LOW-COST ROOFING SYSTEMS FOR DEVELOPING COUNTRIES

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ABSTRACT

The general problems of low-cost roofing for tropical developing countries are discussed and the four main criteria: climate, economic, technical and social, investigated in detail.

Roofing types are examined together with the roof elements (the supporting structure, the roofing substrate, the roof covering) and a comprehensive list of potential roofing materials is included.

A variety of roofing systems are discussed in detail based on the previously outlined criteria and classification. The systems and materials investigated are: "paper systems, metal roofs, bituminous roofing materials, cementitious composites, burnt clay, earth roofs, waste materials, and sulfur composites".

From the data obtained, the author concludes that a definite statement of appropriatness for a particular roofing system in a given region can only be made by recognizing the complex variations in local environmental conditions and economic and natural resources.

RESUME

Les problèmes généraux des toitures économiques dans les pays tropicaux en développement sont l'objet de cette étude, et les quatres critères économique, climatique, technique et social y sont analysé en détail.

Les différents types de couverture sont étudiés en relation avec les éléments du toit (structure de support, partage, recouvrement).On trouvera également une nomenclature des matériaux utilisables.

Divers systèmes de toiture sont étudiés en détail suivant les critères et les principes de classification décrits ci-dessus. Ce sont: les toitures en papier, les toitures métalliques, les toitures asphaltiques, les toitures en composés de ciment, en élément de terre cuite, en terre, en matériaux de récupération, en composés sulfureux.

D'après les données recueillies, l'auteur vient à cette conclusion qu'un système ne peut être applicable directement à une région donnée si seulement l'importance des variations environmentales,des conditions économiques et des resources naturelles est prise en consiéderation.

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1.1. THE HOUSING PROBLEM

The unexpected urban growth, coupled with limited financial and industrial capacity in developing countries, has led to serious shortfalls of basic services, shelter, and full-time employment. The lacking of sufficient medical services, education and public utilities is even greater in rural areas.[1] The increasing importance of money, introduced through trading and specilization, lead to an uncontrollable cityward migration. This influx of migrants to urban areas, everyone dreaming of becoming a wage earner, is taking dimensions no city can handle in conventional ways anymore.

Statistics on urban issues produce startling figures: 60 percent of the population of Latin America is already urban, but the proportion is expected to grow to 75 percent within the next twenty years.[2]

Table 1 Multimillion Cities (UN)

up to 1920	between 1920 and 1960	between 1960 and 1980	
East Asia:	East Asia:	East Asia:	Latin America:
Tokyo	Shanghai	Muhan	Lima
	Beijing	Shenyang	Santiago
	Tianjin	Chongoing	Bogota
	Hong Kong	Guangzhou	Caracas
	Osaka	Luda	Africa:
	South Asia:	Haerbin	Alexandria
	Calcutta	Taipei	Lagos
	Bombay	Seoul	
	Jakarta	Delhi	
	Latin America:	Madras	
	Rio de Janeiro	Karachi	
	Sao Paulo	Tehran	
	Buenos Aires	Baghdad	
	Mexico City	Istanbul	
	Africa:	Singapore	
	Cairo	Manila	

There are approximately 60 cities today which, according to criteria set by the UN, fall under the definition of multi-million cities (cities with more than 2.5 million population). Further 200 cities with a population now between 0.5 and 2.5 million will inevitably move towards the upper category in the not so distant future.[3]

Another prognosis by the UNFPA predicts that Mexico City's population will reach 31.6 million by the year 2000, Cairo 16.3 million, Lagos 9.4 million and Tokyo 26 million. The world-wide need for housing in these next 20 years will amount to 1.14 billion units.[4]

The problems associated with this growth rate are further detailed by the fact that one fourth of those living in the major cities still have no direct water supply; almost two thirds have no sewage facilities. As for shelter, urban growth is five times faster than the supply of planned housing.[5]

Nearly 50 million urban dwellers in Latin America live below the urban poverty threshold. Urban unemployment and underemployment are high, and widespread low productivity and earnings are even more serious problems.[6]

The poor newcomers are forced to live in unplanned settlements, occupying land illegally, often located in peripheral areas where travel to and from work each day may exceed three or four hours. Most of these squatter settlements also occupy land otherwise unfit for development, such as steep mountain slopes, flood endangered areas or leftover areas between highways and railways. The quality of these structures, and roofs in particular, hardly reaches acceptable levels of comfort.[7]

