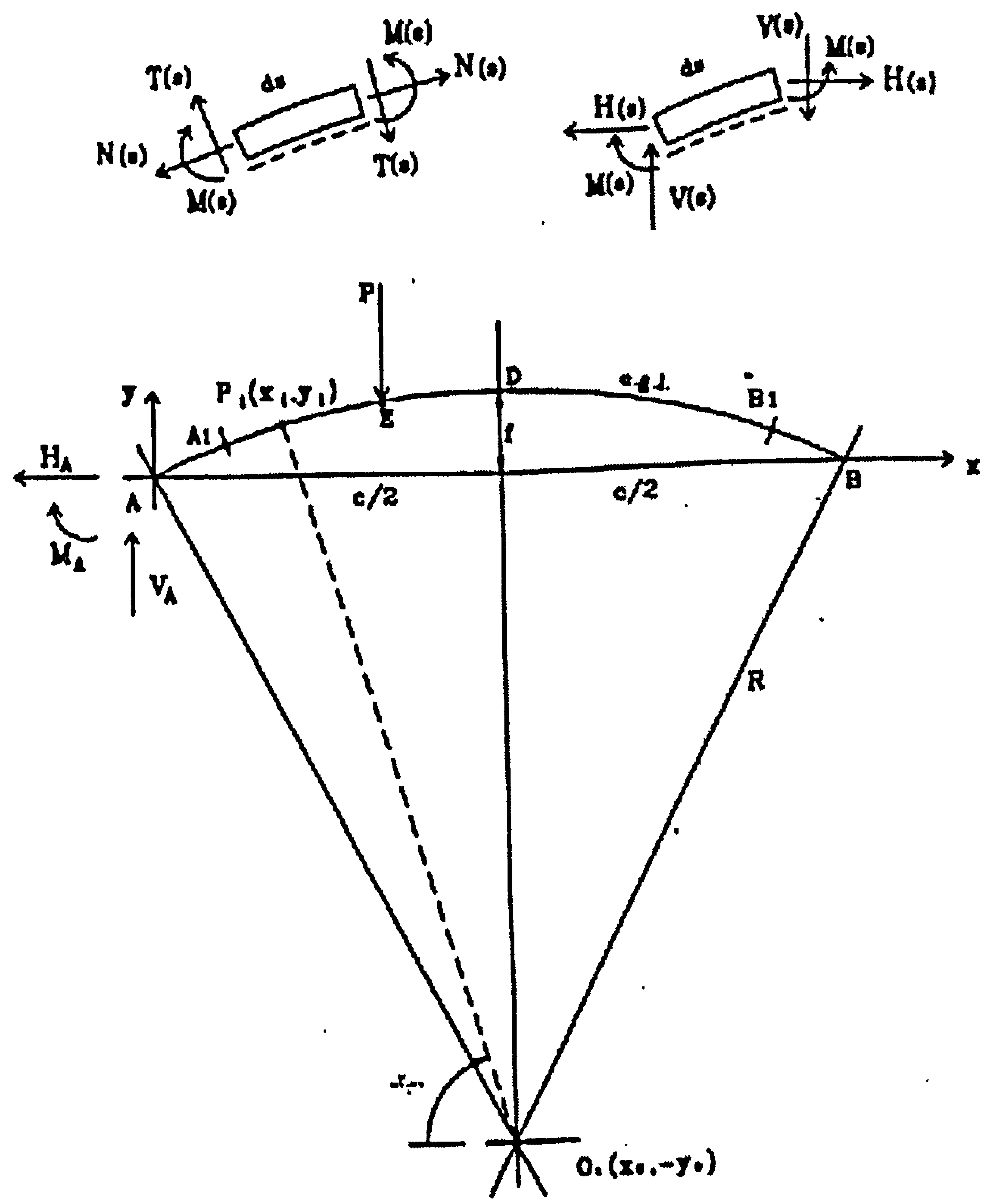


Figure 8.5 Definitions of symbols used by the energy method (27)

The energy method may be used to evaluate unknown reactions at the fixed edge of the arch. Considering the internal forces N(s), T(s) and M(s) at the generic radial sections, the following equation links the vector of internal force Q to the vector of internal force G, where the components H(s) and V(s) are directed towards the second global reference OXY axis (see Figure 8.5)

$$Q = T_S G$$

Eq.(2)

The matrix T(s) shown in Figure 8.5 has the following coefficients:

$$\sin\square \ \ -\cos\square \ \ 0$$

$$T_s = \cos\square \ \ \sin\square \ \ 0 \qquad \text{Eq.(3)}$$

$$0 \quad 0 \quad 1$$

Considering the load conditions represented in Figure 8.5 and the different stiffness of the arch zones, the internal force Q can be calculated as follows:

$$H_A$$

$$G = V_A$$

$$H_A (R \sin\square - y_0) + V_A (x_0 - R \cos\square) + M_A \qquad \text{Eq(4)}$$

For the elements AA_1 and A_1E of the arch:

$$H_A$$

$$G = V_A - P \qquad \text{Eq(5)}$$

$$H_A (R\sin\square - y_0) + V_A (x_0 - R\cos\square) + M_A - P (x_0 - R\cos\square - x_E)$$

For elements EB_1 and B_1B of the arch, x_E is the co-ordinate in the x-axis of Section E. The unknown H_A, V_A and M_A values can be calculated using the following linear system:

$$\square_{Strain} \square H_A = 0$$

$$\square_{Strain} \square V_A = 0$$

$$\square_{Strain} \square M_A = 0 \qquad \text{Eq (6)}$$

Once the reactions shown in Equation 6 have been derived, the strain energy is used to evaluate the vertical displacement of Point E under the load (see Equation 7). Furthermore, the energy method enables the thrust line on the sections to be determined by Equations 7 and 8.

$$e_1(\square) = [H_A(R\sin\square - y_0) + M_A] / [H_A \sin\square - V_A \cos\square] \qquad \text{Eq (7)}$$

For $\square_A \square\square\square\square_E$

and

$$e_2(\square) = [H_A(R\sin\square - y_0) + V_A\ (x_0 - R\sin\square - x_E) + M_A - P(x_0 - R\sin\square - x_E)] /$$
$$[H_A \sin\square + (V_A - P)\cos\square] \qquad \text{Eq(8)}$$

for

$\square_E \square\square\square\square_B$.

In Figure 8.6, the eccentricities $e_1(\square)$ and $e_2(\square)$, are evaluated by assuming thickness s_1 for each of the systems and are calculated along the entire length of the centre line which is developed. Reaction edge A is evaluated using a linear system.

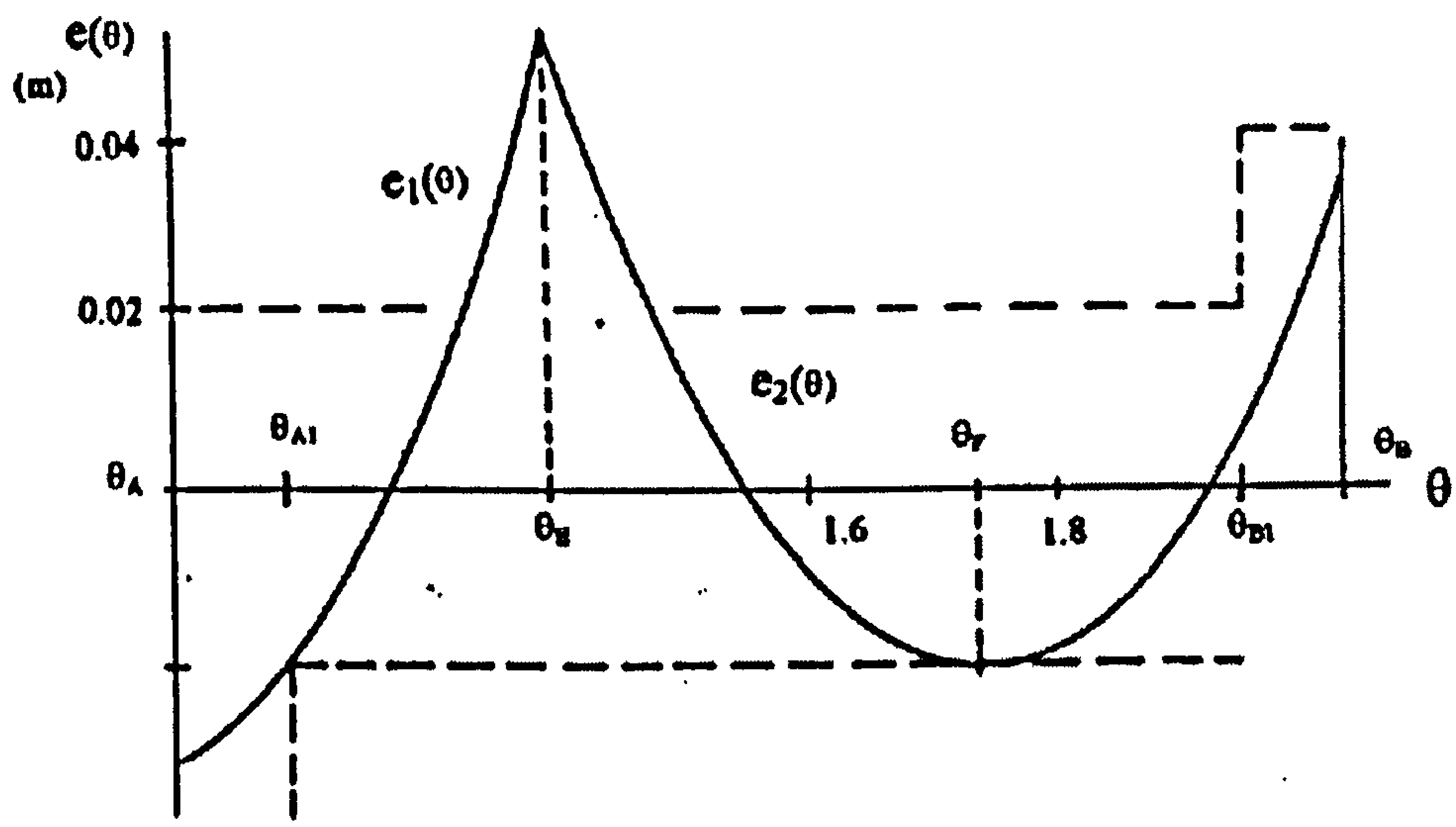


Figure 8.6 Eccentricity of thrust line in the case of experimental model of arch (27)

In the cases where masonry has a relatively low tensile strength, the energy method can be used to evaluate the behaviour of the vault under the collapse load. It may also be used to estimate the value of P when cracks first appear in Section E by considering the known reactions at fixed edge A. In the case of an integral model, P (applied load) is equal to:

$$N(\square_E) = HA \sin \square_E - VA \cos \square_E \qquad \text{Eq(9)}$$

After the load has been applied and the first cracks appear in Section E, the model must be modified to take account of local cracking. As an example of the procedure of identifying damage in a model, an ideal hinge in Section E is considered. In this case, the procedure can be repeated in order to evaluate two unknown reactions, H_A and V_A, at the fixed end.

8.10 Renders for Earth Stabilised Blocks

Extensive research has been carried out to develop mud plasters. However, owing to poor local availability of the stabilisers studied in the research, the mud plasters under investigation have not been used to any significant extent in villages or in low cost housing schemes. Studies were conducted on stabilisers available locally and on those that usually need to be imported from towns.

Renders are generally applied in three layers but, depending on the resistance of the masonry to climate, sometimes two layers suffice. In this study the Cement soil stabilised render is considered. Cement-earth renders can be used on walls stabilised with cement. The cement:earth proportions should be between 1:8 and 1:10. (17). Sandy earth should be used in the mix. Lime-earth renders can be applied to lime or cement stabilised earth walls. The lime:earth proportions should be between 1:5 and 1:10. The addition of 25% cement, and/or 1 part brick dust, improves of lime-earth renders. It should be noted that earth-based renders have better adhesion to walls than sand-based renders. (17)

In this proposed house site mud plaster is considered the most common and easy way for rendering although it is sensitive to rain water. At the same time mud plastering is the one of the daily activities of local women in household. Mud plaster is applied wet to a thickness of 15-25mm. It comprises a mixture of sandy earth and straw, chopped into short lengths. (10)(15) The mixture is usually left to soak prior to application on the walls. By soaking, the amount of shrinkage and cracking in the plaster after application is reduced (15). This kind of plaster requires frequent maintenance and, in villages, householders repair plaster as part of their weekly domestic chores. Mud plaster is suitable for unstabilised earth masonry.

Matting can be used to protect earth (unstabilised) walls from rain and impact damage. The mats can be made out of palm fronds, leaves or grasses, and are either just loosely hung over the wall or hung from battens in a manner similar to thatching. Matting provides the wall with good protection from both rain and impact damage, but harbours insects and is sometimes eaten by animals. The matting or thatch has to be replaced after one or two years. (14) However, in areas of heavy rainfall or monsoons, the matting and thatch needs to be replaced more frequently.

8.11 Summary

This Chapter contains the appropriate structural system for proposed plan house using earth stabilised blocks. In order to use earth stabilised blocks, the structural system must function under compression. It can also be assumed from literature review that earth stabilised blocks provides a number of aesthetic options for building design The earth blocks can be moulded into desired shapes to meet bespoke architectural requirements.

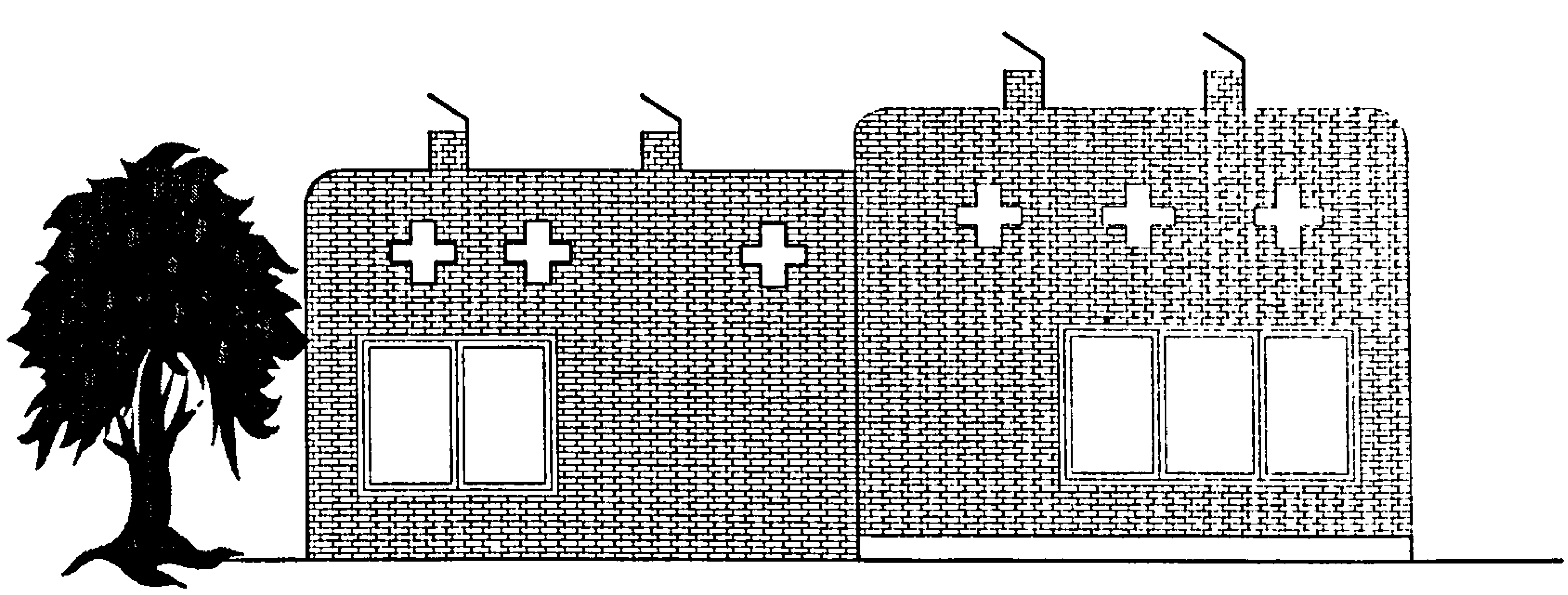
Structures constructed of earth stabilised blocks must be protected from humidity and structural defects. To prevent structure from these defects various design techniques were highlighted. In the case of ensuring structural integrity, the need for stable foundations and the importance of adopting the load bearing wall system has been highlighted.

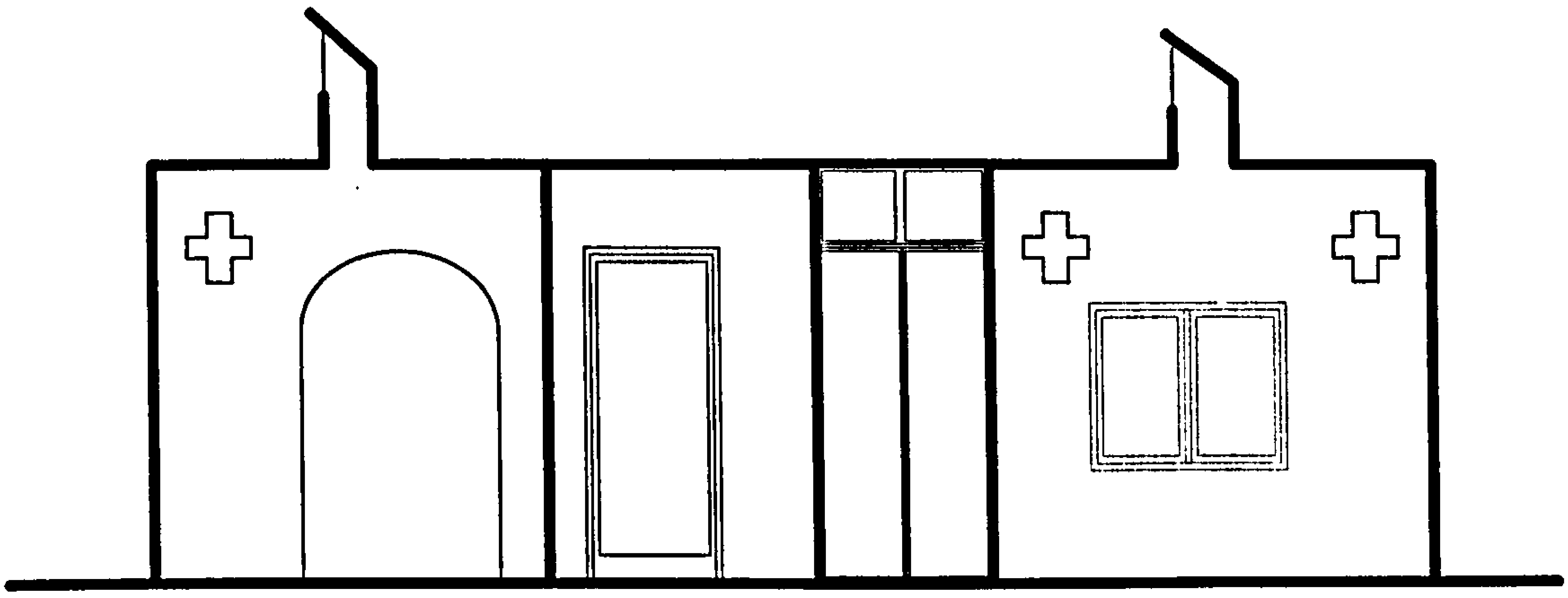
Although earth stabilised blocks are strong under compression, they are weak when subjected to tensile forces and bending moments. Thus, vault and dome roofing system, which operate under compression, are recommended also but flat roof is considered the most appropriate in this case. The energy method is suitable to evaluate immediately the thrust line in the sections and recognise the zone where the cracks may appear at the different levels of load. In the case of experimental situation, considering successively damaged model with hinge at the loaded section, it can be concluded that hypothesis of the elastic material is sufficiently adequate to describe the behaviour of block work vault during the loaded phases.

The appropriate bonding systems for use with earth stabilised blocks were discussed. The percentage of stabiliser in the plaster mix must not be less than that in the earth stabilised block. The use of various options of render was also discussed in the context of various types of earth construction.

The Following figure shows the proposed house plan with various roofing systems: Architectural Proposal by Author with Various options of Roofing with Earth Stabilised Blocks.

Option I



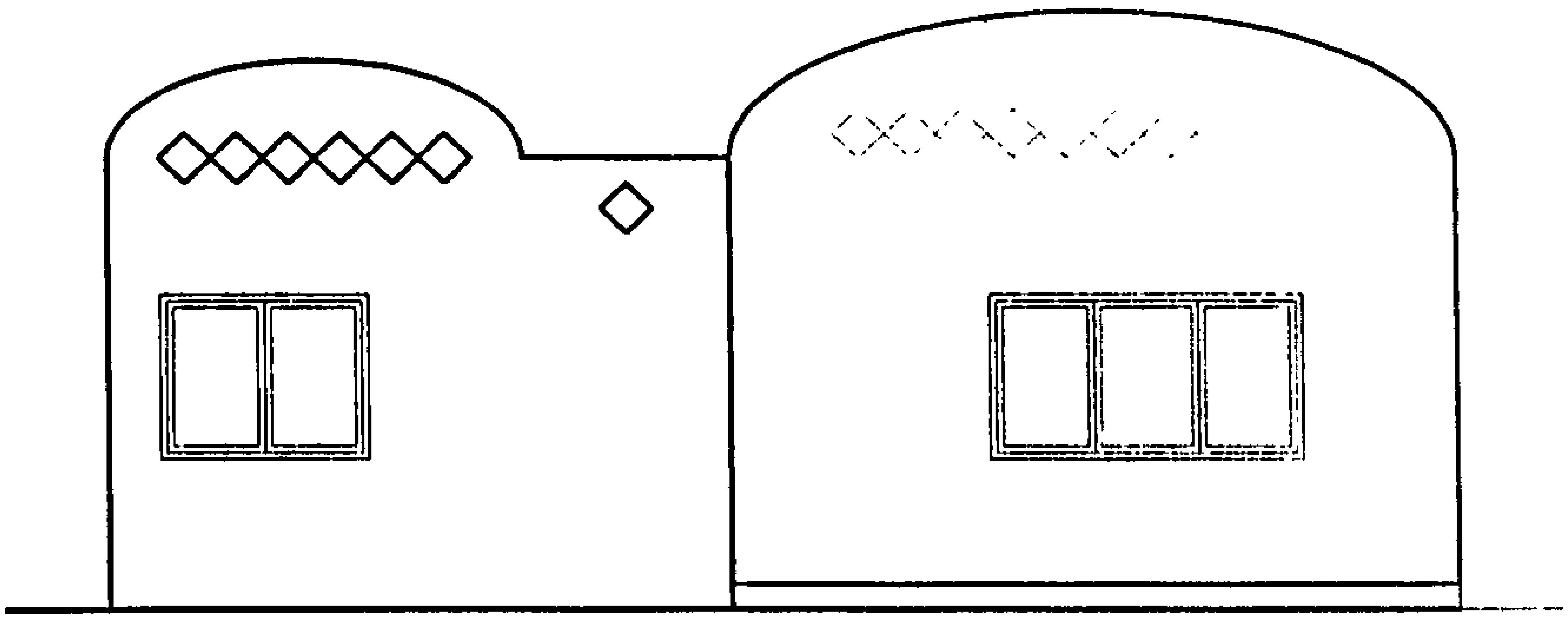


Section

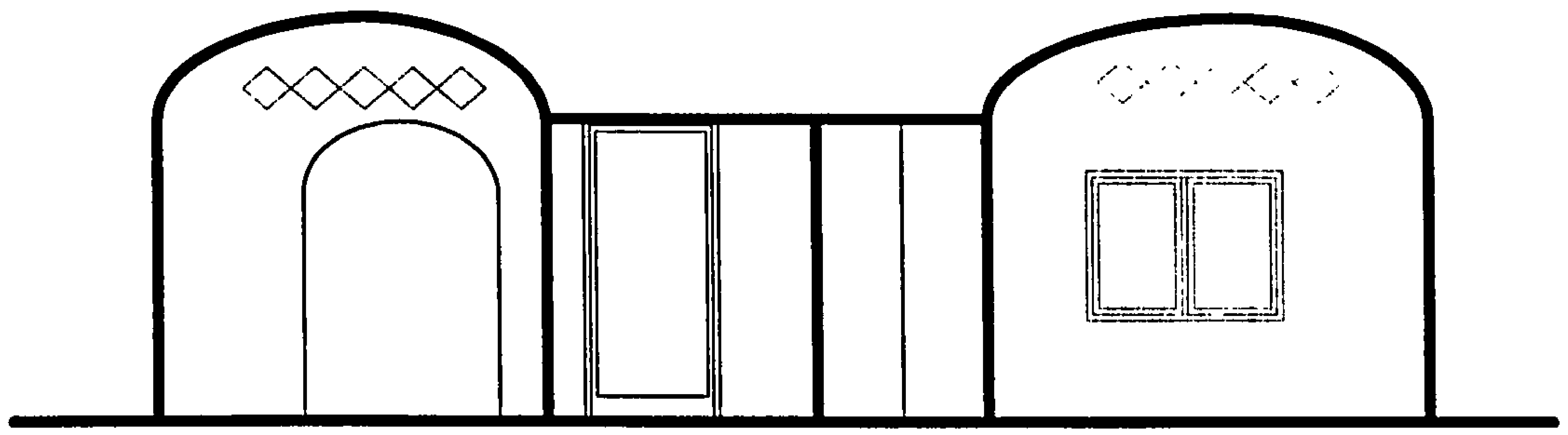
This Option is Adopted by Considering Regional Architectural Elements and the Construction.

