DESIGN TECHNIQUES FOR EARTH HOUSING

by

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15th June 1955

A Thesis submitted in partial fulfillment of the requirements for the Degree of
Master in Architecture.

to........................................
Lawrence B. Anderson, Head,
Department of Architecture,
School of Architecture and Planning,
Massachusetts Institute of Technology.

by:........................................
Thomas A. Markus
The three type-designs presented as a part of the Thesis are then described in detail. They do not represent an architecturally final, or in any sense a detailed, planning, solution. They merely point the way to the type of aesthetic which these new techniques will require and produce, both for economic and architectural reasons. The final chapter sums up some of the detailed problems of design which occur in earth construction.

Two Appendices follow; the first describes the work of the M.I.T. Earth Housing (now Earth Building) Project, in close co-operation with which this Thesis has been worked out; the second is a copy of a paper by the author, shortly to be published, on methods of soil stabilization by the use of synthetic resins.

The 30-page Bibliography is an attempt at presenting all that has been published on earth construction and allied subjects in the last 30 years. It is believed that this is the first time that such an attempt has been made, and it has been done in order to give the fullest possible information to future workers in this field. The Bibliography is an important part of the original work of the Thesis.
52, Fairmont Street,
Cambridge 39,
Massachusetts.

15th June 1955.

Dean Pietro Belluschi,
School of Architecture and Planning,
Massachusetts Institute of Technology,
Cambridge,
Massachusetts.

Dear Dean Belluschi,

In partial fulfillment of the requirements for the Degree of Master in Architecture, I herewith respectfully submit my Thesis, entitled: "Design Techniques for Earth Housing".

Sincerely yours,

Thomas A. Markus, M.A., A.R.I.B.A.
DESIGN TECHNIQUES FOR EARTH HOUSING

by Thomas A. Markus

A thesis presented in partial fulfillment of the requirements for the Degree of Master in Architecture, Massachusetts Institute of Technology, 15th June 1955.

ABSTRACT

The Thesis represents an attempt to apply the most modern engineering and chemical knowledge to the most ancient building technique -- earth building. The potential fields for earth construction are first discussed. This is followed by a critical description and an evaluation (from the three separate viewpoints of economics, engineering and design) of current earth building techniques.

Arising from this evaluation, particularly from the economic one, which is worked out in some detail, suggestions for new types of earth construction are proposed and described in some detail. The basic assumption behind these suggestions is that in order to make earth construction a practical, durable and economic technique, stabilization of some sort is required. Even with very-low stabilizer content, of a traditional type, say cement, this is uneconomic in regions where labour is expensive - a situation which there is reason to believe will be almost universally true in the so-called 'under-developed' regions in the next twenty years or so. In such a world, in order to use as much stabilizer as would be required even in a dry climate, labour time would have to be drastically reduced. It is in an effort to do this that three techniques are here put forward. They are: horizontal compaction by road making machinery, and tilting walls into position; spraying; and extrusion.
My special thanks are due to the following persons:

Professor L.B. Anderson, for help and advice at all stages of the work.

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INTRODUCTION

This study had a curious genesis. It originally represented, as it were, the coming together of modern technology and archeology. During the course of research work carried out in the Department of Architecture at Massachusetts Institute of Technology on the newest of all building materials, plastics, it was discovered that a great body of technical research existed and was being pursued on the use of certain synthetic resins for the stabilization of soils for civil engineering purposes. In trying to find possible use for this research in the building field, it soon became apparent that the whole subject of building in earth would have to be fundamentally re-examined. So, whilst keeping in mind these latest developments in the field of soil science and engineering, many of the older techniques, with a history as ancient as building itself, were investigated, evaluated and used as starting points for possible new developments.

Whilst no attempt has been made to make this a historical study of the subject, in fact no satisfactory comprehensive work on this has been discovered, such past examples of earth building as seemed to offer a specific lesson, even if only in a negative way, have been examined. It soon became apparent that as far as architectural design was concerned, most inspiration could be drawn from the most ancient, and the most primitive contemporary structures. In these, earth seems to have been used in a manner which shows real, intuitive appreciation of its formal properties and a mature imagination. On the other hand its technical and physical properties were little understood and hence these structures often have grave failings of durability, strength and weather resistance. These engineering properties seem to have been understood in the past, and now in more highly developed societies, but with this increased knowledge much of the unique and imaginative design tradition seems to have been lost. So it has been necessary to study the former for their design tradition and the latter for sound principles of construction.
But the main sources for recent technical developments have been outside the field of building construction altogether; they can be found in chemical engineering, mechanical engineering, and road-making techniques. This study does not in any sense pretend to give a complete picture of such technical developments; that is not its purpose. They are briefly described, however, where relevant, in order to show what architectural use can be made of them. Although the last few decades have seen an increasing awareness on the part of architects and designers of the great imaginative opportunities offered by developments in many scientific fields, in earth construction this is not the case. Even the most advanced designers who have attempted to work in this material, have largely relied on crude, rule of thumb constructional knowledge and accepted constructional techniques. Reference to the copious literature on the engineering and scientific aspects of the subject has been made in the text and in the bibliography. It is evident, however, that as far as building is concerned, this is still mostly of an empirical type. No general work of scientific authority, exists as yet, for instance, on such a basic question as what types of soils are suitable for building. Work on this and allied subjects is however in progress. If it is true that, for various reasons, engineers and designers are finding a new interest in earth as a building material, it is hoped that such studies as this will not only follow the technical research, making architectural use of what has been discovered, but in a sense lead it, by making clear what the ultimate aims of designers are. It is only by full co-operation of this kind that the typical time lag which has so often occurred in the past, between a technical advance and its whole-hearted and specific acceptance by architects, can perhaps be reduced or altogether eliminated.

The plan of study has been roughly as follows. First, a search for the potential fields of application for earth buildings. This is a complex question, involving economics, sociology, engineering, climate and other factors. Then a review of past and present techniques of earth construction, with a brief technical description and more detailed reference to the work going on today in the field. These techniques are then evaluated,
briefly from engineering and economic viewpoints, and in more detail from the architectural. These evaluations lead on to the description of the new structural and design techniques which are the chief contribution of the study. These are worked out by means of models and drawings. This section should, if possible, give the lead to much further work, in engineering and architecture, to try and make possible and economic some of the systems proposed, and to search for new and more suitable forms of design. Arising out of the general work on the design of the housing schemes here proposed are more detailed questions of design, concerning the components of earth buildings, which are discussed in the last section.

It is therefore easy to see that the study is bound, by its nature, to be in every way tentative. Some inspiration from history, some guidance from engineering, some limitation by economics and climate, some new directions in visual approaches; that is all. It is a beginning; it is not supposed, or in fact able, to speak with authority; it is supposed to start discussion and not end it.
CHAPTER I
POTENTIAL FIELDS OF APPLICATION FOR EARTH HOUSING

No building material is as widespread, in time and place, as earth. It was the first material to be used in many prehistoric civilizations, and there are few large regions in the world where it is not still used in some form today. In almost every case where it is still used the causes are economic, although the economic causes may have existed for such a long time that a firm tradition of earth housing exists which it would be difficult to replace even if some more economic material could be found. For various reasons interest in earth housing is at present high, and many national and international organisations, as well as individuals, are seeking to extend the use of the material to new regions, to revive it in places where the tradition has died, or to improve techniques where they are defective.

This movement is the outcome of the recognition that there are large areas in the world where the bad housing conditions cannot be improved until some simple economic, climatically and culturally suitable, and durable construction method can be found. Earth seems to provide the answer in many cases. This is not the place to discuss the general need for improvement in housing conditions in these areas. But it might help to see this study in its broadest background to state the magnitude of the problem.

In a recent United Nations publication on tropical housing, it is estimated that 25 million new homes will be needed in Latin America to replace slum and sub-standard houses. In Africa it has been estimated that almost the whole of the population in the area between the Union and the Sahara, amounting to 125 million, needs to be rehoused. In Asia 100 to 125 million families live in houses which are condemned for one reason or another. Other areas show comparable need. The survey from which these figures are quoted is limited to the tropical regions of the
world. It is not unreasonable to suppose that a part, even if much smaller, of the reconstruction needs of North America and Europe could also be satisfactorily met by earth housing. All are agreed that all attempts at economic stability, better health, education, agriculture, industry and in fact any form of human endeavour can, and almost certainly will be frustrated without a basic change for the better in the housing conditions of peoples in the so-called "underdeveloped" countries.

Most of these countries have certain common economic traits. Industry is generally at an early stage of development and localised in a few very small areas. Transport conditions are expensive and difficult. Labour is cheap and mostly unskilled. All these circumstances point, as far as building is concerned, to the use of locally available material, local, semiskilled or unskilled labour, and simple, if any, mechanical devices. True, this economic picture is rapidly changing and there is reason to think that in the next twenty years or so will be radically different in many regions. Industry may have developed sufficiently to alter completely the proportions of town to rural workers; transport will become better and quicker and labour will become increasingly important as a cost factor in building work. Part or the whole of this development has already taken place within limited areas which were considered "underdeveloped" till recently. Not that this makes the housing problems any easier; in many cases where there is wholesale movement of populations toward urban centres, new slums of hitherto unprecedented squalor arise. But it does mean that any long-term view of earth building must take into account the changing economic pattern if it is to succeed. This can have tremendous and direct implications for architectural design, as will be seen later.

The three basic conditions which probably determine the fields of application for earth housing are: availability of suitable material locally; suitable climate and broader economic considerations including
relative material-labour costs. The least limiting of these at the moment is the availability of suitable local material. There are very few regions where earth is not usable in some form for building. It may have to be transported short distances, or it may have to be altered by the addition of elements, such as sand or clay, from a comparatively long distance. At what stage such transport becomes uneconomic in comparison with other building alternatives will depend entirely on the special circumstances of each case. However, accurate economic analysis of this problem cannot be made till the economists know exactly what has to be brought and in what quantities. An this is a question for the architect and the engineer.

A. Suitable Material

More details about suitable types of soils for the different forms of earth construction are given in Chapter 2. It is sufficient to say that most high sand-content soils will be suitable for rammed earth work and most high-clay content soils for adobe or puddled earth. Either of them can be improved by the addition of stabilizers. The suitability of soils for building construction, and the amount of additives or other soil constituents that have to be added is a matter for accurate scientific analysis. This in itself constitutes a limiting factor, since the facilities for such analysis are available in only few instances. Although adequate, simple field tests have been devised, they cannot give all the information required for the highest quality construction or the most economic use of material and labour. Thus the prolific supply of the raw material for earth construction are in a real sense reduced by the lack of facility for determining the nature of the supply. As a result of inadequate knowledge of the soils to be used, earth constructions have frequently failed in a more or less spectacular manner, leading sometimes to the entire abandonment of the technique.

B. Climate

Climate is today a more strictly limiting factor than availability of material. Many aspects of it enter into building design; temperature range, intensity and averages; average and maximum (hourly or daily) rainfall; humidity; wind direction and speeds; sky brightness; ground radiation and a number of other lesser factors which have to be taken into account. The two chief factors which will affect the decision as to the type, if any, of earth construction to be used in a region are rainfall and temperature. The others will be more important in planning and design; wind pressures are unlikely to be crucial, except in so far as they may lead to the choice of an earth wall in place of a lighter type of construction, since by reason of its weight any ordinary earth wall will be able to withstand even the highest wind forces.

Various earth construction techniques differ in their ability to withstand rain. Probably the poorest resistance is offered by adobe block walls, which erode sufficiently to impair seriously their strength in less than an hour of driving rain. Hence, adobe block construction, without adequate wall covering, is not suitable except in hot-dry types of climate, such as parts of Central and South America and Africa, and


even here frequent repair is necessary. Wall coverings of all kinds have been used and experimentally tried, including various soil, lime and cement plasters, paints, linseed oil, asphalt, casein, and other organic substances. The addition of stabilizers to soils has been chiefly designed to increase their resistance to absorption and water erosion. Stabilized earth is more fully discussed in the next chapter but the main types of additives can here be mentioned. Traditionally they have been Portland cement or bituminous asphalt emulsions. Certain natural and synthetic organic substances have also been used. Rammed earth walls, even without the addition of stabilizers, have good resistance to water erosion and absorption. The absorption rate and drying out rates will depend on the density of the wall, and the resistance to erosion on the relative clay, sand and stabilizer content; clay giving low and sand high erosion resistance.

Thus the chief effect of rainfall rates and intensity will be in determining what types of soil and stabilizers will be suitable. In the past, with stabilizers and soil-admixture little practiced, this has been quite a severe limitation. However, with more scientific knowledge becoming available, and with newer stabilizers being investigated, which may be usable with a much greater range of soils than the


5. See Appendix II.
older ones, this limitation may gradually lose its significance. In addition, rainfall will influence the choice of roofs, foundations, wall openings, rainwater disposal systems, wall coverings and finishes in general.

Temperature is an important climatic factor in earth construction. The heat resistance of earth walls and roofs has been one of the chief traditional reasons for using the material. Basically earth is not a good insulating material; the denser it becomes, and density is the chief aim of almost all earth building processes, the poorer its insulation value per unit thickness. Average earth walls have about the same range of thermal conductivity as concrete. However, like most dense materials, earth has a high thermal capacity and this becomes a valuable property when it is used in considerable thicknesses. It gives them the property of acting like a thermal "fly-wheel." That is, they maintain in certain climates a fairly uniform temperature within a building on account of the time-lag between any external change in temperature and a change on the internal face. This of course is only applicable in climates where there is considerable temperature range over short periods of time. This is a particularly marked feature of the hot-dry type of tropical climates. Here the days are hot and the nights cool or even cold; during the day protection is required against excessive heat and during the night the provision of adequate warmth can become a considerable problem. A thick earth wall will be able to resist warming up on its inside face for a period of many hours. Hence it will keep the house interior fairly cool until this happens, thus providing cool surfaces to which the body can radiate heat. When the heat does begin to penetrate it may be when the exterior temperature is already dropping and the heat is beneficial in the interior. Similarly, by the time the interior wall surface has cooled down to room temperature or less, the exterior is again

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beginning to warm. To utilise the thermal capacity fully, it should be accurately measured and then the wall thicknesses designed in such a way that the wall will have approximately a twelve hour "time-lag."

There is room here for much further research. For instance, much of the stored up heat of the wall is radiated to the outside as well as to the inside, during the night. If this could be prevented by a surface covering having properties similar to glass, that is, admitting high frequency waves but being opaque to low frequency ones, much greater warming effect could be obtained during the night. Of course, the surface would have to be sufficiently transparent to the low frequency waves to ensure that all the heat was lost by the time the exterior warming up process began again in the morning.

The thermal capacity of thick earth walls is no advantage in the hot-humid types of climate, such as that of Malaya, where a fairly uniform high temperature is maintained over long periods. Here cooling is mainly a question of air movement, which is a planning and design consideration. Thus earth would not be chosen for its thermal properties in such a climate although it might have other recommendations.

Although much empirical data on climatic effects on various earth walls exist, there has been little scientific information. The accelerated weather tests which have been reported in technical literature rarely give sufficient information, or the type of information, which would be necessary to make the behaviour of an earth wall in the field really predictable.

C. Economic Factors

The third chief limiting factor of earth building is economics. This is a far more complex condition than either of the previous two. In Chapter 3 a more detailed economic evaluation of the various forms of earth building construction at present used is given. Here we are chiefly

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8. op. cit., note 3.
concerned with the type of economic considerations which are likely to be crucial in working out an earth housing project. Four separate cost factors can be distinguished: material, equipment, labour and long-term maintenance of completed structures.

Material

It has already been pointed out that the range of suitable soils is very wide and that therefore there are few regions of the world where the basic raw material is unavailable, even if it has to undergo chemical or mechanical mixture with non-local ingredients. The various estimates of the range of suitable soils vary widely in the technical reports on earth construction; but it is admitted by all authorities that there are extremely few soils which are completely unusable, allowing for admixture of soil elements or stabilizers. Whether in a particular case earth will be the most economic material will depend on the amount of admixture of such extraneous elements that has to be made, the distance it has to be transported, the cost of the manufactured elements in the admixtures (such as cement or bitumen), the relative cost of other building materials in the region and the life of earth houses as compared with other types of construction. In many regions these factors can be simply determined; for instance, there is little doubt that in Egypt, where suitable earth abounds in certain regions, and where almost all building timber is imported and good stone scarce in many regions, earth is the most economic material.\footnote{Little, Arthur D., Inc., Preliminary Report on Egyptian Village Housing, Building Materials, and Methods of Construction to Administration, Cambridge, Mass., April 1952, and "A Model Village in Upper Egypt," Architectural Review, 102, Sept. 1947, pp. 97-99.} A similarly
clear case for earth construction exists in connection with the United Nations earth housing project in Ceylon. True, in these cases other economic factors such as labour, are favourable; these will be considered below. But even as far as materials are concerned there are cases, such as Malaya, where it is possible that other traditional forms of building, timber and bamboo in this case, may cost less or the same. Of course it must be emphasised throughout that the cost of the raw material is perhaps the least important question; the other factors discussed below, are essential to give a complete picture.