The prevalence of disease in such settlements is sometimes as much as 50 percent higher than the city-wide average. Such conditions further erode the productivity of the poor and can lead to a self-perpetuating cycle of poverty.[8] The unhuman living conditions in these squatter settlements also involve a very typical antisocial behaviour of its inhabitants struggling to reach a higher standard of living and to escape this cycle. Gambling ideology and fatalism characterize the general behaviour as sociological surveys reveal; other alternatives than the individual's struggle for improvements of living conditions are not sought.[9] Some countries with socialistic experience, like Peru, have had some success with colletive efforts for improvements, organized by authorities instead of leaving these slums to their own resources and thus only allowing a few strong individuals to escape, leaving the slum behind as it is.[10]

Two decisive factors eminent for success of any project for improvement of squatter settlements or new low-cost housing schemes have emerged during my research into the general housing problems in developing countries:

1.1.1. Land Tenure:[11] The definition of illegality of squatter settlements which, according to quoted statistics, make up for four fifths of new housing in developing countries, create a conflict situation for settlers as well as authorities.[12] If housing is an acknowledged basic right and authorities or the free market cannot deliver, the authorities have to legalize these settlements through land reforms, giving the settlers land tenure, without which they have no incentive to invest into improving their shacks as they could be torn down by the authorities any time.[13]

1.1.2. Credit facilities: Although squatter socities are very industrious and have developed very capitalistic mechanisms, they have little or no access to credit facilities. As most people in the lowest income bracket are working in the informal sector, which hardly provides a regular income, they have a known bad payback ability.[14]

The lacking of credit facilities for this group makes it very difficult if not impossible for them to start improvements of their shelter after obtainment of land tenure. The sudden value of their plot is a temptation to sell it only to start over again and being caught in a dead cycle.[15]

One could ask, what do land tenure and credit have to do with roofing? - A great deal I think!

The problems of human settlements in developing countries form a chain with numerous elements, some of which are crucial for survival, others less, but all of them are interdependent. After food and sanitation, which are primary elements, follow shelter. The poorest of the poor never reach a higher level than just being able to satisfy more or less these basic needs, and they are always at the mercy of others.[16]

But as soon as a dweller manages to reach a level where he can think of improving his shelter, other factors come into play. Some of these factors are imminent and have to be improved before others can be.

As the improvement of a house (extension, renovation, etc.) is a major commitment for any dweller, whether rich or poor, he will never risk the investment without having tenure on the land (leasehold or ownership), and will therefore rather buy movable goods than a new roof.

Our economies are functioning only on the basis of well structured credit systems, enabling almost everybody to get credit, especially for improving real estate. If those economic facts are true, why should they not be true for developing countries?[17] Some examples in South America have proven that people working in the informal sector are very industrious and do not have as bad a payback record as is sometimes believed.

The roof plays a primal role in our lives. The most primitive buildings are nothing but a roof. If the roof is hidden, if its presence cannot be felt around the building, or if it cannot be used, then people will lack a fundamental sense of shelter.

Christopher Alexander et Al.[18]

1.2. THE ROOFING PROBLEM

A wide range of historic and prehistoric shelters is still found today as contemporary dwelling forms in developing countries around the world. This great variety of indigenous housing forms has one distinct characteristic in common: the emphasis put to the roofs.[19] In fact, many of the temporary shelters consist of no more than a roof structure and its covering. The roof is usually that part of a dwelling which gives most difficulties to the builder and it has undoubetdly always been the most important of all the elements of shelter; it provides protection from environmental conditions and often meets cultural needs as well. In developing countries it serves many other functions; there the roof can be a sleeping area during the dry season, a water collecting system, a storage area, a food and clothes drying area, or it can also serve as a refuge from flood waters. In low-cost housing, the roof is the single most expenditure and thus the design of the roof becomes the moderator of all conceptions.*[20]

The search for appropriate low-cost roofing systems for a particular region naturally starts with investigating local traditional materials and methods for roofing. But looking for solutions amongst indigenous traditions of building is of little or no help, as Koenigsberger says, they are

* Between 30 and 50 % of the total construction costs in low-cost housing are made up by the roof structure.

based on conditions which have ceased to apply universally.[21] Rural housing has never really been a problem compared with that arising from urbanization. Koenigsberger uses the following example, underlining the difference of the situation:

> "With the exception of a few rice growing areas, the equatorial tropics used to be regions of low population density. Houses were dispersed and would, therefore, be roofed with inflammable materials. It did not matter that these materials had to be renewed frequently. They came from plants that grew in the vicinity of the houses and were available practically free of cost. Agricultural activities were seasonal, and left spare time for the repair and renewal of houses and roofs."