Option II

Adoption of Vaulted Roof with Earth Stabilised Blocks



Elevation



Section

Figure 8.7. Options for proposed plan roofing

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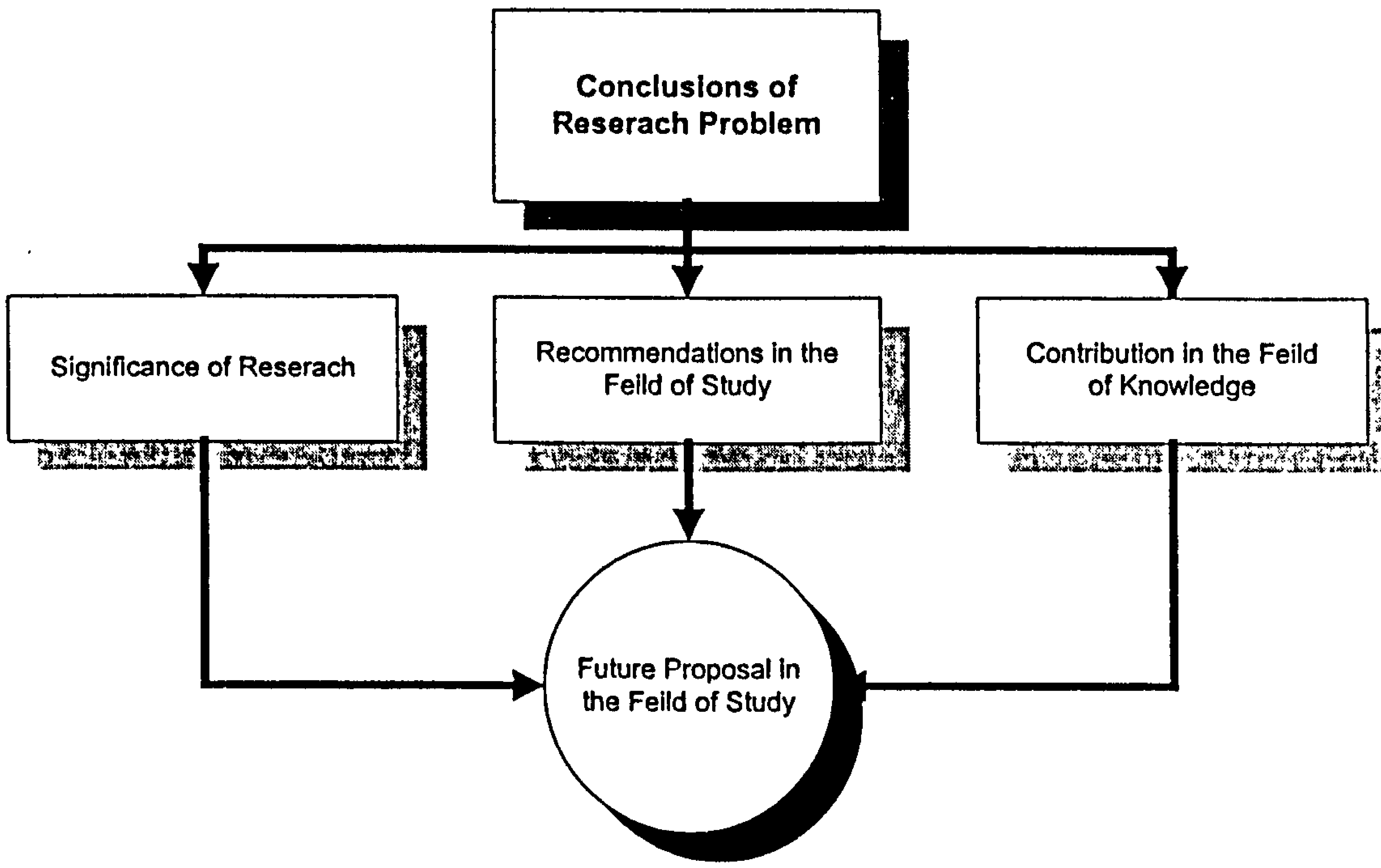


CHAPTER NINE

Conclusions and Recommendations

Chapter Nine

Conclusion and Recommendations

9.1 Research Conclusion

This study aims to promote indigenous technology for rural housing with particular reference made to the effective use of earth as construction material. It is well-established fact that earth is basic traditional building material for rural housing in all parts of world. In Chapter 2 shows the use of earth is recorded more than 70% in Sindh.

It is also investigated that earth in its original form does not meet the basic requirements for construction material, such as strength, durability and resistance to water erosion. It has also a low resistance against various climatic elements. Earth stabilisation refers to the method for improving the engineering properties of earth by adding other materials. The criteria for choice of material to be added were made according to three main parameters:

Composition of the raw material

Before making decision to choose additives it is important to understand the nature of earth material. In terms of earth's particle size distribution and effect of an additive on the physical, chemical properties of earth. For example some additives bring physical alterations and some chemical alteration. The important factor is to understand these alterations. It should be evaluated that at what extent these alteration brings strength and water resistance in material. The effect of the additives with particles of earth is further explained in section 3.5.

Local Availability of the Material

Second important factor was to consider during the selection of additives is the availability of additive on-site of project. It should not be imported but may be locally produced. It will reduce the risk of shortage of material during the project implementation. The local availability of the additives also makes to use it easily due to the familiarity with the material to the particular region.

Cost of the additives

Third factor was cost to consider during the making decision. The high cost of additives may not be feasible to the project. This study is aims to identify the affordable solution to the problem so the cost of additives should be within the range of budget.

To improve the engineering properties of earth it is important to define its nature.To understand its nature, earth is subjected to the numerous tests, the majority of which not standardised, or regulated. From the engineering and scientific point of view, it is always important to submit earth construction materials to the widest possible of series of analyses, tests and trials.

There were two types of tests discussed: (i) Field-tests and (ii) Laboratory tests. Field tests are the important tests, which should be conducted on the site. It may also be used for small projects. These tests are easy to handle by non-technical person. Laboratory tests were used to confirm the accuracy of the field tests. It is not always necessary to conduct laboratory tests if once the standards and specification of earth satbilised blocks for the region has developed. Until the technology of earth satbilised block is immature the laboratory tests is the source for further experimentation and trials. Especially conducting performance testing on the stabilised earth blocks gives the opportunity to compare it with other construction material and justify its functionality. Further more laboratory tests was adopted the conduct the research and record the results in quantitative manner.

In Chapter 4, the problem statement was defined and then the research methodology was discussed. The problem statement provided the reference framework for carrying out the overall research. All the research processes and testing methodologies required to determine the suitability of a clay-rich earth for construction purposes were identified and incorporated into the programme of research.

It was found that the earth imported from Sindh Province for use in this research study has a high clay content and is not a suitable construction material in its raw state. The term 'suitable' was used in the context of this study to mean acceptable engineering properties for use in construction, i.e. adequate waterproofing characteristics and compressive strength.

Tests were carried out to determine the effect of adding locally available sand on the particle size distribution of this clay-rich earth. It was found that by adding 20-30% sand, the particle size distribution was improved and the earth became more stable and more suitable for use as a building material.

The effects of adding four different types of stabiliser to sand-earth specimens was then investigated. The additives used to stabilise the specimens were cement, lime, linseed oil and calcium chloride. The amount of stabiliser used was based on recommendations found during the literature review.

Ordinary Portland Cement imparted good compressive strength on the test specimens, with water absorption values being less than the recommended 15%. Therefore, clay-rich earth mixed with sand and stabilised with cement produces blocks are recommended for use in construction.

The specimens stabilised with hydrated lime also exhibited reasonably high compressive strength, but also high water absorption values. In order for lime stabilised blocks to be recommended as a suitable construction material, they must be used in conjunction with the application of a waterproof rendering.

Stabilisation of the specimens with linseed oil provided an economical approach to waterproofing, but the compressive strength of the blocks was inadequate. However, the results indicate that the use of vegetable oil in the stabilisation process should be investigated in a future programme of research.

Although recommendations for the use of calcium chloride as a stabiliser were found in the literature review, it was apparent from this study that calcium chloride is not a

suitable stabilising material. In the water absorption tests, the specimens stabilised with calcium chloride dissolved completely after immersion in water for 24 hours.
The cost of the stabilising additives was another variable investigated in the study (Figure 9.1). It was found that, with reference to the cost model, lime provided the most cost-effective solution to the research problem. (See Chapter 7) It is proposed that client, planners and builders should choose the stabilising option that best meets their design needs and investment budget. This means that if a building with a long design life is required, then the cement would be the ideal stabiliser. If, on the other hand, the client has only a limited budget to construct the building, lime or linseed oil would be the preferred options.

However, mixing with sand was found to be the alternative as opposed to using the other stabilisers. The imported earth has a high density and the addition of sand helped to decreases the slippage of earth particles under the pressure.

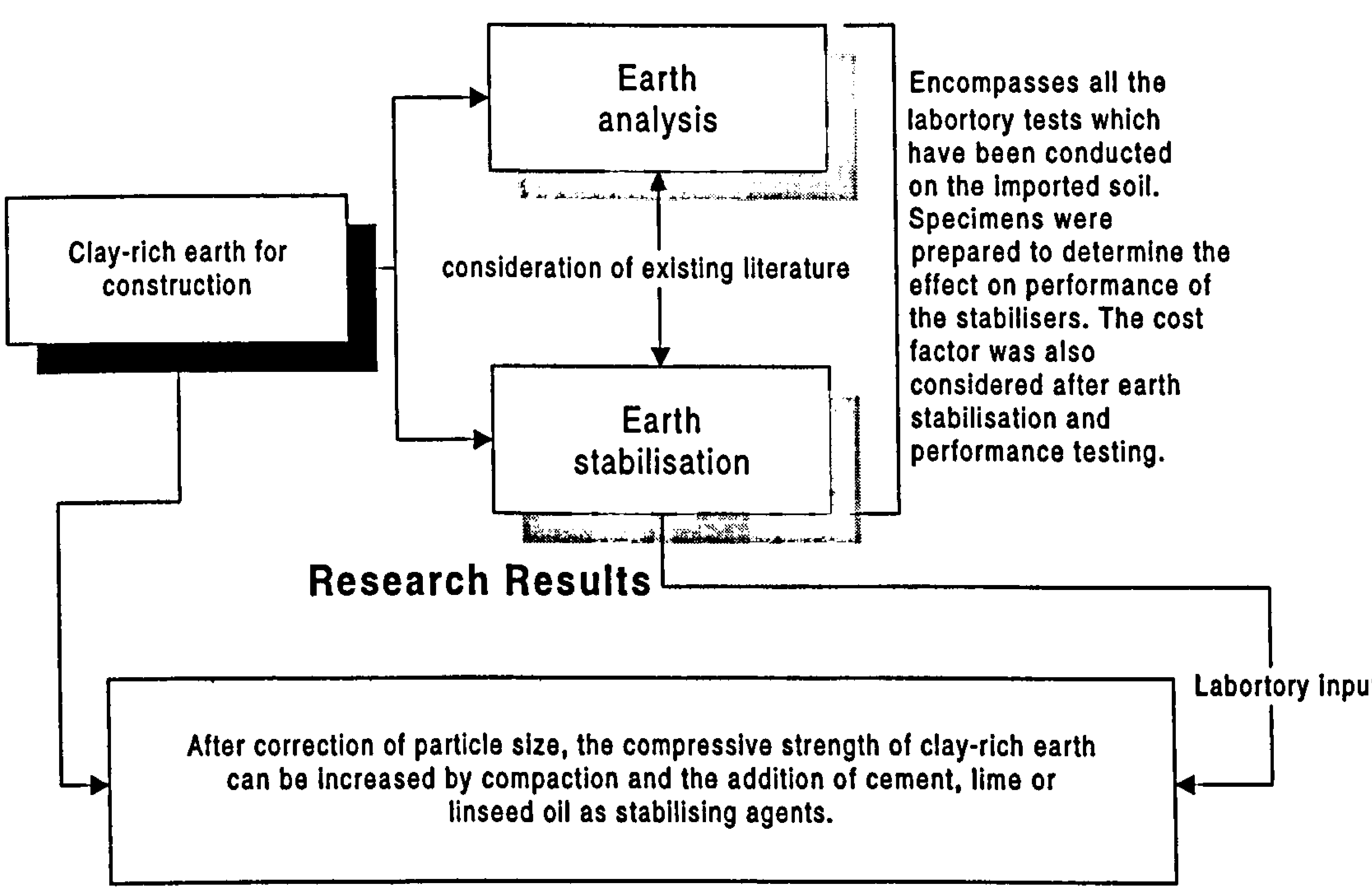


Figure 9.1 Research Conclusion Process

The research methodology of the study was divided into two sections: Problem Description and Problem Solutions.

(a) Problem Description

- Chapter 1 concluded that the most urgent challenge is to gain mass acceptance of appropriate technology, with particular reference to the use of earth as a building material. This will involve overcoming widely held preconceptions and prejudices that earth is a building material for poor and underdeveloped areas. Therefore, social researchers, who are involved in the implementation of appropriate technology, will need to raise social awareness about the merits of using earth.(See Chapter 1 & Section 1.10)

- The parameters for technological improvement to solve the rural housing problem in Sindh were identified in this study. It is recommended that the choice of technology should be based on 'technology blending', (see Chapter 1 & Section 1.4, 1.5) i.e. the innovative combination of traditional and modern construction technologies. Technology blending is considered by the author to be the best approach to solving the current housing problem in Sindh. It takes advantage of the latest advances in technology, whilst preserving the benefits inherent in indigenous technologies, such as energy saving, harmony with the environment and ease to use.

- Three main construction methods are used in Sindh, classified according to the materials and structural systems involved. In rural areas of Sindh, 80% of construction is Katcha. This means that earth is the most commonly used material for house construction. (See Chapter 2 & Sections 2.3, 2.4)

- There is a clear lack of affordable construction materials in rural Sindh, with survey data showing that the mean number of people per house and per room increased between 1981 and 1989. Further survey data indicates that the demand for housing increased during the period 1993-1998. There is also an obvious lack of implementation of housing policy in rural areas. (See Chapter 2 & Section 2.6)

- In low-income residential areas of Sindh, most of the shelter and related services are provided by agencies on an informal, ad hoc basis. There is a need to replace the present system of service provision with one incorporating the use of technically oriented agencies to advise on the choice of material technology, the most appropriate construction methods, etc. (See Chapter 2 & Section 2.10)

- Replacement of earth as a construction material with more durable and weather resistant high technology materials may cause a huge drain to the economy. The relatively expensive high technology materials would not be accessible to rural communities or low-income groups in the region. The economic implications of using modern construction materials drives the need to research more appropriate technologies. The term 'appropriate' technology in this context means that which meets the needs of the user through low cost and ease of handling. (Refer to Chapter1 & Section 1.7, Chapter 2 & Section 2.12, 2.13).

- Traditionally, earth has been used as a construction material for walling, roofing, flooring and foundations. Three different modes of application are commonly used: sun dried mud, wattle and daub and puddle (where mud is applied to walls as slurry). Thatch and bamboo also has a traditional application in the construction of houses in Sindh. (Refer to Chapter 3 & Section 3.2 & 3.3).

- Recent research work in Pakistan indicates that new innovations in construction technology may provide viable solutions to indigenous housing problems, particularly in cases where modern materials provide a cost-effective alternative to current practices. However, the modern construction materials reviewed in this study, require high-energy input.(See Chapter 3 & Section 3.4)

  Evaluation of these modern materials is still at the experimental stage. By contrast, ample data exists from the practical application of, for example, concrete. Use of modern materials is not yet cost-effective, in terms of production costs, when compared to traditional materials. (The new materials may, however, provide benefits such as greater durability that are critical to some projects.) (Refer to the Chapter 3 & Section 3.4).

- The cost of conventional materials used in the construction of modern houses is so great that they are unlikely to be affordable by those currently living in earth dwellings for decades to come. In order to make earth a more effective construction material, current analytical and process methodologies must be improved. This will enable the engineering performance and functionality of earth to be enhanced with respect to evolving construction needs. (See Chapter 3 & Section 3.4).

- Field studies by author identified two main causes of damage to houses constructed with earth (Refer to the Chapter 3 & Section 3.3 (3.3.1, 3.3.2, 3.3.3)):

i. Moisture Migration.

Clay particles in earth are sensitive to the presence of water. Where clay-rich earth has been used as a construction material, the absorption of water commonly results in the propagation of cracks. This is because the clay-rich earth blocks swell in the presence of water and are then subjected to high shrinkage on drying.

ii. Structural Defects

Structural defects also arise when earth stabilised blocks are used on unstable ground or an inappropriate structural system has been adopted. Earth should only be used as a construction material in structures that are designed to act under compression (Figure 9.2). This is because earth has poor strength when under tension or subjected to bending moments.

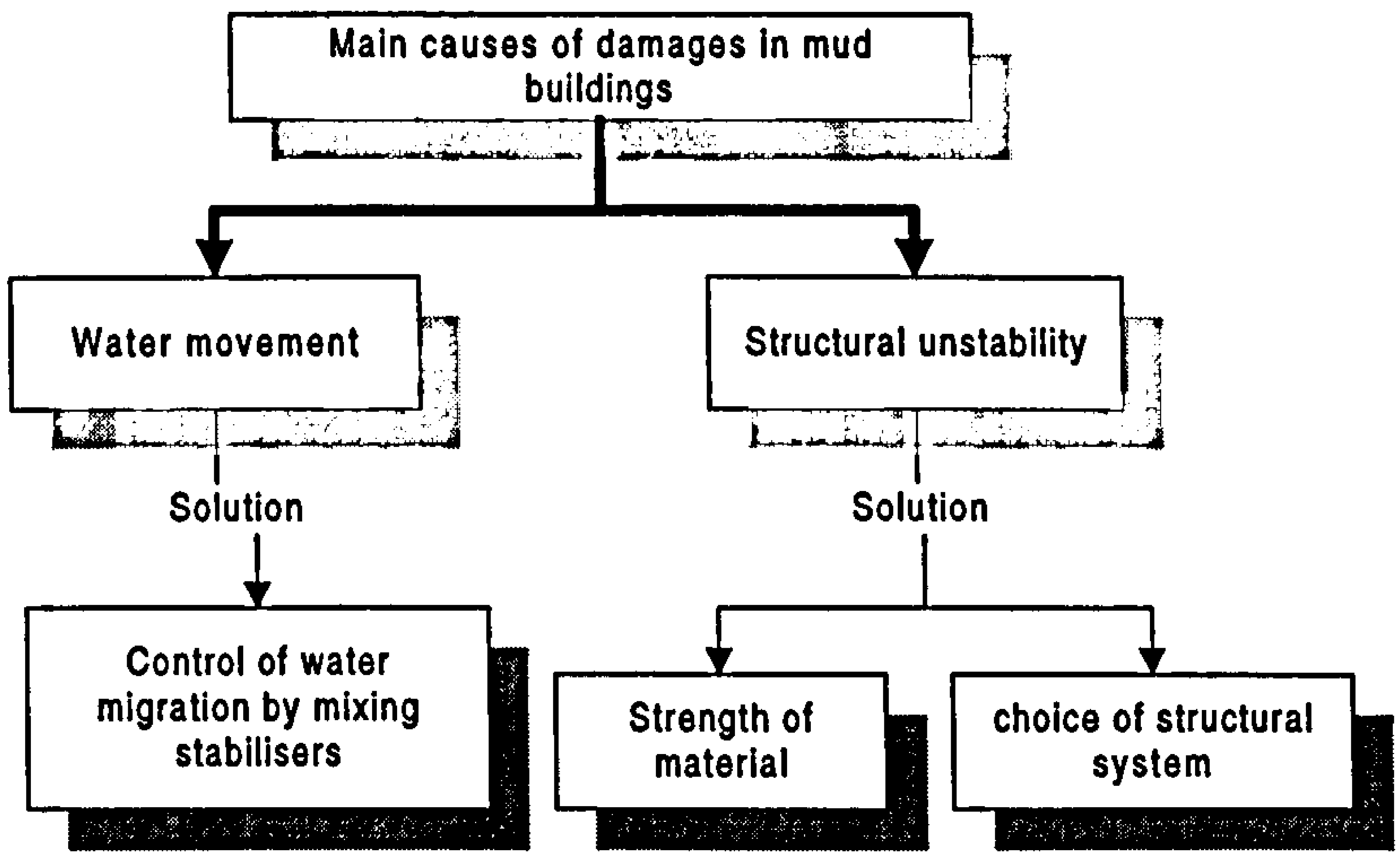


Figure 9.2. Causes of Damages to Mud Buildings and the Solution Path

- During the study of earth and its properties, it was established that earth is created by a long process of erosion of parent rock, followed by physico-chemical evolution of the debris. There are a wide variety of types of earth, which can be described and classified according to their physical and chemical characteristics. (See Appendix B (I)).

- Earth consists of four main types of particle: gravel, sand, silt and clay. Each of these particles plays an important role in governing the stability of the earth. In particular, the activity and amount of clay in the earth affects the structural integrity of a building - even if the earth has been stabilised. (See Appendix B (I)).

- At this stage of the study, the research problem was divided in three sub-problems. These sub-problems were further divided into categories to enable the problem to be more easily addressed. Three main variables were identified; the stabiliser is the dependent variable, with engineering properties and production cost being considered as the dependent variables.(Refer to the Chapter 4).

(b) Problem Investigation

- An earth sample was imported from Sindh and underwent critical field and laboratory tests in order to identify its properties. The index tests indicated that the earth is clay-rich and contains approximately 96% of particles smaller than

0.002mm. The linear shrinkage tests showed that samples placed in a 600mm long mould shrunk by approximately 65mm, i.e. 12-15% linear shrinkage. (See Chapter 5 & Section 5.4 (5.4.1, 5.4.2, 5.4.3)).

- The compressive strength of earth was found to be a function of the friction between particles and was correlated to the density of the material.(Refer to the Chapter 5 & Section 5.4.1)

- All index tests confirmed that the earth requires correction of particle size distribution. They also showed that the material must be stabilised in order to decrease its sensitivity towards water and increase its durability for construction purposes. (Refer to Chapter 5 & Section 5.4).