As part of the basic material cost must be considered any exterior or interior wall surface covering that is used. The poorer, and hence, generally cheaper, the earth wall itself, the better type of additional surfacing is required to make the wall resistant to weather and to avoid frequent and sometimes relatively expensive repairs. These factors have to be weighed against each other.

Equipment

In traditional earth construction, equipment has been simple and cheap. For block work all that is required is a set of molds, usually wooden, and a rammer, if the blocks are not adobe. The molds are reusable several thousand times, with reasonable care (which involves frequent oiling and good stacking in storage). In rammed earth the wall forms are complex and for varied house types a large number will be required. However, they are usually timber, can be made on the site and should be usable for several years of constant work with reasonable care. One form at South Dakota State College was in continuous use for thirteen years without showing signs of need for replacement. In addition rammers

10. Middleton, G.F., "Building Techniques in Ceylon," Prefabrication, 2, 17, March 1955, pp.203-206; also valuable information was obtained from the files on the earth housing schemes carried out under United Nations sponsorship in Israel and Ceylon by kind permission of Mr. J. Weissmann of the United Nations.

11. Patty, R.L. and Minium, L.W., Rammed Earth for Farm Buildings, Agricultural Experiment Station, South Dakota State College, Bulletin No. 277, (Revised), June 1945.
are required and some means of carrying the soil to be placed in the
form. These are the basic items of equipment. Increased efficiency can,
of course, be obtained by any degree of mechanisation. Mechanical mixers
can be employed, pneumatic rammers, or even a complex block making machine
which does the whole series of operations on a mass-production basis.12
Once again, only the very broadest generalisations about these altern-
atives are possible here. The degree of mechanisation will depend in
every case on local circumstances. The cost of the skilled labour neces-
sary for the handling and maintenance of mechanical aids has to be compared
with the cost of the unskilled labour which can normally do the job
manually. Again, if the machinery is complex, to be economic it must be
kept at a maximum production rate over long periods of time; this may
involve moving it from one site to another over large tracts of country
and the quality of the roads as well as the distance apart of the sites
may possibly be crucial. Cost of fuel, replacement of parts, the
relative quality and durability of hand-made and machine-made work, and
the kind of ownership and rental system for any machines are all going
to be relevant. It is obviously an economist's task to assess these
matters. But it is going to be impossible for him to do this efficiently
without full information from the architect and engineer on the structural
and design problems involved.

A more detailed economic evaluation of present day earth building
techniques is attempted in Chapter 2; however, it must here be pointed
out that many proposals for earth housing which may be economically
sound today may cease to be so in a few years. This is mainly because,
on the whole, present techniques only demand unskilled labour, which in

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12. Whiskin, H.P., "Man-Build in Situ Concrete Walling," Prefabrication,
February 1955, pp.33-35; Cordes, T.K., "Stabilized Earth - A Building
Machine, Hans Sumpf Co., Fresno, California.
most tropical regions is to be had at very low cost. This pattern is rapidly changing however in many regions, and it is in view of this fact that some schemes are presented in this report which involve quite a high degree of mechanisation and skilled labour. It is possible to see that any earth building which is only economic on account of using cheap labour is doomed as a long-term policy. Therefore more research is necessary on new techniques which cut down on the amount of labour required and give a more satisfactory, controllable product at the same time.

Labour

This labour factor is, in fact, the chief argument used by most advocates of earth building. The need for only unskilled or semi-skilled labour has made it possible to choose earth construction in many of the "self-help" housing schemes. Where prospective owners or tenants are building their own houses under such a scheme it is difficult to envisage any situation in the future where the comparatively large amount of labour required will constitute an economic barrier; this, as has been pointed out above, will happen on the whole only in large-scale housing schemes where organised building labour is used. So the task of the designers and engineers now seems to be twofold: first, to improve the simple primitive techniques as much as possible without the use of mechanised aids and skilled labour, in order that earth construction can be successfully used in the "self-help" schemes of technically primitive regions and in order that even mass housing on a large scale can be carried out without upsetting the present economic equilibrium to such a degree that all advantage would be lost. Second, to devise new methods of stabilization, block production and ramming which will permit the most

economic and sound use of material and the fastest construction time with the minimum of labour, in order to introduce these schemes by gradual stages into such countries where the changing economic pattern permits or even demands it.

Maintenance

The last of the four economic factors is building maintenance. Here soundly built earth housing offers distinct advantages over many other techniques. In homogeneous earth walls there are no joints to be maintained. If the surface is protected by an applied finish, this may require considerable maintenance, but many new finishes are being tried which offer excellent solutions. The best solution however, is to use a system where no applied coating is necessary, such as stabilized rammed earth or stabilized adobe block. The amount of surface maintenance will also depend on the care with which roof, openings and other details have been designed. Earth walls have perhaps the best resistance of all building materials to three hazards commonly met in the tropical regions: fire, earthquake, and termites or other insect and fungus attack. Its resistance to termite and similar attack depends on the complete removal of organic matter; this usually is possible by not using soil from the top 18" or 2' deep layer of earth. For earthquake resistance, what is chiefly required is lateral strength. Values in the order of 80 lbs/sq.ft. give sufficient strength to resist most normal tremors and shocks. Such values are fairly easily obtained in massive earth walls, especially where the thickness is over 12". In National Bureau of Standards tests on various types of earth walls, monolithic and block, both stabilized and unstabilized, transverse strengths of up to 159 lbs/sq.ft. were obtained on a cement stabilized wall; the lowest average value of 59 lbs/sq.ft. was for adobe block.

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15. op.cit. note 3, pp.16-41, and Table 10, p.23.
One other factor makes earth walls in certain regions easy to maintain; they are usually free of the freeze-thaw cycle which is so destructive of masonry and concrete in more temperate climates.

Raw material, climate and cost - they are certainly the three decisive factors today in any decision about earth housing. Later in this report, methods will be suggested in which some limitations imposed by the limiting trinity can be overcome, and hence the potential field of application broadened. But there are a few other possible new applications which may have the same effect and which ought to be mentioned in this chapter.

Other Factors

One of these is defensive construction. Scientific tests carried out during World War II have already established the suitability of earth for defense work against "traditional" weapons. Its chief suitability lies in the cushioning effect of the material against flying fragments, debris and projectiles. In this respect it is much superior to concrete or masonry, which spalls under such impacts and hence needs frequent repair. But since the advent of thermonuclear weapons, earth has even stronger claims for use in defense. It is especially the heat capacity of the wall which would recommend it as a protection against the intense but short-lived heat flash of an atomic weapon.

Another possible use might be in temporary housing in remote areas for construction workers, defense personnel and emergency housing. Lastly, perhaps earth construction would find favour in highly developed and climatically temperate countries if new design and finish standards were possible. One field in which it could first be experimentally used is that of vacation housing. Its final acceptance in some quantity as a


construction material in countries where neither climate or economics make it necessary will depend on its imaginative architectural use.
CHAPTER II. PAST AND CURRENT EARTH BUILDING TECHNIQUES

A. Description

Before giving a description of some of the more widely practised earth building techniques a few of the more obscure ones are summarized briefly below. These may have principles or details which could usefully be combined with new techniques to be developed.

1. Wattle and Daub

This is probably one of the most ancient systems of earth construction. It has been used by many ancient primitive civilizations, it was widely practised in connection with timber framed houses in medieval Western Europe, and is still used in some countries. The structure consists simply of a network of interwoven twigs, branches and straw fixed to a timber frame of some kind, and the interstices are filled with lumps of earth whilst a smooth earth coat is given to the exterior as a finish. The large proportion of organic material makes it vulnerable to insect or fungus attack and therefore it is not suitable for most tropical regions. However its adaptation has recently been advocated by an Australian authority on earth construction, G. F. Middleton. This might be done by the use of metal lath or wire mesh to replace the twigs and straw. Owing to the internal non-soil core, the wall can be made quite strong in even small thicknesses.

2. Cob

There are several usages of this word. Basically it always describes a technique of building out of rough, damp lumps of earth which are placed on the wall in situ. The craft was widespread in England at one

18.

Williams-Ellis, C. and Field, E. Eastwick, Cottage Building in Cob, Pise, Chalk and Clay, London, 1947, gives a detailed explanation of all these terms.
time and is still practised in some rural areas. The material consists of a fairly stiff mixture of water and a clay soil, with straw or other fibrous binder usually incorporated. Consecutive layers of the mix are applied, without use of shuttering, and the wall is roughly trimmed to uniform thickness, either as the work proceeds or when it is complete. Special cob knives are used for this. A variation of this technique is used in West Africa, where, after the earth has been prepared and kneaded by foot in the earth pit, balls of earth about football size are formed by one man and then passed on to another who builds the wall, forming openings, corners and other features as he proceeds. Once the wall has gained some height, the second man usually sits astride on the top and the first throws up to him the pressed balls of earth which are then beaten flat on the wall. An interval of one to three days is allowed between successive courses. 19

During the drying out of cob buildings considerable shrinkage takes place, causing numerous small cracks, but none of these impairs the structural soundness of the wall. Protective surface coverings are usually applied; in England often whitewash, in the West African example mentioned, sometimes a kaolin clay. Often courses or individual stones or burnt bricks or tiles are included in the wall.

3. Turf Walls

In many primitive communities huts are still produced by this method. Large blocks of turf or sods are cut from the ground, and piled up roughly to form a wall. Due to the crudeness of the blocks, corners and angles are impossible to form, which results in the characteristic circular or curved plan forms of these structures. The walls

19. op. cit. note 6, p. 46-47.
are afterwards roughly trimmed with a sharp instrument to approximately uniform thickness. There are several American Indian tribes who still practise this method of building.

Apart from the above techniques, which seem to have little application without considerable modification for permanent buildings today, there are three chief forms of earth construction; they are the most widely used today and will offer, perhaps in radically altered forms, the solutions for earth construction in the future. They are adobe, rammed earth or "pise" and stabilized earth.

4. Adobe

The word is simply Spanish for mud. In one form or another it is the most ancient of all building materials. It was used extensively in Egypt, Mesopotamia, China and America many thousands of years ago. Historically, it is more usually known as sun-dried or sun-baked brick. Several variations of it exist, but basically they all have certain features of manufacture and property in common. All soils used for adobe have a high clay content. The soils are mixed or "puddled" at a relatively high water content, into a plastic mud of varying stiffness. Adobe blocks or walls are always sun-dried; if firing of any sort takes place there is a basic change in property and the new material, with which this report is not concerned, can be classed as a fired brick or "red" brick.

a. Soils for adobe

All adobe soils have a high clay content. The clay particles are surrounded by a mica-like film of water, which is known as "absorbed" water. The thickness of this film has a direct relationship to the plasticity of the clay and this in turn is closely related to its strength.
This clay-water structure acts as the binder or adhesive in a general mass of clay soil. Without the addition of extraneous chemicals, usually known as stabilizers, this clay-water structure will become plastic again upon the addition of water, and will lose its adhesive power in the degree to which this plasticizing takes place. The actual physico-chemical relationship of clay particles, water, and the other soil particles is a complex field of study on which a great deal of scientific data is available. Much of it is of a basic soil science type, and some of it has been applied to such civil engineering work as road and airstrip making. But little scientific work on soil properties for building exists.

The higher the proportion of clay and silt particles are in a soil, the greater will be the amount of moisture necessary to bring it to a given mechanical state; plastic or liquid. This is because these particles are the finest soil components and where there is a high proportion of them a greater quantity of water will be required to give each particle its film of water than where the coarser, sand and gravel particles; predominate. Each soil has set properties in connection with its moisture-strength ratio. These are defined as the plastic limit and the liquid limit, each being an expression for the percentage of water needed to make the soil "plastic" and "liquid", states which are specified according to standard tests. Perhaps the most important soil property for building work is its "optimum moisture content." This is an expression defining the amount of moisture necessary at the mixing and compaction stage of a soil block to give the dried specimen maximum possible density for that type of soil. Here several requirements are in opposition to each other. In order to obtain the least porous, and hence least permeable wall, the highest density is required. This will be obtained

See Appendix II which gives an outline of the Earth Housing Project being carried out at the Massachusetts Institute of Technology.
with high clay content soils; but since these will have a high optimum moisture content, they will shrink more during drying than more sandy soils, thus causing cracks. Also, the clay component will not be weather resistant and if there is little sand or gravel present the wall will rapidly disintegrate under the effect of rain. The cracks formed in the clay soils during drying can be structurally serious; but even where they are not, they will cause the wall to be permeable and weak at the small cracks and this will involve repair and applied facings.

So in adobe work, these conflicting requirements have led to the choice of soils which have a sufficiently high clay content to give a plastic, workable mud, but also a sufficient sand content to prevent excessive shrinkage and water erosion. Numerically it is difficult to define what types of soils will give these properties. Here are some of the better known estimates:

a. 25% - 36% clay. 21
b. Minimum 50% clay content. 22
c. Up to 85% clay content. 23
d. Maximum of 50% clay. 24

There is thus considerable variation of opinion even on the necessary proportions seen as the result of mechanical soil analysis. But it is well established that mechanical analysis alone cannot give all the information required. Physical tests, giving the liquid and plastic limits, shrinkage characteristics and density-moisture relationship should all be known to assess a soil adequately.

One of the chief characteristics of high clay content soils, as has been noted above, is their high shrinkage on drying, due to the high

23. op. cit. note 1.
24. Harrington, E. L., Adobe as a Construction Material in Texas, School of Engineering, Texas Engineering Experiment Station, Agricultural and Mechanical College of Texas, Bulletin No. 90, 1945, p. 22.
moisture contents required to make the clay into a workable, plastic substance. For this reason adobe has almost always been used in block form; here any shrinkage that does take place occurs before the block is placed in the wall and is not likely to affect the wall strength seriously. The blocks are usually limited in weight to about 40 lbs., beyond which it is laborious and uneconomical to handle them. Poured in place, monolithic adobe walls have been executed, but difficulty occurs with shrinkage control. The addition of straw or other fibrous substance can reduce this, but also weakens the structural strength of the earth wall, contrary to ancient and popular belief. In poured adobe work, the formwork is either erected to the full height or moved up the wall in small distances as the work proceeds.

b. Manufacture of adobe blocks

The earth is usually mixed in a pit, some of the organic matter and larger stones having been removed. Water is added to the mix as required, the amount depending on the type of soil. This may be as high as 20% for a soil with a 60% clay ratio. A more usual amount is 12% - 15% of the dry weight of the soil. If straw or other fibers are added they are mixed into the soil at this stage; usually straw is chopped into 4" - 8" lengths and about 125 lbs. - 150 lbs. of it is added to material sufficient for making 1000 4" x 12" x 18" adobe blocks. As has been pointed out above, this fibrous additive adds nothing to the strength of the material; in most cases it considerably weakens it. The shrinkage propensities of the soil are, however, reduced. In some climates, mainly due to the peculiar type of soil used, a time interval is allowed between mixing and use, during which certain chemical changes take place. Notable examples occur in certain lateritic (high in iron and aluminium compound content) soils of West Africa. Here the hydration of the ferric hydroxide takes place during this interval and gives a very stable soil

25. op. cit. note 24, p. 19, and op. cit. note 6, p. 32.
after drying out, since the hydrated colloid becomes almost completely irreversible and thus reabsorption of water by the colloids will not occur.\textsuperscript{26}

When the mud is adequately mixed it is placed into forms of some kind, or, occasionally, formed by hand into a convenient shape and immediately used. One example of this latter technique is the "tubali" wall used in Nigeria, where the earth is moulded into small, pear-shaped blocks, which are laid with their narrow ends up and the next course is then fitted into a soft mud placed between these ends. (Fig. 1.). The ordinary moulds are usually made of timber and can be of any degree of complexity; some provision of often made for removing one side so that the block can be released more easily. The moulds simply provide a lateral frame; the bottom is given by any nonadhesive floor (canvas, dry grass, or paper is often used) and the top is left open (Fig. 2.). The blocks are removed and stacked for sun-drying as soon as they are able to bear the handling and stacking. Little pressure is used during the moulding process.

The wall building technique is similar to that used for any block wall. The mortars used vary widely; often it is a mud mortar of the same type as the block mixture, mixed with a greater amount of water. Sometimes a lime or cement mortar is used. Where mud plaster is used, it is often at the joints that the first water penetration will occur.