The urban environment and the changing lifestyle of the masses in need of housing today bring about the need of inorganic, non-inflammable and reasonable durable materials which exclude those utilized in most traditional methods. The choice of a material, as we will see later, is the main step in the design process for a low-cost roof as it influences most other decisions to be made. The use of local materials is not impossible, on the contrary, it is desirable to utilize local resources where and whenever possible if they can be processed or modified to meet the new requirements.

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2. roofing criteria

The process of finding an optimal low-cost roofing system for any specific location means translation of information in the form of requirements, constraints and experience into potential roofing solutions.

A comprehensive catalogue of roofing criteria is the inevitable basis of the process.

In this multiproblem-solving process, one has to cope simultaneously with:

- climatic
- economic
- technical
- social

problems, without losing sight of the general planning context of the task.

Whatever the model for solving these problems might be, one will have to go through the three stages of analysis, synthesis and evaluation at the various levels of the process of finding roofing solutions.

Naturally the evaluation stage is the most crucial one in any problem solving process.

We aim at methods of evaluation for easier decision making and justifying them, but it is impossible to establish an order of priority or universal evaluation scale dealing with these problems.

Perhaps the only scale against which priorities should be plotted is that of "human misery". In fact, as we are not only dealing with quantative, measurable aspects but mostly non-measurable ones, the evaluation of an option could best be described as follows: if the roof in low-cost housing is the moderator of the conception, it must not preclude the solution of any of these aforesaid problems but promise to solve a good number of them in a convincing manner,[2]

It is tempting in low-cost housing to use a single quantifiable criterion of choice, cost, associated with each option or combination of options, to make it possible to find that feasible solution which best satisfies the criterion. But it is clear that the compromise will always have to be sought between several criteria which are never capable of being related to a single scale of measurement.

As I do not believe that a rigid methodology can be of great help in finding appropriate roofing solutions, a more flexible way of identifying those solutions has to be sought.

Perhaps a weighted matrix technique could be of a better help than a ratio or ordinal scale would be.

But before I am able to draw any conclusions or make any statement of what kind of roof is appropriate and under what conditions, the roofing criteria have to be discussed.

To summarize the four main criteria (climatic, economic, technical and social), we can say that a roof has to provide protection from: sun, rain, storm, fire and theft; be cheap and easy to transport and erect; provides effective resistance to the transfer of heat from the outside; be durable and above all be accepted by the dweller on social grounds.[3]

From this summary, it is evident that these four main aspects have to be studied in detail before a proposed roofing system can be evaluated properly.

2.1. CLIMATIC ASPECTS

It is the countries of the tropics which suffer most from a severe housing shortage and the climatic factors in these regions are a considerable design criterion.

In those tropical and subtropical regions, heat is the dominant problem and the annual mean temperature is usually not less than 20°C.[4]

A widely accepted classification, as suggested by G.A. Attkinson in 1953 and used by Koenigsberger, divides the tropical regions of earth into the following three major climatic zones with each of them having a subgroup of relative little difference:[5]

a) warm - humid equatorial climate
warm - humid island or tradewind climate;

b) hot - dry desert, or semi desert climate
hot - dry maritime desert climate;

c) composite or monsoon climate
tropical upland climate;

These three climatic zones have the following characteristics and are predominant in the following locations:

a) Warm - humid equatorial climate:

- high ambient temperatures;
- high humidity;
- high and fairly even distributed rainfall;
- small diurnal and annual variations of temperature;
- little seasonal variations;
- light winds and long periods of still air;

Examples of cities in this zone:

- Lagos, Dar-es-Salam, Mombasa, Colombo, Singapore, Jakarta, Quito and Pernambuco.