- Particle size distribution was corrected by blending the earth with well-graded sand. Three percentages of sand addition, 10%, 30% and 50%, were chosen at random. The dry densities and optimum moisture contents of the earth-sand mixes was then measured. The optimum blend for the purposes of stabilisation was considered to be 70-80% earth: 20-30% sand. (Refer to Chapter 5 & Section 5.7)

- The engineering properties of earth are governed to a large extent by the material's physical properties and behaviour. They can be modified through the correction of particle size distribution and the addition of stabilising material. Thus, earth can provide an important contribution to overcoming housing problems and the rising energy costs associated with construction in developing countries. Refer to the Chapter 5 & Section 5.10).

- The earth sample was stabilised using four different additives. Tests were then conducted in order to assess the engineering properties of the stabilised specimens, i.e. compressive strength and water absorption values were determined. The test results showed that cement and lime made the most suitable stabilisers in terms of improving engineering properties of the earth-sand mix. Linseed oil was also considered to be of value as an earth stabilising agent, particularly as it imparted better water resistance than the three other stabilisers under review. However, calcium chloride was not considered suitable for use as a stabilising agent, contrary to recommendations uncovered during the preliminary literature study. (Refer to the Chapter 6 &Section 6.5)

The American Transport Board uses liquido calcium chloride as a stabiliser for ground improvement. As the findings of this study indicate that calcium chloride is not suitable for stabilising clay-rich earth, it is recommended that its use be investigated further in a future programme of research. Certainly, the practical application of this material should not be promoted without warning about its limitations.

- In terms of Proposition I, 70% earth : 30% sand proved to be the optimum mix for improving engineering properties without the addition of stabilisers. However, water absorption remained high. (See Chapter 6 & Section 6.4 (6.4.3 and 6.4.2)).

- The durability of earth stabilised specimens is contingent on the amount and type of additive. Cement as a stabiliser exhibited an adequate durability and low porosity. The durability and porosity tests showed that both cement and lime are suitable for use as stabilising additives (see Chapter 6 & Section 6.4.4).

- All of the proposed stabilisers provided cost-effective means of improving the engineering properties of earth. Cement was the most expensive stabiliser under review, followed by lime. However, where a long design life for a building is required, earth stabilised with either cement and lime provides a more cost-effective solution than concrete. Linseed oil provides the most economic means of waterproofing. (Refer to Chapter 7 & Section 7.4).

- In terms of Proposition II, cost was found to be directly proportional to the type and amount of stabiliser used. (See Chapter 7 & Section 7.5)

- Cost was also found to be directly proportional to compressive strength, i.e. if greater strength a is required, then the cost increases. In other words, performance of the earth stabilised blocks was found to be directly proportional to investment(See Chapter 7 & Section 7.5):

$$\textbf{Cost} \propto \textbf{performance}$$

$$\textbf{Performance} = f\ \textbf{(Stabiliser+compaction force)}$$

$$\textbf{Again, Performance} = f\ \textbf{(type of stabiliser)}$$

$$\textbf{Cost} = f\ \textbf{(type and amount of stabiliser)}$$

NB. Performance = water absorption +compressive strength + porosity & durability
Low water absorption and high compressive strength can achieve an adequate performance. This quality can also be confirmed by achieving low porosity and high durability percentages (See Chapter 7 & Section 7.5).

- The specimens stabilised with cement showed the highest compressive strength of all the stabilised specimens. However, cement is the most expensive additive and lime was found to provide satisfactory engineering properties at lower cost. These results help to identify an appropriate additive for stabilising processes in Sindh (See Chapter 7 & Section 7.5 Figure 7.11).

- The structural system chosen when using earth stabilised blocks must, due to the nature of the construction material, be one that operates under compression. (See Chapter 8)

- Although earth has many limitations as a construction material, it is able to provide various aesthetic perspectives in terms of building design. The architectural flexibility of earth stabilised blocks stems from the ease with which the material can be moulded into desired shapes. (See Chapter 8).

- Structures built of earth and earth stabilised blocks must be protected from moisture, including high humidity, and structural defects caused by, for example, unstable ground. Structural stability of a building requires stable foundations and the design of appropriate load bearing systems. This statement was made in the field testing section. (Refer to Chapter 3 & Section 3.4 and solution to this problem was discussed in Chapter 8 & Section 8.3)

- The bonding system for blocks was identified as an important contributing factor to the increased stability of block masonry. (Chapter 8 and Section 8.5)

- It was found that earth is unable to accommodate the application of significant tensile forces or bending moments. Thus, in terms of roofing systems, vaults and domes provide the most suitable options. (Refer to Chapter 8 & Section 8.9)

- The amount of stabiliser in renders must correspond to the amount used for stabilisation of the blocks to facilitate bonding between mortar and masonry. Use,of a wide variety of renders to cover block masonry structures was reviewed in this study. (Refer to Chapter 8 & Section 8.10)

9.2 Recommendations

The following recommendations are made based on the findings of this study:

9.2.1 Architectural Considerations

There is a need to conduct further research on the architectural flexibility of construction materials. In particular, the capacity of stabilised earth to be integrated with contemporary architecture forms and functions should be investigated. It is uncertain at this stage whether earth stabilised material can meet the demands of variation in design, not only in terms of form perspective but also in terms of ornamentation and decoration. Special attention should be given to sustainable and energy saving design considerations. Compatibility of stabilised blocks with various walling and roofing systems also needs to be evaluated.

The properties of different earth stabilised blocks must be investigated to determine, for example, the most suitable additives for use in different climatic conditions. Clearly, areas with heavy rainfall will require the use of additives that impart waterproofing properties to the stabilised blocks. This measurement and material investigation should encompass the use of overhangs and projections to protect structures from the elements.

9.2.2 Effect of Stabilisers on the Thermal Conductivity of Earth

An important consideration when determining the suitability of a stabiliser is its effect on the thermal conductivity of the earth. In particular, the stabiliser should not reduce the insulating properties of earth. Nonetheless, some additives that modify the thermal conductivity of earth are widely used in the stabilisation process because they impart other beneficial characteristics. For example, bitumen is a popular choice where good protection against water is required. However, it is recommended that future research should focus on materials that neither increase nor reduce the thermal conductivity of earth e.g. in the case of bitumen it can be assumed that heat absorption rate of material/block increased due to additive material's properties.

The following factors should be considered in conjunction with the stabiliser's effect on thermal conductivity of the earth:

- The amount of stabiliser used should be based on the linear shrinkage of the earth after correction of particle size distribution. The research showed that it is essential to correct particle size distribution prior to stabilisation process. The addition of sand may reduce the amount of stabiliser required and, hence, cost. The relationship between addition of sand and reduced cost of stabilisation needs further investigation.

- Locally availability and ease of handling by local people must both be considered when assessing the suitability of a stabilising material. A locally available material will ensure minimal transportation costs and negate the need for foreign currency transactions to secure overseas supplies.

- The choice of stabiliser should take into account health consideration, e.g. respiratory problems have been linked to the use of bituminous material.

- Extensive data should be available on the impact of a stabilising material on the engineering properties of earth before it is considered as an option for practical application. This will reduce the risk of the construction material failing to meet the required specifications of the project.

9.2.3 Structural Systems

When earth stabilised blocks are used in conditions of soft or unstable ground, concrete must be added to the foundations. Previous research has also shown that earth stabilised blocks can only be used to construct buildings to a maximum height of three stories. It should be noted, though, that adobe buildings, such as those in Yemen, have been built historically to greater heights. The choice of structural system and design plays a key role in determining the stability of mud buildings. It should be born in mind that earth is suitable for construction purposes only where structures are under compression.

Wall masonry and bonding patterns must be designed carefully. In addition, plasters and renders should be prepared using the same percentage of stabiliser as the blocks. Care must also be taken in roof design and where, for example, vaults and domes are considered appropriate, a skills audit of local labour should be carried out prior to formulation of the project's feasibility document. Proposed roofing techniques might not conform to traditional construction methods in the area and, in such cases, training of the workforce will be necessary prior to commencement of the project. (Refer to the Chapter 8).

9.2.4 Increasing the Tensile Strength of Earth Stabilised Blocks

There is a great need to find ways of increasing the tensile strength of earth in order to improve its architectural flexibility. Research is required to determine whether tensile strength might be significantly increased by reinforcing stabilised blocks with fibres of, for example, steel, straw, polythene or plastic. Earth stabilised slabs, produced by adding coarse sand and longitudinal reinforcement, might prove suitable for flat roofing. In this situation, protection of the roof against water would also have to be considered.

Many ideas and techniques used in concrete technology might be applicable to increase the tensile strength of earth for roofing systems. Recently from Internet surfing the Nadir Khalili's (CAL Earth) work came prominently with reference to increasing tensile strength of super adobe houses by using steel wires. However, the use of steel wire will definitely increase the cost of construction.

9.2.5 Standards and Specifications for the Production of Earth Stabilised Blocks.

It is important that specifications are developed for the production of earth stabilised blocks in Pakistan. The provision of regional specifications will require more extensive research in this field. Codes and specifications can be developed by referring to international codes and practices, as well as by arranging seminars and discussion groups on earth construction technology.

9.2.6 Socio-political Awareness for Adoption of Appropriate Technologies

A critical factor of success in the adoption of appropriate technologies is adequate promotion to ensure public awareness of the use traditional materials. It is essential that this awareness pervades all levels of construction practice, government planning and new research into ways of modifying traditional materials and construction techniques. Government policies for rural housing and urban low-income housing should contain proposals for the effective use of indigenous technologies.

It was found during the study that, in many rural areas of Sindh, there is a long established practice of community involvement in the construction of earth dwellings. This involvement gives occupants an understanding of earth buildings, which means that they understand the importance of proper maintenance and repair. Thus, the occupants will take responsibility for construction, maintenance and repair of the house.

9.3 Significant Contributions to the Field of Earth Stabilisation

The body of research undertaken for this study makes a significant contribution to the field of earth stabilisation and, more broadly, construction technology in developing countries. Fundamentally, this research has established that the physical properties of the raw material must be taken into account when deciding on the choice of stabiliser.

The stabiliser must be capable of modifying the engineering properties of earth by one of three modes: mechanical, physical or chemical. These modes operate through the following methods: densification, reinforcing the earth, binding earth grains, (ii) creating linkages between earth grains, reducing water permeability or water repulsion.

This study presents the following key research findings that contribute to the field of earth stabilisation:

- In previous research, lime has been found to be the most suitable additive for use in the earth stabilisation process. The findings of this research indicate lime is not the most suitable stabilising additive in all cases. In clay-rich earth, for example, it did not provide the greatest improvement to engineering properties among the stabilisers tested. The lime stabilised specimen exhibited high water absorption, which rules out its use in wet or semi-wet regions.

- It is not necessary to use stabilisers to improve the engineering properties of earth. Significant improvements can be made by correcting particle size distribution alone.
- Linseed oil stabilised specimens exhibited excellent water resistant characteristics. Further research is required to assess the suitability of vegetable oil as a stabilising agent. Although the imported earth possesses adequate compressive strength, it is highly sensitive to water. Under these circumstances, oils might prove to be highly effective stabilisers.

9.4 The Significance of the Research

This study emphasises the benefits of technology blending in which the optimum use of indigenous technologies is made, in conjunction with the latest advances in construction technology. By leveraging the benefits of indigenous technologies, Sindh can be self-reliant in terms of construction materials and technologies. Earth stabilised blocks have low production costs and consume less energy during manufacture than modern construction materials, e.g. concrete. In addition, there are no environmental hazards associated with the production of earth blocks.

In their drive for modernisation, many developing nations utilise technologies that have been borrowed or slightly adapted from developed countries. By placing such reliance on developed countries to meet their technology needs, these developing nations are often encumbered with expensive, ill-adapted and socio-economically damaging technologies. The socio-economic damage stems from the displacement of traditional skills and indigenous materials, resulting in local labour and other resources being under-utilised. This sort of damages has focused much attention on constraints on technological development in developing countries.

Most national policy makers and development experts now agree that indiscriminate technology transfer is not a source of self-sustaining growth for developing countries. This research supports the agenda of self-sustaining, low cost and environmentally friendly housing solutions for regions and countries.

This study provides a template for the effective use of indigenous technologies, with particular reference to improved earth-based construction. It is intended that the provision of this information will help to promote the best uses of traditional technologies. Figure 9.2 shows the process of research and adaptation of technologies.

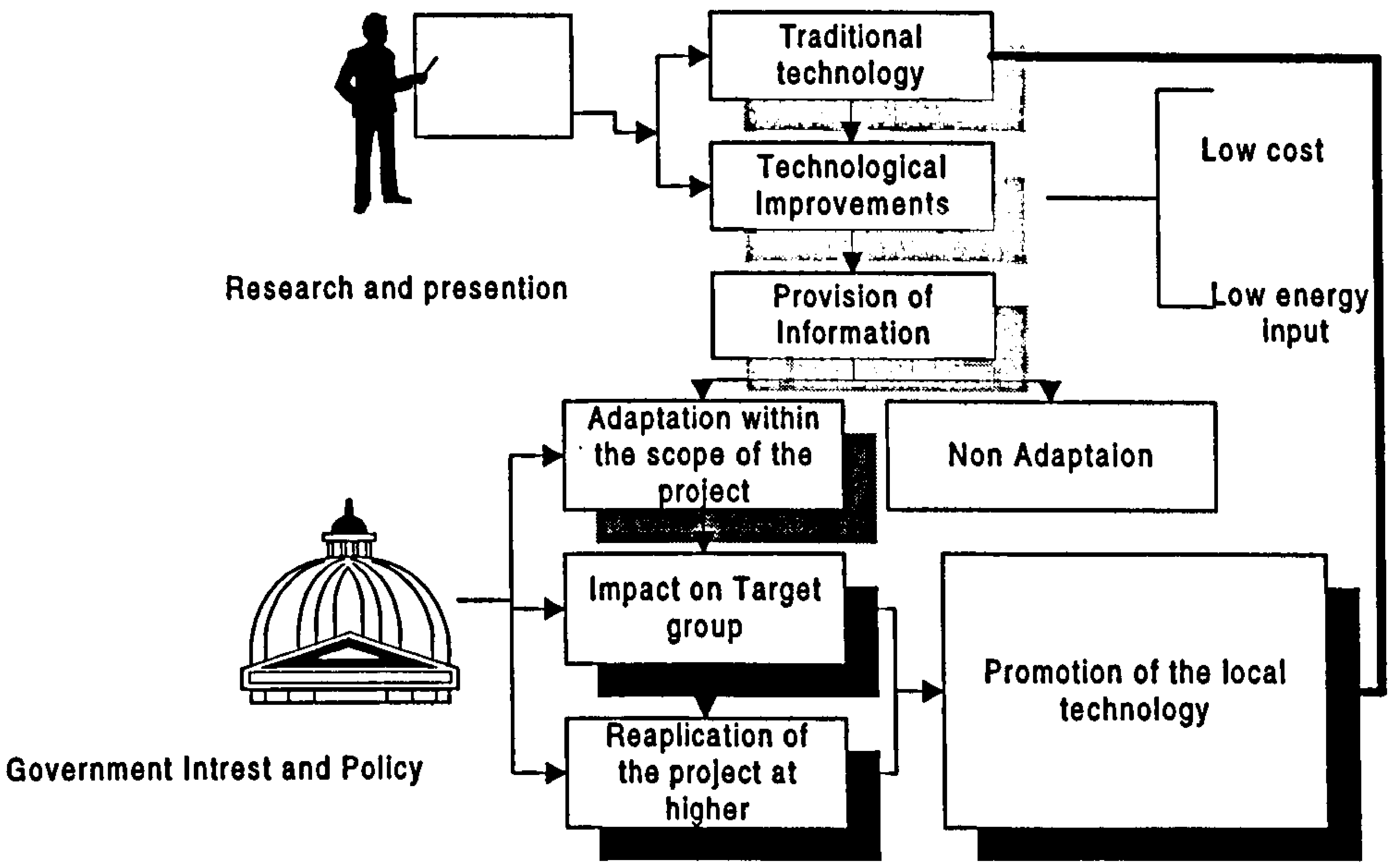


Figure 9.2. Promotion of Technologies

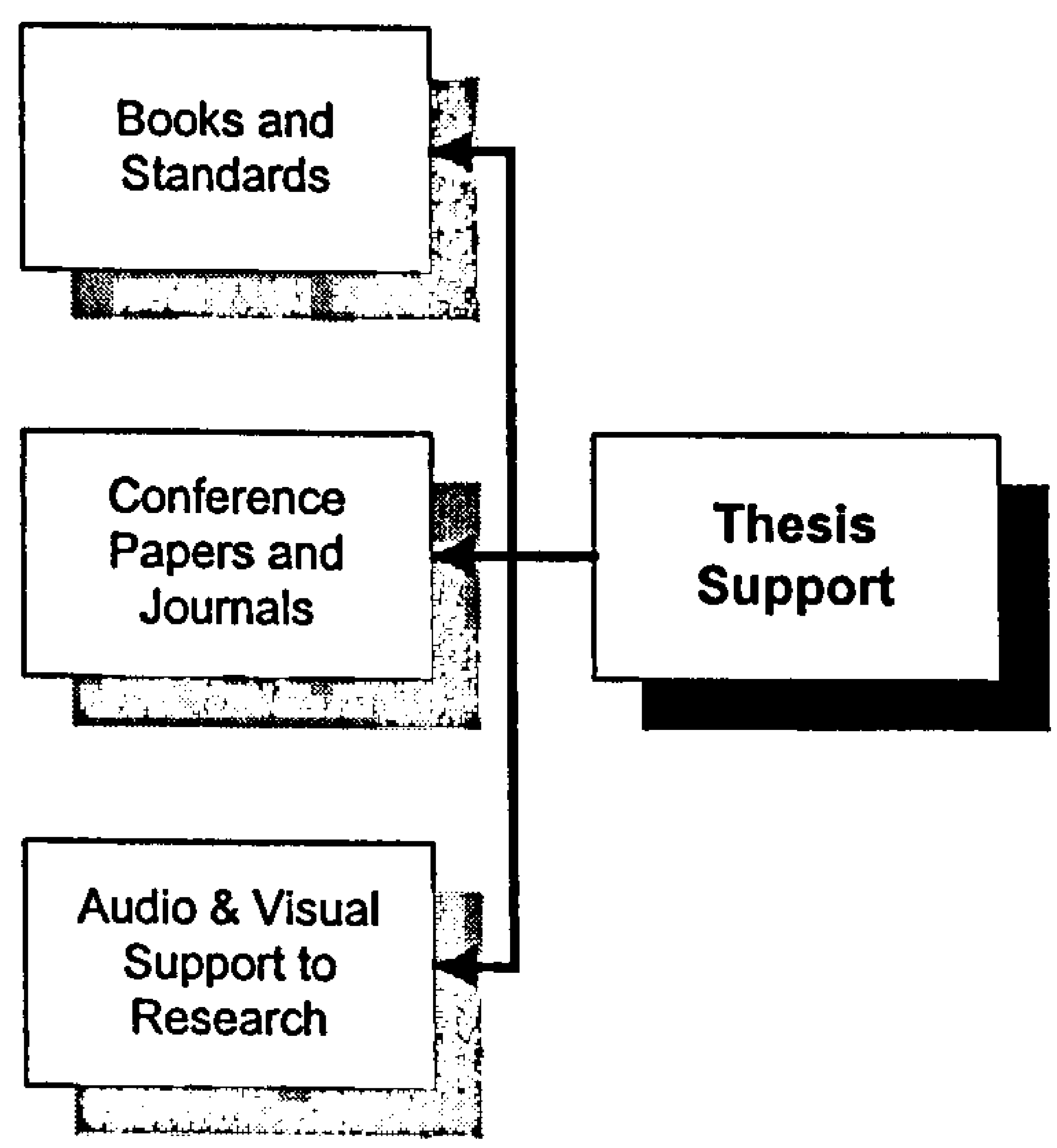
9.5 Proposal for Future Research

This study demonstrated that clay-rich earth, stabilised with a choice of different additives, makes a suitable construction material. However, it was found that the low tensile strength of earth places a significant limitation on its functionality as a construction material. For example, its low tensile strength restricts the variety of designs that can be achieved and, in particular, earth can not be specified for use in flat roofing systems with any confidence. Thus, the proposed research will examine different ways in which earth blocks might be used in roofing systems.

The proposed programme of research should evaluate a greater diversity of additives and their effect on the engineering properties and thermal conductivity of earth. Attention should also be paid to the nature of testing to determine physical and chemical properties of the earth. In this study, the engineering properties of stabilised earth specimens were determined using mostly laboratory-based tests. However, these tests were developed originally for earth stabilisation in road improvement projects. It is, therefore, considered necessary to develop bespoke laboratory tests that will provide the specific information about engineering properties of earth stabilised specimens that building and construction practitioners require. In addition, the proposed research should also include a programme of development for on-site testing to meet the needs of the building materials sector.

A further area of the proposed research is the development of a computerised database containing all data for various types of the earth. Without recourse to further analysis, this knowledge-based system should enable users to establish whether correction of particle size distribution in a particular sample is needed. If correction is necessary, the software should provide details about the fraction to be removed or the amount and grade of material to be added. The programme will also support decision-making in terms of the selection of stabilising material based on the properties of the earth. For example, such a computer package would indicate the need for a binding agent, waterproofing agent, stabiliser to create linkages between grains and etc.

This type of knowledge based system would establish the feasibility of a whole project quickly and at low cost. This type of computer programme can be developed using FORTRAN and C++ languages in the case of available resources and time to researches.