Although opinions vary on the weather resistance (chiefly resistance to rain erosion) of unstabilized adobe walls, there can be little doubt that it is very poor. More details are given later in this chapter under the engineering evaluations. But most authorities agree that

\textsuperscript{26} op. cit. note 6, pp. 44-45.
some form of more or less impermeable wall covering is required. Various materials have been used; they include various cement and lime plasters, waterproofed mud plaster, size, bituminous and tar paints, oil-bound paints, linseed oil, and various synthetic organic compounds. All of them require periodic renewal. 27

Most of the technical guides on adobe construction lay down minimum wall thicknesses, in terms of ratios of wall height (usually about 1/10 of height) and in terms of absolute minima (usually 12" for exterior walls and 9" or so for interior, non-loadbearing partitions). Much greater thicknesses than these are often found; sometimes the reason is to give more heat protection, occasionally it is because of the height of the walls, but more often than not it is the result of many years of repair having added a small amount on to the thickness each time. Some Mexican walls have increased as much as ½” each year by this method. Present design techniques, both in adobe and the other types of earth construction described below, will be briefly described and evaluated later.

Mechanical aids in adobe work

Any of the production or building stages of adobe work can be mechanised. What this means in terms of economics is, again, evaluated below. But a short description of some mechanical aids might be useful here. Mixing is traditionally carried out by hand, foot trampling, animals, or with pitch-forks. A simple improvement on this is paddle mixer, easily constructed on the site (Fig. 3.). Plaster mixers or bituminous pug-mill type mixers give very good results and have been used on larger schemes. (...) For the complete operation, from

27. op. cit. note 21, p. 36; op. cit. note 11, pp. 22-24; op. cit. (Patty) note 4; op. cit. note 22, pp. 35-37.
mixing to finished block, several excellent machines exist; although these can be used for adobe blocks they are designed for producing high-pressure, rammed earth types of products, and will therefore be described under the rammed earth techniques. No mechanical methods of laying adobe blocks, or of forming them into large panels have been employed.

5. Rammed Earth or Pise

A far more durable, and scientifically controllable material than adobe is rammed earth. In primitive forms it is probably as ancient as the previous technique. However, in the last few decades, probably much more improvement in rammed earth techniques has been made than in adobe work. And it seems likely that most of the new technical and building research will be directed towards improving this field. Basically this is because rammed earth offers and incomparably better product; chiefly from the point of view of weather resistance. Also its methods of production lend themselves more easily to mechanical improvement.

a. Rammed earth soils

As with adobe, the estimates of suitable soils for rammed earth work vary widely. These are some typical ranges:

1. Not more than 50% clay (including loam and silt) and not less than 50% sand, (including gravel and other granular material). Ideally 30% - 35% clay and 65% - 70% sand. 28
2. Clay and colloid content 18% - 32%, sand and coarse aggregate 68% - 80%. 29

29. op. cit. note 21, pp. 8-14.
3. Less than 40%, preferably less than 30% sand. Anything up to 80% sand.30
4. Sand content from 40% to 75%, with the latter as the optimum figure. Unsuitable below 30%-35% sand content.31
5. 20% clay, 80% sand and gravel.32

Although the figures have a wide range, they indicate that in any case a high sand content and a low clay content is required. A proportion of half to half is permissible but not promising. This type of mixture defines, of course, the whole of the characteristics of rammed earth walls and of the techniques involved.

The high sand and gravel content, consisting as it does of large particles which do not absorb water, give the structure excellent moisture and water erosion resistance. The clay acts as a cementing or adhesive agent. Because of the coarse particles, considerable pressure is required to obtain a reasonably dense wall, as free from air cavities and passages as possible, which make the wall far too porous for weather resistance and weaken its structural properties. Also a much lower optimum moisture content will be required for mixing, for the same reason, and the mixture will be dry and stiff compared to the wet, plastic adobe material. Even more than in adobe work, the mechanical and physical properties of the soil are essential to the decision as to what this optimum content is; tremendous variations in resultant densities, and

31. op. cit. note 11, pp. 16-17.
32. op. cit. note 6, p. 13.
hence strengths and weathering properties, of the same soils have been obtained by varying the moisture content as much as 10% - 15%. An average figure for rammed earth construction, with a soil of about 35% sand content, would be in the region of 9%. For an adobe wall of the same constituents it would be about 15% - 20%.

The difference in moisture content accounts for the great difference in shrinkage and for the increased structural and resistance properties of the former. The amount of water required in rammed earth is probably roughly inversely proportional to the amount of sand used, within certain ranges, as Patty has shown. So, the general conclusion can be drawn that the best rammed earth soils are those with the highest sand and gravel content allowable within the requirements of adhesion, and that the actual proportions will be determined by the physical and mechanical properties of the constituents as well as by the available pressures during ramming; evidently for a very dry, high-sand content soil, very high pressures will be required.

b. Ramming technique and equipment

The soil is prepared in a pit or other receptacle. Organic matter and stones over a certain size (a walnut has been traditionally used as a reference) are removed, and any additives, of sand, clay or other items, are mixed as the water is added. Rammed earth can be used, as adobe, in block or in monolithic form. The latter is more widespread today, since it eliminates a whole stage of the labour involved. When used in block form, it is rammed in wooden or metal moulds and then laid in much the same manner as masonry or adobe, using a lime or cement mortar. The moulds are of much stouter construction, to resist the pressures created. (Fig.4.). For monolithic work, the soil is laid in horizontal shuttering,

33. op. cit. note 11, pp. 11-14.
consisting basically, of two parallel layers of boards, the distance between them being the wall thickness, supported on the outside by stout vertical supports and separated from each other by bolts or timber separators. (Fig. 5.). The height of the forms is usually about 3' and the length varies with the type of plan for which they are used. The layers of earth are rammed into it by means of iron rammers weighing from 5 - 20 lbs., wielded by the men standing in the form. The work is carried on in layers of about 3" - 4" at a time. After each layer has been rammed for the full length the form is moved and fixed again.

Special problems occur in rammed earth construction at corners and openings. In order to avoid weak butt joints here, special corner forms and stopped-end forms for openings are required (Fig. 6.). The life of well-made rammed earth forms can be as long as 15 years, even with continuous use, provided they are periodically oiled, regularly cleaned and properly stacked. Recently some improvements have been made in traditional form design which result in considerable labour saving. One is the Australian roller-supported form, in which the dismantling and re-erection process from one wall section to another takes one man 8 minutes as opposed to 1½ hours for three men with the older type. (Fig. 7.). Another new design is the "Man-Build" form, originally designed for concrete work, which makes the building of a cavity wall possible. It has already been used for building lateritic earth wall panels between the structural members of a 7-storey Hong Kong hospital. 34

Rammers are of a wide variety of designs and weights. Some typical ones are illustrated. (Fig. 8.). Great economies of time can be made with pneumatic rammers; whether these result in overall economies is discussed below.

34. op. cit. note 12, ("Winget Pressure Block Machine").
Earth block construction has recently been completely mechanised in some areas; for this purpose efficient hydraulic presses have been designed which are capable of a high continuous output. The best known is the English Winget Pressure Block Machine (Fig.9.), and the South African Landcrete (Fig.10.). Two French machines, the Guilhon-Barthelemy and the Hourda-Bonnet are also successfully being used; the latter is a dry compacting machine. All these machines can produce stabilized or unstabilized earth blocks, sand blocks and clay products of various sections. The pressures used are far higher than is obtainable by manual labour, with the result that a much drier mix is used and a denser product obtained. Pressures varying from 1200 psi to 2500 psi are used in these machines.

The design techniques, present and past, that have been evolved for rammed earth technique are discussed below.

6. Stabilized Earth

In a sense this is not a separate type of earth construction. It is a modification of either of the two previous systems. However, the product differs from them so radically that it has been considered as a distinct group.

Many of the engineering faults of rammed earth or adobe can be removed by the addition of additives, usually known as stabilizers. Sometimes these are foreign chemical substances, at other times they are soil constituents. The basic methods of soil stabilization have been very thoroughly worked out in connection with highway construction in the past. Most of the existing knowledge of the subject in fact comes

from this field. In Appendix II, where some of the better known experimental and traditional stabilizers are described, some reference is made to the copious literature on this subject that exists. The bibliography is, however, nothing like exhaustive. But it included some reference to the work most likely to have building applications now or in the future.

Soil stabilization, by which is meant the alteration of its properties with regard to elasticity, permeability, water-resistance, volume-change propensity, chemical inertness, surface wearing properties or mechanical strength, can be carried out by three main means:

a. Mechanical or physical

b. Chemical

d. Additives

Which of these will be used depends on all the special conditions of the particular case.

Of the mechanical systems described in Appendix II, grading probably has the most far-reaching applications to building work. This simply means introducing into the soil certain elements it lacks, these elements being for this purpose considered mainly in terms of size of soil particles. Thus sand or gravel can be added to a soil in which there is too much fine, clay constituent, or clay to one which suffers from the opposite need. Often this is the cheapest way of improving the material, if the additive material is locally available or readily transported.

If it is likely to be uneconomic to add soil constituents, or if

36. To give an adequate summary, a slightly different system of classification has been used in Appendix II.
in addition to this other properties which they cannot give are desired, the soil can be altered by chemical or additive stabilization. The former has not been used in building work; even for highway construction their use has been chiefly experimental. The substances used have included silicates, chlorides, synthetic organics such as acrylates and furfurals, and natural substances, such as molasses, oils, lignin, rosin and certain sugars. These substances react with soil chemicals or with other additives, and produce various types of chemical reaction. They are described in more detail in Appendix II.

However, it is the additive types of stabilizers, particularly Portland cement and bituminous emulsions, that have found widest use in building work. These act as cementing or waterproofing agents rather than in a chemical manner. A great deal of experimental and theoretical work on these two stabilizers exists, and some of it is listed in the Bibliography.

Portland cement has been used mainly with high-sand-content type soils, that is, for rammed earth construction. The resulting material has been variously described as "terracrete," "beton-de-terre," soil-cement, earth-concrete and cement-stabilized soil. Its action is a cementing one, giving greater density and less porosity. As a result, the treated soil product becomes much more resistant to water erosion and also increases considerably in mechanical strength. The proportion of cement added varies with the soil and the required result. In experiments at Bogota, Colombia, it was found that cement proportions as low as 2% gave sufficiently good properties to all but two of a hundred widely different soils, to make them suitable for building and allow them to be considered as permanent building materials. More usual figures that

37. op. cit. note 1.
have been quoted are from 6% - 12%. 38 Soil cement has been used in exactly the same way as rammed earth up to the present; that is, it has been made into blocks, manually or mechanically, or rammed into forms to make monolithic walls. One variation has been "plating" with soil-cement, where only the external surface, jambs and corners are thus treated by laying a cement or other facing material into the bottom of the rammed earth block moulds first, the earth then being rammed on top of this layer.

The bituminous asphalt tar or oil emulsions used are mainly applicable to high-clay content soils, where they act as waterproofing agents; they surround the clay particles with an impervious coating and thus stop water from penetrating to them. They do not seem to give increased mechanical strength to blocks or walls, but, in adobe work in any case, it has been the water-resistance and not the mechanical strength which has been in question. The product, which has been commercially exploited by several companies in the United States as well as abroad, is often known as "bitudobe." Considerable success has attended the use of such earth walls, especially in such climates where, due to the high rainfall, adobe type of construction was previously impossible. Egypt has many examples of excellent recent housing with bitumen type stabilized earth. Some also exist in the Southern States of the U.S.A. and in various tropical countries. 39

38. A great deal of technical literature exists on cement stabilization. The references given here are a selection of some of the most useful items; more references will be found in the Bibliography. Middleton, op. cit. note 22, p. 39; op. cit. note, p. 33; A.S.T.M. Methods of Tests for Soil Cement Mixtures, American Society for Testing Materials, Philadelphia, Pa; Application of Soil Cement to Low-Cost House and Farm Building Construction, Portland Cement Association, Chicago, 1946; op. cit. note 21, pp. 20-23; op. cit. note 10; op. cit. note 14; MacDonald, F., Terracrete; Building With Rammed Earth-Cement, Chestertown, Maryland, 1939; Soil-Cement Mixtures Laboratory Handbook, Portland Cement Assoc., Chicago, 1950.

39. op. cit. note 9 (A.D.Little), and op. cit. note 6, pp. 33-34.
One other stabilizer seems to offer considerable promise for building work. It has already been widely used for highway and agricultural work; it is common lime. Pure hydrated lime added to a soil of high clay content probably increases its mechanical strength although Patty found the opposite to be the case. Its reaction with the soil is of an ion-exchange type and the result is a reduction in plasticity index and a consequent increase in strength. The great practical variations found in its use are probably due to the very widely varying types of clays with which it has been used.

All these methods of soil stabilization have the effect of very substantially increasing the range of soils suitable for building work. True, it also increases the cost. In some areas, where the chemicals required are expensive, it makes it completely uneconomical to use the system, even where only very small quantities are required. But, if sufficient equipment was available and skilled persons to make analyses of the soils and determine the quantity and quality of stabilizers required, this may be the answer to a great many problems. Having described briefly the main forms of earth construction, it is now necessary to evaluate them from three main standpoints, economic, engineering, and aesthetic, in order that the most hopeful directions for new developments, outlined in the following chapter, can be found.

B. Evaluation

Although not in any way exhaustive, the above descriptions of the three main types of soil construction today used, together with Appendix II outlining the main types of stabilizers used, should sum up the extent of

present knowledge and practice. In a way, this second part of the chapter is the raison d'être of the whole Thesis. It is by evaluating the present techniques that some very grave faults can be seen and, at the same time, a whole vista of genuine possibilities open up which make it worthwhile to give the material a thorough technical and architectural study. The separate forms of earth construction will be considered together now, but under three main headings, which correspond to the three kinds of criticism of any building material is likely to come up against. One is from the client; how much does it cost? One is from the engineer; how does it compare with other building materials in strength, durability, insulation and other physical properties? And the last is from the designer or architect; what use of its aesthetic possibilities has been made, and what use could be made? For an architect, this last question is crucial and it is from his viewpoint that this whole Thesis has been approached.

1. Economic Evaluation

It has already been noted that the four major cost considerations in earth construction are: material, equipment, labour and maintenance. To give detailed cost records for any of these here would be impossible and pointless; more necessary is it to give some relative figures for earth housing in the past and some concrete idea of the kind of cost limit within which any future construction will have to keep. The labour involved in each case for all the work preparatory to the actual mixing of the earth, that is excavation, sifting, removal of unwanted constituents and so on, has been omitted. For comparison purposes, a wall 8' long, 8' high and 1' thick has been chosen. This represents 64 sq. ft. of 12" walling, or approximately 2.36 cu. yards of compacted walling material. If in the block types a block of 12" x 8" x 6" is assumed, with a volume of 0.335 cu. ft., it will need approximately 200 blocks to build the wall. The man-hours involved are given below, based on information given in the most recent earth building manuals. It is assumed that all operations are manual in the
first three types of construction. Naturally, mechanisation of any one or more operations will decrease the total number of man-hours.

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>MAN-HOURS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adobe block</td>
<td></td>
</tr>
<tr>
<td>Mixing 2.36 cu. yds. of earth by hand</td>
<td>1</td>
</tr>
<tr>
<td>Moulding, 200 blocks by hand in wooden moulds</td>
<td>20</td>
</tr>
<tr>
<td>Stacking</td>
<td>4</td>
</tr>
<tr>
<td>Building wall and making mortar</td>
<td>8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>33</td>
</tr>
<tr>
<td>Rammed earth block</td>
<td></td>
</tr>
<tr>
<td>Mixing</td>
<td>1</td>
</tr>
<tr>
<td>Ramming into moulds</td>
<td>50</td>
</tr>
<tr>
<td>Stacking</td>
<td>4</td>
</tr>
<tr>
<td>Building</td>
<td>8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>63</td>
</tr>
<tr>
<td>Rammed earth monolithic wall</td>
<td></td>
</tr>
<tr>
<td>All operation, from mixing to finished wall</td>
<td>24</td>
</tr>
<tr>
<td>Block-making machinery</td>
<td></td>
</tr>
<tr>
<td>a. &quot;Winget&quot;</td>
<td></td>
</tr>
<tr>
<td>Making 200 blocks</td>
<td>6</td>
</tr>
<tr>
<td>Building</td>
<td>8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>14</td>
</tr>
<tr>
<td>b. &quot;Landcrete&quot;</td>
<td></td>
</tr>
<tr>
<td>Making 200 blocks</td>
<td>0.25</td>
</tr>
<tr>
<td>Building</td>
<td>8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>8.25</td>
</tr>
<tr>
<td>c. Hand-operated block-pressing machine</td>
<td></td>
</tr>
<tr>
<td>Making 200 blocks</td>
<td>1.5</td>
</tr>
<tr>
<td>Building</td>
<td>8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>9.5</td>
</tr>
</tbody>
</table>
From these figures one can readily find the number of man-hours per square foot of a given type of earth wall. When this is translated into the wage rates of a particular region and scheme, the figure obtained can be subtracted from the total allowable cost per square foot of wall for the region concerned, and the remainder is the allowable cost of materials and equipment.