Warm - humid island or trade wind climate:

- the characteristics of this zone are similar to the warm - humid equatorial climate except that in this zone we find a dominance of trade winds which facilitate heat loss by convection and evaporation;

Typical examples for this climate are:

- the Caribbeans, the Philippines and other island groupes in the Pacific Ocean;

b) <u>Hot - dry desert, or semi desert climate</u>: -

- high day temperatures;
- low night temperatures;
- low humidity;
- low precipitation;
- large diurnal and annual ranges of temperature;
- distinct seasonal variations between hot summer and cool or cold winters;
- little air movement except for local thermal winds and seasonal dust storms;

Typical examples of settlements in this zone are:

- Assuan, Baghdad, Alice Springs and Phoenix;

Hot - dry maritime desert climate:

In this zone, where sea and desert meet, we find three distinct differences to the main zone:

- higher moisture content in air;
- humidity tends to reduce diurnal variations;
- thermal breezes from and to the sea;

Typical examples are:

- Kuwait, Jeddah, Antifagasta and Karachi;

c) Composite or monsoon climate:

This zone can have two, three or four distinct seasons:

- one similar to arid desert climate;
- another warm humid;
- and a third one with
  - cold nights;
  - sunny warm days;
  - low humidity;
  - little precipitation;
- transitional periods of varying lengths may occur between the clearly discernible seasons;

Examples of cities with composite climates are:

- Lahore, Mandolay, Asuncion, Kano and New Delhi;

Tropical upland climate:

is similar to above but with added complications of night frost and in some areas snow. The incoming and outgoing radiation is of greater importance in this zone.

We find the following cities with this climate:

- Addis Ababa, Bogota, Mexico City and Nairobi;

The main climatic elements to consider in roofing design are:

- temperature;
- humidity;
- precipitation, driving rain;
- wind;
- sky conditions;
- solar radiation;

But in addition to the macro-climatic information as outlined with the six climatic zones, the site climate has to be specially studied for each individual project.

The site climate can deviate from the general pattern of the climatic zone due to the following factors:

- topography (slope, orientation, exposure, elevation);
- ground surface (reflectance, permeability);
- three dimensional objects (trees, fences, walls, buildings, hills or valleys);

2.1.1. Climatic Performance Standards

I have not found a better way of describing climatic performance standards for roofs in the tropics than the way Koenigsberger has done it:[6]

"A building is acceptable from a climatic point of view if it provides indoor conditions which permit sound sleep at night and the persuit of normal physical and mental activities by day without strain from excessive heat, cold or humidity."

The roof is the most important element of the house from this point of view of climatic protection. To be satisfactory a roof must therefore, apart from being impermeable, absorb as little radiant heat as possible and offer, depending on the climatic zone, almost complete resistance to heat flow from the outside to the inside.

For the three climatic zones, the following conclusions for application can be made:

a) Roofs for warm - humid climates: As there is a very small diurnal variation of temperature in this climate, a building cannot cool off sufficiently at night-time to allow the storage of heat during the day, The roof should therefore have very low thermal capacity.

It cannot improve the indoor conditions but at least, if well designed, it can prevent the indoor temperature increasing above the outdoor air temperature, and keep the ceiling temperature around the same level as other surfaces.

The study, "Roofs in the warm humid tropics" by Koenigsberger and Lynn, concludes that a ceiling belongs to the minimum requirements to be insisted upon even in houses for the poorest of the poor! And further they stated that under other than aluminium roofs the ceiling should be supplemented by a layer of aluminium foil.* [7]

Taking a house in this climatic region roofed with corrugared asbestos cement and no ceiling, the under-side of this roof would measure 48°C at an outdoor air temperature of 22°C.

A cheap kraft paper ceiling, faced with aluminium foil on the upper surface, adding 3 to 4 % to the total roofing costs, would improve the situation to 34°C.

Apart from protection against heat flow, rain water drainage is of particular importance in this climatic zone. As rainfall is rather high in these regions, a pitched roof will most often be used, preventing the penetration of water during tropical rainstorms best.

These rainstorms can be accompanied by winds of more than 40 km per hour in areas that are not endangered by hurricanes or typhoons, a point to be considered with regard to the roofs structure and the method of fixation of the roof cover. Roof gutters are breeding grounds for mosquitos

* This, of course, will hardly anywhere be the case; the compromise often lies in changing the lifestyle, using rooms at nights only or carrying out certain activities outdoor during daytime.

spreading Malaria and are therefore prohibited in most countries of the warm humid tropics. They are also not permitted on grounds of Yellow Fever control.

Roofs for warm - humid island or trade wind climate: This variety of the warmer humid climate does not change the basic climatic criteria for roofs from those stated in the preceeding chapter except for the fact that most of these islands lie in the tropical cyclone belt. Roofs, and the entire structure therefore, must be designed to withstand winds up to 250 km/h!