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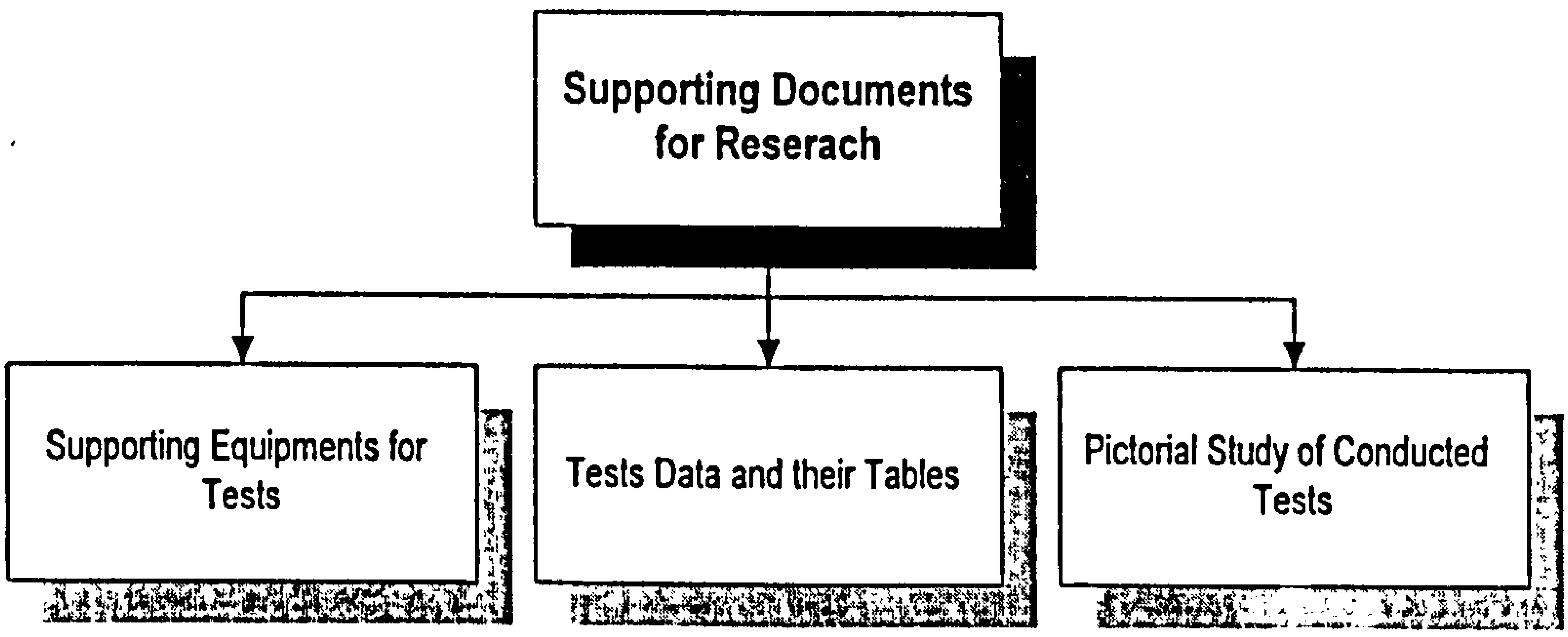
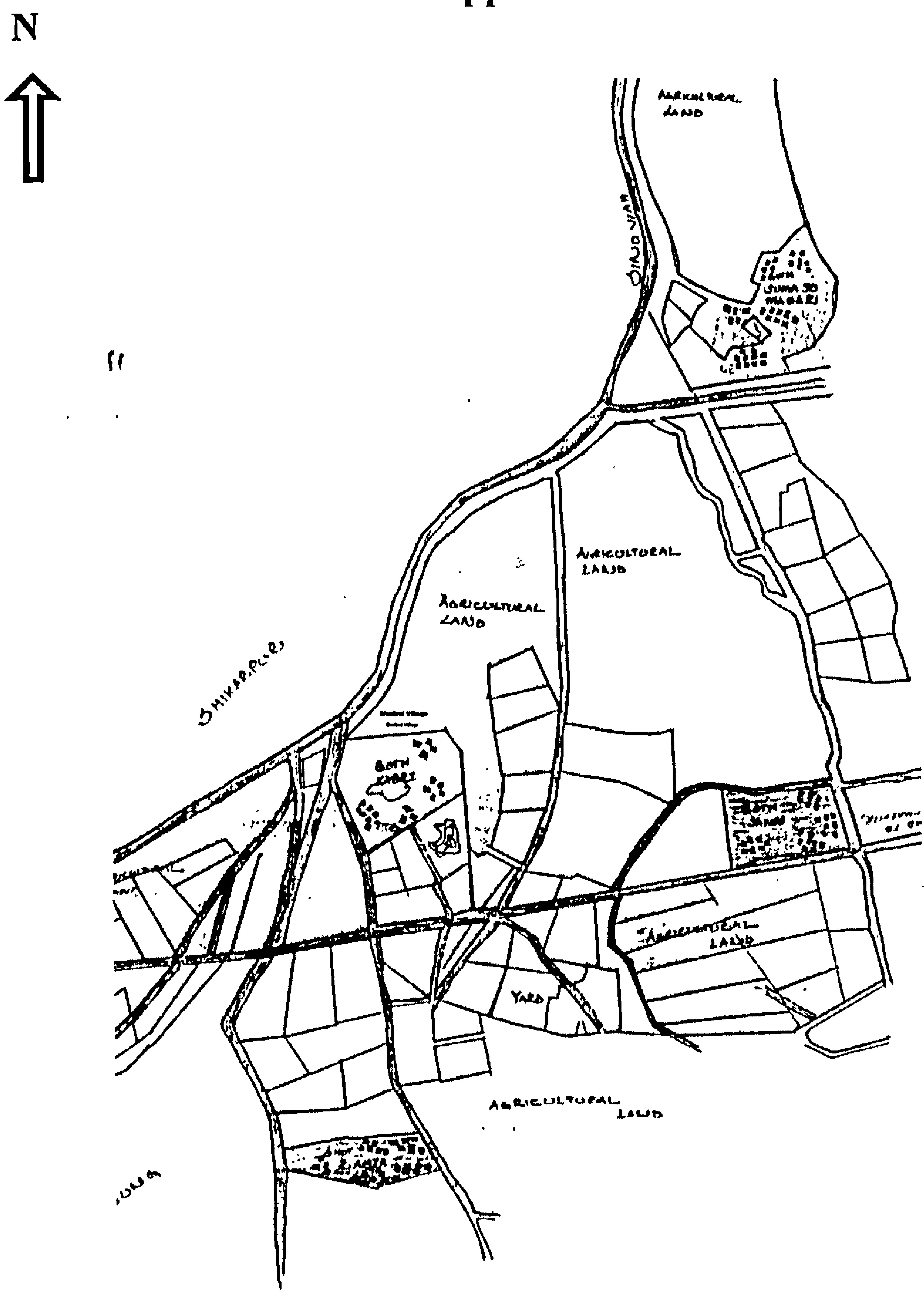

Supporting Documents for Reserach
Supporting Equipments for Tests
Tests Data and their Tables
Pictorial Study of Conducted Tests

APPENDICES

Appendix A

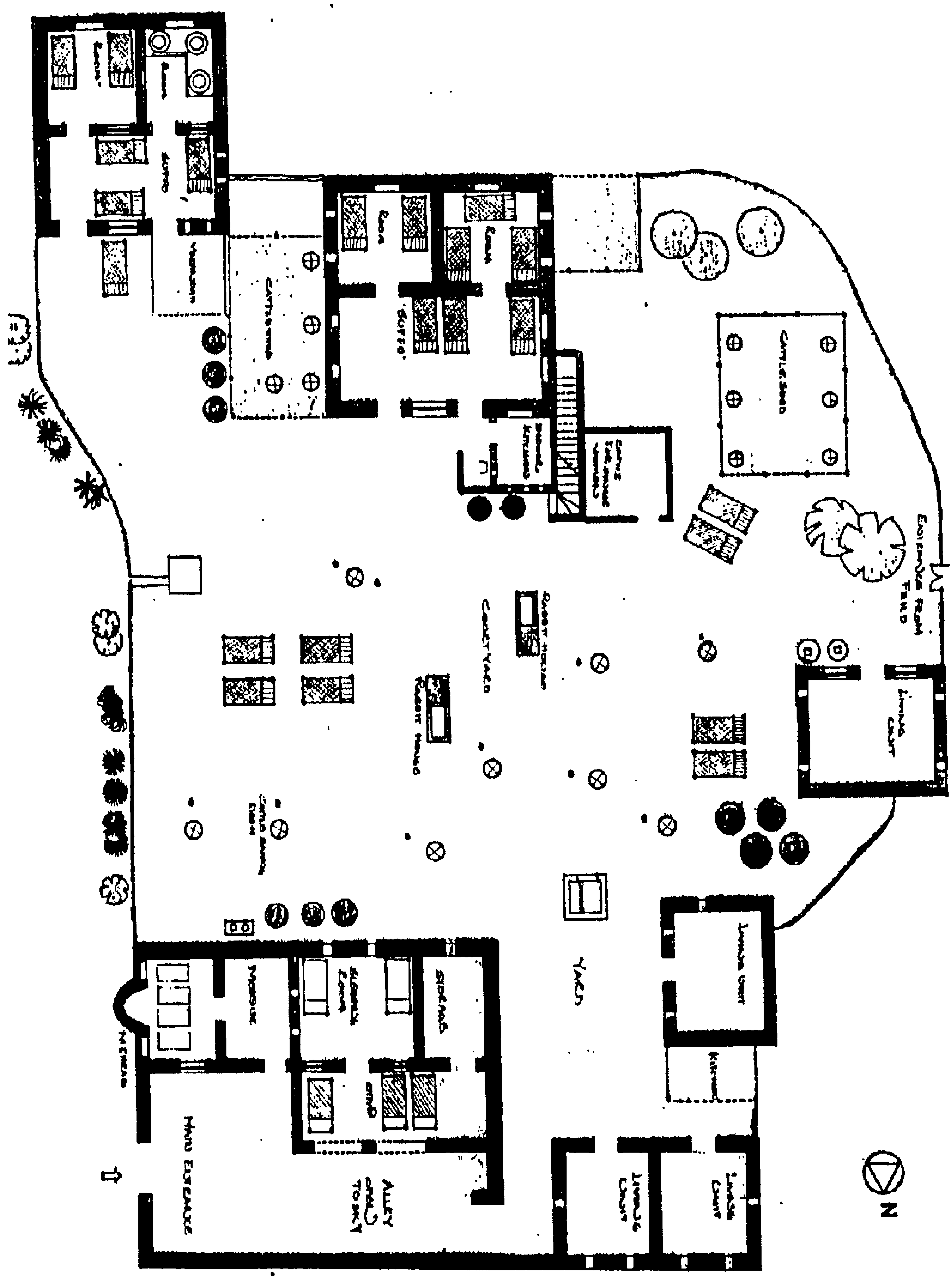


Location of villages surrounded by agricultural land and water channels

Deh Taayab
District Shikarpur
Division Sukkur
Scale: 1 inch = 1660

Shaded area = Villages
Cultivated and uncultivated land

Appendix B



A House Plan Consists of Three Units

Appendix B (I)

Use of Earth as Building Material

To understand the nature of earth as building material, it is necessary to investigate earth formation. This is the process of erosion of the parent rock and its physico-chemical deterioration due to climatic influences. The characteristics of earth are described prior to studying improvement that can be made when used for construction. The composition of earth is also discussed. The presence of air and water in earth encourages deterioration in the materials structure. Thus study of the particulate system and nature of earth, as well as its deformation, is necessary in order to understand the transformation of forces within earth grains. The availability, thermal performance and energy consumption of earth as building material is also considered when evaluating the use of earth in a rural context.

Dwellings constructed with earth range in scope and scale from huts to splendid palaces and ranging from small villages to Imperial City. (1)(2)(3) These are three main methods for using earth as building construction material: (i) Structural (ii) Monolithic (iii) Brickwork.

Table 3.1 Structural Method

Earth-sheltered space	The structure which is built with other material and covered with earth or encased with earth.
Fill-in	Earth is used to fill-in the hollow material used as frame work
Straw clay	Slurry consisting of clay earth bound with straw fibre to produce a fibrous material
Cob on posts	Earth applied in a thin layer to fill the posts' support
Daubed earth	Clayey earth mixed with fibres is applied in a thin layer to fill in a support.

(3)(3)

Table 3.2 Monolithic Method

Dug-out	Shelter directly dug out of a layer of the earth's crust
Poured Earth	Earth in a liquid state is poured in form work or moulds serves as kind of concrete
Stacked Earth	The piling of earth balls on top of one another.
Direct Shaping	Walls are built up by manual shaping of plastic earth.
Rammed Earth	Earth poured in form work and compressed it by static or vibrating presses

(2)(3)

Table 3.3 Masonry Method

Tamped blocks and compressed blocks	The walls made of compressed blocks with specific pressure and moulded or in form work.
Cut blocks and sod	Blocks directly cut from the ground
Extruded earth	A powerful machine extrudes an earth paste from wheel building elements are then made.
Machine moulded adobe/Hand moulded/Hand shaped adobe	The earth is moulded by hand or by wooden moulds into various shapes.

(2)(3)(4)

Nature of Earth Material

Earth is a product of the decomposition of solid rock. Wind, water and ice can all act to slowly turn rock into earth. (5) Rocks can be categorised into three basic types; igneous, sedimentary, and metamorphic. (6)

Earth can be defined in process terms as a 'heterogeneous collection of mineral and organic fragments whose disintegration has been brought by physical, chemical and biological forces working singly or in combination. The formation and development of the earth is the result of the more or less simultaneous interaction of three different processes. (3)(7)(8) These are described below:

(i) Transformation of the parent rock

When parent rock is laid bare by erosion, a number of climatic factors immediately start to act on it e.g. sun, rain frost and wind. The parent rock, which may be hard (e.g. granite, schist, sand), soft (e.g., chalk, marble, clay), or loose (e.g. sands, scree, loess), is cracked, broken up into smaller components, and dissociated. Finally, climatic factors bring about chemical changes.

ii) Further alteration by organic material

The dissociated and altered earth, composed of minerals, is then colonised by flora and fauna, which enrich it with chemical and organic substance known collectively as humus. The properties of the humus differ with climate, the parent rock, and the vegetation.

Under the influence and of organic matter climate, the minerals in the earth continue to be altered. The new undeveloped earth is homogenous and its physical, chemical and biological characteristics are constant. (9)

iii) Vertical leaching of soluble minerals

In leaching, the soluble minerals migrate downwards. In the areas with high evaporation rates and dry weather the minerals migrate to the surface, enriching the earth. The speed of migration of minerals and organic compounds is determined by climate, permeability of the earth and the kind of humus formed. It creates more or less distinct layers of earth, which constitute horizons, or profiles by pedologists, or earth scientists. (10)

There are two main groups of earth. (i) Young and (ii) Developed earth. Young earth is a shallow earth, not much different from the underlying rock, and often comprises of a single horizon. 'Developed' earth, is deep, and typified by a succession of leached and enriched horizons. (11)

Earth Composition

Earth is basically made up of varying proportions of four types of material: gravel, sand, silt and clay. However, there are two more materials contained in earth; colloids, and organic matter that may also be considered in context of earth stabilisation process. (12)(13)

Each component material behaves in characteristic ways; for example when exposed to variations in humidity. Some will change in volume, others will not. Sand and gravel are stable, silt and clay unstable. This notion of stability, i.e. the ability to maintain physical conditions of altering humidity and dryness is fundamental importance in a building material. (14)(15) (16) Following are the description of particle composing earth.

Description	Grain Size
Gravel	60.00 mm to 2.00 mm
Sand	2.00 mm to 0.06 mm
Silt	0.06 mm to 0.002 mm
Clay	less than 0.002 mm

British Standards Grading, BS

Description	Grain Size
Gravel	100.00mm to 5.00mm
Sand	5.00 mm to 0.08 mm
Silt	0.08 mm to 0.002 mm
Clay	less than 0.002 mm

American Society for Testing Material, (ASTM).

Gravel

This is made up of pieces of rock of varying hardness, the size of which ranges between approximately 2mm and 60mm (BS grading) or approximately 5mm to 100 mm (ASTM grading). They form a stable constituent of the earth. Their mechanical properties do not undergo any detectable change in the presence of water. (13)(16)

Sands

These are made up of mineral particles, the size of which ranges between approximately 0.06 and 2mm (BS grading) or approximately 0.08 to 5.0 mm (ASTM grading). There are also stable constituents of earth, but lack cohesion when dry and have a high degree of internal friction, i.e. great mechanical resistance to movement between the particles. When moistened, however, the particles display apparent cohesion as a result of the surface tension of the water occupying the voids between them. (14)

Silts

Silts are made up of particles the size of which range between approximately 0.002 and 0.06mm (BS grading) or 0.002mm to 0.08 mm (ASTM grading). They have little cohesion when dry and as their resistance to movement is generally lower than that of sands, they display cohesion when wet. When exposed to different levels of humidity, silts swell and shrink, changing perceptibly in volume. (13)

Gravel, sand and to a lesser extent silt, are therefore characterised by their stability in the presence of water. When dry, they have little or no cohesion and so cannot be used on their own as building materials. (15)

Clays

Clays are the finest fraction of earth, having grain size of less than 0.002mm according to both BS and ASTM standards. They have completely different characteristic compared to gravel, sand and silt. Clays consist mainly of microscopic mineral particles, such as - Kaolinites, Micaceous and Montmorillonites groups.

Some experts discussed that the most common clay types can be classified based on the following groups: Montmorillonites (extremely expansive), Mica, Vermiculite, Chlorite, Kaolin (inert), and Interstratified. It has also been argued that, mineralogically and chemically clays can be divided into five main fractions: Kaolinites, Vermiculite, Illite, Chlorite and Montmorillonites. (13) Clay particles are coated in a film of adsorbed water and are so minute and are light in weight compared with the surface tension forces occurring in the film of adsorbed water. Thus volume forces are low relative to surface forces. (13)

The film of adsorbed water adheres strongly to the clay layers and links micro-particles of the earth together. It is this adsorbed water that gives clay its cohesion and most of its mechanical strength. It can only be eliminated by advanced desiccation. (9) Clay imparts its cohesive properties to earth, acting as a binding agent between the coarser particles, which form the skeleton of the earth's structure. (12)

Unlike sand and gravel, however, clays are unstable and are very sensitive to variations in humidity. They are hydrophilic and, as the moisture content rises, the films of adsorbed water become thicker and the volume of the clay increases visibly. Conversely, as the clay dries, shrinkage cracks can appear, reducing its compressive strength. When later exposed to moisture, these cracks form channels through which water can penetrate to the heart of the material. These phenomena form what is known as the 'swelling-shrinkage' property of the earth. This property is more pronounced in clay-rich earth and varies with moisture content. (11)(12)

Colloids

Colloids are fine particles, less than 0.002mm in diameter, which form gluey substances. They result from the decomposition of minerals and organic matter in the earth. Clay is the main mineral colloid. (16)(17)

Organic matter

Organic matter comprises micro-grains and fibres resulting from decomposition of plants and earth fauna. It has a spongy or stringy structure and smells like decaying wood. The particles of organic matter can range in size from several millimetres to several centimetres. (16)

Air and water presence in earth

Air

The presence of air weakens the earth and so is undesirable when the material is used for construction purposes. It also entraps micro-organisms and water vapour, both of which can cause deterioration of earth structures. (18)

The presence of air in earth may also facilitate the entry of bacteria and moulds through air voids. This can then cause health problems for the building's inhabitants, particularly at night due to the exothermic properties of earth walls. This aspect of using earth as a construction material requires further research. In addition, air channels allow the penetration of water vapour.

Water

Water plays an important role in determining the properties of earth. (24) Five mechanisms of water penetration are studied:

1. Free water moves under capillary action, which is affected by gravity, ground water movement, atmospheric pressure and temperature. However, water that accumulates in fine pores on the surface of grains is not absorbed. This water is eliminated at room temperature.(24)
2. Pore water is retained in fine pores within the earth when capillary forces are greater than hydrodynamic forces. This water can be eliminated at room temperature after a long drying period, or when dried in a kiln at between 50-120^{o}C. (24)
3. Adsorbed water forms thin films that adhere to grain surfaces by polar and electrostatic forces and ionic hydration. These bonds are weak and so the water can be eliminated at room temperature.

4. Absorbed water also forms thin films that adhere to grain surfaces by polar and electrostatic forces and ionic hydration. These bonds are strong and so the water can not be eliminated.
5. Structural water is the term given to hydroxyl groups that form solid crystalline networks. In order to eliminate structural water, the earth must be heated to approximately $600^{\circ}C$. (25)

The moisture content of earth varies from site to site because of different types and amounts of entrapped water, as well as variations in relative humidity in the atmosphere. In tropical and arid areas, the moisture content of earth varies as a result of temperature fluctuations, which increase movement of ground water. (23)

For the purposes of routine earth testing, moisture content relates only to the water that can be removed by oven drying at $105\text{-}110^{\circ}C$. Therefore, the water described under Mechanism 1 above is not taken into account in the determination of moisture content because it is eliminated at room temperature. Oven drying of tropical earth should be avoided due to the possibility of structural water being eliminated. (9) Moisture content is calculated on the basis of oven-dry mass of the earth and is usually expressed as a percentage. If the mass of water removed by drying at $105^{\circ}C$ is denoted by m_w , and the mass of dried earth by m_D, the moisture content, w, is given by the equation: (26)(27)

$$w\ (\%) = m_w / m_D \times 100$$

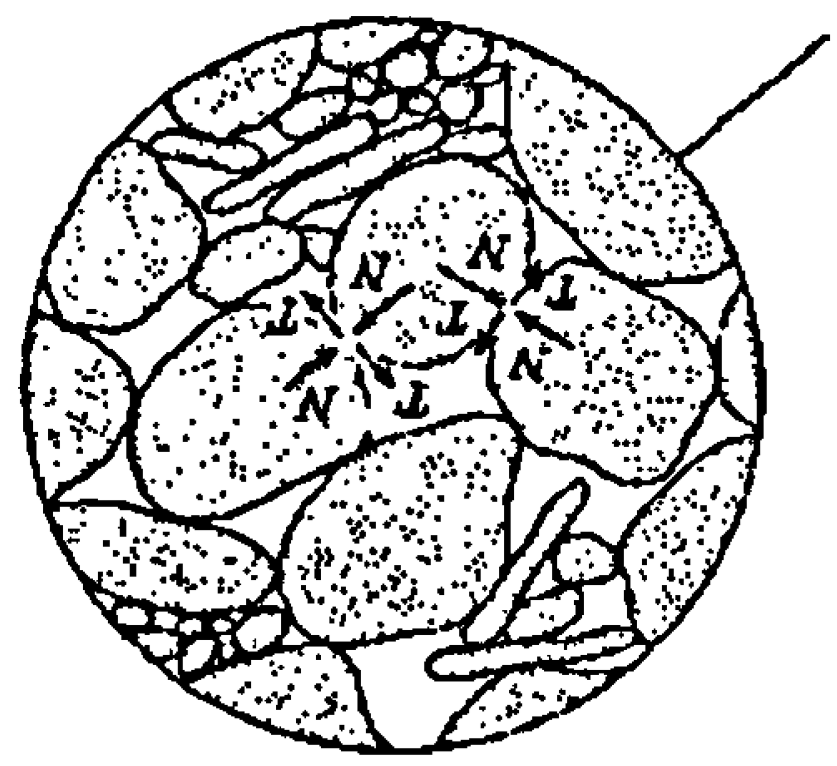
The Particulate Nature of Earth

The word 'particulate' is defined as "of or pertaining to a system of particles". (25)(27) Earth is composed of discrete particles, many having such a fine grain size that they can only be resolved using microscopic techniques. Only weak bonds exist between these discrete particles and so they are relatively free to move with respect to one another. However, the degree of movement is much less than that found in a fluid. The fact that earth is inherently a particulate system distinguishes earth mechanics from solid mechanics and fluid mechanics. Indeed, the science that encompasses the stress-strain behaviour of earth can be thought of as 'particulate mechanics'. (27)(28)

The following section examines the consequences of the particulate nature of the earth.

Nature of earth deformation

The nature of earth deformation can be analysed by transmitting an applied force through the material. Contact forces develop between adjacent particles and can be resolved into components that are normal (N) and tangential (T) to the contact surfaces (see Figure 3.1). Individual particles deform as the result of these contact forces. The most usual type of deformation is elastic strain in the immediate vicinity of the contact points. (27)

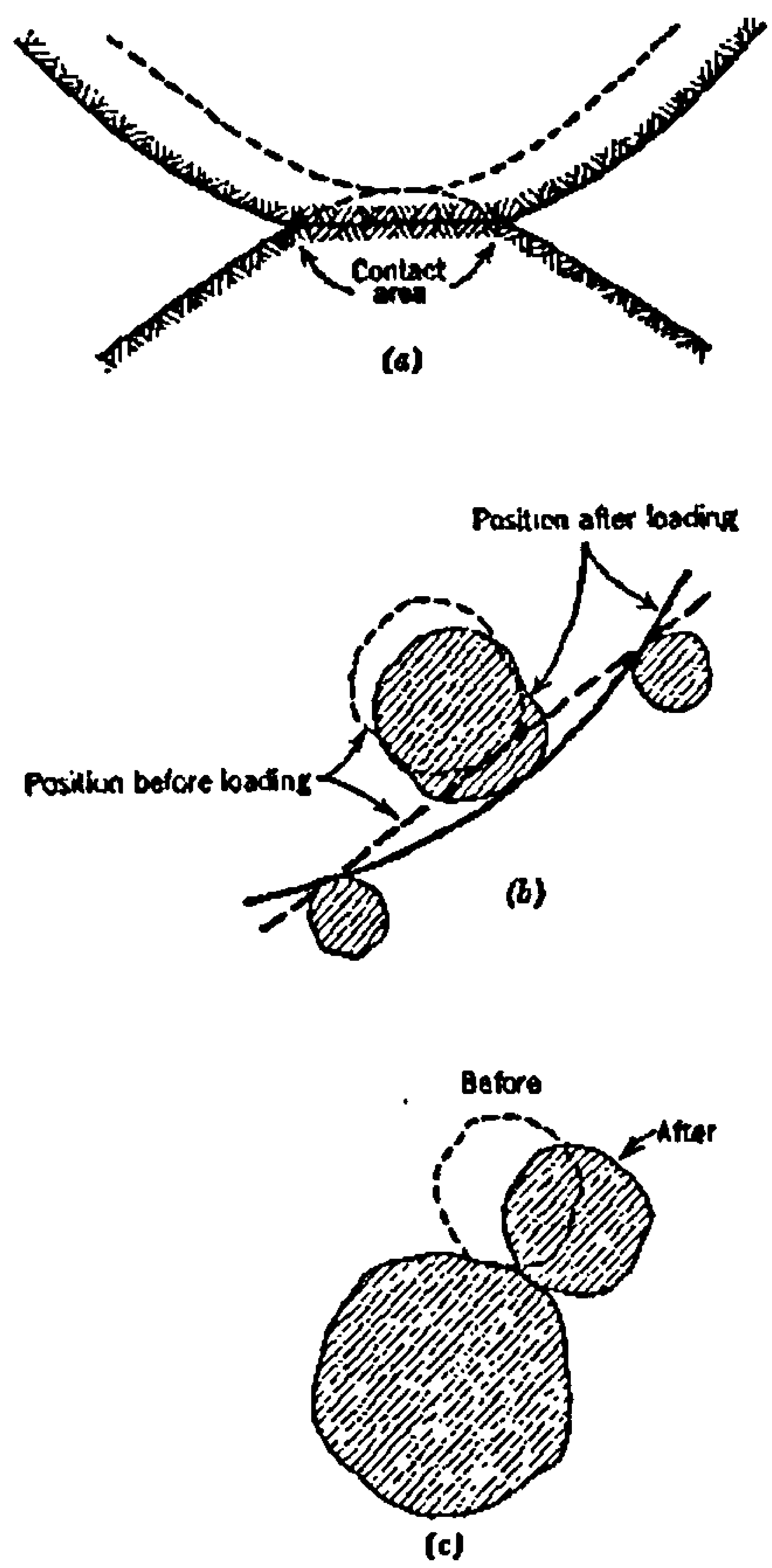


(27)

Figure 3.1 The nature of earth's transmission of applied forces

Deformation associated with any crushing of particle forces the centres of particles closer together and results in enlargement of the contact area between particles, as shown in Figure 3.2a. Once shear resistance develops at a contact point, relative sliding between particles occurs (see in Figure 3.2b). In addition, any plate-like particles in the earth will bend, as in Figure 3.2c, allowing adjacent particles to move relative to each other.