As is to be expected, the manual techniques have the highest man-hour rating. Of course, these can be cut down by even partial mechanisation of any stage; for instance, a pneumatic rammer will decrease the ramming time by 30% - 50% and a concrete mixer the mixing time by 50% - 75%. As long as wage rates remain low, these more or less traditional techniques will provide an adequate solution for low-cost housing. And in such schemes as "self-help" housing they will probably remain unchallenged for very many years. However, the real problems occur in those regions where labour, even unskilled, is expensive. Here earth housing may not be able to compete at all with other kinds of construction materials. This means that other, quicker, possibly less desirable methods will be used, or industrialised, imported housing will be erected. Since the present labour pattern is rapidly changing, the techniques needed for making earth a really competitive material in the future involves not only better materials and design, but a considerable reduction in labour costs.

One of the major limitations, as we have noted, on the use of earth in any instance is the availability of suitable material. Where the material is unsuitable, or where even suitable earth is to be improved, additives of chemicals or soil constituents have to be made. This involves transport, storage and raw materials costs. Obviously, the amount that can be spent on such additives depends on how much of the total allowable cost for wall construction has been consumed by labour. So we have a paradoxical situation; those techniques which involve most labour allow least possibility for improvement of the soil; on the whole
they need it most, since there is no adequate control over the earth used and the forming methods are less efficient than those of the block-making machines. Those techniques which, through mechanisation or other efficient use of labour, involve less man hours, give greater freedom for even further improvement by allowing a larger proportion of the cost for materials and equipment. Naturally, if the equipment is expensive, again little may be left for additives.

A few examples may help at this point. In the South West of the United States a reasonable figure for a modest building would be a total cost per square foot of wall of 35¢ - 40¢. Assuming a wage rate of 60¢ per hour for the unskilled labour required, the labour would cost about 30¢ per square foot in adobe block. In rammed earth (monolithic) this figure would be about 21¢ per square foot. Rammed earth blocks in this case would be already out of the picture because the labour alone would amount to about 60¢ per square foot. So about 5¢ worth of additive can be used for each square foot of the adobe wall and about 15¢ in the rammed earth wall.

Similarly, in certain areas of East Africa earth structures have to keep under about 20¢ per square foot of wall to be competitive with other materials; or, in fact, to make it possible to build many of the schemes which would otherwise be too expensive. Although labour rates are low, even so no part of the cost can be apportioned to additives at this cost figure; the labour is all one can afford. True, some good stabilised earth housing schemes have been carried out, in Uganda for instance, but the money available in these cases was far more; in one instance the walling cost about 57¢ per square foot, of which 50¢ was for the cement-soil blocks, manufactured and supplied, and only 7¢ for labour. If this was divided in the way we have followed up to now,

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with all the labour as one item and all material and equipment as another, the figures would be 23\$ and 34\$ respectively.

All this points in one unmistakable direction: much more economical ways of using labour in earth building. This means even more economical than the most highly mechanised systems can give at the moment. If one were able to find ways of building the sample wall outlined above in something like 1-5 hours, one would be at the beginning of really fruitful possibilities. It would then become feasible to spend considerable sums on specialised machinery, skilled labour, and sufficient soil additives. It is this potential field that has prompted the suggestion for new construction and design techniques which follow in Chapter 3 of this Thesis. It has not been thought impractical to suggest several ways of building which will even need special, new equipment which may cost many thousands of dollars per single machine, and which will need a highly trained team to travel around with it at all times. By such means it is thought possible to broaden the application of earth construction to such a degree that demand will rise, hence the machines will be in increasingly continuous use with decreasing amounts of time spent in unproductive long distance travelling, and thus the economic picture is altogether changed. In highly developed regions the machines can be manned by local labour; in underdeveloped regions, the expert teams will arrive with the machine. So there would seem to be a way of breaking down not only the limitation of availability of suitable local material, but also of the limitation of local labour. Finally, the new and much improved material will withstand far greater weather variations and extremes than the present product, so that even climatic limitations will grow less significant.

2. Engineering Evaluation

Several specific properties of earth walls have to be evaluated, in

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42. Many sources have been used for the compilation of these figures. The chief ones were: op. cit. note 11; op. cit. note 3; op. cit. note 6; Colonial Building Notes, England, Nos. 5, 8, 14 and 16; and op. cit. note 30.
relationship to other building materials, in order that the structural limitations can be known and to give direction to future soil engineering research as applied to building.

Perhaps the most important properties for building are: structural strength (including various types of stresses and tests), heat insulation or transfer values, sound insulation, weathering properties and resistance to chemical attack.

a. Structural properties

Many factors will influence the strength of a soil; these will include the type of soil; the method of mixing; the method of compaction; the amount of moisture present during compaction; the amount and nature of additives and permeability of the finished product. A great deal of research on some aspects of soil properties already has been done and will continue to be carried out. Much of this is, however, of a basic type; in so far as it has been applied to practical construction it has been chiefly for highways. There is a very great need for both basic and applied research on soil properties required for earth building. The setting up of the Earth Housing Project at Massachusetts Institute of Technology is a recognition of this need.

The characteristics of a particular soil will depend on its mechanical and physical properties. The mechanical properties refer to its composition in terms of particle sizes and the proportion of each size present. Unfortunately most of the rule-of-thumb field testing methods that have been used have depended on a mechanical analysis, which in itself does not make the behaviour of the finished product predictable. Standard tests for physical properties exist; they need not be described here, as they can be found in any adequate manual of soil engineering. The properties are given by certain constants; the chief of these are the
plastic limit, the liquid limit, the plasticity index, (these are standardised systems of expressing the water content at which the soil reaches specific "plastic" or "liquid" conditions), the shrinkage limit, and the centrifuge moisture equivalent. Given these, the behaviour under test conditions can be fairly accurately predicted.

The most important single factor which affects the strength of a given compacted soil is the moisture content at which it was compacted. Every soil has an "optimum moisture content" which is an expression as a percentage of the weight of the soil of the moisture necessary to reach maximum density. Below or above this moisture content, the mechanical strength of the compacted soil falls off, slowly at first, and then rapidly. This optimum will vary roughly from 6% - 15% according to the type of soil. The high sand content soils will have the lowest percentages and the clay soils the highest. At moisture contents below the maximum the particles will become locked together in an open, porous structure; above the optimum not all the energy used goes into compaction but some of it is dissipated into causing sideways movement of the particles.

**Compressive strength** will vary roughly in the range of 100 psi - 500 psi. With Portland cement or other stabilizer the values range from 600 psi - 1200 psi. For normal single story building a strength of 200 psi is a minimum requirement. Average fired brick ranges from 400 psi - 1000 psi.

Values of resistance to **concentrated loads** range from 600 psi for adobe blocks to well over 1000 psi for soil-cement samples.

**Transverse load** resistance is in the range of 50 psi for adobe to 160 psi for soil-cement monolithic walls. Such resistance can become crucial for wind resistance where tornadoes are encountered and in regions where earthquakes occur. Normally a resistance of 80 psi - 100 psi will be adequate for the worst conditions.
Impact strengths of earth walls are better than that of many masonry or brick walls, and the material has good recovery from impact.

**Racking resistance** is in the region of 2000 lbs/ft - 6000 lbs/ft, as compared with about 2000 lbs/ft for normal timber frame walls and 3000 lbs/ft - 4000 lbs/ft for ordinary masonry and concrete block work.

b. **Heat properties**

It has already been pointed out in the previous chapter, that the requirements of heat insulation and strength are opposed to each other as far as earth walls are concerned. The former improves with porosity and volume of entrapped air spaces in the thickness of the wall, the latter reaches its maximum at maximum density. Therefore, since density is usually required for other reasons, the thermal properties which an earth wall should be required to give should rely on its thermal capacity rather than its thermal resistivity. Few scientific tests on thermal properties have been made; the figures given here are put forward with some trepidation, since they do not give a sufficiently clear picture of the density and other characteristics of the specimens from which they were obtained; also, moisture content is a vital factor in heat transmission. Without accurate moisture data, heat transmission measurements have little meaning.

The **thermal conductivity (k)** of an earth wall has been variously given as: 3.3 B.T.U., $10.4$ B.T.U. - $15.2$ B.T.U., and $2.3$ B.T.U.\(^\text{43}\)\(^\text{44}\)\(^\text{45}\)


\(^{44}\) op. cit. note 3.

These variations can be accounted for by the differing densities of the specimens employed. Making allowances for various factors it is reasonable to suppose that for rammed earth, compacted by pressures anywhere in the region of 100 psi, the k value will be about 10.0. This does not compare favourably, as has been erroneously stated by several engineers, with brick, stone or concrete, for which commonly accepted values are 8.0, 6.5 and 10.0 - 12.0 respectively.

On account of the density and mass of most earth walls, the heat capacity is likely to be high, and it has been shown how this may be useful in certain types of climate. In addition the heat flow may be retarded by the incorporation of insulating materials, or by the construction of hollow walls with an air cavity. Much can also be done by surfacing. For instance, a white and highly reflective surface on the exterior will make great differences to the amount of heat absorbed. The incorporation of such a reflective layer as aluminium foil is also a possibility.

Thermal expansion and shrinkage generally increase gradually with increasing moisture content, up to the optimum content, beyond which the coefficients increase rapidly. This points to the importance of avoiding excessive moisture during mixing, thus enabling the number of expansion joints to be kept to a minimum. The addition of certain stabilizers, such as cement or plaster helps to reduce the coefficient. An unstabilized soil may have a shrinkage of 2.5% of its volume; this can be reduced to about 0.5% with the addition of 6% cement. Very much more research needs to be done on the various thermal properties of walls and different facings before satisfactory data is available. This is one aspect of soil science which has little relevance to highway construction and therefore it is least developed experimentally.

c. Sound insulation properties

No reliable data on this has been discovered. There is good reason to believe that the mass and weight of earth walls will act as
reasonable insulators to airborne sounds and excellent ones to structureborne ones. It is known that where loose sand is used as insulation, unequalled high insulation values are obtained; the loose particles, by friction against each other, dissipate a great volume of noise before it has the chance to penetrate even a comparatively thin layer of wall. Possibly this fact could be utilised by using sand-filled cavities in internal partitions.

d. Weathering properties

A fair amount of experimental data and a very large amount of information from actual existing housing schemes is obtainable on these properties. Although different soils have widely varying qualities in various climatic conditions, a few general facts are noticed.

There is little doubt that the poorest resistance to moisture absorption and erosion is offered by high clay content soils. These are normally used in adobe block work. In less than an hour of driving rain, or under half an hour immersion in water such blocks are likely to disintegrate altogether. Adobe work, for this reason, is unsuitable except in the very dryest of climates; certainly where the annual rainfall is under 20" and the maximum monthly rainfall under 4". Rammed earth has much better resistance, but it is generally agreed that, unless protected by a protective surface covering or by widely overhanging eaves or other projections, it is not usable in rainy regions without serious deterioration.

Stabilization is the answer to weather erosion problems. For clay soils, the stabilizers traditionally used have been bitumen emulsions (needing no heat for mixture), road oils and asphaltic compounds, or other waterproofing agents. These lend little or no increased structural strength to the dry soil. For sandy soils Portland cement, which also gives a greatly increased mechanical strength, has been traditionally used. Certain base exchange stabilizers, such as calcium chloride and
ferric chloride have also been successfully used, especially in roads. Much research on stabilizers is at present going on and a summary of the various approaches tried is given in Appendix II.

Accelerated weathering tests suitable for simulating as closely as possible conditions found in a building still need to be devised. Work on this has recently commenced. Even more important perhaps, at the moment, is an analysis of the material used in the past on existing structures; this too is a part of the above mentioned research being carried out at Massachusetts Institute of Technology.

3. Aesthetic Evaluation

Some serious criticisms of current earth building techniques have been made from the economic and engineering viewpoints. Yet they are, perhaps, less serious than the judgement that must be passed on these structures by the architect. It is understood, of course, that no architectural criticism is worthy of the name which does not take into account engineering and economics. It is hoped that the architectural criticisms will further demonstrate the need, already shown to exist, for developing altogether new approaches to the problem.

Many people deal with soil in one form or another. Many exploit some of its qualities. But few today are concerned with exploiting its potentialities as a three-dimensional sculptural material offering immense freedom and at the same time imposing a design discipline as strict as that of any material with many natural limitations. Eckbo has made this point strongly: "The soil is handled horticulturally, structurally, sentimentally, naturalistically, conservationally; but seldom as a material with definite three-dimensional sculptural quality apart from, or in addition to, these other factors." 46 Curiously enough,

even he is unable to view earth as anything but a plastic heap of loose material; he does not envisage creating a new building material, plastic and massive perhaps, out of it. He says that earth has several distinctive qualities the "...strongest of these is its very obvious subservience to gravity." It cannot hold a steep slope. This gives it a "pyramidal quality" apart from and because of which "... the sculptural potential of earthwork is endless." 47

The whole history of earth building has gone through two cycles which are typical of many other building materials. First, in ancient times and today's primitive civilizations, the material was used with little technical skill but with immense feeling for its visual qualities; thus a strong tradition of "rightness" of certain forms evolved. Then, in more recent years, perhaps the last thirty or so, a new kind of scientific interest has been aroused. The material is undergoing a kind of renaissance. The people "rediscovering" it are generally not architects; those that are, have no tradition of "rightness of form" behind them; so the easiest thing was to regard earth as a cheap substitute for other materials, and use it with designs which, even if they had been carried out in the material for which they were first made, were often pitifully inadequate. So earth has come to be regarded as a convenient substitute for block construction of all kinds; stone, concrete block, burnt brick. This of course, was exactly the kind of obstacle which hindered the use of concrete for almost a hundred years after its reinvention (really the invention of Portland cement); nobody thought that anything but concrete blocks offered a suitable use of the material. Then, with the development of scientific theories for reinforced concrete, towards the last quarter of the nineteenth century, it came to be used for the rigid framed structures of post and beam type which were derived from timber, iron and, more recently, steel. In fact, it has not been until the last few years that any widespread appreciation of the visual and economic potentialities of reinforced concrete has grown up. At

47. ibid., p. 83.
last engineers and designers are agreed that its real place is where large, thin, structural planes are required, often in complex curves impossible to execute in any other material.

It may be useful to examine briefly the ancient and primitive forms in which earth is used. It is characterised by three main features; first, a massiveness of form and an absence of thin, precise structural members. Second, an absence of angles and straight planes and the frequent use of curved wall plans and curved roof sections. Third, a sparing use of openings (often dictated by climatic conditions) and their placing in such positions that the minimum amount of walling had to be built around them. Typical of these forms is the early Egyptian house with its arched entrance, single rounded window opening and roof terrace. Again, in the multi-story beehive-like hut of Menelinde in Tunisia (Fig. 11.) there is a sure feeling for the stability, plasticity and massive character of earth. Often earth was used in two forms in primitive dwellings; first as an excavated hollow in the ground, usually circular or oval, and then as a thick roof covering over this, usually applied to a substructure of beams, planks, branches or grass. The American Indians were specially fond of this form. In Africa, Asia and Australia these hollowed out, curved dwellings were used for hundreds of years. Today's typical "rondawel" or round hut of the South African Bantu is based on the same form. Whole towns have grown up with a cell-like structural growth about their plans, in which these individual circular units agglomerate into complex patterns. Kano, in Northern Nigeria is a superb example (Fig. 12) and here even in the detailed sculpture on the earth walls a respect and imaginative understanding of the material is shown. (Fig. 13.) Often, as in the case of the Cameroon huts, functional reasons of strength and rain disposal give fine sculptural walls. (Fig. 14.) Very different from these has been most earth structure design in more recent years in the technically more advanced countries, or where experts from these countries have been in charge of new housing schemes in underdeveloped countries under government or other sponsorship.

48. One of the finest sources for literature and models of every type of primitive house is the Peabody Museum, Harvard, Cambridge, Mass.
It is easy of course to pick bad designs, illustrate them, and poke a jeering finger at them. Those illustrated here (Fig.15.) have been picked with an honest effort to choose the best from all recent publications and manuals on earth housing. Some are positively offensive, and would be so in any material, in their lack of any understanding for form, proportion, texture or vitality. Others are evidently straight, perhaps simplified, copies of masonry or timber structures and these fail mainly in their total lack of vitality. The original materials may have avoided this, in their use of colour and especially due to the texture of a wall with numerous brick or stonework mortar joints. One or two show an understanding of the form the material demands, but have not used it with courage. Such is the Indian example, fully described by S. R. Mehra. In another, an Israeli example, an altogether new and daring form, the parabolic hyperboloid roof of double curvature, has been used, but it is carried out in reinforced concrete with earth walls. This form and its problems are referred to in the next Chapter. Probably the best examples, from the designer's viewpoint, to date, can be found in some recent Egyptian villages where many of the ancient arched and domed forms have been used. These do not, however, represent any new departure; at best they are a return to sound, existing local tradition. One scheme in Egypt, however, does show a genuine attempt, with a great measure of success, at using these old forms in new ways. This is the village of Gourna (Fig. 16.) designed by the architect Hassan Fathy Bey. Some of the great masters of modern architecture have used earth in various housing schemes. Fine as some of these are, none of them have contributed to developing a language of form for earth design. Corbusier in his Sainte Baume scheme (Fig. 17.) uses it for party walls, capped by a shell concrete roof. Neutra has experimented for many years

49. op. cit. note 43.
50. op. cit. note 9, (A. D. Little) and op. cit. note 9 (Architectural Review).
with a type of earth wall; diatomaceous material is used, together with resinous binders, all steam cured, to give a thin highly finished building slab. The process is entirely industrial and actually bears little relationship to earth construction proper; but it may give a basis for the development of highly industrialised building products using soil constituents as raw materials.