I do not see how this requirement can be made compatible with low-cost; the experience of Darwin in Northern Australia has shown that it is impossible to withstand such forces even with high standard housing.

b) Roofs for hot - dry desert or semi desert climate: The large diurnal temperature variations necessitate roofs of large thermal capacity. These will absorb most of the heat entering through the outer surface during the day, before the inner surface temperature would show any significant increase. The method will only be effective if the heat stored during the day can be dissipated during the night. Residential structures in this climate would therefore need to have a time-lag of 9 to 12 hours.[8]

In regions where the night temperature does not fall below the comfort zone, roofs should have a high resistive insulation instead of large thermal capacity. The traditional mud roof construction is still prevailing in this climate and also very effective.

But the need of heavy mainbeams and numerous timber joists make this heavy structure more and more expensive, especially in urban areas, and the need of continued maintenance less and less attractive.

Like in all other climate zones, the roof alone cannot control the indoor climate; especially in this climate it needs some "managerial control". The occupant can improve the thermal performance of his house if he ventilates it during the night hours when the external air temperature is lower than the corresponding internal air temperature.

The performance of conventional mud roofs as well as concrete slab roofs can be considerably improved in this climate through the use of simple shading panels made of local materials such as reed.[9]

Such reed panels can reduce the maximum ceiling temperature by 5°C and prolonge the time-lag by one hour. They should be rolled or folded away during night time to allow the roof to loose most of its gained heat to the cool night sky reducing heat transfer to the inside. (Figs. 2.1 and 2.2)

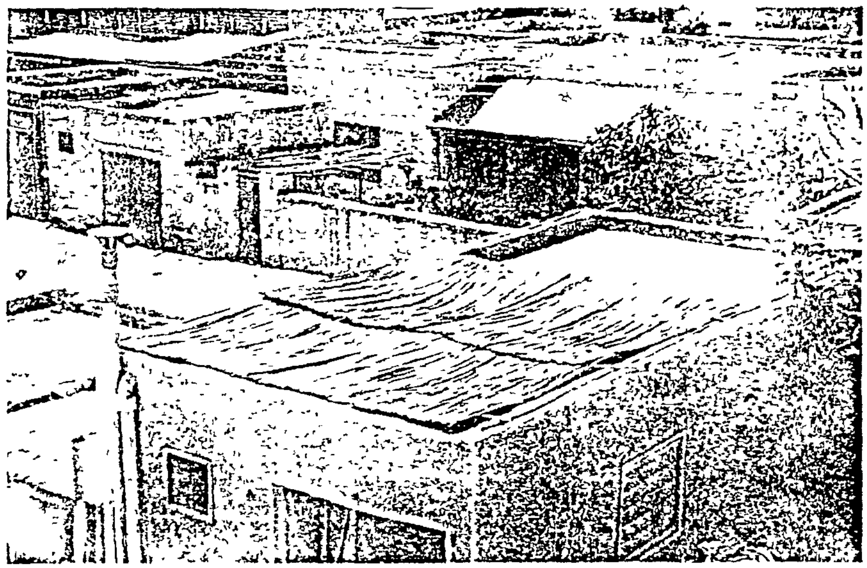

Fig. 2.1 An experiment in the reduction of day-time ceiling temperatures by simple local techniques (OBN 164)

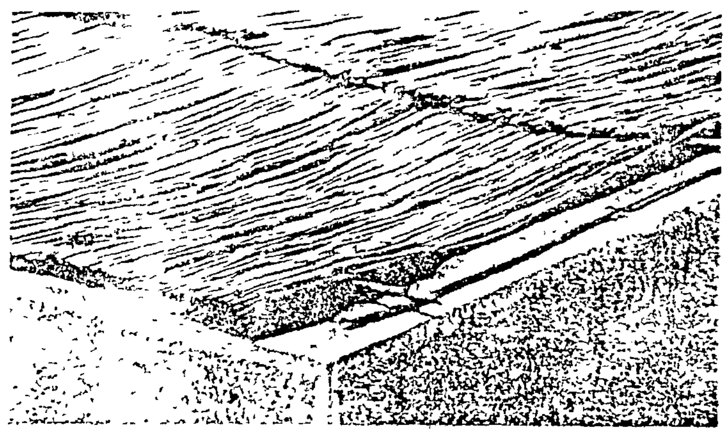

Fig. 2.2 Detail of reed panel after 36 months' exposure (OBN 164)

Roofs for maritime desert climate: The difference from the hot - dry desert region is the high humidity and thermal winds.