The overall strain within an earth mass results partly from deformation of individual particles. Thus, due to earth's particulate nature, deformation results from interactions, especially sliding, between individual particles. Since the sliding of particles produces irreversible deformation, the stress-strain behaviour of earth is strongly non-linear. This means that when stress-strain data are plotted, a straight line can not be drawn between data points. However, this is not unusual for materials subjected to load-unload cycles. (27)(28)



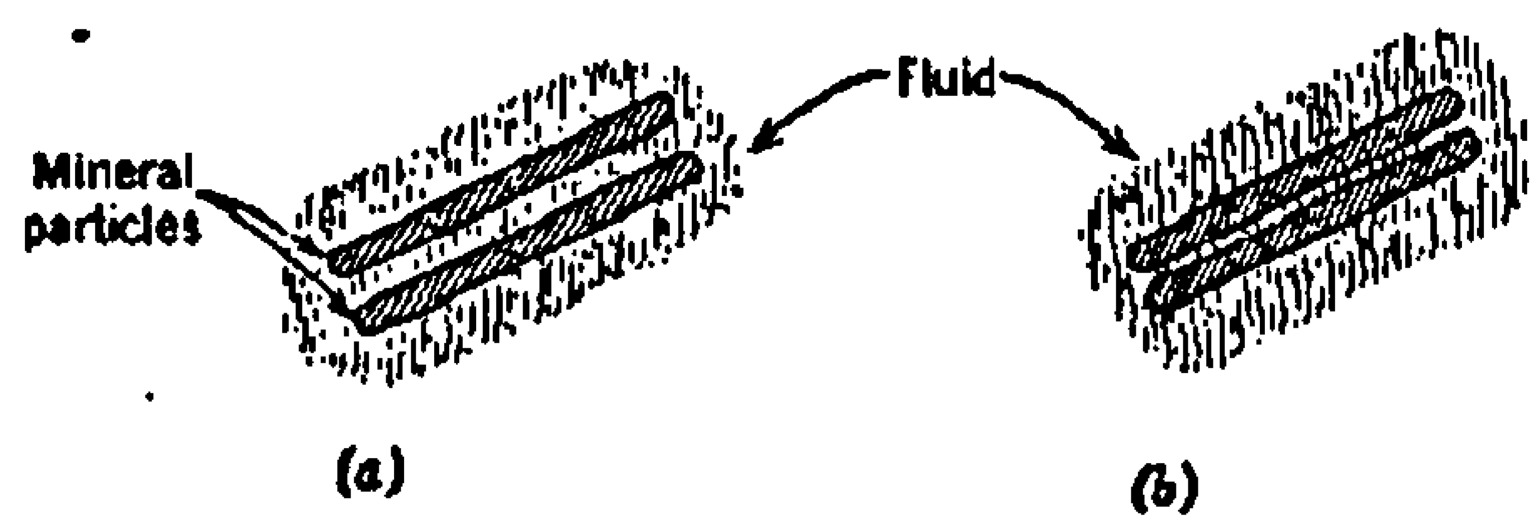
(27)

Figure 3.2 the nature of earth's particle deformation

When a load is applied to earth, there are three phases of transformation of forces and particle interaction:

Phase I: Chemical interaction

The spaces between earth particles are called 'pore spaces'. They are usually filled with air and water (with or without dissolved materials). Thus, earth is inherently a multiphase system consisting of a mineral phase, called the mineral skeleton, plus a fluid phase, called the pore fluid. (27)(28) The nature of the pore fluid influences the magnitude of the shear resistance between two by introducing chemical matter to the contact surface. In the case of fine-grain earth particles, the pore fluid may completely intrude between the particles (refer to Figure 3.3). (27) Although these particles are no longer in contact, they remain in close proximity and can transmit normal and, possibly also tangential, forces. The spacing of these particles increases or decreases as the transmitted compressive force decreases or increases. As already noted, earth is multiphase, with the constituents of the pore phase influencing the nature of the mineral surfaces and, hence, affecting the processes of force transmission at the particle contacts. This interaction between the phases is called chemical interaction. (27)



(27)

Figure 3.3 The role of pore phase of earth: chemical interaction

2 Phase II: Physical interaction

Physical interaction is related to the property of permeability. This property is a measure of a material's capacity to allow the flow of fluid, such as water, through it. Earth being particulate in nature, allows passage of water. The more permeable the earth, the greater the flow of water for a given pressure. The water flowing through earth interacts with the mineral skeleton and alters the magnitude of the forces at the contact points between particles. This affects the compression and shear resistance of the material. (27)(28)

Phase III: Sharing the load

As earth contains a multiphase system, both the pore fluid and the mineral skeleton bear any load applied. This 'sharing of the load' is analogous to the concept of partial pressure in gases. As in the physical interaction phase, application of a load causes water to move through the earth. During compaction, porosity is reduced over time and so the role of pore fluid in the transformation of load is also reduced. In addition, the reduction in porosity changes the engineering properties of the earth. (27)

Types of Earth

There are several of types of earth, the names of which are associated with specific disciplines, e.g. agriculture, earth engineering and earth sciences. These include laterites, Terra Rossa, Terra Fusca, etc.

A lateritic earth is produced by tropical weathering of parent rock and is found throughout the tropics. As laterites are characterised by deep weathering, which causes the removal of soluble silica and alkalis and the concentration of alumnae and ferric oxide; they tend to be reddish in colour. Laterites occur in distinct strata, or 'horizons', of differing texture and composition. The term 'laterites' was first used in Southwest India where, when freshly dug, they are soft enough to be cut into blocks, but harden on exposure to air. (29) Some studies have indicated that laterites have a pozzolanic reaction when mixed with lime, and are thus well suited to stabilisation.

The dry density of lateritic earth is approximately 1500 Kg/m^3, i.e. about 75% that of structural concrete. Laterites have an Optimum Moisture Content of 8-30%, indicating that they fall within the Kaolinites clay fraction group and exhibit reasonably high volumetric changes of 10-50% at the liquid limit. Most loam-type earths have a specific gravity in the range 2.60-3.40. (23)

Terra Rossa is found in most Mediterranean regions. The term refers to very slowly decarbonating clays formed over thick layers of hard limestone. Terra Rossa is red, and is distinguished from Terra Fusca by its degree of rubefaction. (6)(8)

Black cotton earth is found in wet tropical areas and was deposited over volcanic rocks, such as basalt. Its name derives from the fact that cotton is often grown on this type of earth. It is usually black, deep grey or brown in colour, rich in calcium carbonate and has a high clay content. The predominant clays found in black cotton earth are montmorillonites, which have a very high ion exchange capacity. (7) Up to 90% of the clays may have a diameter of less than 0.0015mm. They are noted for their remarkable capacity to absorb in moist conditions and equally severe shrinkage upon drying. (21) (22)

Loess earth is fine, homogenous earth. It has a silty texture, low sand content and contains 10-20% calcium carbonate. This type of earth comprises material eroded from desert regions or areas close to large glaciers. Loess layers range in thickness from several tens of centimetres to 20 metres. (6)

Clayey rock earth constitutes the majority (80%) of sedimentary rock. Of these, the plastic clays of the phyllosilicate group are the best example. The granularity of this earth is hard to determine because it hardens and dissolve badly in water. (17)

Alluvial earth is deposited along the margins of rivers and streams in wide valleys. It is a mineral-rich earth that is subject to a continuing weathering process. The texture of alluvial earth varies, though finer material is usually found at the surface (fine sand, silts, clays), becoming coarser with depth. Colour varies from brown ochre on higher ground, grey on the flood plain to black in marshy areas. (17)

Saline earth is rich in either sodium chloride ($NaCl_2$) or sodium sulphate (Na_2SO_4). It is encountered in semi-desert areas and dry, tropical climates where high evaporation rates prevent the natural drainage process. This type of earth has a high salt content or else the surrounding ground water is salt-rich. (27)

Peat is produced by the decomposition of vegetable matter exposed to the air, often in shallow lakes or in marshland. It is usually dark brown in colour and contains plant matter, which can be clearly identified as such. (23)

Characteristics of Earth as a Building Material

Availability

Earth is readily available in almost every part of the world. Clay and laterites suitable for use in construction constitute 74% of the earth's crust. (29) Traditionally, earth used for building has been excavated on-site, or in close proximity to the construction site. This contributes to lower construction costs, because raw earth rarely needs to be purchased and does not usually require transportation over long distances. Therefore, it is cheaper than any alternative walling materials. For this the reason, earth remains widely used for construction in many parts of the world. (30)

Energy consumption

The use of earth as building material reduces energy consumption both during construction and habitation. For example, the fact that earth does not have to be transported to site during construction results in significant energy savings. Also, earth has excellent insulating properties compared to many other construction materials. Therefore, once earth buildings are occupied, energy savings of 20-30% are possible for heating or cooling the building. (21) In hot regions, such as south west United States or Pakistan, earth buildings need very little energy input to keep the inside temperature comfortable. Experts argue that the production of industrially manufactured building materials and semi-finished products consumes excessively high amounts of energy. (21)(22) This is illustrated in the following table, prepared by the CRATerre-Eag:

Table 3.4 Energy consumption of various materials. (21)

Building Material	kWh/m 3	kWh/k g
Solid bricks	1 140	
Perforated brick	590	
Porous light weight bricks	400	
Sand lime bricks	350	
Cement		1
Concrete	500	
Precast concrete	800	
Earth	5-10	
Timber	600	
Chipboard	1 100	
Mineral wood	100	5
Glass wool	150	5
Flat glass	15 000	6
Steel (plates)	6 100	7.7
Aluminium (sheets)	195 000	72.5
PVC	12 800	9.5
Polystyrene Foam	470	19

From the above table, it can be seen that the energy consumption of concrete is approximately 100 times that of earth. The reason for this is that concrete requires energy not to produce cement, but also to pulverise, pack and transport it to site. However, for the production of adobe bricks or for the construction of rammed earth walls, no energy is needed for the material it self and only very little for transportation and handling on site.

Thermal performance

The ability of earth to store energy and stabilise temperature is called the 'thermal mass' effect. In addition to energy savings at the production stage, completed unbaked earth buildings require less heating and cooling to maintain room temperature. This is because the insulating properties of earth walls help to reduce heat loss and maintain 'thermal comfort' for occupants. Thermal comfort is defined by the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) as 'that condition of mind, which expresses satisfaction with thermal environment'. (31)(32) Human responses to the indoors thermal environment are affected by several variables, which can be categorised according to climatic factors. The environment or climatic factors include; air temperature, relative humidity, mean radiant activity and time. For example, thermal comfort is achieved in a hot, dry environment by spacing buildings close together to provide mutual shade. Thick walls, adobe blocks and roofs made of rammed earth, are used to provide high thermal mass.

The thermal conductivity of a material, known as its *K* value, is the rate at which a unit area of material, of a given thickness, transmits heat from one surface to another when there is a unit difference in temperature between them. The lower the *K* value, the greater the insulating properties of the material. The 'U' value, or air-to-air transmission, is the rate at which heat per unit surface area and per unit difference in air temperature is transmitted from the air on one side of a wall or roof to the other side. (33)(34) It is argued that sun dried adobe bricks are better than fired bricks and concrete in terms of thermal performance. (33)

Acoustic properties

Earth buildings have good noise absorption properties, a desirable attribute in house design. (33)(35) The mass and weight of earth walls provides reasonable insulation from airborne noise and excellent insulation from structural-borne sounds.

Sound absorption properties are improved by using loose sand as an insulating material. The friction between loose particles of sand dissipates a great volume of noise before it has the chance to penetrate even a comparatively thin layer of wall. This observation supports the use of sand-filled cavities in internal partitions. (36)(37)

Versatility

Earth is a highly versatile building material, particularly in the form of earth bricks, and can be used to create a variety of structures, including forts, minarets, palaces, houses, hospitals and many other types of building - both modern and traditional. Earth has great cultural and architectural importance. The wide variety of methods for building in earth can offer regional variation that reflects traditional differences and, according to some authors, an alternative to cultural 'imperialism'. (34)

The Engineering Properties of Earth as Building Material

Engineering properties of earth depend on the nature of the constituent particles and the complex ways in which these particles interact. The characteristics and fundamental properties of the dominant type of particle determine the behaviour of earth. The following factors are presented to understand the engineering properties of the earth:

Strength of earth

The strength of earth is a measure of its ability to resist the application of forces. These forces can be tensile, compressive or shear. Tensile strength is defined as the maximum tensile stress that can be applied without breaking the material:

$$\text{Tensile strength} = \frac{\text{Maximum tensile forces}}{\text{Original cross-sectional area}} \qquad (34)$$

Compressive and shear strength values are calculated in similar fashion, using values for maximum compressive or shear forces. The unit of strength is the Pascal (Pa), with 1Pa being equal to1N/m^2. Strength values often run into millions of Pascal (MPa), with 1MPa being equal to 10^6 Pa, i.e. 1 million Pa. (34)(38)

Earth is a heavy material with low compressive strength and is considered by some to be a kind of lean concrete. (38) Pursuing the comparison of earth with other materials, the following analysis is possible:

i. Low quality earth has poor engineering properties and also has low strength relative to a given specific gravity as compared to conventional mineral materials, such as concrete.
ii. High quality earth materials have strength values comparable to those of conventional mineral materials.

The dry compressive strengths of raw adobe, after curing for 28 days, and rammed earth are both approximately 2 MPa. The wet compressive strengths of raw adobe, after curing for 28 days, and rammed earth are 0-0.5 MPa. (39)

Stiffness

Stiffness is measured by bending an element of a material, with one surface being stretched as the opposite face is compressed. The more the material bends, the greater the amount by which the stretched surface extends and the compressed surface contracts. Thus, a stiff material is one that undergoes a small amount of strain when subject to such stress, resulting in a small strain/stress value, or conversely, a large value for stress/strain.

For most materials, the initial plot on a stress/strain graph shows a straight-line relationship. A high stress value relative to strain results in a steep slope. The 'Modulus of Elasticity', sometimes called Young's Modulus, is a measure of the relationship between stress and strain. (39)(41)

$$\text{Modulus of elasticity} = \frac{\text{Stress}}{\text{Strain}}$$

The units of the Modulus of Elasticity are the same as those for stress, since strain has no units. Stabilised adobe and rammed earth have a reported Modulus of Elasticity of 700 MPa. (36)(38)

Toughness

A tough earth is one that resists breaking and requires more energy to break it than a less tough one. There are numerous measures of toughness, or resistance to crushing. For example, when a length of material is stretched by an amount X_1, as a result of a constant force F_1, toughness is calculated as: (41)

$$\text{Toughness (work)} = \text{force x extension}$$
$$= F \times X$$

The resistance to crushing by an eccentric load of adobe and rammed earth is 0.40-0.50 and 0.30-0.40, respectively. By mixing the adobe and rammed earth with 5-9 % bitumen, resistance to crushing is around 0.20-0.30 and >0.50, respectively. (9) The bending strengths (uniform horizontal pressure-wind) of raw adobe and rammed earth are $0.2x10^{-3}$ to $0.3x10^{-3}$ MPa. For adobe earth, stabilised with 5-9% bitumen emulsion, the figure is around $0.3x10^{-3}$ to $0.4x10^{-3}$ MPa. Rammed earth, mixed with 8% of cement, has a resistance to crushing of approximately $0.5x10^{-3}$ to $0.6x10^{-3}$ MPa. (21) The values given above are obtained from published results. (21) These figures provide an indication of data to be expected from the stabilised earth samples tested in this study.

Hardness

The hardness of earth is a measure of its resistance to abrasion or indentation. A number of scales are used for hardness, depending on the method used to measure it. Hardness is roughly proportional the tensile strength of a material. Thus, the harder the material, the higher the tensile strength. The tensile strength of raw rammed earth is 0.5-1.0 MPa. (21)(26)

The potential of earth as building material is confirmed by the extant earth structures that have survived through the centuries. Earth in earth form is still used in Sindh for housing and, through the development of appropriate technologies, for many other purposes such as food storage and cattle shelters. The importance of earth as a building material is emphasised by the fact that nearly half of the world's population today lives in earth buildings. Modern construction materials are so expensive that it is unlikely that most dwellers of earth houses will be able afford to build with them for many decades to come.

Earth is the product of a long process of deterioration of parent rock. The form and characteristics of the earth depends on the type of parent rock and climatic conditions to which it is subjected. There are a wide variety of earth types, which can be described and classified in terms that convey their characteristics clearly and concisely. Earth contains four basic materials that influence its engineering properties: gravel, sand, silt and clay. In particular, clay minerals can cause serious damage to buildings, even where the earth has been stabilised. Therefore, a thorough study and analysis of earth and its properties are necessary before evaluating its use for construction and the earth stabilisation process.

The particulate nature of earth influences the three phases of transformation of forces and particle interaction: chemical, physical and sharing the load. The nature of earth deformation and the role of the pore phase determine the material's stress- strain behaviour. This behaviour emphasises the affects of density and friction between particles on earth's high compressibility and strength. The chemical interaction affects the density, and hence strength, which earth will attain under a given load. The physical interaction between pore fluid and the mineral skeleton affects the stability of the earth.

The characteristics of earth as building material are particularly relevant to developing countries suffering from rising inflation and energy costs. The engineering properties of earth are governed to a large extent by its physical properties and behaviour, so careful visual inspection together with a few key tests can provide a valuable first appraisal of the material. These tests are discussed in Chapter 5.

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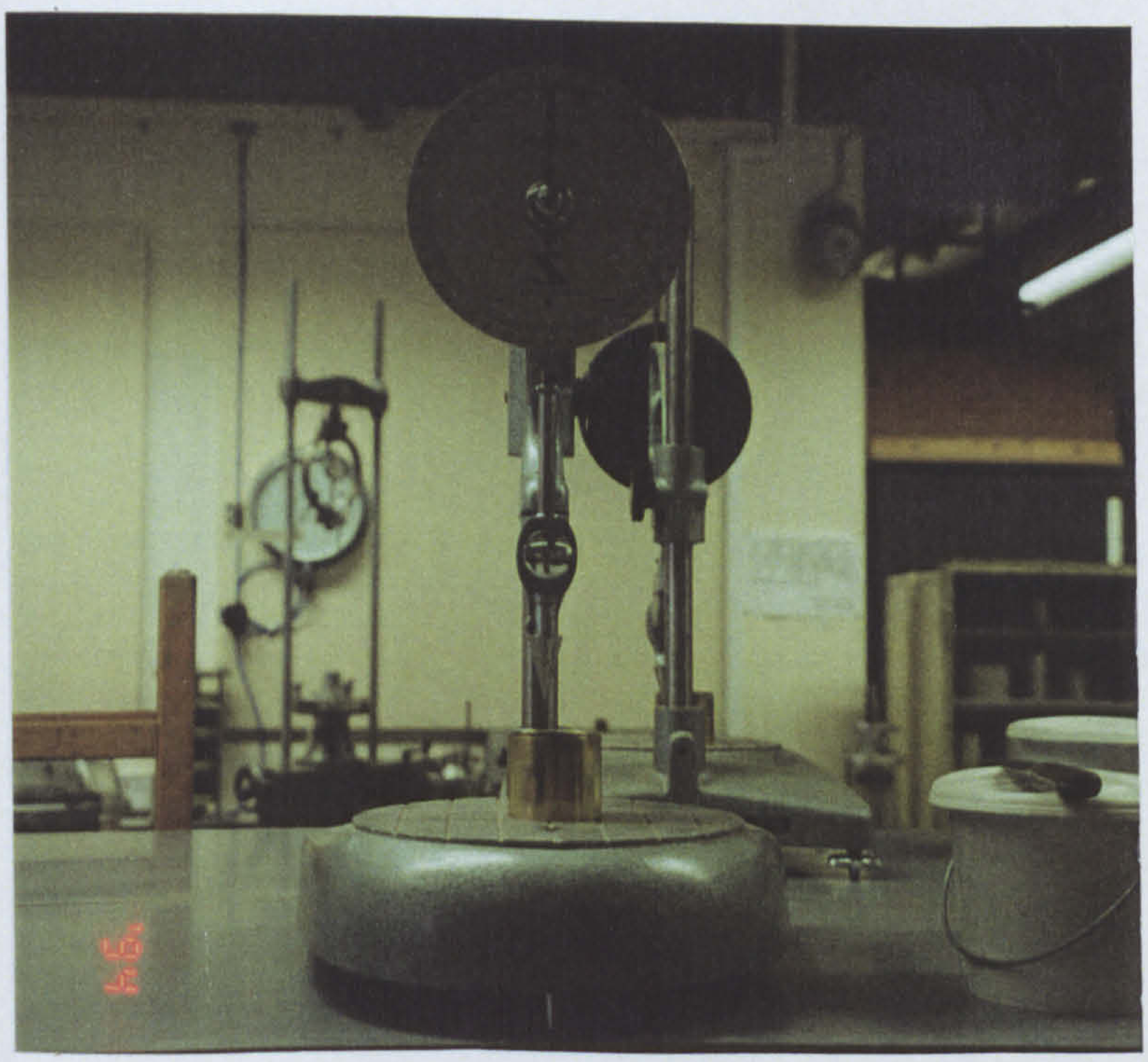
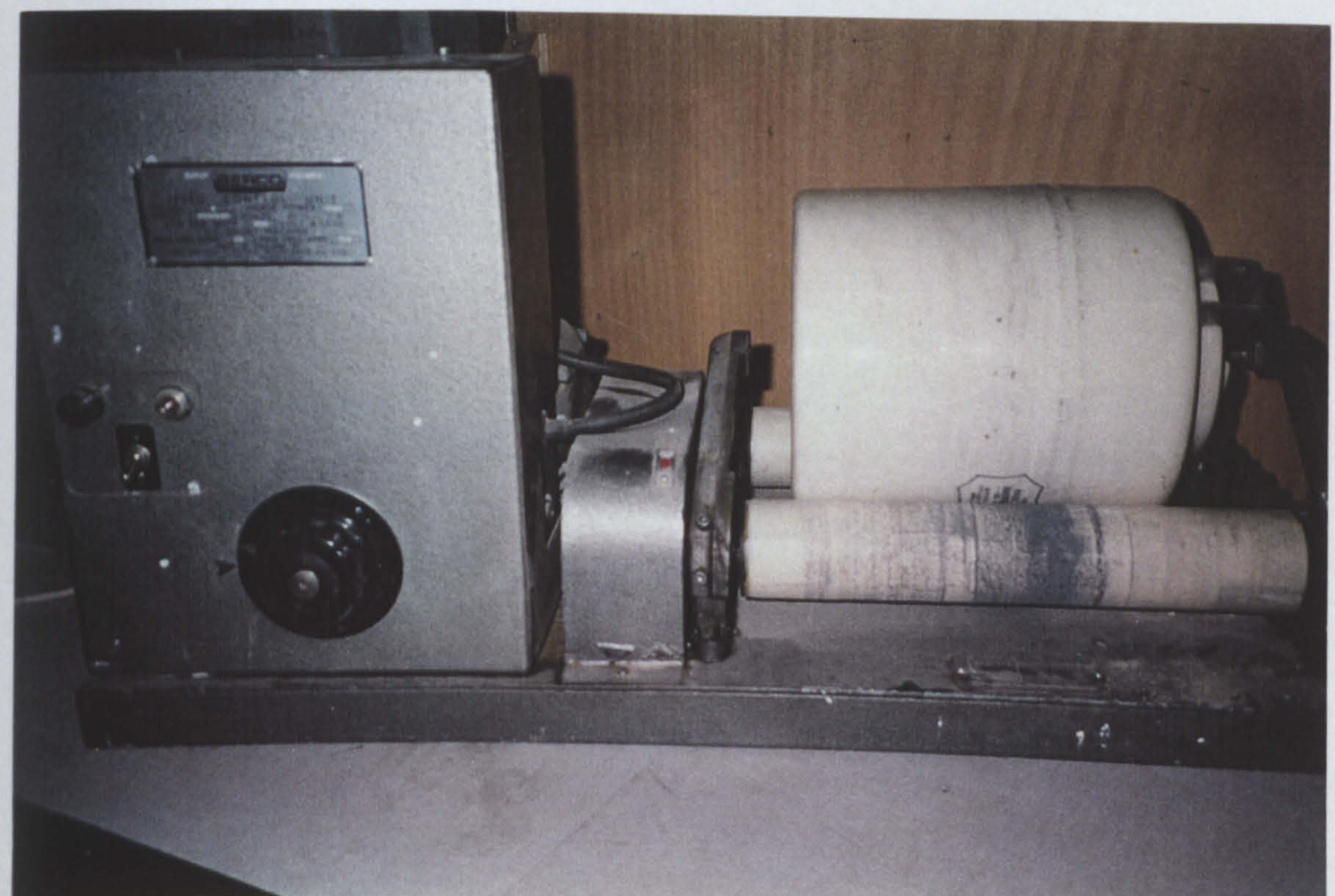
Appendix C