What lessons then, can be drawn from these studies? Perhaps they make one ask oneself a series of basic questions. Why should plans follow rectangular, right-angled forms? Why should walls have plane surfaces, uniform thicknesses and vertical edges at the profile? Why should windows be large, rectangular openings in the centres of wall areas, filled in by glass or other extraneous material? Can the roof be executed in earth, economically and with design advantages, and what forms are best suited to this? What is the place of reinforcement in earth construction, perhaps making possible forms otherwise limited to concrete? These and many other questions have been tentatively raised and discussed, and a few suggested solutions to them found in the designs which form the body of this work and in the following chapter which describes these designs.

The point of departure has therefore been reached. From the economic, engineering and aesthetic criticisms of current techniques some new direction for future development may emerge. Whether it will be the directions suggested below is immaterial. No special claim for these ideas are made, beyond the fact that they offer promise of answering some of these criticisms. Possibly the growth will entail questions and answers even more basic than these. But whatever the direction, it will certainly involve a critical evaluation of past work and such an evaluation must be allowed to lead architects and engineers into logical new solutions.

CHAPTER III. THE SEARCH FOR NEW EARTH HOUSING TECHNIQUES

A. Constructional Systems

Whereas for evaluation purposes three standpoints were taken, that of the economist, engineer and architect in turn, and from each of them salient critical conclusions about present techniques drawn, during the process of actually designing earth houses which seemed in some degree to avoid existing pitfalls it was soon found impossible to approach the problem using such a division. Simply to try and find "better" designs without some point of departure was pointless; what in fact is a "good" design for an earth structure? No matter from what direction the problem is approached it soon becomes evident that the inevitable starting point is the construction technique.

It has been seen how traditional construction systems are wasteful of labour and it has been argued that if earth housing depends for its execution on a large pool of cheap labour being available, then its days of usefulness are counted; in many regions this pool is rapidly disappearing (the West Indies are a good example) and it is reasonable to suppose that within the next twenty or thirty years the picture will have completely altered in most regions. At the same time, it has been shown that such economies are also necessary to overcome the engineering limitations of soil; and finally all this must be done with a view to creating a new visual, formal tradition such as has existed in the past for this material.

The first decision has been to consider earth as a monolithic building material. In nature soil is similar to concrete; it is a large mass of plastic substance which can be freely moulded into a great variety of forms and which, when dried, takes on a permanent form. Monolithic work seems the first answer to the use of such a material. Then the detailed man-hour analysis has shown that, uneconomic as the manual systems of earth construction are, the monolithic rammed-earth technique
is by far the least time consuming. But a practical problem arises even here, which has not so far been mentioned. The stratification caused horizontally in a rammed earth wall is inevitable due to the stages in which the wall is rammed; usually it is about 3" - 4" in height per layer. This stratification can be reduced by careful control of drying out, making sure that sufficient moisture is present to give proper bond to the next layer. But even with very skilled control, difficult to obtain in practice, weaknesses occur in these layers. Expansion or settlement cracks will probably form here if anywhere and also any defects in weather resistance will first happen at these points. In fact, rammed earth is not a truly monolithic technique. The development of one that is offers the kind of design possibilities which architects are searching for also.

Having decided that monolithic construction offers the most hopeful solution to all the problems, and having seen the impracticability of pouring monolithic clay soil walls and the drawbacks to manual ramming of sand-soil walls, the idea of some form of mechanical production is the only alternative. Three approaches are possible; first, the use of existing machinery, widely available, for performing a new task; second, the adaptation of some type of mechanism to function in a new way; third, the design and production of a basically new type of machine. In order to include as many possible developments as possible, and to give as broad a lead as possible to any future work on this subject that may be carried out, an example of each approach has been tried and a specific house type designed suitable for showing the problems each of the three processes will raise and their potentialities.

1. Making a Vertical Road

One of the great difficulties with any traditional type of earth construction, but particularly monolithic rammed earth, is the increasing difficulty of building the wall as it increases in height. Special
scaffolding is necessary for transporting the material up to the upper levels; changing the forms at a height involves temporary scaffolding and possibly cranes or hoists; and other handling difficulties occur at high level, with windows, door lintels and tamping tools, for instance. But the chief reason for improvement is the comparatively large amount of labour the present technique involves.

If the idea of ramming is accepted, that is the compaction of soil by the exertion of high pressures, there is another way of doing this; horizontally. In reinforced concrete work the principle of casting many large flat members, both floor and roof slabs and walls, on the ground, is rapidly becoming increasingly widely accepted. Much labour is thus eliminated; erection of formwork and supporting scaffolding being the chief item. But also great time economies are made in placing the reinforcement, mixing and placing the concrete and in forming openings and other features. All these reasons apply with equal force in rammed earth work.

There seems to be no reason why tilt-up type of wall construction, already widely used in concrete, should not be used for earth walls. But for earth construction, a further development of this idea suggests itself, which would make the system even more economic. Would it not be possible to consider the construction of the walls horizontally rather as a road making process than a building operation? The chief drawback, as has been pointed out, to large scale mechanisation and the use of complex equipment in the so called "under-developed" countries, is the lack of skilled labour, the difficulty of making the equipment locally and the cost of importing foreign machines and crews. But there is one type of civil engineering operation for which highly developed equipment already exists and is handled by local labour in almost every region of the world. This is road-making equipment. It would be perfectly possible to utilise this for the horizontal compaction of large areas, or long strips of walls, which are later somehow divided into the necessary pieces for tilting into position.

One of the great advantages of using such equipment is that most of the scientific work on soil stabilization has been done with respect to road construction; all the stabilizers are familiar, special equipment for stabilization and soil compaction on a large scale is standard (Fig. 18.); where this special equipment does not exist, simple items such as scrapers, tillers, rollers and pub-mills are capable of carrying out all the operations. The normal thickness of earth wall, 12" - 14", might easily be rammed or rolled in a single thickness, or two thicknesses at the most. This would make a truly homogeneous wall, without any of the stratification which can be so detrimental. The degree of compaction obtained with heavy road-making equipment would be superior to any that could be obtained by a manual technique. As for the labour involved, it is difficult to estimate this without a specific scheme and layout in mind; but it is obvious that all the operations, from beginning to end, for building a 12" thick wall, 8' wide and 8' high would not take more than one to two hours as compared with 24 hours by manual ramming. It would probably be in the region of 20 - 30 minutes in a large scheme.

For such a system to be truly economic, carefully considered architectural planning and layout is required. In a large housing scheme the position, dimensions and tolerances for walls would have to be so designed, from the very start, that some kind of continuous process was possible over the whole area of the houses. True, one could roll the walls in one central location and transport them to the various local sites in the form of the dried slabs as they were required. But the maximum economies of the system would not thus be obtained. Fully accepting this technique would involve planning in such a manner that continuous strips of walls, like a roadway, say 8' wide, could be rolled right through the site; the tilting and lifting apparatus would then follow, lifting each section into position without any horizontal movement being necessary. This also involves placing parting strips between the sections, in the thickness of the rolled slab, which, when lifted out one by one, would give foundation channels for each wall.
The sequence of operations would be roughly as follows. First, the unusable topsoil would be removed by a scraper, bulldozer or other means, to the necessary depth. Next a layer of say 12" of soil, to be used for the walls, would be bulldozed off the site, being arranged in continuous piles along the proposed slab strip, or in regular piles, on either side. The layer below this, say to a 6" or 8" depth would then be treated to make it suitable for the floor. Exactly what was to be done would depend on the class of floor that was required and the degree of finishing that would be applied to it later. For instance, the soil could be cut, a waterproof stabilizer added and mixed and then rolled smooth.

Once the floor was compacted and dry, the wall slab strip could be carried out by one of two ways. Either separate pressed metal, wooden or plastic forms for the separate sections would be laid end-to-end, with the parting strips between them, and then the previously removed earth spread over them, or, sheets of paper or other parting material laid in a continuous roll, and the earth spread on top of this. The first system would be suitable where the forms were designed to take all the edge and bending stresses created during the tilting operation; the second would be used where special reinforcement to take these stresses was used.

All the equipment used for the cutting, mixing and compaction of the earth will be of standard road making types. The procedures for
the floor and the wall slabs will be similar. Separate mechanical equipment can be used for each stage, or, if available, single-pass stabilizers or pavers can be employed. These carry out in one operation the cutting and mixing of the soil, the even distribution of the stabilizer (which can be of any desired type), mixing in with the soil, adding water and spreading. All that remains is for the slab to be compacted by a sheepsfoot roller or rubber tired roller, finally to be finished with a smooth roller. Even an ordinary truck or tractor will probably give sufficient compaction with its wheels for earth walls. For wet mixes, vibrator types of compactors may be used. The choice of equipment available is very wide; but the usefulness of the whole system is that the very simplest mechanical equipment can be used if none other is available. A tractor, with a bulldozing attachment and a crane assembly, a drag harrow, rotary tiller and a truck could do the entire job.

Building components can easily be incorporated with the slab before compaction takes place. Window and door frames, or simply transparent material embedded in the walls; reinforced beams or reinforcing rods; service pipes and ducts; flues and other parts can all be formed in the pre-compacte wall. Any external or internal wall finishes can be applied by placing the damp mix in the bottom of the form before the soil is spread on it (this is similar to the well known technique of "plating") or by rolling or spraying a surface finish onto the finished slab. Textures or patterns can be obtained by using a rough or patterned base to roll on or by using a grooved or other pattern on the final roller.

Curved sections with simple curvature, could be produced by several methods. One would be to place the loose soil inside a curved metal form, lying on the ground on its convex side, placing inside the form a heavy roller, (wood, metal or concrete) which is attached to a tractor and pulleys, or a horse, and simply pulling the roller to and fro inside the form. Another way to do this would be to place the curved form on
the ground, perhaps in a slightly excavated hollow, with the convex side uppermost; the soil is then placed over the form and compacted by rolling with a truck or other means. Yet another technique would be to use a form of great length, curved in cross-section, into which a matching, curved roller would fit. The resulting curved slab could then be cut up into whatever size sections were required.

Of the three main techniques here suggested, this seems to offer most immediate possibility, chiefly because it utilizes existing machinery, techniques, materials, and skills. This type of equipment is almost inevitably present on a building site in any case; it could thus be made to carry out a far greater proportion of the work. If new stabilizers were tried, such as the acrylates, still no basic change in equipment or processes would be needed. But it cannot be over emphasised that without adequate architectural planning and careful site organisation, the great advantages would be lost and the economies much reduced. If properly used it would be perfectly feasible, with a team of four men and all the necessary equipment, to prepare and finish the floor and all the main walls for a row of 6 to 8 houses per day.

Roof units could be similarly constructed and lifted into position later. Here again careful design of reinforcement is required, and the exact lifting position would have to be known. A folding hook or other device might have to be embedded into the earth during the compaction to be used for this. Cylindrical shells, "folded".shapes, flat roof slabs, and corrugated slabs (for which a corrugated roller is used) are all possible shapes.

2. Spraying

Many efficient and compact mechanical devices for spraying concrete, plaster or cementitious materials have been devised. One of the best known for concrete work, in the United States, is the "Gunnite" system. With some adaptation there is no reason why such equipment should not
be suitable for earth construction. The equipment would probably have to rely on the "splatter" type of spread rather than on high pressure atomisation through a controllable nozzle; although this latter would also be possible if sufficiently careful control over the size of the soil aggregate could be obtained. In any case, whichever system was used, the soil would have to be much more carefully sifted, graded and broken down than in the previous system.

For this reason it would seem to be better to use spray for such areas where not a great volume of material is required. For instance, a finely controlled earth aggregate with a special stabilizer added, say bituminous emulsion, might be used to give a $\frac{1}{4}$" or $\frac{1}{2}$" finishing coat to the exterior of an earth wall. Or it might be feasible to spray the full thickness of a structural or, semi-structural member of not too great a thickness. For instance the hyperbolic paraboloid roof used in one of the presented designs could be sprayed earth on a reinforcing backing of wire mesh, or rods. Also, many of the double curvature roofing forms common in concrete could be quickly carried out in earth by this process. In one of these, where parabolic ribs are placed at set distances from each other, and canvas is draped over them, the weight of the applied material itself will give the counter-catenary curve between the ribs; the total thickness of such constructions can be limited to about 2" - 3". It might be argued that if this technique, so similar to concrete work, is to be used, it would be better to use ordinary concrete, since in any case, a very much higher proportion of cement or other additive will be required than for normal stabilized earth where more massive layers of material are used. This is a valid point. There is no point in using earth simply to show the structural acrobatics which the material can perform. In many cases, where good local aggregate is available, concrete will be the answer. But where this is not so, genuine economies may result from using earth.

Even greater possibilities might be found for this material in performing certain finishing functions in construction which might be complicated in other methods. For instance, junctions between adjacent slabs of earth wall might be deliberately
left open, in order that a sprayed-earth in situ junction can later be formed. It might also be possible to spray earth onto any light weight core, such as paper honeycomb, woven bamboo, chicken wire, plastic foam or expanded metal, to give excellent internal partitions.

If equipment for dealing with crude, almost ungraded material can be designed, tremendous freedom of form might be possible using sprayed earth techniques. No backing would be required; the material would simply be mechanically piled up in desired shape; but close control over the amount of additive and the moisture content would be possible.

3. Extrusion

This is the technique which will demand basically new equipment. True, extrusion is already a well known technique in several industries. One of the newest of these is the plastics industry, where extruders are now being made to handle reinforced thermoplastics of fairly-bulky types. But the dies here are rarely more than a few square inches in area. More relevant are the traditional extruders used in brick manufacture and in the ceramics industry. These are designed for handling crude material in large volumes, and large dies of almost any desired section are available. The extruders used in producing the cement cores for the foundry industry are also of similar design. But all of these would need considerable adaptation to make them suitable for earth construction on the site.

First of all they would have to be small enough to be portable. Second, they would have to be capable of handling rougher material than more or less refined clay or cement mixtures. Third, the pressures created, at least for certain types of stabilizers where little water is a desirable feature of the mixture, would have to be greater than in most ceramic type equipment. The great advantage of any extrusion system is the continuity of production that can be obtained. For earth
construction this would require a considerably mechanised digging, pulverizing and mixing process to keep up with the extruder. But the work could be done quite independently of the speed with which building was carried out. Accurate estimates of the requirements would be made at each site, and as soon as the extruder had produced the necessary parts it would be moved to the next one.

Where a large housing scheme is concerned, it might be an advantage to have an extruder which moved itself back from the extrusion rather than having the customary moving belt or trolley moving away from a stationary machine. By this means, and careful site planning the machine could drop the necessary slabs, say at each position on the site, ready for tilting into position when dried.

The variety of shapes possible is almost infinite. The simplest shape, a flat slab would be no easier to produce than a complex "Z" section. Single curved roof or wall surfaces could be produced by cutting to uniform length a number of "Z" or other interlocking sections and building them into whatever shape was required. Some barrel vaults of this shape have been shown on one of the designs. Double curved shapes, such as domes, could be extruded into concave forms of the required external silhouette. The continuous ribbon extrusion, mixed to a fairly plastic state, could be wound round in a revolving drum and allowed to set hard. The dome could be lifted out and placed into position. One dome shown in the design has a hexagonal external edge, which is formed by an internal wheel mandril pressing against the winding extrusion as it proceeds.

Reinforcement in the form of bars running in the direction of the extrusion can be incorporated by having a reel of reinforcement which feeds into the die at a specific point. For a special housing scheme, where the desired extrusion shapes were limited to two or three, one special die with reinforcement arrangements, might be used for the whole
process. The dies, of course, would represent a great expense in terms of machining and tooling up, so as far as possible schemes would have to rely on a few selected, standard sections.

There is little difficulty envisaged in producing all manner of hollow sections, for light weight, "brise-soleil" types of blocks (cut from long sections) and ribbed strip sections for building grilles and open walls.

Considerable work has been done and is now being carried out on the mechanics of applying certain soil stabilizers, of the acrylate group, in construction work. Several extrusion systems have been tried in the course of this work and have proved to be suitable, with some modifications. There is little reason why these should not be successful with traditional stabilizers also.

B. Description of Typical Designs Presented.

The designs which have been worked out as the major portion of this Thesis, have been selected from a great number of early ideas, with several aims in view. First, in them, all the above techniques are utilised, and some of the design problems involved are tentatively solved. Second, as a quite distinct problem from that of production techniques, plans have been worked out to show what type of design might be suitable for different climatic and economic considerations. Also, they have been designed with a view to being capable of combination in a large number of various patterns on a civic scale. Third, again a purely architectural problem, the possibilities of color and sculpture in earth have been exploited in various ways. Most of the drawings are largely self-explanatory, so this description has been kept as brief as possible.