The only solution to this is to provide alternative spaces:

- a roof with high thermal capacity, for use at night, with no wall openings towards inland;
- a roof only providing shade with a low thermal capacity over daytime used areas, the walls having openings to both sides, sea and inland;

c) Roofs for composite climate: The changing seasons in this climate make it difficult to find a roof satisfactory for all seasons.

The analysis shows that the cold season, being the most important, requires a high thermal capacity roof. This roof with a 9 to 12 hour time-lag in heat transmission will also be useful during the hot dry season.

For the warm humid period, good ventilation or a lightweight structure sleeping area could improve a lot on comfort.

Roofs for tropical upland climates: Roofs in this climate can have a smaller thermal capacity with a time-lag of 5 to 8 hours,

2.2. ECONOMIC ASPECTS

Most developing countries are in very dynamic economic situations and constantly short of foreign exchange. To improve and stabilize this situation, the evaluation of low-cost roofing systems should put high priority towards minimizing foreign currency requirements and maximizing the use of locally available materials to mention only two of the critical factors.[10]

The owner builder will naturally always be looking for the cheapest acceptable solution of the time, often ignoring other important criteria involved and this at the expense of the dweller's comfort, limiting the proper use of the house. If developing countries' economic situations are to improve appropriate low-cost roofing systems have to have a positive local, regional or even national economic impact.[11]

This need of a positive impact on the economy makes the discussion of technology exchange the most important development issue of today. In that respect, it is important for the building industry of developing countries, often controlled by big foreign companies, that labor intensive technologies are preferred over capital intensive ones as they will lead to the formation of local industries and blind production* of building materials and thus be favourable to small scale and self help building operations.

Considering these general economic issues, cost will always be the central criterion in the decision process; but all the social and economic benefits to a region do not help the low income dweller if he cannot afford what is supposed to be best for the community.

The cost factors to consider are:

Material cost: they can be minimized through the use of local materials and manufactured components of low energy value.

The total material cost of the roofing system is depending on the cost balance between the supporting structure, the roofing substrate and the roof covering.

Labor cost: can be minimized through the use of local resources (materials, processes) but depends on the roof type and skill required to construct it.

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* 'Blind production means production of materials which can be used in a variety of applications rather than a single one. This term is often compared with the Gutenberg principle.
Concrete examples of components produced in blind production are bricks, tiles, etc. In comparison, in a closed building system, a single component can only be used for the function and in the location it has been designed for.

Transportation cost: is in direct dependence to location of building site and used materials and can therefore be minimized through the use of local, regional or national available products and materials.

Equipment cost: can be eliminated or minimized through the use of easy to handle components and sample processes to assemble them.

General expenses:* are usually in proportion to the complexity of the overal construction process and should be marginal for low-cost roofing systems if no overheads for foreign organisations and consultants have to be calculated.

Maintenance cost: depends on the initital investment and system used and can only be minimized if the owner can carry out maintenance himself without considerably diminishing life span.

If materials and processes are found which are of economic benefit to a region or country and are within that

* General expenses include charges for banking, taxes, licences, permits, security and administration.

economic environment considered low-cost*[12], the owner builder will ask for his cost benefits.

- Life cycle costing is often not a big help for evaluation, as for the low-cost builder initial cost is crucial and with no credit facilities available, he cannot take advantage of spreading the cost and for that matter choose a more durable but more expensive roofing system.
- A social cost-benefit analysis can help in this case much further.

As high durability of a roof increases its initial cost and this in most cases beyond the threshold of affordability, maintenance becomes an important issue. Therefore, a cheaper material which can relatively easy be maintained is usually chosen over the more durable one.

The responsability of maintenance, to make it work, has to be tied to ownership.

* Low-cost per definition is a relative term. I could find the two following definitions, one on an absolute basis, the other one on a comparative one:

Low-cost in an absolute basis can be defined as that of the most price-competitive alternative roofing. This, in most cases, has been corrugated galvanized iron which ranges in cost from 3.20 to 3.50 US-$/m2 (including shipping; on local market).

A more relative definition reflecting the rather large differences between different countries is the rule of thumb for housing that can be afforded to be to to 2 1/2 times the family annual income of the lower 50% income group.

2.3. TECHNICAL ASPECTS

are closely linked with economic ones and usually have a direct impact on each other.

Material, labor and equipment in this case can be grouped together under installation. Other technical aspects to consider are transportation, durability and maintenance.