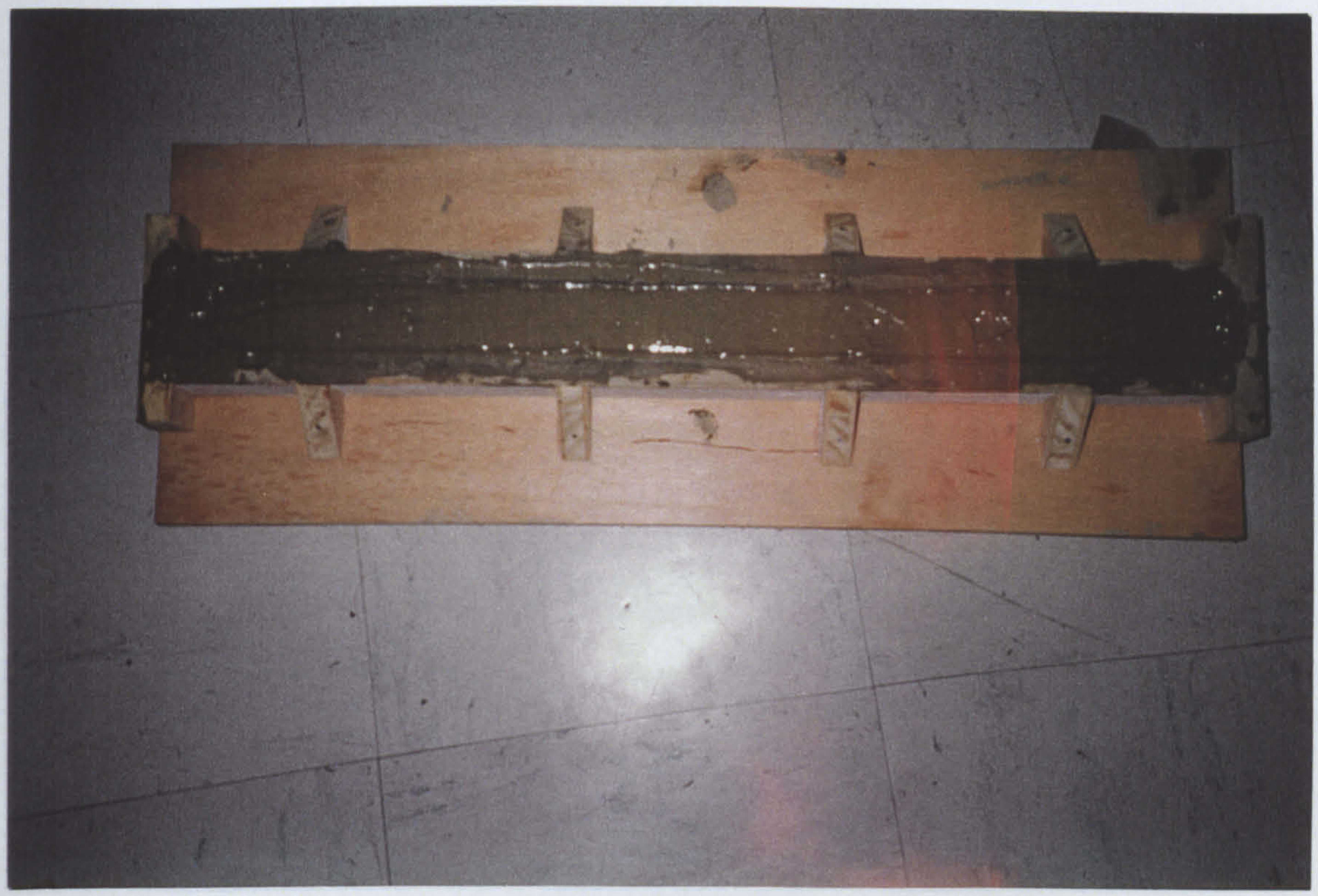


Penetrometer used for Liquid Limit test



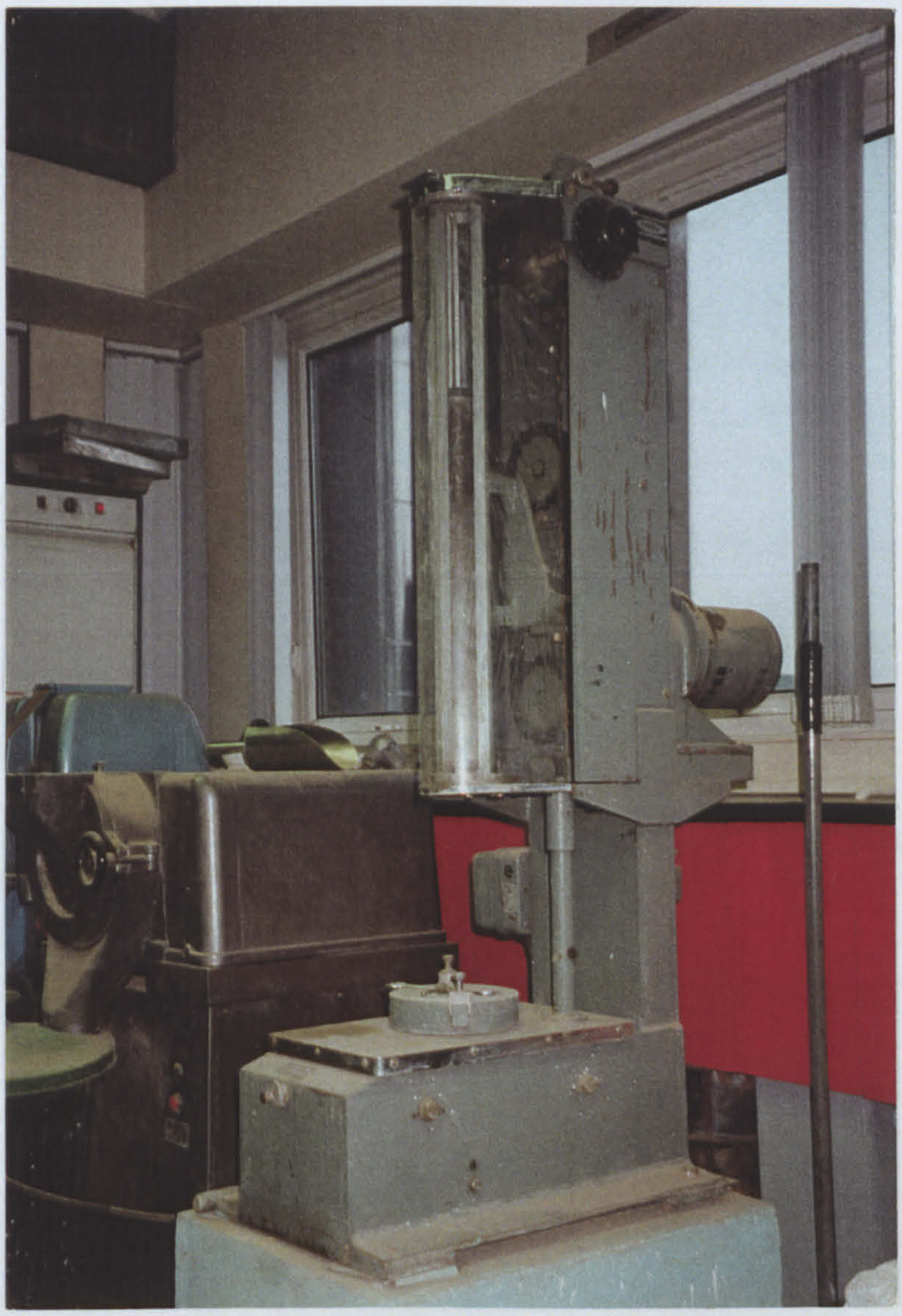
Grinder Machine was used to break large lumps of imported earth

Sieve Machine used for dry particle size distribution

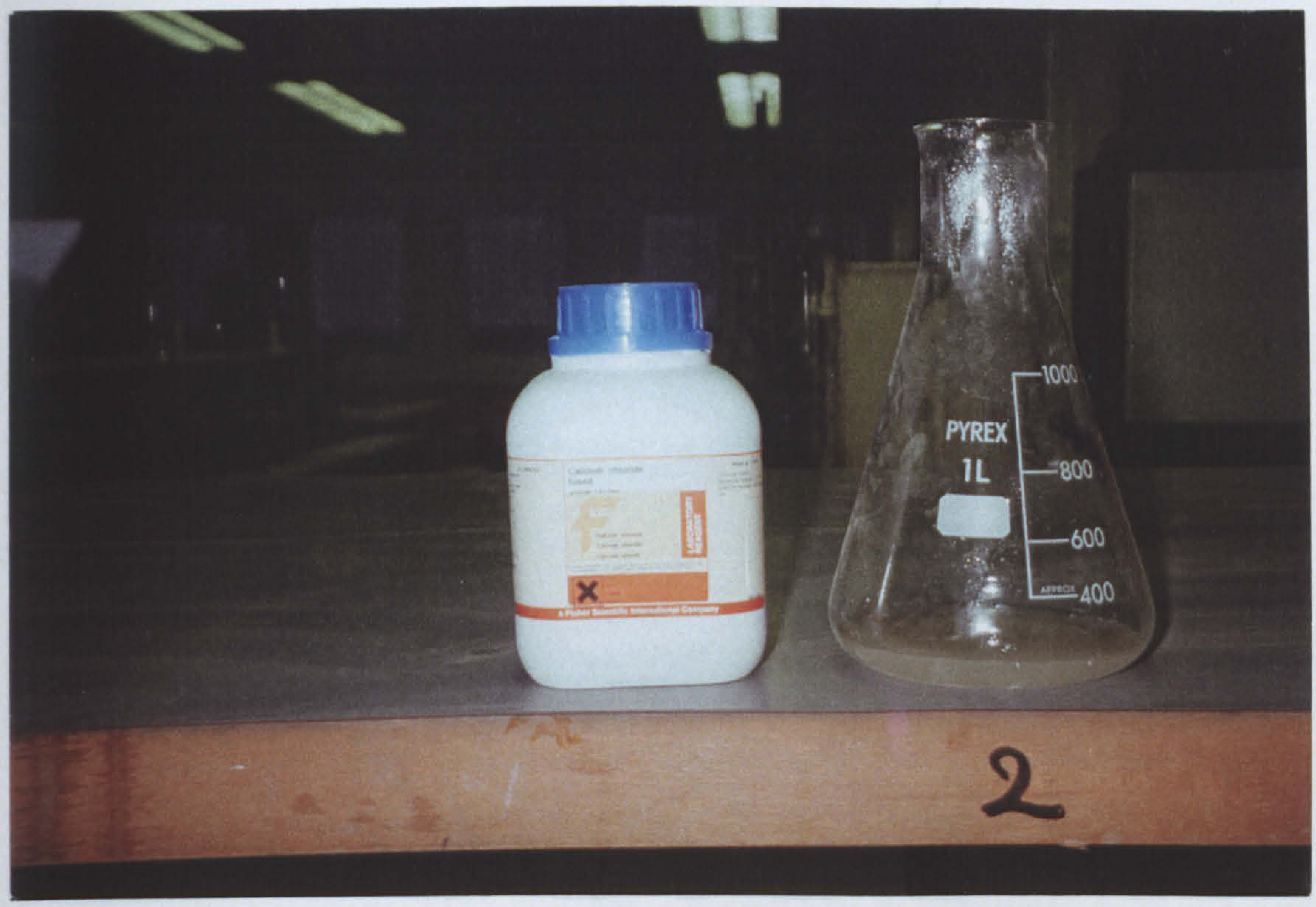


Wooden box used for linear shrinkage test (wet sample)

Wooden box used for linear shrinkage test (dry sample)



Compaction Machine for Proctor test with hammer of 2.5Kg

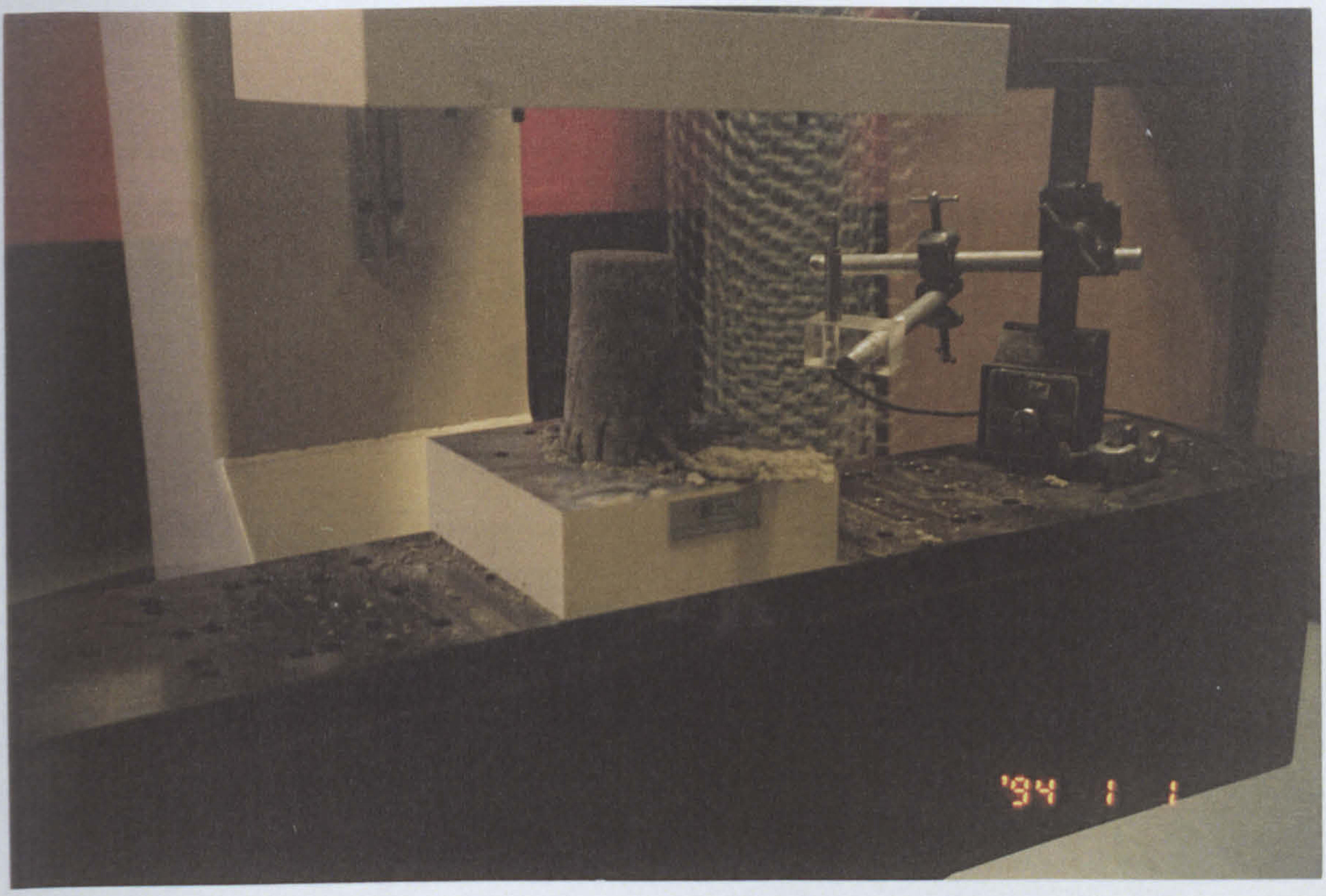


Dissolved Calcium Chloride in water for mixing with earth sample

Mould used for producing the specimens (slightly compacted before applying actual compaction load)

Specimen under water absorption test

Specimen under water absorption tests after 24 hours



Specimen under the compressive strength machine


A shear strain in specimen

Appendix D

Wet Sieve Analysis

Initial earth mass used: 708grams = m_1

R1 = 0.435 %
R2 = 0.207 %
R3 = 0.878 %
R4 = 5.559 %

R = Retained amount of earth/initial amount of earth (100)

$$R1 = \frac{ms1}{m1} x100$$

Ms_1 denote the mass retained on the first sieve used;
Ms_2 that on the second sieve used; and so on
The % retained on the first sieve, denoted by R1

The percentage passing this sieve, P, is given by

$$P1 = 100 - R1 - \left\{ \frac{ms1}{m1} x100 \right\}$$

The % retained on the second sieve is

$$R2 = \frac{ms2}{m1} x100$$

And % passing is

$$P2 = P1 - R2 = P1 - \left\{ \frac{ms2}{m1} x100 \right\}$$

$$P3 = P2 - R3$$

Similarly So on for calculation has been conducted for finding the Percentage of particles.

Particle Percentage according Wet sieve analysis

Particle	Percentage
Gravel	0.008 %
Medium Sand	1.131 %
Fine Sand	6.691%

Silt and Clay	92.09 %

Sedimentation Analysis of Imported Earth Sample

Three experimental tests were conducted to find average results. The following Figures shows the tests results:

Sample 1

Minisucus correction (Cm) = 0.5

Particle specific gravity (G) = 2.6

Soil mass (m) = 22.1

Date	Time	Temperature	Elapsed Time Seconds	Minutes	Hours
13.5.97	10:08:00 AM	21	0		
13.5.97	10:08:30 AM	21	30		
13.5.97	10:09:00 AM	21	60	1	
13.5.97	10:10:00 AM	21	120	2	
13.5.97	10:12:00 AM	21	240	4	
13.5.97	10:16:00 AM	21	480	8	
13.5.97	10:23:00 AM	21	900	15	
13.5.97	10:38:00 AM	21	1800	30	
13.5.97	11:08:00 AM	21		60	1
13.5.97	12:08:00 PM	21		120	2
13.5.97	02:08:00 PM	21.5		240	4
13.5.97	04:08:00 PM	22		360	6
14.5.97	10:08:00 AM	22		1440	24

Reading Rh	Corrected Reading Rh + Cm	Determined from Nomograph Chart B	V	D
-------------	----------------------	--------	----------	-----------
10.20	10.7	11.4	0.35	-
10.20	10.7	11.4	0.18	0.065
10.20	10.7	11.4	0.08	0.045
10.20	10.7	11.4	0.042	0.031
10.15	10.65	11.4	0.022	0.022
10.15	10.65	11.4	0.011	0.016
10.15	10.65	11.4	0.0055	0.011
10.10	10.6	11.4	0.0028	0.008
10.00	10.5	11.4	0.0013	0.0058
9.00	9.5	11.3	0.0006	0.004
8.00	8.5	11.2	0.00035	0.0026
5.50	6	11.2	5.5E-O5	0.0021
				0.0008

Mt	Rh+Mc	K%
---------	---------	--------
0.18	10.88	80
0.18	10.88	80
0.18	10.88	80
0.18	10.88	80
0.18	10.83	80
0.18	10.83	80
0.18	10.83	80
0.18	10.78	79
0.18	10.68	79
0.27	9.77	72
0.47	8.97	66
0.47	6.47	48

Percentage of clay = 65

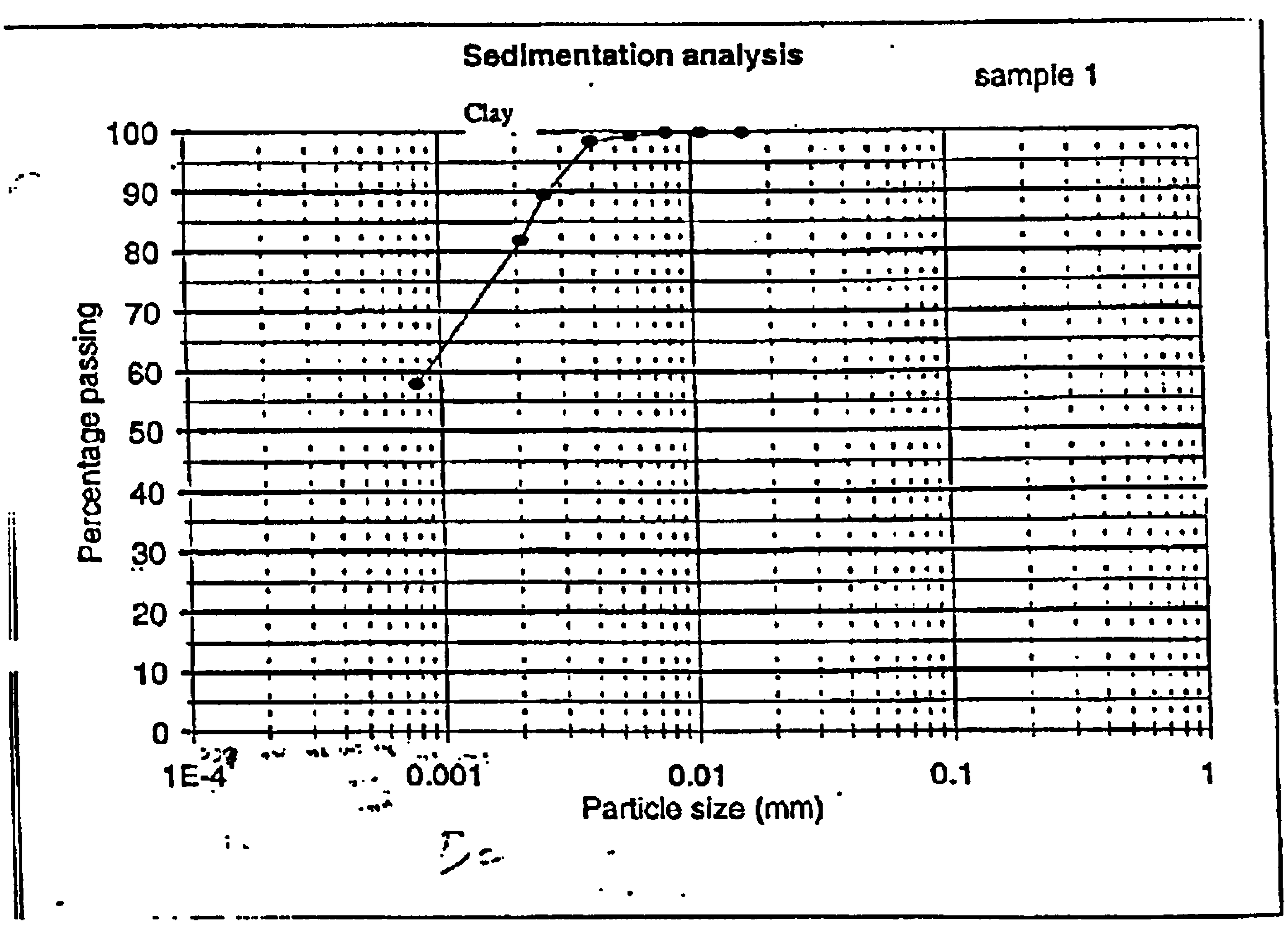
Following Figure represents the sedimentation test on Logirthmatic scale