1. The Domed House Type (Fig. 19)

This design is based almost entirely on the idea of utilising extrusion techniques. The roofing form is one of two alternatives, both 8'-0"
external diameter and 6" thick hemi-spherical domes. One is circular for its entire external plan, the other changes into a hexagonal base in its lower portion, in order to make the junction over the hexagonal supporting members simpler.

The plan consists of an agglomeration of hexagons. Each of these is formed by 12" thick surrounding walls, the perpendicular distance between which is 8'-0" centre to centre. This gives a 7'-0" clear internal dimension as the minimum for each hexagon. The plan unit is completely elastic and can be grouped in any pattern and in any numbers suitable for a particular family. This also makes for easy addition or alteration. Also, it can be combined in any desirable pattern for a village or community. The design shown in the perspective is intended to be a "closed", probably tribal community, in which a link is made between each house and yet a completely private unit is available for each family. The link is in the form of an open barrel-vaulted store shed, which joins on to the house opposite a half dome of the same diameter as the vault; a similar half dome covers the entrance porch.

Each unit is provided with a completely secluded internal patio, according to traditional Moslem and Middle Eastern pattern, which serves as the communication link between the various rooms. The house here presented is designed for a hot-dry type of climate. For this reason the walls have been kept thick (the roof is thinner but has air ducts in its thickness and is also covered with a white, reflective surface on the exterior) and windows have been kept high. This reduces the amount of light from ground reflection. Direct sunlight into the rooms is avoided by the angle of the window reveals. In addition, small triangular openings are provided in the window walls, which will give permanent ventilation; they can be blocked temporarily or permanently if necessary, as they might, for instance, during a sand-storm, by means of wooden blocks or with a roll-down screen.

Where a larger room is required than a single hexagon, two or three hexagons can be combined; where two are required, a simple lintel, of the same extruded slab as the walls, is placed across the junction line; where three are joined, three lintels in a star-beam pattern are placed across.
If the domes with the hexagonal bases are used, these star beams are unnecessary and the domes simply abut against each other. The wall junctions are so designed, in the extrusion die, that any type of two-way or three-way junction is possible with the same slab. Where an obtuse exterior angle occurs, or where the jambs of a single slab have to be finished, a special extruded diamond-section junction strip is used. This has a higher stabilizer content than the remaining work, so that it should present weather and structural resistance at these exposed points. These junction pieces are spiked through to the walls from each side (see detail sketches on the drawing) in such a way that all three pieces are locked together in a mutually self-supporting system. The spikes do not have to possess any abrasive hold, since once both are driven, they exercise restraint in a purely shear fashion. Any lintel or beam always thrusts against the obtuse side of a two-way wall junction, with the result that it is resisted with the maximum amount of stability; thus no thrust tending to overturn the wall is exerted at any point in the structure, but all thrusts are resisted by angular stiffness.

Three sections of extrusion are required only for the whole scheme, and they might be combined in one and the same die, which can perhaps be re-fixed for each operation. The first is the plain wall slab, roughly 4½' wide, which has "pointed" edges. These slabs are cut up from a continuous slab extrusion into whatever height is required to the under side of the dome. The walls with the window and small openings in them are formed by pressing into the slab metal frames of the required outline, and 12" deep, whilst the earth is still soft. Reinforcing is incorporated along each edge of this slab, in the form of a single rod, to provide stiffness during lifting.

The second part is the dome. This is executed by the system previously described; and the two previously mentioned shapes are possible alternatives. The "Z" section, with a circular hollow along the center, is a continuous extrusion and is also used, in equal lengths, for the barrel-vaulted storehouse link. This "Z" section is also reinforced with two small, flexible wires along its edges.
The third part is the diamond section cover strip, provided with a central reinforcing rod. This is produced out of material more highly stabilized than the remainder of the parts, in order that it should withstand the hardest weather and human wear at the exposed angles where it occurs.

When the three major sections have been erected on the previously stabilized floor and foundation (possibly combined in one 12" thickness) three hand operations will be required for finishing. One will be the filling in of the iterstices between the dome bases on the roof, in such a way that water should not lodge at any internal intersections, but should run off to the exterior walls, where it can safely run down certain wall positions. The second is the building of an earth cover strip between the floor and the wall, and sinking a small channel all round the exterior circumference. The third and last is the covering of the roof with a waterproof lime or cement wash, providing a white, reflective surface, and covering the wall base and cover strip with a waterproof membrane, say asphalt.

In order to obtain maximum air circulation in this house, the exterior doors have been constructed of pierced, aluminum plate, and the interior ones of an open-weave straw or fibrous material. The kitchen and the bathroom, each in a separate unit, will have fixtures according to local custom and permissible cost. None of these details are here suggested beyond the actual location of the different areas.

2. The Parabolic Roof House (Fig. 20)

This design has been worked out for a similar hot-dry climate, as the last one. The production techniques used, and the forms are far simpler, however, and would be suitable in technically less developed countries. All parts for this scheme are rolled or rammed on the ground. The drawing shows the various stages in the process. First, the top soil is cut and removed, to whatever depth is necessary to reach soil free from a large percentage of organic matter. Next the sub-soil is cut, to about a 12" depth, stabilized and compacted, to form the finished floor and the foundations for the houses. Next metal or wooden forms, of parabolic outline and flat base, are laid on
this floor, with loose earth piled into them. This is then compacted by manual-mechanical methods. Overall rolling by truck or rollers is impracticable in this instance, due to the shape of the forms which make it impossible to lay them next to each other in any sort of continuous slab.

Next curved forms of half parabolic shape are laid on the floor and filled with loose earth. This is compacted, with any necessary stabilizing agent previously added, by placing a heavy concrete, metal or wooden roller along these forms (several can be bolted together and rolled as one) and dragging it to and fro by means of a tractor or human power. Two wooden wedge blocks placed at each end of the form prevent it from moving and stop the roller from rolling out.

When both these compaction processes are complete, the walls are tilted into position in the order schematically indicated on the drawing. Each half parabola is 4' wide, and is temporarily supported by a strut till the other half is tilted against it. Covering for the roof and finishing at the base of the wall can be similar to the last example.

The parabolic forms have a projecting pattern applied to their interior which give the external patterns to the slabs as shown. This can later be picked out in color if desired by use of colorwash or pigmented earth layers.

The plan is basically a long, parabolic tunnel. All the sleeping and storage accommodation for the houses is contained within this line. The internal span at the base of the parabola is 12'-0" and the height at the centre is 11'0". This tunnel is broken every now and then by a 12'-0" wide court; one of these occurs to each house. The size of each house can be determined by altering the spacing of these courtyards. At right angles from the main tunnel, and projecting from the courts, are a series of similar, but shorter, parabolic structures, which will contain the living quarters of each house. On the opposite side of the court is an open parabolic roof arching over a wall curved in a horizontal parabola on plan (made out of two of the roof units placed one on top of another) which is divided down the centre to give a kitchen and a toilet space. Both of these are therefore open to the sky, in the traditional manner of areas of Africa and Asia. These long tunnel lines can be combined to, form streets or squares; patterns of
complexity or simplicity as desired.

Over the central court, or a portion of it, some additional covering may be desirable. This would shield the doorways to all the rooms from sun and rain and give extra protection to the open portion of these walls, above the doorways, constructed of hollow block panels. In the design presented, this covering is in the form of three sturdy timber framing elements with a rush or reed mat woven between them. It could, however, be any other suitable and available material; canvas, wiremesh, or even hand-laid earth would be suitable.

The flat, "gable" walls are of three shapes: one filling the full area of the gable, one going up to an 8' height but of full width, and one of the same height, but with the doorway width taken off on one side. All three wall slabs can be formed within the same form, which is provided with two movable partitions to cater for this. On top of the 8' high wall a hollow block, pierced wall is built, the blocks for which are produced by cutting up long channel-shaped sections, as shown in the detail sketch.

All walls, both flat and curved, are 1'-0" thick, and will be stabilized as and when necessary. If the parabolic sections are lifted by means of the forms, no reinforcement will be necessary in them. Otherwise mesh reinforcement might be used, either near the concave or near the convex surface, depending on the direction in which the slab will be lifted; probably it will be lifted straight out of its form as it is tilted, which means that tension will develop along its convex surface.

It would be easy to create more plastic, freer forms, by this very same method of construction; that is, by using curved slabs for both wall and roof construction, in one piece. The comparatively simple design used here, largely based on some of the most ancient primitive housing known (such as the beehive structures of Mycenaean times) was deliberately chosen to show the vast improvement of design obtainable with even modest innovation in techniques. But one's imagination could certainly run wild here.
3. The Hyperbolic Paraboloid Roof House (Fig. 21)

It will be immediately evident from the plan of this type that the design is intended for hot-humid kinds of climatic regions. That is, instead of thick surrounding walls, small and high openings and thick roofs, the plan is arranged for maximum amount of through ventilation. Each house consists of three (this number can be altered according to needs) enclosed units, covered with a single 13' by 13' roof composed of hyperbolic paraboloid type of curves. These have straight edges on all four sides; also the stresses in the roof itself are entirely composed of membrane stresses, so that the roof is not required to be reinforced to resist any bending. Support along two parallel edges, with reinforced small beams along the other two gives sufficient stability.

Each room, or living area, covered by such a roof, is planned in such a way that it has at least two opposite sides partly open to the direct open air. This means, the housing being planned in a line perpendicular to the direction of the prevailing wind, that a breeze will circulate throughout the entire structure. In addition two courtyards are formed inside each unit, one open to the sky and the other covered; the latter serves as the entrance patio for each of the three units. These units can be used as desired, and can be internally sub-divided into two if necessary. Normally there would be two sleeping areas and one living and eating area. In addition, off the central court opens the kitchen and the toilet.

The kitchen and toilet of each house, the plans of which are alternatively mirrored, come against a common partition wall. This enables all the plumbing, sewage, rainwater disposal for both houses and both stove flues to be contained within one wall section. These actual services will be placed into the ramming form on top of a base layer of earth, and the remaining soil will then be carefully packed around them. Ramming of this section will have to be carried out manually, in order not to dislodge or damage these pipes.

The remaining walls are of two kinds: 12" thick main, longitudinal walls, which support the roof panels along two edges, and 6" thick cross
walls which act merely as infilling panels on the other two sides of each unit, and do not come up to the roof. The space thus left, giving maximum ventilation, can be closed by means of fold down shutters or roller blinds from the interior, if necessary.

The roof panels will be formed on a single shaped form as shown. Instead of such a form, the shape could be worked in earth, stabilized, compacted and dried, and then used as the mould for all successive panels by using paper or other separators. The form of the roof makes it possible to lift it by the centre, for which purpose a small hook will be embedded in each panel at this point. A high proportion of cement or other stabilizer will probably be required for the roof panels; it may be in the region of 15%. This may be justified if good local concrete aggregate is not available. The overall thickness is 6"; for this type of climate nothing is gained by having a thick roof; dead weight would only increase the otherwise very low membrane stresses in the roof. A reflective surface on the exterior would, however, be a great advantage.

The flat walls, of both thicknesses, will be rolled by road-making equipment and then stabilized, as in the system previously described. This rolling can take place on the already compacted 12" layer of earth which acts as foundation for the walls; the floor consists of a further 6" layer of compacted and stabilized soil formed by rolling in situ. The color of the end panels on the exterior could be colored cement wash or oil-bound pigment paint.

As with the second design, this house type is also essentially a linear type, capable of aggregation into larger units by forming streets, squares or other patterns. Probably all the rows will have to be parallel to each other, since the house is specially planned to receive cross-ventilation in the direction of the prevailing wind.

It will be readily seen that no details of accommodation, fittings, openings, or structural refinements have been worked out for any of the designs. This is not the present purpose. The three type designs presented are merely pegs on which to hang certain ideas relating to possible new
construction techniques. At the same time, they represent a real attempt at discovering a visual language for earth construction which uses both contemporary space idioms and old established forms.
CHAPTER IV. SOME DETAILED PROBLEMS OF DESIGN

In connection with new earth housing designs, several problems of a technical or visual nature will arise, which will need quite new approaches to be solved adequately. The individual items considered below are not treated exhaustively, rather each little section raises a number of questions which designers might well ask themselves before attempting to solve these problems.

1. Openings.

Probably no single factor has been so mishandled in recent earth houses than the design and placing of openings. Whereas in timber or masonry it is as logical to place openings in the centre of a wall area, framed all round as at the edge, in any system where framing is impossible, without using other materials, and where every arris or corner presents additional difficulty of weathering, making and maintaining, this is not the case. It ought to be possible to regard door and window openings in earth walls rather as the spaces left between adjacent simple slabs than as holes in them. This means planning space with a series of overlapping planes rather than right angle corners.

If possible, openings occurring in the plane of a wall should stretch the full height of the wall, or perhaps some other, light-weight panel can be used above and below the opening. Corners are suitable locations for openings, although reduction in stability thus results. Instead of filling in window openings with complex frame sections and glazing, a thing difficult to manage with such comparatively crude dimensional tolerances as earth gives, would it not be simpler to embed a transparent or translucent pane of material into the wall thickness and mould the wall around it? Again, there seems little reason, if some such glazing solution is used, why window openings should be rectangular. A freer shape might give better weathering properties and minimize the structural weakness presented by a hole in a wall. Much further work is required to find suitable infilling materials for doors and windows.
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2. Roofing Forms.

There is no necessity for using earth in roof construction for earth walls. Often other materials will be more practicable. However, where earth is used, several requirements have to be met. The weather resistance of the surface has to be excellent, even for hot-dry climates with low rainfall. It will certainly have to be better than that normally necessary for the walls. Often such resistance may be only possible, economically, by the application of a finishing coat of a waterproof membrane; a bitumen or asphalt layer might be suitable. Curved structural forms will give the lowest bending stresses within the roof layer; in some, as we have seen, only membrane stresses will occur. Rainwater must be quickly and efficiently drained. Overhangs may be necessary to protect insufficiently resistant walls, or openings.

The possibility of combining the roof and wall members in one piece should be explored; many difficult junction problems could thus be avoided. Apart from some primitive and ancient examples, the Indian house illustrated in Fig. 16 is the only executed recent example which has been found where this has been done. Few earth building manuals make any evaluation or suggestion for earth roofs. Curiously, the most imaginative one was published by the Board of Economic Warfare during World War II.55

Perhaps the difficulty of forming a suitable roof in earth, and of protecting the walls, could be solved by providing a large, over-all cover of a tent type; it could actually be a translucent plastic film, canvas or synthetic fabric. This would stretch well beyond the boundaries of the plan, possibly even covering several houses or a small community group. Thus, it would also give a degree of climatic control over areas adjacent to the houses, which might be used for cultivation, stables, home crafts, storage, or other use.

3. Foundations.

Foundations for present earth structures are invariably the same or

55. op. cit note 21, p. 14
similar in principle to traditional foundations for masonry walls. This involves digging trenches, laying concrete or stones, and possibly reinforcing. However, since few earth structures will be built in regions where a freeze-thaw cycle takes place, there seems little reason to keep foundations below ground level. There does not, either, seem to be any need for a change of material; earth makes an excellent foundation. Since rolling, extruding or other mechanical techniques are going to be used, it would seem to be most efficient to utilize the floor or sub-floor layer for wall foundations as well. Since this will normally be at least 12" thick, and probably fairly heavily stabilized, it should be capable of withstanding the shear stresses set up and will, in addition, give a much more even distribution of loads on the ground below than narrow strip foundations.

Many authors recommend bringing concrete foundations up at least 6" above ground level, in order that the earth should not be made to withstand the heavy rainwater erosion normally occurring at the junction of wall and ground. (Fig. 22) Several solutions to this problem are possible. First, by adequate channel drainage and sloping surfaces, water can be quickly conducted away from this point. Second, the lower portion of a wall might be more heavily stabilized during compaction than the remainder, making a "beton-de-terre" at this portion. Third, special cover strips of earth could be built to cover this junction, and the whole area, including some height of wall above and some ground sloping away, can be covered with an impervious adhesive layer.