Installation

Ease of installation is important to minimize the need of skilled labor and variability in the performance of the roof due to improper construction. Installation and maintenance should be possible without the use of high tech. tools. A single roofing component or element should not exceed 100 kg so that it can be handled without mechanical lifting devices.

Apart from the roof's normal structural performance, the mechanical strength and rigidity of the roof covering should be sufficient to support a person for the installation and repair of it, but minimizing truss and purlin requirements.

"Easy installation" is defined as the skill required for installing corrugated galvanized iron sheet, which is usually nailed directly in large panels to fabricate the roof.[13]

Transportation

—is in direct relation to cost and should therefore be minimized where ever possible.

Transportation, similar to building material costs, is comparatively much more expensive in developing countries than in industrialized ones. But transportation of raw materials to production centers and transportation of the components from there to the building site cannot be avoided.

It is therefore very important that the location of a production facility is well planned in that respect. As roads in developing countries are usually not in very good conditions, transportation of building materials is more critical.

Certain materials do not have good enough resistance for transportation on rugged roads and higher than normal breakage occurs. This cannot easy be prevented or reduced and is of consideration when calculating quantities.

Ideally, the manufacturing of the component takes place on the building site with raw materials available nearby and the need of little or few materials to be transported to there.*

* Good examples are fibre-cement sheets on site produced or ferro-cement elements, but also burnt clay tiles if locally produced are paying respect to these criteria. Most traditional systems are based on these principles anyway as transportation was even more critical in the past.

Durability

Durability is a measure, in an inverse sense, of the rate of deterioration of a material or component. It can also be defined as the quality of maintaining a satisfactory appearance and satisfactory performance of required functions. This parameter is usually measured in terms of the minimum number of years of satisfactory life (life span).

Maintenance is an economical mean to extend life span without usually the need of replacing components.

Durability factors are:[14]

Environment: weather factors, pollution, insect and fungal attack, soil aggression;

Use: "fairwear and tear" and excessive damage;

Design: design detailing and selecting the correct materials for design or designing appropriate to the materials available;

Workmanship: quality

Of all these factors the weather factors are the most significant elements leading to deterioration of the roof covering, notably: moisture, temperature, solar radiation, atmospheric gases and salt-laden winds.[15]

The roof structure, most often made of wooden trusses and purlins, is usually prone to insect attack as the timber used for building purposes is soft wood of the higher-weight hardwoods and therefore not resistant to termites or fungal decay.

As structural elements have to serve the entire life span of the roofing system, preservation treatment for wooden elements is absolutely necessary in the tropics.

Maintenance

can never make up for bad workmanship or unconsiderable design but it can, with good management and judgement, extend the life span of even the cheapest of the low-cost roofing systems.

The most common, effective and usually least expensive maintenance of a roof is the renewing or application of surface coating preferably as near to white as possible. For all roofing types and most covering materials a well maintained surface coating can extend the life span beyond normal expectations and will also improve or maintain climatic performance of the same.

2.4. SOCIAL ASPECTS

Social aspects related to low-cost housing deal with the quality of housing or in this case how this quality is influenced by the roofing system.

The quality of housing has a direct impact on the wellfare of the dweller because of its influence on human health, safety and living comfort.[16]

The following criteria relevant for evaluating a roofing system can be identified and grouped in those of direct concern to the user and those affecting the decision process:

Direct user related criteria are:

Safety: safety from fire, structural safety including resistance to heavy winds, flying debris and in many cases earthquakes are of major concern to the dweller.*

Usability: it is of great importance that the dweller can use the roofing system according to his traditional needs, for example as a storage area or to dry food, but notably in urban areas as a sleeping area in the dry season.

* These physical aspects are also of consideration under the other three, climatic, economic and technical criteria, but are classified under this group as they have an impact on the quality of housing seen in a social context.

Physiological performance standards should be set to allow indoor activities during day and sleeping at night without affecting the health or comfort of the occupants. The roof's acoustical performance should be so that in regions of heavy rain and winds the noise from these elements is reduced to a bearable level.

Psychological aspects for a roofing system include considerations of privacy for the dweller. But moreover the concern of status symbolism or social prestige fall under this category and should not be ignored. Status symbolism like in North America goes together with measurable advantages for the dweller, even if his choice is based on one dominating characteristic and thus accepting sometimes considerable negative aspects. Poor people prefer a high status but substandard cement block tin-roofed house to a lower status but higher quality mud house, for example, not for social prestige reasons only!