Sample 2

Minisucus correction (Cm) = 0.5

Particle specific gravity (G) = 2.6

Soil mass (m) = 45



Sample 2

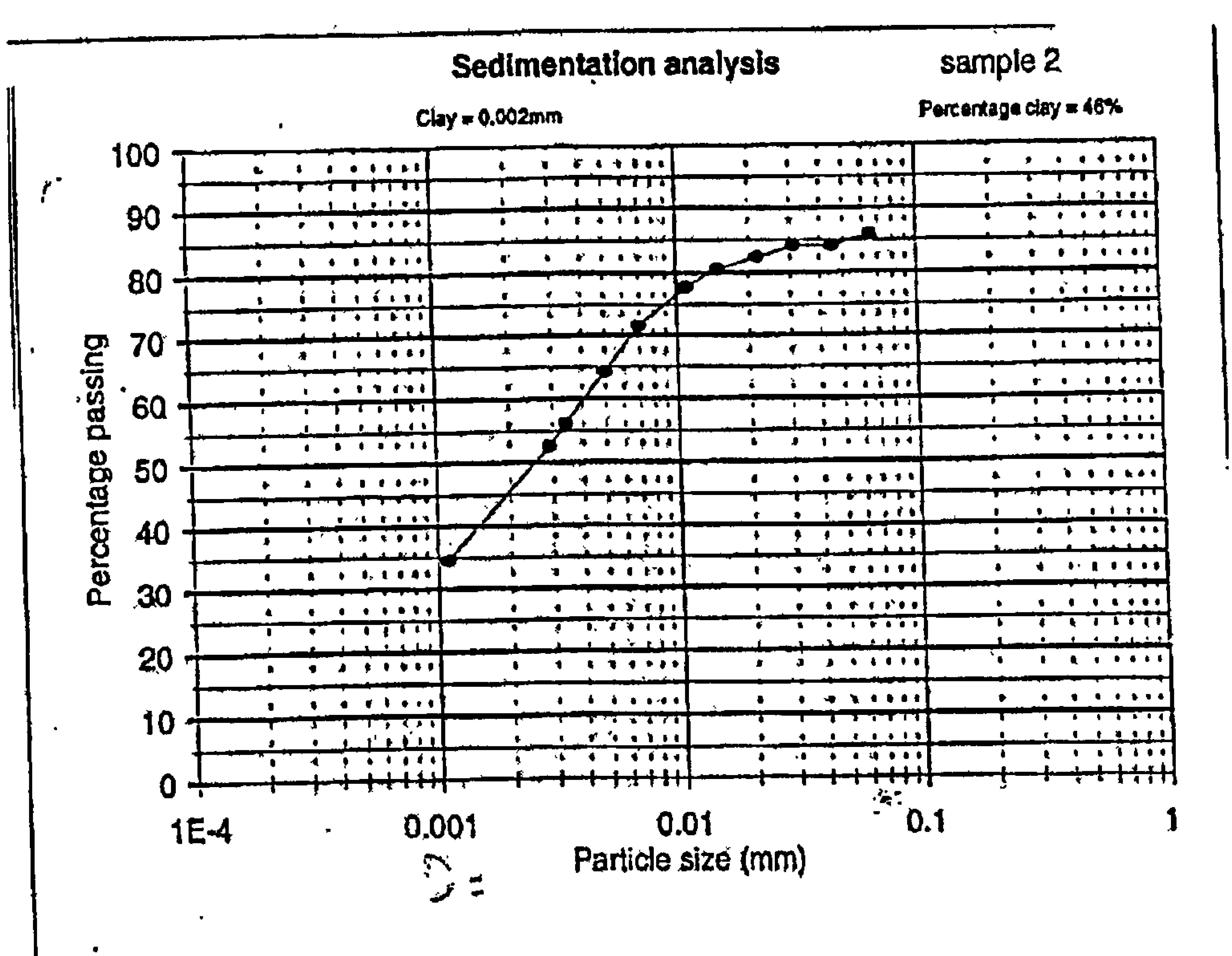
Date	Time	Temperature	Elapsed Time Seconds	Minutes	Hours
15.5.97	11:45:00 AM	24	0		
15.5.97	11:45:30 AM	24	30		
15.5.97	11:46:00 AM	24	60	1	
15.5.97	11:47:00 AM	24	120	2	
15.5.97	11:49:00 AM	24	240	4	
15.5.97	11:53:00 AM	24	480	8	
15.5.97	12:00:00 PM	24	900	15	
15.5.97	12:15:00 PM	24	1800	30	
15.5.97	12:54:00 PM	24		69	1.15
15.5.97	01:45:00 PM	24		120	2
15.5.97	03:45:00 PM	24		240	4
15.5.97	04:45:00 PM	24		300	5
16.5.97	9:45:00 AM	23		1320	22

Reading Rh	Corrected Reading Rh + Cm	Determined from Nomograph Chart B	V	D
-------------	----------------------	--------	----------	-----------
---------	-----------	-------	-------	-
22.50	23	10.6	0.4	--------
22.00	22.5	10.6	0.19	0.065
22.00	22.5	10.6	0.09	0.045
21.50	21.50	10.6	0.045	0.031
21.00	21.00	10.6	0.022	0.022
20.25	20.25	10.6	0.012	0.015
18.50	18.50	10.6	0.00045	0.011
16.50	16.50	10.6	0.0025	0.007
14.25	14.25	10.6	0.001	0.005
13.25	13.25	10.6	0.00075	0.0034
8.50	8.50	11	0.0001	0.0029
				0.0011

Mt	Rh+Mc	K%
---------	---------	--------
--------	---------	-------
0. 8	23.8	86
0. 8	23.3	84
0. 8	23.3	84
0. 8	22.8	82
0. 8	22.3	81
0. 8	21.55	78
0. 8	19.8	72
0. 8	17.8	64
0.8	15.55	56
0.8	14.55	53
0.58	9.58	35

Percentage clay = 46

Following Figure represents the sedimentation test on logirthmatic scale



Sample 3
Minisucus correction (Cm) = 0.5
Particle specific gravity (G) = 2.6
Soil mass (m) = 45

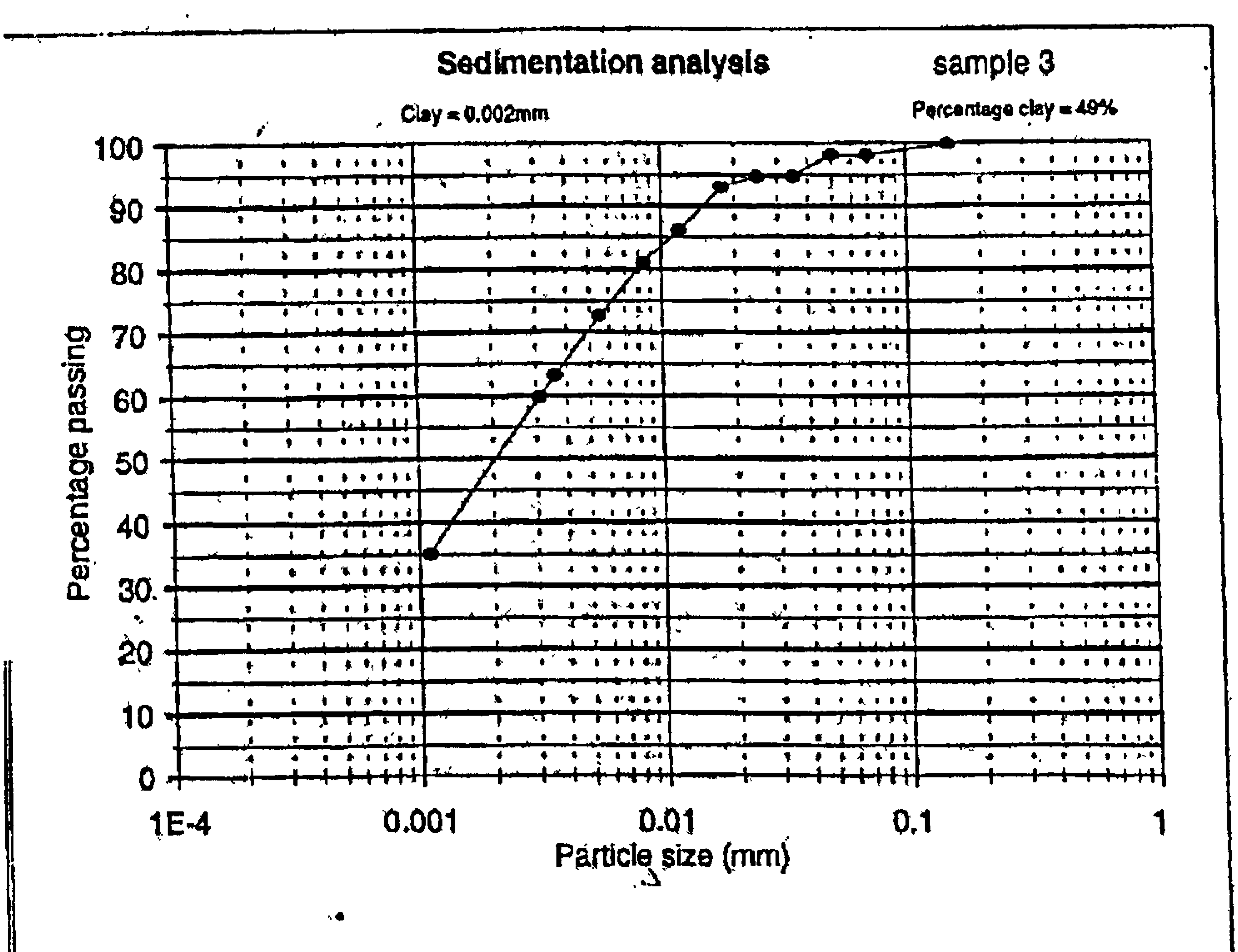
Date	Time	Temperature	Elapsed Time Seconds	Minutes	Hours
15.5.97	11:55:00 AM	24	0		
15.5.97	11:55:30 AM	24	30		
15.5.97	11:56:00 AM	24	60	1	
15.5.97	11:57:00 AM	24	120	2	
15.5.97	11:59:00 AM	24	240	4	
15.5.97	12: 03:00 PM	24	480	8	
15.5.97	12:10:00 PM	24	900	15	
15.5.97	12:25:00 PM	24	1800	30	
15.5.97	12:55:00 PM	24		60	1
15.5.97	01:55:00 PM	24		120	2
15.5.97	03:55:00 PM	24		240	4
15.5.97	04:55:00 PM	24		300	5
16.5.97	9:55:00 AM	23		1320	22

Reading Rh	Corrected Reading Rh + Cm	Determined from Nomograph Chart B	V	D
-------------	----------------------	--------	----------	-----------
28.00	28.5	10.6	1	0.15
27.50	28	10.6	0.45	0.07
27.50	28	10.6	0.22	0.05
26.50	27	10.6	0.11	0.035
26.50	27	10.6	0.055	0.025
26.00	26.50	10.6	0.026	0.018
24.00	24.00	10.6	0.013	0.012
22.50	22.50	10.6	0.0065	0.0085
20.00	20.00	10.6	0.0029	0.0055
17.25	17.25	10.6	0.0012	0.0036
16.25	16.25	10.6	0.0009	0.0031
9.25	9.25	11	0.00011	0.0011

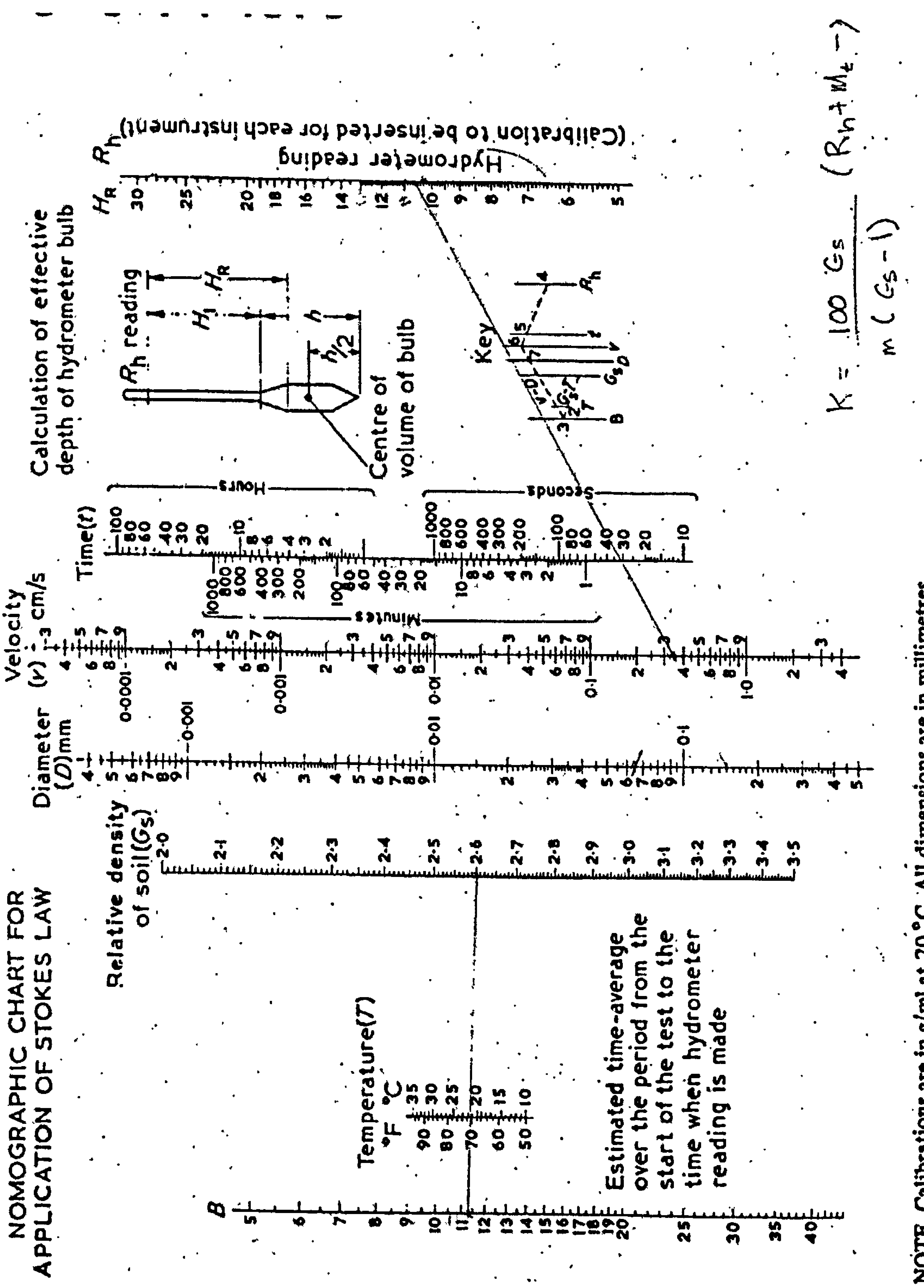
Mt	Rh+Mc	K%
---------	---------	--------
0.8	29.3	100
0. 8	28.8	98
0. 8	28.8	98
0. 8	27.8	95
0. 8	27.8	95
0. 8	27.3	93
0. 8	25.3	86
0. 8	23.8	81
0. 8	21.3	73
0.8	18.55	63
0.8	17.55	60
0.58	10.33	35

Percentage clay = 49

Following Figure represents the sedimentation test on logirthmatic scale



The Following Nomographic Chart used for sedimentation tests during working with Hydrometer.



Appendix E

Sample Preparation: Preliminary Readings
Earth: Sand: Cement

Clyd. No.	Sand Percentage	Types of Stabiliser	Stabiliser: Soil	Date of Moulding	Time of Moulding	Compacting press load.
1	30%	Cement	1: 15	20^{th} Jan. 1998	10.10 am	2-10 MPa
2	30%	Cement	1:15	20^{th} Jan. 1998	10.40 am	2-10 MPa
3	30%	Cement	1:15	20^{th} Jan. 1998	11.12 am	2-10 MPa
4	30%	Cement	1:15	20^{th} Jan.1998	11.33am	2-10 MPa

Date: **20.01.1998** **Taken by: Rubina Shaikh**

Sample Preparation: Preliminary readings
Earth : Sand: Lime

Clyd. No.	Sand Percentage	Types of Stabiliser	Stabiliser: Soil	Date of Moulding	Time of Moulding	Compacting press load.
1	30%	Hydrated Lime	1: 17	20th Jan. 1998	12.40 PM	2-10 MPa
2	30%	Hydrated Lime	1:17	20th Jan. 1998	1.32 PM	2-10 MPa
3	30%	Hydrated Lime	1:17	20th Jan. 1998	2.04 PM	2-10 MPa
4	30%	Hydrated Lime	1:17	20th Jan.1998	2.46 PM	2-10 MPa

Date: **20.01.1998** **Taken by: Rubina Shaikh**

Sample Preparation: Preliminary readings
Earth : Sand: Linseed oil

CLyd. No.	Sand Percentage	Types of Stabiliser	Stabiliser: Soil	Date of Moulding	Time of Moulding	Compacting press load.
1	30%	Linseed oil	1/2: 15	21st Jan. 1998	10.05 am	2-10 MPa
2	30%	Linseed oil	1/2:15	21st Jan. 1998	10.56 am	2-10 MPa
3	30%	Linseed oil	1/2:15	21st Jan. 1998	11.13 am	2-10 MPa
4	30%	Linseed oil	1/2:15	21st Jan.1998	12.40 am	2-10 MPa

Date: **21.01.1998** **Taken by: Rubina Shaikh**

Sample Preparation: Preliminary readings
Earth: Sand: $CaCl_2$

CLyd. No.	Sand Percentage	Types of Stabiliser	Stabiliser: Soil	Date of Moulding	Time of Moulding	Compacting press load.
1	30%	$CaCl_2$	1: 15	21st Jan. 1998	1.50 PM	2-10 MPa
2	30%	$CaCl_2$	1:15	21st Jan. 1998	2.40PM	2-10 MPa
3	30%	$CaCl_2$	1:15	21st Jan. 1998	3.33 PM	2-10 MPa
4	30%	$CaCl_2$	1:15	21st Jan.1998	4.08 PM	2-10 MPa

Date: **21.01.1998** **Taken by: Rubina Shaikh**

Appendix F

Earth Stabilised Specimens Curing Process

Sample No. : 1

***Description:** Soil + Sand + Cement*

***Test:** Curing status of specimens*

***Date:** De moulding date was 20^th^ of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460 grams	Dying effect appeared dimensions were same.
7th day	49.8mm D x 99.8mm L	459.8grams	There was little change in dimension and specimen shows drying effect.
10th day	49.7mm D x 99.7mm L	459.6 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day			

Sample No. : 2

***Description:** Soil + Sand + Cement*

***Test:** Curing status of specimens*

***Date:** De moulding date was 20th of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460 grams	Dying effect appeared dimensions were same.
7th day	49.9mm D x 99.9 mm L	459.9grams	There was little change in dimension and specimen shows drying effect.
10th day	49.85mm D x 99.93mm L	459.8 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day	49.8 mm D x 99.8 mm L	440 grams	Very perfect in size

Sample No. : 3

Description: *Soil + Sand + Cement*

Test: *Curing status of specimens*

Date: *De moulding date was 20th of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460grams	Dying effect appeared dimensions were same.
7th day	49mm D x 99.1 mm L	459 grams	There was little change in dimension and specimen shows drying effect.
10th day	48.9mm D x 101.4mm L	458.6 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day	48.88 mm D x 100.8mm L	438 grams	Sample was dried completely

Sample No. : 4

Description: *Soil + Sand + Cement*

Test: *Curing status of specimens*

Date: *De moulding date was 20th of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100mm L	460 grams	Dying effect appeared dimensions were same.
7th day	49.8mm D x 99.8mm L	469 grams	There was little change in dimension and specimen shows drying effect.
10th day	49.8mm D x 99.8mm L	468.7 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day	49.7mm x 99.7mmL	466 grams	Sample was dried

Sample No. : 1

***Description:** Soil + Sand + Lime*

***Test:** Curing status of specimens*

***Date:** De moulding date was 20th of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460 grams	Dying effect appeared dimensions were same.
7th day	50mm D x 100 mm L	460 grams	There was no change in dimension and specimen shows drying effect.
10th day	49.8mm D x 99.8mm L	459.7 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day	49.7mm D x 99.6 mm L	456 grams	Perfect in Shape

Sample No. : 2

***Description:** Soil + Sand + lime*

***Test:** Curing status of specimens*

***Date:** De moulding date was 20th of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460 grams	Dying effect appeared dimensions were same.
7th day	50mm D x 100 mm L	460 grams	There was no any change in dimension and specimen shows drying effect.
10th day	49.6 mm D x 99.65 mm L	459.2 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day	49.49 mm D x 99.60 mm L	458 grams	Near to perfect in shape

Sample No. : 3

***Description:** Soil + Sand + lime*

***Test:** Curing status of specimens*

***Date:** De moulding date was 20th of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460 grams	Dying effect appeared dimensions were same.
7th day	50 mm D x 100 mm L	460 grams	There was no any change in dimension and specimen shows drying effect.
10th day	49.5 mm D x 99.67mm L	459 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day	49.5 mm D x 99.67 mm L	456 grams	Sample look dense and strong and in shape

Sample No. : 4

***Description:** Soil + Sand + lime*

***Test:** Curing status of specimens*

***Date:** De moulding date was 20th of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50mm D x 100mm L	460 grams	Dying effect appeared dimensions were same.
7th day	49.45 mm D x 99.65 mm L	459.75 grams	There was little change in dimension and specimen shows drying effect.
10th day	49.4 mm D x 99.6mm L	459.6 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day	49.4 mm D x 99.6 mm L	452 grams	Sample was in shape

Sample No. : 1

***Description:** Soil + Sand + linseed oil*

***Test:** Curing status of specimens*

***Date:** De moulding date was 21st of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100mm L	460 grams	There was not any dying effect appeared in sample, dimensions were same.
7th day	50mm D x 100 mm L	460 grams	There was not any change in dimension and specimen shows drying effect.
10th day	49.9 mm D x 99.7mm L	459.6 grams	Sample is not yet shows prominent drying effect but it must've been dried due to slight change in dimension.
28th day	49.9 mm D x 99.7 mm L	459.2 grams	Sample was dried and wet in look