4. Multi-Story or Single Story Work?

When stabilized earth, even at low stabilization contents, reaches compressive strengths in the region of brick or stone, as it often does, there is no inherent reason why multi-story load bearing walls should not be constructed. One of the largest recent schemes, a French one at Longpres-les-Corps-Saints, is three stories high. (Fig. 23) There is no reason why this should not be exceeded. Of course, earth walls maybe used as panel, infilling walls for building of any height and they may have some advantages in this field in cerating regions. For instance in Stanton House, a recently erected hospital in Hong Kong, the panel walls for the exterior of the
entire seven-story structure were built of lateritic earth. 56

5. Reinforcement.

There are many situations in earth building when it may be necessary to reinforce slabs or members; sometimes this becomes more economic than to increase the quantity of earth (which also increases the quantity of any stabilizers used and the cost of labor). One of the difficulties, which is less pronounced in concrete work, is to obtain adequate adhesion of the comparatively rough, granular material to the reinforcement. If the latter can be of a twisted, barbed wire, or rough surface type, this may be no problem. Bamboo has recently been successfully used for reinforced concrete work; there is no reason why it should not be equally successful in earth. It can have a tensile strength of 8,000-10,000 p.s.i., and a compressive one of 4,000-6,000 p.s.i. Its preparation is important to its success, and a considerable body of knowledge exists now on its use. 57 It may have more significance for earth than concrete construction, since the shortage of steel is likely to be most acute in those regions where Portland cement is also in short supply and expensive.

Probably the most effective type of reinforcement for large areas, as for rolled or extruded slabs, is a mesh of some type. There is little difficulty in incorporating a mesh in any of the three construction systems suggested in this report.

6. Wall Finishes.

Where an earth wall does not in itself have sufficient weather resistance, a suitable choice of an applied protective coating will have to be made. A

56. op.cit. Note 12 (Whiskin) p. 35
great many materials have been tried. Amongst them have been: mud plaster, dung, lime plaster, cement plasters, oil-bound paint, bitumen emulsions, bitumen paints, tar, linseed oil, various natural gums, limewash, size and some synthetic resins. Most of these have met with considerable success. Although much research might still go on to find suitable and economic surface treatments, more thought could perhaps be given to the methods of application.

If road making techniques are used, it would be a simple matter to incorporate the external surface as the base layer or to roll or spray it on the finished, compacted slab. In spraying a similar technique to the actual wall construction would be used; it would merely require a change of mixture in the spraying container. Where cranes are used on a site and large wall and roof sections are fabricated, it might become feasible to dip the members into a suitable solution, say asphalt emulsion.

For internal wall finishes almost any of the materials used in other types of construction could be used. However, one should not overlook, both for exterior and interior purposes, that many soils when dry have fine inherent color potentialities. Where earths of several colors are available on a site, this would almost certainly provide an excellent means of architectural expression, and the surfaces should be transparent protective coatings, such as linseed oil or size.

7. Floors.

A great variety of floor surfaces can be used; but rising damp still remains a problem. Several methods of damp proofing can be used; in some cases, where a waterproofing type stabilizer has been used, such as a bitumen, it is assumed that this in itself will provide an adequate moisture barrier. Alternatively, if the floor is compacted in two or more layers, a sandwich type membrane can be incorporated. If it is not, this membrane can be placed under the entire floor and foundation layer. Where the floor is cement stabilized, the admixture of an extra proportion of cement to

58. See note 4.
the final surface before compaction will give a good screed type floor.59

Perhaps the most important design consideration to be remembered in earth housing which is produced by one of the fast methods here suggested is that the floor level should bear some useful relationship to the level of exterior compacted earth surfaces; terraces, approach roads, foundations or whatever they may be. By this means one may be able to avoid having to add an extra layer of earth to the floor once the walls are erected, which, at that stage, would cut out mechanical production means and would certainly mean laborious hand spreading and ramming.

8. Services.

In most earth building manuals the placing of pipes, conduits and other services is shown to be chased into the wall thickness after completion of the structure. This seems a wasteful procedure. There would seem to be no reason why, where wall slabs are compacted or sprayed horizontally, one should not lay and fix these items in position, fill in with soil around them, and then compact them into position. If the pipes are substantial in diameter, and come near the surface, and if they are made of hard brittle substances such as earthenware, ramming may have to be done carefully and by hand near the pipes. This might be avoided by using more flexible pipes and tubes, such as plastics, impregnated paper or bitumen products.

Flues and electric wiring, or conduits, ventilation ducts, and sewage and water pipes could all be dealt with in a similar manner. If possible as many of these services should be concentrated into one wall section so that hand ramming and special precautions are limited to the minimum. In one of the designs presented the entire sewage, water, rainwater disposal and flue system for two houses has been incorporated in an approximately 8'-0" wide section of wall.

9. Furniture

Although there is a risk in trying to stretch the uses of earth to too many parts of the house, there may be good reason to consider it for furniture. There are many cases where a house is only occasionally inhabited; for instance a vacation or week-end house, houses for semi-nomadic peoples, defense housing or housing used in emergency evacuations and dispersals. In such instances it would be advantageous to have fixed furniture and fittings. Again, in regions where termites and rot attack almost all organic materials, this might be an essential, in the absence of more industrialized furniture of metal. True, one cannot design earth furniture on the same assumptions as lightweight, mobile units.

The solution may be to regard furniture as part of the walls and floors which are constructed of earth already. Tables can be simple rectilinear or curved plateaus arising from the floor. Beds can be recessed shelves of earth in the wall, or projecting slabs or platforms. Seats, stoves and storage spaces can be similarly conceived. The bath too, and perhaps even the other sanitary fixtures, can be built in simple earth forms; it may be nothing more than a shallow recess in the floor, finished with a smooth and impervious surface such as granolithic cement, or a sprayed-on plastic (vinyl for instance). It is possible to envisage an interior of really free plastic and gracious forms, functionally conceived, using earth in this way.

A few examples already exist. In many primitive societies earth has been traditionally used for furniture; good examples can still be found today in many American Indian adobe huts and in certain African regions. Recent work by contemporary architects also has exploited some of these ideas. Girard's house at Santa Fe has earth fireplaces, table and seats (Fig. 24) Some of the feeling which such forms will give can be appreciated from the New York Olivetti showrooms where the typewriter display stands, although not constructed of earth, rise as free form from the floor and have continuous surfaces with it. (Fig. 25)

10. Sculpture and Color.

This has been left to the end merely because unlike the other uses of earth in building, this is an entirely architectural matter. Because this
is so, and because so few architects have been interested in earth housing in the past, the potentialities have almost entirely been ignored. This is curious, since in using earth in a natural way there are amongst its most obvious qualities: great color variation between one soil and another, even from the same pit or region; wide color range, especially amongst the reds, yellows, oranges, ochres, browns and blacks; natural tendency to form broadly sweeping surfaces with an absence of edges or hard lines when wet; and the ease with which any shape can be cut or imprinted into it when it is damp or dry. All these properties should be fully utilized, both in the interiors and the exteriors.

True, color can be applied freely by other means; in most of the designs presented this has been done. Oil bound pigments, color-wash, colored cements, colored plasters and certain vegetable and fruit extracts, can be used. A tremendous scope would be offered by the smooth earth surfaces or plaster for imaginative color design such as many peoples feel to be an essential part of their environment but which the European type house they are forced to live in often does not permit. Then, too, color can be used in conjunction with three-dimensional patterns and forms in the earth itself.

There are many ways in which these three dimensional forms can be created. It may simply be an over-all pattern of some kind obtained by having a relief pattern in the bottom of the moulds or by using a patterned roller or instrument for the finishing. Or it may be that the forms are built up by modelling technique, by hand, in wet mud. Much imagination could be used in giving some sculptural quality to such features as pierced earth window openings, or "brise-soleil" screens, screen walls and furniture. The sculpture on the Kano house (Fig. 14) has already been noted; we have to go to the Olivetti showrooms again to see what can be done in stabilized sand. (Fig. 25).
APPENDIX I

For many years chemical and engineering research has been carried out at the Massachusetts Institute of Technology on soil testing analysis, stabilization, highway and civil engineering soil problems, and allied subjects. Recently it has been decided to use the unique facilities, staff and experience which the Institute possesses to make a study of earth housing. The following pages are all copies of various announcements, descriptive leaflets and questionnaires issued in connection with the earth housing project.

First is a preliminary statement on the aims of the project. This is followed by a later abridged statement of aims. Next comes a questionnaire which has been, and is going to be, sent to government authorities, housing authorities, building research institutes and individuals working on earth housing; the object is to gather data, from all parts of the world, on which testing and evaluating methods can be developed.

Finally, there is a copy of the author's own aims as they were originally set out before the work was commenced. Close contact has been maintained at all stages of the work with the M.I.T. Soil Stabilization Laboratory.
The M.I.T. Soil Stabilization Laboratory has initiated a long-range program of research on earth housing. This program has two objectives: First, obtain basic information on the chemical, physical and mineralogical characteristics of soils most suitable for earth housing. Second, using this information, study methods of improving unsuitable soils by the addition of natural soil constituents known to have beneficial effects on conventional materials such as Portland cement, or trace chemicals. In the pursuit of these objectives, due consideration will be given to the limitations imposed by design and climate.

The M.I.T. Soil Stabilization Laboratory is uniquely qualified to carry out this program because of its specialized laboratory facilities and many years of experience in the fields of soil technology and soil stabilization.

The following method of operation will be employed: Interested countries are asked to furnish the Soil Stabilization Laboratory with undisturbed samples of soil from earth houses in their countries, together with information concerning the design, method of construction, etc., of earth houses in their country. The Soil Stabilization Laboratory will then conduct an exhaustive testing program on the furnished samples. In return for its cooperation, each country will be given a report of the study.
The M.I.T. Soil Stabilization Laboratory has initiated a long-range program of research on earth housing. This program has two objectives: First, obtain basic information on the chemical, physical and mineralogical characteristics of soils most suitable for earth housing. Second, using this information, study methods of improving unsuitable soils by the addition of (1) natural soil constituents known to have beneficial effects, (2) conventional materials such as portland cement, or (3) trace chemicals. Consideration will be given to the environmental conditions existing at the various house sites and to the architectural design of the house.

The M.I.T. Soil Stabilization Laboratory is uniquely qualified to carry out this program because of its specialized laboratory facilities and many years of active research in the fields of soil technology and soil stabilization.

The following method of operation will be employed: Interested countries are asked to furnish the Soil Stabilization Laboratory with undisturbed samples of soil from earth houses, together with information concerning the design, method of construction, etc., of earth houses in their country. The Soil Stabilization Laboratory will then conduct an exhaustive test program on the furnished samples. In return for its cooperation, each country will be given a full report of the study.
COPY
INFORMATION ON EARTH HOUSING

Note: We suggest that the requested data be based on a particular example of earth housing which is typical of the work done in your country. Also, since a questionnaire of this type cannot be all-inclusive, we would appreciate the inclusion of any additional material on earth housing which is available. For example, drawings, photographs, and publications would be helpful, along with any suggestions you have which may contribute to the success of this program.

General Information: The following data are requested concerning the earth housing to be described in the report.

1. Location within country: ____________________________

2. General climate in this locality:
   a. Mean annual rainfall (inches) __________
   b. Peak annual rainfall (inches) __________
   c. Mean annual temperature ________________
   d. Maximum temperature _________________
   e. Minimum temperature _________________
   f. Other pertinent information (e.g. excessive daily rainfall)
      ____________________________

3. Age of house __________

4. By whom was it built? (Give name if possible) ______________
   a. Government agencies __________________________
   b. Private company __________________________
   c. Private individuals __________________________

5. What type construction?
   a. Blocks __________________________
   b. Monolithic (i.e. rammed earth) ____________
6. Name of person or organization answering this questionnaire:

Name  ________________________________

Address  ______________________________________

Design and Architectural Data:

1. Give a general description of the structure including:
   a. Floor area  ________
   b. Number of stories  ________
   c. Amount and nature of structural framing (if any)  ________

2. Exterior Walls:
   a. Height  ________
   b. Thickness  ________
   c. Maximum laterally unsupported length  ________
   d. Reinforcement (other than stabilizers)  ________
   e. Moisture barrier between wall and foundation  ________
   f. Describe and evaluate exterior finish with respect to durability and moisture resistance  ________

3. Foundations:
   a. Materials  ________
b. Dimensions ____________________________

4. Roof:
   a. What form was used? Domed ______ Vaulted ______
      Pitched ______ Flat ______
   b. Describe construction and materials used (if earth, give thickness and nature of reinforcement and surface finish) ______
      ____________________________
      ____________________________
      ____________________________
      ____________________________
   c. Method of rainwater disposal (including overhang of eaves)
      ____________________________
      ____________________________
      ____________________________
      ____________________________

5. Describe any components (i.e. plumbing, sanitary fixtures, heating, openings, built-in furniture) specially designed for earth housing.
      ____________________________
      ____________________________
      ____________________________
      ____________________________

Description of the Soil Used in the Housing:

1. Give a complete visual description of the soil used in the construction__
      ____________________________
      ____________________________
      ____________________________
      ____________________________

2. Where was this soil obtained (on site or otherwise)?
      ____________________________
      ____________________________
      ____________________________
      ____________________________

3. State the probable geologic origin of this soil__
      ____________________________
      ____________________________
      ____________________________
      ____________________________
4. Describe and give the results of any laboratory tests which were performed on this soil.

5. Were organic materials either added or removed prior to construction? (i.e. roots, straw, etc.) Why?

6. Soil additives (stabilizers):
   a. What additives were used?
   b. What proportion (by weight)?
   c. Where were they used? (floor, walls, roof, etc.)
   d. Evaluate their effectiveness with respect to the improvement of:
      (1) Strength
      (2) Weather resistance

Construction Methods:

1. Preparation of materials:
   a. Describe the steps taken in preparing the soil for construction. Give quantitative data with regard to water content, particle size, etc.
b. If additives were used, describe in detail when and how they were incorporated.

c. Describe any specialized equipment used in the preparation (i.e. pug mills, etc.).

2. Actual Construction:

a. If blocks were used, describe how they were formed.

b. If blocks were used, what kind of mortar was employed?

c. If monolithic construction was used, give a concise description of the procedure.

d. If monolithic, describe the equipment used.
Economic Data:

1. Give a detailed unit cost of the principal components of the house.

2. How many man-hours were required in its construction?

3. Estimate the cost and number of man-hours necessary to construct a wall of the following dimensions:

   10 feet long, 1 foot thick, 8 feet high

Evaluations:

1. Evaluate the suitability of earth housing for your country.

2. Evaluate the possible future of earth housing in your country.
OUTLINE OF RESEARCH ON:
"DESIGN TECHNIQUES FOR EARTH HOUSING"

Proposed research to find new architectural solutions for technical problems raised by earth construction. Engineering and technical research on soils, stabilization and traditional earth building techniques (adobe, pisé and stabilized earth) will be reviewed, in order that potential design techniques should be thoroughly related to the latest work in soil engineering. Special consideration of acrylate and other recent stabilizing agents developed at M.I.T. and elsewhere.

However, the basic approach will be that of the architect, in order to give a broader interpretation to the already very large volume of technical research.

The type of questions which will be raised and discussed in the main body of the work will be:

1. The fields of application for earth housing. Tropical development schemes, vacation housing, defense schemes, etc.

2. The potential advantages of monolithic earth wall techniques over using earth in blocks or bricks merely as a cheaper substitute for clay or cement products.

3. Investigation of possible monolithic techniques: pouring-in-place, massed earthwork by bulldozer and temporary counter pressure of moveable shield, spraying earth-stabilizer mixture (possibly onto light weight paper or wire core), and use of pressure or vacuum-bag to obtain consolidation of walls, extrusion.

4. As a result of the above techniques, development of new, simpler
and freer forms for house plans. Is there any need to rely on accurately formed right angles, straight walls, uniform wall thicknesses, etc., or could curved shapes, and other forms give greater economic as well as architectural advantages?

(5) Roofing forms. Suitable forms in earth. Domed, arched, flat (reinforced?). Traditional precedents: Africa, Asia, South and Central America. Protection of walls – overhangs, etc. Possibility of large, tent-like roof over one or more housing compounds, giving absolute protection from rain, at the same time, being translucent, admitting light.

(6) The problem of components. Doors, windows, sanitary fixtures, etc. – new design techniques that may be involved in providing such items for comparatively crudely shaped openings, and plan forms. Possibilities of various in-situ formed foams, sheets, films and cores. Furniture perhaps itself integrated with earth masses of walls and floors.

(7) Finishes - external and internal. Applied finishes, color, possibility of decorative textures in earth faces by textured formwork, "earth-sculpture" (stabilized in-situ), etc. Floor finishes.

By raising these questions and attempting to find various solutions to them, it is hoped that an imaginative design technique for earth housing may be developed. The research will culminate with the design of a few actual schemes for specific locations and functions; drawings and models will be presented. It is also hoped to execute a full size model house, or portion thereof, in the construction of which technical problems can be studied.
APPENDIX II

This is a general paper giving a brief review of current and past techniques of soil stabilization. The paper is due to be published in Modern Plastics in the September or October 1955 number. Special emphasis has been laid on the work in synthetic resin stabilizers, although all other methods are briefly described. Soil stabilization has been here chiefly considered as a problem in highway construction, although the information given on the various stabilizers will have direct application to the building field.
SOIL STABILIZATION BY THE USE OF SYNTHETIC RESINS

by

Thomas A. Markus, MA, ARIBA

In many building, civil engineering, agricultural and military operations, the need arises to alter, temporarily or permanently, the properties of the soil found on the site. The properties which may need alteration include any one or more of the following:

- Mechanical strength (including tensile, compressive and shear strength as well as cohesion)
- Elasticity
- Permeability
- Water-resistance
- Volume-change propensity
- Chemical inertness
- Surface-wearing properties

There are three approaches to a soil which is in some manner unsatisfactory:

1. **By-passing**, as for instance when load bearing piles are driven through to a rock stratum.
2. **Removal** of the defective soil and replacement by new materials.
3. **Treatment** of the soil by one of three main methods; mechanical, physical or chemical. The division among these three systems is often not clear cut, as a system may have stabilizing effect as a result of both physical and chemical processes.