Sample No. : 2

***Description:** Soil + Sand + linseed oil*

***Test:** Curing status of specimens*

***Date:** De moulding date was 21st of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	470 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	470 grams	Dying effect appeared dimensions were same.
7th day	50mm D x 100 mm L	469.5 grams	There was not any change in dimension and specimen shows drying effect.
10th day	49.7mm D x 99.5 mm L	469 grams	Sample is not yet shows prominent drying effect but it must've been dried due to slight change in dimension.
28th day	49.7 mm D x 99.57 mm L	469 grams	Wet look very solid

Sample No. : 3

***Description:** Soil + Sand + linseed oil*

***Test:** Curing status of specimens*

***Date:** De moulding date was 21st of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50mm D x 100 mm L	460 grams	Dying effect appeared dimensions were same.
7th day	50mm D x 100 mm L	460 grams	There was not any change in dimension and specimen shows drying effect.
10th day	49.67mm D x 99.6 mm L	458.2 grams	Sample is not yet shows prominent drying effect but it must've been dried due to slight change in dimension.
28th day	49.67 mm D x 99.6 mm L	458 grams	Wet Look but Solid

Sample No. : 4

***Description:** Soil + Sand + linseed oil*

***Test:** Curing status of specimens*

***Date:** De moulding date was 21st of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460 grams	There was no drying effect appeared, dimensions were same.
7th day	49.7mm D x 99.76 mm L	459 grams	There was no any change in dimension and specimen shows drying effect.
10th day	49.6 mm D x 99.6 mm L	458.6 grams	Sample was in drying process and a slight change in dimension. Sample looks dense and strong.
28th day	49.6 mm D x 99.6 mm L	458.2 grams	Wet look but dense

Sample No. : 1

***Description:** Soil + Sand + $CaCl_2$*

***Test:** Curing status of specimens*

***Date:** De moulding date was 21st of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460 grams	No drying effect appeared, dimensions were same.
7th day	49.8mm D x 99.8 mm L	459 grams	There was little change in dimension and specimen shows drying effect.
10th day	49.7mm D x 99.7mm L	458.7 grams	Sample was in process of curing and a slight change in dimension. Sample looks dense and strong.
28th day	49.7 mm D x 99.7 mm L	449 grams	Dried but rusty

Sample No. : 2

***Description:** Soil + Sand + $CaCl_2$*

***Test:** Curing status of specimens*

***Date:** De moulding date was 21st of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100mm L	460 grams	There was not any drying effect appeared, dimensions were same.
7th day	49.8mm D x 99.7 mm L	459.5 grams	There was little change in dimension and specimen shows drying effect.
10th day	49.7mm D x 99.6 mm L	459.2 grams	Sample was drying and a slight change in dimension. Sample looks dense and strong.
28th day	49.7 mm D x 99.6 mm L	457 grams	Rusty from Surface

Sample No. : 3

***Description:** Soil + Sand + $CaCl_2$*

***Test:** Curing status of specimens*

***Date:** De moulding date was 21st of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 101mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 101 mm L	460 grams	Dying effect appeared dimensions were same.
7th day	49.7mm D x 100.6 mm L	459.67 grams	There was little change in dimension and specimen shows drying effect.
10th day	49.67 mm D x 100.4 mm L	459.67 grams	Sample was half of dried and a slight change in dimension. Sample looks dense and strong.
28th day	49.67 mm x 100.4mm L	458 grams	Rusty from outside

Sample No. : 4

***Description:** Soil + Sand + $CaCl_2$*

***Test:** Curing status of specimens*

***Date:** De moulding date was 21st of January 1998*

Duration	Dimension of the sample	Wt. of Sample	Appearance of sample
1st day	50mm D x 100mm L	460 grams	After de-moulding, Moist, smoothed and exact dimension of sample.
24 hours	50 mm D x 100 mm L	460 grams	There was no drying effect appeared dimensions were same.
7th day	49.7mm D x 99.76 mm L	459 grams	There was no any change in dimension and specimen shows drying effect.
10th day	49.6 mm D x 99.6 mm L	458.6 grams	Sample was in drying process and a slight change in dimension. Sample looks dense and strong.
28th day	49.6 mm D x 99.6 mm L	447 grams	Rusty from outside

Appendix G

Crushing load on Earth specimen and their displacement rate

R	Load Input (KN)	Displacement (mm)
	UN 13:45	:26 27-02
I KN	1.58E-03	-0.381918
*	0.494985	3.84528
*	0.524343	3.84963
*	0.591211	3.85306
*	0.64002	3.85772
*	0.646922	3.86074
*	0.694215	3.86365
*	0.724555	3.86533
*	0.79779	3.86962
*	0.808709	3.87193
*	0.857871	3.87555
*	0.893663	3.87632
*	0.938412	3.88159
*	0.964633	3.88604
*	1.02487	3.89524
*	1.04489	3.89887
*	1.12166	3.90266
*	1.15225	3.90527
*	1.1939	3.9082
*	1.27185	3.91097
*	1.31614	3.91581
*	1.35142	3.92046
*	1.41882	3.92532
*	1.46847	3.9266
*	1.52344	3.93
*	1.52949	3.93343
*	1.62689	3.93868
*	1.63501	3.94144
*	1.71313	3.94626
*	1.78497	3.94841
*	1.82873	3.9543
*	1.85317	3.95721
*	1.90866	3.96187
*	1.98395	3.96648
*	2.01968	3.9705
*	2.07393	3.97511
*	2.13183	3.98243
*	2.20839	3.98617
*	2.21683	3.98926
*	2.28316	3.99188
*	2.34461	3.99642
*	2.38264	3.99939

*	2.45433	4.00496
*	2.51073	4.00931
*	2.57054	4.01661
*	2.6252	4.02093
*	2.70499	4.02626
*	2.71765	4.0303
*	2.82318	4.03565
*	2.84602	4.04195
*	2.94349	4.04748
*	2.9894	4.05485
*	3.08141	4.06356
*	3.13043	4.07113
*	3.21642	4.08294
*	3.27542	4.09563
*	3.34507	4.10932
*	3.41449	4.12509
*	3.48268	4.14293
*	3.55707	4.15916
*	3.67107	4.18444
*	3.70681	4.20405
*	3.8152	4.22796
*	3.89939	4.2521
*	3.98151	4.28173
*	4.0801	4.30454
*	4.15824	4.33791
*	4.25391	4.363
*	4.35092	4.39299
*	4.40707	4.42269
*	4.48447	4.4547
*	4.58442	4.48363
*	4.68127	4.52006
*	4.76627	4.55182
*	4.84016	4.59611
*	4.88993	4.63254
*	5.01966	4.68075
*	5.08785	4.72783
*	5.16068	4.78422
*	5.25443	4.83494
*	5.32259	4.89846
*	5.41304	4.95947
*	5.46119	5.05677
*	5.52249	5.17881
*	5.56459	5.4617
*	0.169518	14.1516
*	-0.387405	1.56885
H	ALT 13:52	:39 27-02
R	UN 13:57	:49 27-02
*	0.496459	0.190357
*	0.546606	0.211502

*	0.596408	0.265442
*	0.602038	0.330209
*	0.664171	0.429754
*	0.699288	0.524576
*	0.746918	0.585352
*	0.78668	0.619859
*	0.833787	0.673082
*	0.87714	0.724153
*	0.900235	0.795181
*	0.94203	0.856109
*	1.00633	0.938017
*	1.01037	1.00864
*	1.07523	1.1043
*	1.11617	1.18545
*	1.1774	1.29228
*	1.23196	1.38536
*	1.25868	1.51216
*	1.28968	1.63125
*	1.37221	1.79363
*	1.4093	1.94288
*	1.44804	2.11838
*	1.50281	2.23312
*	1.55187	2.36672
*	1.58054	2.49854
*	1.62918	2.6984
*	1.69472	2.92588
*	1.70381	3.34585
*	1.59984	3.9637
*	0.340124	13.9846
*	-0.382798	3.8253
H	ALT 14:00	:27 27-02
R	UN 14:04	:18 27-02
*	0.502939	-3.80595
*	0.510849	-3.80437
H	ALT 14:04	:25 27-02
R	UN 14:04	:46 27-02
*	0.500433	0.003925
H	ALT 14:04	:49 27-02
R	UN 14:04	:52 27-02
*	0.480033	0.005601
*	0.505928	0.005908
*	0.582196	0.010198
*	0.61072	0.015163
*	0.645787	0.020706
*	0.68088	0.025569
*	0.755899	0.032995
*	0.796227	0.040163
*	0.819237	0.052206
*	0.848631	0.062805

*	0.904524	0.078792
*	0.938501	0.096277
*	0.997408	0.124668
*	1.01594	0.149782
*	1.0744	0.195644
*	1.14003	0.240982
*	1.15977	0.305532
*	1.19361	0.366382
*	1.24962	0.462537
*	1.30677	0.555773
*	1.36113	0.695087
*	1.39213	0.840572
*	1.43666	1.06354
*	1.45325	1.323
*	1.4778	1.74144
*	1.30489	1.92361
*	-0.403795	9.60718
*	-0.377737	-2.77745
H	ALT 14:07	:08 27-02
R	UN 14:11	:42 27-02
*	0.489576	-5.95404
H	ALT 14:11	:45 27-02
R	UN 14:12	:01 27-02
*	0.528717	2.91E-03
H	ALT 14:12	:04 27-02
R	UN 14:12	:10 27-02
*	0.503741	2.77E-03
*	0.559162	0.007177
*	0.560732	0.010761
*	0.64771	0.015369
*	0.653929	0.020746
*	0.708265	0.027528
*	0.768195	0.040788
*	0.796929	0.048725
*	0.855925	0.063804
*	0.862532	0.074914
*	0.911834	0.091285
*	0.946408	0.108335
*	0.995364	0.126499
*	1.04022	0.147005
*	1.10073	0.173896
*	1.11668	0.208993
*	1.20281	0.257417
*	1.2198	0.309513
*	1.27787	0.383918
*	1.33	0.438423
*	1.38104	0.478218
*	1.3922	0.489788
*	1.48193	0.523657

*	1.52854	0.559318
*	1.56043	0.605053
*	1.6274	0.652719
*	1.6623	0.710485
*	1.7052	0.769903
*	1.76979	1.31595
*	1.82629	1.54944
*	1.88493	1.85028
*	1.92112	2.05442
*	1.97216	2.23922
*	2.03251	2.38289
*	2.0875	2.5929
*	2.15365	2.78718
*	2.21894	3.02727
*	2.24028	3.24707
*	2.28092	3.51943
*	2.36617	3.77776
*	2.41301	3.80835
*	2.40966	3.95471
*	0.631516	13.7317
H	ALT 14:15	:44 27-02
R	UN 14:18	:31 27-02
*	0.527965	-5.10126
H	ALT 14:18	:34 27-02
R	UN 14:18	:50 27-02
*	0.501248	0.004209
*	0.539854	0.008358
*	0.595232	0.027545
*	0.639624	0.038656
*	0.659851	0.055717
*	0.702211	0.072101
*	0.767346	0.092313
*	0.805681	0.118604
*	0.823178	0.153022
*	0.872773	0.186788
*	0.924956	0.243301
*	0.946493	0.29632
*	0.997846	0.364338
*	1.05014	0.428568
*	1.09262	0.514507
*	1.14117	0.589029
*	1.18911	0.697727
*	1.22608	0.783922
*	1.29129	0.915199
*	1.30327	1.02164
*	1.365	1.14387
*	1.43226	1.23152
*	1.46113	1.30904
*	1.53394	1.38105

*	1.58704	1.47162
*	1.61769	1.54986
*	1.6681	1.66434
*	1.70879	1.9078
*	1.75389	2.26179
*	1.8112	2.53418
*	1.85369	2.83655
*	1.91491	3.11091
*	1.98195	2.86202
*	2.00647	3.14905
*	2.07092	3.92499
*	0.947036	9.21414
H	ALT 14:21	:48 27-02
R	UN 14:27	:05 27-02
*	0.513443	-5.64014
H	ALT 14:27	:08 27-02
R	UN 14:37	:49 27-02
*	0.535267	0.025663
*	0.535205	0.027582
*	0.595461	0.028274
*	0.656435	0.028940
*	0.707016	0.030630
*	0.734129	0.031396
*	0.771456	0.037452
*	0.790984	0.042778
*	0.869117	0.046720
*	0.899526	0.052402
*	0.955362	0.055961
*	0.980218	0.059083
*	1.0443	0.065292
*	1.07363	0.067338
*	1.12524	0.070655
*	1.16286	0.074342
*	1.20796	0.076517
*	1.26683	0.078872
*	1.3223	0.081855
*	1.36879	0.087436
*	1.41162	0.092594
*	1.4603	0.097459
*	1.52512	0.102321
*	1.57246	0.107494
*	1.60675	0.112728
*	1.68353	0.12087
*	1.73957	0.125734
*	1.78663	0.134054
*	1.84473	0.143051
*	1.90285	0.148017
*	1.94145	0.155057
*	1.98856	0.158182

*	2.06067	0.162469
*	2.08741	0.165847
*	2.15978	0.169023
*	2.18063	0.170559
*	2.28396	0.173132
*	2.31697	0.177995
*	2.36902	0.182041
*	2.4163	0.184242
*	2.47053	0.191179
*	2.52854	0.197988
*	2.59154	0.207117
*	2.63541	0.215614
*	2.73096	0.226188
*	2.76676	0.236478
*	2.83426	0.25033
*	2.87875	0.26103
*	2.98286	0.276825
*	3.04806	0.289215
*	3.11532	0.304882
*	3.14026	0.319065
*	3.21273	0.334732
*	3.30908	0.351347
*	3.36024	0.370968
*	3.44455	0.387352
*	3.50285	0.407001
*	3.58269	0.425382
*	3.64803	0.449752
*	3.72248	0.470489
*	3.85355	0.497612
*	3.90572	0.52206
*	4.01579	0.552704
*	4.09006	0.577842
*	4.18356	0.608511
*	4.25131	0.635391
*	4.35654	0.667749
*	4.43093	0.696371
*	4.53187	0.733106
*	4.59664	0.764671
*	4.70609	0.804941
*	4.77061	0.841163
*	4.85223	0.883596
*	4.92799	0.918463
*	5.01721	0.964311
*	5.10326	1.00396
*	5.19133	1.05487
*	5.2705	1.10108
*	5.37889	1.16131
*	5.46284	1.21402
*	5.54877	1.28343

*	5.61193	1.34379
*	5.69628	1.42872
*	5.785	1.51107
*	5.86919	1.63293
*	5.91535	1.75806
*	0.828997	13.4578
H	ALT 14:45	:03 27-02
R	UN 14:47	:32 27-02
*	0.515715	-5.22734
H	ALT 14:47	:35 27-02
R	UN 14:47	:49 27-02
*	0.522304	0.005687
*	0.521993	0.008708
*	0.610623	0.013238
*	0.642064	0.017080
*	0.683462	0.020433
*	0.71108	0.023864
*	0.743901	0.027101
*	0.789046	0.029970
*	0.854307	0.034013
*	0.898374	0.037418
*	0.908309	0.041118
*	0.97672	0.044855
*	1.01848	0.050014
*	1.0564	0.055543
*	1.11054	0.062711
*	1.1423	0.069982
*	1.17668	0.07825
*	1.22184	0.084907
*	1.30628	0.096862
*	1.32078	0.108024
*	1.37977	0.123333
*	1.44405	0.138282
*	1.4947	0.156292
*	1.53154	0.17324
*	1.57025	0.191967
*	1.61772	0.209886
*	1.691	0.232427
*	1.71987	0.250167
*	1.8111	0.274589
*	1.83015	0.295019
*	1.90318	0.319147
*	1.9793	0.338909
*	2.00829	0.367134
*	2.03747	0.390224
*	2.12117	0.420715
*	2.17467	0.445392
*	2.23551	0.475563
*	2.24971	0.500601

*	2.3429	0.530168
*	2.40923	0.55756
*	2.44469	0.591287
*	2.48502	0.619959
*	2.56971	0.654262
*	2.59142	0.683166
*	2.65278	0.720567
*	2.73952	0.753387
*	2.78317	0.796638
*	2.84149	0.83235
*	2.92118	0.876446
*	2.94203	0.916281
*	3.0297	0.969656
*	3.07065	1.01258
*	3.19051	1.06721
*	3.22724	1.11357
*	3.32211	1.17345
*	3.35251	1.21935
*	3.47756	1.27661
*	3.50436	1.32082
*	3.61061	1.3675
*	3.66478	1.4046
*	3.75139	1.4476
*	3.83471	1.48419
*	3.95651	1.53418
*	4.03859	1.57993
*	4.10374	1.63453
*	4.18991	1.68212
*	4.26874	1.75046
*	4.37676	1.80952
*	4.43021	1.88321
*	4.54356	1.95154
*	4.61054	2.04745
*	4.68245	2.13603
*	4.75414	2.27272
*	4.26487	2.53197
*	-0.371448	2.83724
H	ALT 14:54	:03 27-02
R	UN 14:56	:09 27-02
*	0.528089	-3.43248
H	ALT 14:56	:12 27-02
R	UN 14:56	:26 27-02
*	0.525705	0.005311
*	0.552205	0.007102
*	0.613791	0.007844
*	0.605586	0.009330
*	0.670344	0.013118
*	0.71127	0.014347
*	0.783376	0.017175

*	0.785936	0.020555
*	0.822731	0.023563
*	0.861005	0.027967
*	0.94298	0.032293
*	0.959398	0.035621
*	0.987508	0.039051
*	1.05512	0.043607
*	1.12541	0.048484
*	1.14098	0.052427
*	1.19	0.057790
*	1.25955	0.062040
*	1.27783	0.068389
*	1.32395	0.072843
*	1.36507	0.077707
*	1.44928	0.081138
*	1.49185	0.08764
*	1.52543	0.093118
*	1.57535	0.099519
*	1.61878	0.106481
*	1.69715	0.113803
*	1.76294	0.121023
*	1.80626	0.130687
*	1.85329	0.138366
*	1.88657	0.14693
*	1.94857	0.155685
*	2.03008	0.169534
*	2.02993	0.180492
*	2.11213	0.196031
*	2.13779	0.209802
*	2.2289	0.225931
*	2.28406	0.2406
*	2.32724	0.258417
*	2.37569	0.272241
*	2.46479	0.289674
*	2.47534	0.303909
*	2.54154	0.321725
*	2.62107	0.338392
*	2.6708	0.357811
*	2.74216	0.374706
*	2.78888	0.393777
*	2.86953	0.410879
*	2.91287	0.430168
*	2.9558	0.447448
*	3.06578	0.468683
*	3.11491	0.486553
*	3.18915	0.508198
*	3.2618	0.527141
*	3.33163	0.54912
*	3.35757	0.568781

*	3.48994	0.592191
*	3.5168	0.612543
*	3.63255	0.636646
*	3.68658	0.658687
*	3.80072	0.686142
*	3.83931	0.708645
*	3.97462	0.738188
*	4.06093	0.763302
*	4.12558	0.791614
*	4.21659	0.817035
*	4.28847	0.847589
*	4.37459	0.874391
*	4.49539	0.906084
*	4.55166	0.931967
*	4.66728	0.963159
*	4.70885	0.989656
*	4.80371	1.0226
*	4.87916	1.04958
*	4.97117	1.08486
*	5.0401	1.1144
*	5.13097	1.15294
*	5.237	1.18522
*	5.31716	1.23069
*	5.36121	1.27032
*	5.45511	1.33149
*	5.52448	1.39805
*	0.51805	8.55465
*	-0.365674	2.37528
H	ALT 15:03	:23 27-02
R	UN 15:05	:52 27-02
*	0.543837	-3.92288
H	ALT 15:05	:55 27-02
R	UN 15:06	:09 27-02
*	0.522955	0.006181
*	0.563594	0.005926
*	0.62117	0.007436
*	0.617463	0.008358
*	0.654197	0.006746
*	0.71545	0.007923
*	0.777176	0.009445
*	0.773546	0.008678
*	0.834718	0.009189
*	0.885493	0.010469
*	0.921462	0.013259
*	0.977566	0.014846
*	1.03877	0.018573
*	1.04612	0.020826
*	1.10239	0.024806
*	1.18403	0.025165

*	1.21037	0.029157
*	1.24464	0.033561
*	1.31926	0.035455
*	1.3675	0.038528
*	1.40885	0.041547
*	1.43465	0.044696
*	1.50498	0.049215
*	1.55129	0.053823
*	1.5803	0.060108
*	1.65098	0.064922
*	1.69332	0.069362
*	1.76698	0.074636
*	1.78222	0.081254
*	1.85082	0.086067
*	1.89442	0.093439
*	1.95064	0.100172
*	2.01134	0.108301
*	2.06296	0.114854
*	2.11789	0.123661
*	2.15888	0.131851
*	2.20752	0.141811
*	2.25201	0.150924
*	2.34607	0.161369
*	2.40792	0.169714
*	2.43681	0.180069
*	2.48098	0.189542
*	2.57405	0.200677
*	2.60433	0.210149
*	2.67248	0.221963
*	2.72683	0.231283
*	2.8006	0.243879
*	2.86835	0.253938
*	2.93195	0.26638
*	2.96682	0.276876
*	3.04964	0.290239
*	3.10747	0.301504
*	3.20463	0.314739
*	3.23404	0.325746
*	3.31066	0.339264
*	3.39709	0.350322
*	3.45243	0.36366
*	3.52546	0.375078
*	3.62957	0.390232
*	3.67083	0.402059
*	3.80928	0.416946
*	3.84663	0.428671
*	3.94336	0.444057
*	4.01743	0.456653
*	4.12381	0.471666

*	4.18443	0.482572
*	4.33249	0.497638
*	4.37518	0.509874
*	4.49365	0.52663
*	4.54881	0.539224
*	4.6353	0.554943
*	4.72855	0.567871
*	4.79636	0.583282
*	4.88422	0.596903
*	4.99382	0.612121
*	5.04873	0.624077
*	5.12842	0.63973
*	5.22558	0.650533
*	5.32764	0.664614
*	5.36177	0.676672
*	5.49448	0.689268
*	5.59058	0.701607
*	5.63222	0.714763
*	5.72758	0.725797
*	5.78944	0.740391
*	5.8637	0.750681
*	5.97327	0.764454
*	6.04996	0.776537
*	6.15736	0.79013
*	6.20178	0.800575
*	6.31746	0.814899
*	6.38149	0.825702
*	6.48854	0.83913
*	6.53408	0.848345
*	6.65609	0.861259
*	6.70095	0.872423
*	6.81241	0.885183
*	6.87253	0.895883
*	6.97382	0.908159
*	7.08023	0.918861
*	7.13997	0.931455
*	7.20667	0.942796
*	7.29573	0.954817
*	7.4045	0.964903
*	7.48788	0.97829
*	7.52759	0.989914
*	7.62314	1.00445
*	7.69164	1.02826
*	7.79829	1.40148
*	7.89973	1.57152
*	7.95098	1.73446
*	8.02562	1.84738
*	8.15238	1.95311
*	8.23123	1.94451

*	8.27758	1.62356
*	8.39056	1.63324
*	8.50534	1.55605
*	8.56354	1.70353
*	8.61761	1.84967
*	8.69132	1.94951
*	8.79967	2.05106
*	8.8727	2.12855
*	8.9824	2.2118
*	9.04493	2.27782
*	9.15829	2.3579
*	9.22926	2.42233
*	9.32773	2.50592
*	9.40572	2.57672
*	9.47645	2.66149
*	9.55779	2.73734
*	9.66121	2.8319
*	9.70837	2.91201
*	9.79061	3.01949
*	9.85092	3.11354
*	9.95257	3.23733
*	10.0396	3.35366
*	10.1507	3.5276
*	10.2134	3.71388
*	10.2804	4.07005
*	10.253	5.09824
*	-0.356398	6.59494
H	ALT 15:17	:52 27-02