The mechanical system chiefly employed is the compaction of soil. By this means its density, and hence its strength, permeability, compressibility and other engineering properties can be altered.
Physical systems include the grading of soil by carefully balanced proportions of fine and coarse material; thermal treatment, by which some soils can be permanently dehydrated and others can be temporarily frozen, thus altering their engineering properties; and electrical treatment of soil, by which means drainage can be improved and new structural qualities can be added to the soil. By this latter means, pore water will flow towards one of the electrodes (a phenomenon known as electro-osmosis), this flow is accompanied by a volume change in compressible soils. In addition, ion-exchange will take place between ions attached to the surface of soil particles and ions present in the pore water or carried in the electric current, and, also, metal salts may be deposited in the soil pores as a result of the electrochemical decomposition of the electrodes, which salts may combine chemically with soil particles, thus having a cementing action.

Although mechanical and, to a much lesser degree, physical methods will continue to be used, they have the limitations of not being universally applicable. Many soils, particularly those containing clay, will not be satisfactory, even after mechanical treatment. For this reason, a third means of stabilization, although usually more expensive, has for some time been investigated; this is chemical stabilization. In this process, materials are added to the soil which change its properties either by a physico-chemical interaction with the soil particles themselves or by the formation of a matrix between the soil. The reaction involved may be simply a phase change, or it may be the formation of a new material through a chemical reaction, or a combination of both these. Most of the chemical stabilization systems currently practiced are of the matrix-forming type in which the two most important materials are Portland cement and bitumens.

Portland cement is used as an injected grout in undisturbed soils
and as a powder mixed into natural soils and then compacted. It acts as a binding cement. Since the resulting substance is fairly rigid, a sound base is required to prevent cracking, and this limits the use of the system.

Bitumens used are of the tar or asphalt types (the latter chiefly limited to cut-backs, road oils, emulsions and other liquid asphalts). Here again a fairly strong base is required, since the soil-bitumen is able to spread the load over a limited area only. Other difficulties present themselves in using this method of stabilization; first, it is only suitable for use with specified types of soils, second, the setting action can only take place in suitable weather conditions, third, heat-producing equipment is required unless a volatile cut-back material or a water-emulsion is used. The curing time required is considerable, which is a strong disadvantage when emergency (say military landing) operations are involved.

The chlorides, especially sodium and calcium, have been tried as stabilizers and have had some acceptance. Calcium chloride furnishes calcium for ion exchange and also helps to control the water content of the soil. Although the chlorides have certain desirable effects, chiefly that of reducing the freezing propensity and also making the soil structure more open and therefore quick-drying, they do not seem to give any increased strength to the soils.

The strictly chemical type of stabilizers depend on four types of reaction:

a. Ion exchange; here one ion attached to the soil is replaced by a different ion from the admixture, and thus the soil properties can be basically changed.
b. Precipitation; an insoluble compound can be obtained from the reaction of several compounds which will precipitate and thus act as cementing agents. The precipitation of calcium silicate from solutions for sodium silicate and calcium chloride is an example, as is the action of Portland cement.

c. Polymerization; many substances can be made to polymerize either with each other or by themselves, to form long-chain molecules. Polymerization can be either of the condensation type, where water is produced, or of the addition type, which generally requires an oxidizing agent.

d. Oxidation; the stabilizing agent can be produced by oxidation. An example of this system is the chrome-lignin method developed at Cornell University.²

Natural Resins

Although this paper is concerned with giving a survey of the work-in the synthetic resins that has been done, it may be relevant to note a few experiments in the use of natural resins and other organic substances in soil stabilization.

Vinsol. Vinsol is a resinous substance obtained from an extraction process of pine with benzol. Its chief value in soil stabilization is in its water-repellant qualities. Much work has been done on this both in Britain and the U.S.A.³

Rosin. As early as 1935 experiments using this material were carried out in Russia.⁴ It is also produced from pine stumps, and its chemical composition is chiefly abietic acid. Its stabilization effect is chiefly caused by the formation of a gel after reaction with certain metallic salts, the best results being obtained with rosinates formed with iron and aluminum salts. Rosin derivatives, such as Resin Stabilizer 321 and
Stabinol have also proved effective. The first is a salt composed of one molecule sodium abietate and three molecules of abietic acid. Treatment with this substance reduces the moisture absorption of soils. When combined with three parts of Portland cement, it gives Stabinol, a material which seems to be effective in the waterproofing of all soils. Two patents for the use of pine wood rosins and other substances are held by Miller (No. 2,323,929, 1943 and No. 2,357,124, 1944).

Lignin. This resinous alkali liquor, of which great quantities are produced as waste in the paper industry, has been used as a soil stabilizer. It has definite waterproofing properties, although they are inferior to that of Vinsol.

Natural Resins (tropical). Wallaba Resin, Manila Copal, Damar, Belgian Congo Copal, Hal Resin and Niger Paste have been tried. Of these, the only success has been with Manila Copal and Wallaba Resin. Derivatives of these have also been used, but all of them had only limited success.

Oils. A number of natural and modified oils have been tried to render polyvinyl acetate (see below) water repellant. Amongst these are: tung, linseed, soybean, perilla, turpentine, cottonseed, citicica, etc.

"Plasmofelt". Recently much work has been done in the U. S. Marine Corps on beach-sand stabilization with this substance, which is a polymerized asphaltic fuel oil and powdered dehydrated molasses composition. The aldehydes in the sugars of a completely dehydrated molasses are polymerized, by means of high temperature and a suitable catalyst, with the phenols of the asphalt base of the heavy residual fuel oil, while, at the same time, the molasses carbohydrates are converted into asphaltic hydrocarbons. The soft mixture thus becomes a hard, resinous material with many of the characteristics of both a natural asphalt and a synthetic resin or of a natural
asphalt containing a high percentage of synthetic resins. Some promising results were obtained with this substance. It has also been successfully tried for building bricks. In combination with a rubber latex, it gives a tough, elastomeric product.

**Synthetic Resins.** Much of the recent research on the chemical stabilization of soil has been in this field. The chief aim has been to find a material which will impart such mechanical strength to the soil that it will be able to bear loads in a comparatively thin membrane of treated soil. Thus, instead of a thick build up, perhaps totalling 8" - 12", consisting of one or more base layers and a thick surface of high shear strength, the load could be carried by a thin layer, perhaps only 3" thick, which had been given tensional properties and was elastic, thus deflecting under a local load but spreading it over a wide area.

**Aniline-furfural resins.** This was perhaps the first group of synthetics to be thoroughly investigated in this connection. Hans F. Winterkorn was responsible for most of the research. The experiments Winterkorn carried out on various resins of the cheaper group, such as urea-formaldehyde, urea-furfural, analine-formaldehyde and aniline-furfural showed the latter to be the most promising. It was found that the most effective proportion of substances was that of about one part of furfural to two parts of aniline. Its probable chemical formulation is this:

\[
\begin{align*}
H & \quad H & \quad H & \quad OH & \quad H \\
\text{C} & \quad \text{C} & \quad \text{C} & \quad \text{C} & \quad \text{C} & \quad \text{C} & \quad \text{N} & \quad \text{C}
\end{align*}
\]

After field tests the proportion of 30:70 respectively was finally recommended. The aniline furfural seemed to act in the soil mainly as a binder; it was said to compare favorably with cement in this respect. It also had a waterproofing effect which was said to be equivalent to the effect of
liquid asphalt. It was found that the most effective proportion of resin to soil was about 2:100 by weight, although this had to be varied with cohesionless soils and heavy clays, where greater quantities were required. The best catalyst seemed to be aluminum chloride, with ferrous chloride as a close second best. In the early experiments, Winterkorn, Mainfort and others, depended mainly on the formation of a trimer for success. To increase the effectiveness of these resins, molecular chains of greater length were attempted. Pitch and other classical materials have been employed in an attempt to do this; however, it was found more successful to do this by the introduction of poly-functional units. The new modifications tried out by the Navy Department were named X-25 and X-26. Most of the experiments were carried out on beach sands, where an excellent load bearing surface was obtained in two hours or less from the addition of the resin and catalyst. Test roadways, where the soil was impregnated to an average 6" depth have also been built and good experimental results have been obtained. The resulting pavements proved to have excellent water-resistance, but were unable to withstand an unlimited amount of traffic from the frictional point of view, without further resin treatment.

Urea-formaldehyde. Both Winterkorn\textsuperscript{12} and Olmstead and Klipp\textsuperscript{13} made experiments using this resin. The latter tried experiments on Urac 103 and Urac 180, as supplied by the American Cyanamid Corporation, and also on the U.S. Plywood Corporation urea glue, "Weldwood". Although the experiments showed some success, the stabilized sands broke down under a moisture content higher than 5% of the dry weight of the sand.

Urea-furfural and phenol-furfural. Winterkorn also experimented with these substances, but the results were poor, whether used alone or as
mixtures of aniline-furfural or resin. Recently the original aniline-
furfural resins have been modified by the use of poly-functional amines. Phenol-formaldehyde. No success has been obtained with this material so far, due to its inability to set at low temperatures without pressure. British Patent #569,469 by Blott covers a system for soil stabilization with phenol-formaldehyde in some detail.

Calcium-sulfamate-formaldehyde. Winterkorn's tests do not show promising results for this material; but little work has been done on this resin so far, and the fact that the resin is easily formed by exothermic reaction may hold promise for future research.

Furfural-alcohol and sulfuric acid. So far, laboratory results for the resin formed by the interaction of these two substances have been very promising, and show good strength as well as water-resistance in sand and loam soils. Oven-baking increased the strength greatly.

Polyvinyl-alcohol (P.V.A.) Several grades of P.V.A. have been tried and good results have been obtained with dry specimens. However, the polymerized substance is slowly washed out of soil by water, so, for effective use it has to be combined with a water-repellent. Amongst those tried are various natural oils such as cottonseed, perrille, tung, Mexican oiticica, soybean, etc. Other water-repellents tried included melamine, ethocel, dimethylol urea and vinsol.

Ethocel. Ethocel lacquers have been tested but did not give promising results.

Methyl urea and melamines. Varying results have been obtained, the best being dimethylol urea; but the wet strength of all were low. The melamine used is an alcohol modified formaldehyde melamine. Although good results were obtained from dry specimens, upon immersion in water there was a 50%
loss of strength. The resin will eventually set at room temperature. "Resorsabond". This is a two-component substance, containing resorcin and an aldehyde, with a filler. By varying the proportions of the components different soil stabilizing properties were obtained. Laboratory tests carried out so far have not shown much success.

Acrylates. Probably the most promising field of research in recent years has been in the field of the acrylates, chiefly calcium acrylate. Most of this work has been carried out at Massachusetts Institute of Technology, under contract with the Army. Calcium acrylate is an organic salt with this formula:

\[ \text{H}_2\text{C} = \text{C} - \text{O} - \text{Ca} - \text{O} - \text{C} - \text{H} = \text{C} - \text{H} \]

Its soil stabilization effect is the result of a double process; first, the acrylate ionizes in the presence of water (either added with the acrylate or already present in the soil) to form, among other ions, a positively charged calcium acrylate ion. This can become attached to the soil particle by replacing (say) a sodium ion in a typical base-exchange reaction. The displaced sodium can react with a negatively charged acrylate ion to form sodium acrylate. The second stage is the actual polymerization of the acrylate, both that attached to the soil and that remaining dissolved in the water. Long chain polymers are formed, thus chemically linking the soil particles and the solution in a complex, three-dimensional chain.
The catalyst used to carry out the polymerization is a redox system that is a combination of an oxidizing agent and a reducing agent. Ammonium persulfate is used for the former and sodium thiosulfate for the latter. Experiments have been made to find other, more effective catalysts, with no definite results so far.19

The result is the formation of a strong, flexible product with considerable tensile strength, water-repellent, impermeable, resilient, with a much decreased volume-change propensity under the action of water content changes. The gel formed is thus permanent and gives the soil altogether new qualities. A comparatively thin layer of treated soil, say about 5", will support some traffic, but further tests are necessary before its value can be determined.

The time taken for the formation of the gel is effected by the amount of catalyst and by the total soaking time. The calcium acrylate can be improved with the co-polymerization of other monomers; the only published information is on N-methyloacrylamide.20 Lead acrylate has also been used under heat and pressure as a polymerizing agent in sodium-montmorillonite soils.21 The action of calcium acrylate is more marked in fine grained sand than in coarse. The amount of water and oxygen present during mixing and polymerization is crucial.22 When the gel is dry, it is hard but becomes plastic again under the action of water.23
The amount of acrylate required is dependent on the soil and the use to which it is put; a very approximate general estimate might be 4% - 8% by weight as compared with about 6% - 12% for Portland cement or bituminous stabilizers. The chief advantages of the acrylate stabilizers are the speed of setting, applicability to soils not treatable by cement or bitumens satisfactorily, and their ability to treat soils with high water contents. The cost of the material is greater at the moment than for traditional stabilizing agents, since no large scale plant production is in progress. But a commercial forecast for uses of the acrylate show that it might compare favorably with these other materials when in quantity production. In addition to mixing the acrylate into the soil by mechanical means, it can be injected into inaccessible positions. Experiments in spraying it from the air, i.e. in military beach-stabilization actions, have yet to be carried out.

The equipment needed for mixing the acrylate with the soil is comparatively simple. So far the standard bituminous pug-mill has been found to be the most suitable, although, ideally, a new piece of equipment would be required. Although acrylates may have great advantages over other stabilizers, their use will be limited by their high cost, a factor which may remain unchanged for a considerable time.

Stabilization of soils for civil engineering purposes has been widely practiced. In this field the synthetic resin stabilizers may, as we have seen, play a very important part in the future in replacing stabilizers which have limited properties and applicability. But another important field may open up, in the building industry. The stabilizers traditionally used for monolithic or block earth construction have been cement and bitumen-emulsions. Each of these has its limitations, with
regard to moisture resistance, structural strength or other properties. There is great scope for new stabilizers here, and the synthetic resins seem to have promising potentialities. Of course, allied to the chemical and engineering research on finding suitable stabilizers, some imaginative research on the architectural possibilities of earth construction is required. It may thus be possible to find new ways of producing earth structures in which far less soil is required and, hence, less stabilizer, which is in direct proportion to the amount of soil. This may mean that some synthetics would become economic within a much shorter space of time than is at present envisaged.
FOOTNOTES
TO APPENDIX II


    b. op.cit. note 3.c., pp. 49-52.

6. op.cit. note 3.c., p. 52 and note 16, p. 64.

7. a. op.cit. note 3.c., p. 53.
    b. Lignin Extract as a Stabilizing Agent for Road Foundations, by Guillaume Piette, Roads and Bridges, p. 70, Sept. 1945.
    c. Road Research Laboratory, D.S.I.R., Great Britain, RN/402.
d. U. S. Patent No. 2,575,019 by A. B. Miller (Hercules Powder Co.).

8. a. op.cit. note 3.c., p. 54.


12. ibid.


16. op.cit. note 15.

17. op.cit. note 3.c., pp. 8-9.

   b. Chemical Injection Processes, by T. W. Lambe, Paper read to


19. op. cit. note 18,a., p. 142.

20. op. cit. note 18,e., p. 6 et seq.
22. op. cit. note 18.i., p. 24.
23. op. cit. note 18.g., p. 88.
25. op. cit. note 18.d.
26. op. cit. note 18.c., p. xi.
This Bibliography attempts to give a complete list of all publications on earth building construction and related subjects. It is over twice as long as the previous longest one, published by the United Nations. This increase in size is due mainly to the inclusion of many works on basic soil science and stabilization which will be applicable if the schemes suggested in this Thesis become practised. Also, many items on highway engineering and mechanical equipment have been included for a similar reason.

Many of the shorter, mainly anonymous articles, which are listed and which were published in various popular journals, may have little direct use for architects and engineers. They have been included here, however, in order to give as detailed a picture as possible of what has been done, and where, for future research workers. It is possible that such a list of existing structures (for that is what those portions of the Bibliography really amount to) may be of great value when samples of soil are analysed from existing structures and the tests are related to climatic and other factors.

A. BIBLIOGRAPHIES

In addition to those listed here, some excellent special bibliographies appear in some of the works listed in the other sections of this Bibliography.


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**Bee, R. J.**

The Application of Engineering research to Tropical Problems, Singapore.

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*L'Oasis Moderne.*

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