Aesthetic considerations should be based on local ideas of aesthetical expression and preferably reflect traditional art forms as well as materials and colors.

The decision process is often influenced by political factors beyond the owner builder's control. Especially in large scale government organized low-cost housing schemes we find these criteria often limiting choice:[17]

The colonial heritage — can influence decision making severely and is often expressed by animosities towards materials, architectural forms or methods of construction which have been established during the colonial period.

Corruption — is wide spread in most poor countries and influences the decision process a great deal. These countries are in Myrdal's term "soft states" with great discrepancy between authority and control and the relative autonomy of indiginous political processes at the local level.[18] For example, a few local "industrialists" may obtain effective control of government policy insofar as it affects their industries and tariffs; government contracts, tax laws and the like may then be manipulated accordingly.

Development aid can limit or influence the choice unreasonably due to political reasons or idealistic views of the senior officials involved. Basic policies in development projects can then read like: "Any roof system selected should be compatible with the policies of the local government and USAID", for example.[19]

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3. roofing types

A roof is usually made of several components with the assembly of these components forming the roofing system.

A roofing system can comprise the following elements either singly or in combination:[1]

- the supporting structure;
- the roofing substrate;
- the roof covering;

Low-cost roofing systems for housing have one distinct characteristic, they are short-span only (average spans are between 2.40 m and max. 6.0 m).

Roofs are commonly identified by their shapes:

- flat roofs;
- low pitched and shed roofs;
- gable roofs;
- hip roofs;
- gambrel roofs;
- vaulted roofs;
- domes;
- folded types;

But for easy classification, other criteria are more suitable. Roofs can be simply grouped into:

- self supporting systems, and
- supported systems.

This simple classification includes the great variety of structure systems and covering materials used for roofing.[2]

The <u>structure systems</u> used for low-cost roofing are:

- homogenous slab - post and beam	)	bulk active structure systems
- arch mechanism - truss mechanism	)	vector active structure systems
- folded systems	)	surface active structure system

Other structure systems like, space, pneumatic and suspended structures are used for long-spans mainly and are therefore not considered suitable or economical for low-cost roofing.

Besides the roof shape, the covering material is most often used to characterise or identify a roof (thatched, zinc or tiled roof are commonly used descriptions for roof types); we can devide these <u>covering materials</u> into three groups:

- tiles or shingles;
- sheets or panels;
- built up roofs;

Roofing covers (membranes) applied in the form of three groups are often complemented with a waterproof coating and/or a sarking* if necessary.[3]

* Sarking is an impervious membrane applied under roof covering to prevent penetration of occasional drops of water during driving rain, mainly needed for low pitched roofs.

With all the roofing criteria discussed and the "roofing vocabulary" listed, I have to elaborate on the three roofing elements and the variety of materials before I can discuss and value the various roofing systems selected.

3.1. THE SUPPORTING STRUCTURE

Ideally, a low-cost roofing system is lightweight, self supporting and satisfies all other aspects of roofing. Unfortunately, the self supporting solutions are not always affordable or acceptable so that in most cases a supported solution is chosen.

Normally, room dimensions in low-cost housing lead to roof spans which do not require trusses for supporting the roof purlins or the roof battens.[4]

The roof purlins or battens can rest either directly on walls or partitions or on simple rafters. However, there may be situations where roof trusses are needed to allow larger roof spans.

The most common material used for support structures is sawn timber, but also bamboo, palm fronds and stems as well as branches of all kinds of trees are used. These are usually locally available materials and relatively cheap as compared with other structural materials such as steel and reinforced concrete.

Except for a heavyweight roofing system (earth roofs) or those which require higher structural capacities (accessible roofs) steel and concrete are not used in low-cost housing for supporting structures.

Durable timbers are too expensive to use for building purposes too, because of first cost or the cost of processing. The less durable timbers, most likely to be acceptable for building purposes, that is soft woods or the lighter-weight hardwoods, can normally be made sufficiently durable for most situations by the use of one of the following preservative treatments:[5]

- pressure;
- open tank;
- double vacuum;
- diffusion;
- immersion;

If treated properly the risk of timber being attacked by decay fungi, insects or termites can further be reduced by appropriate design.

Support structures in low-cost roofing are very often over dimensioned and are therefore uneconomical. (It is mainly for heavyweight roofs where the design of the support is critical for safety.)

The study of roofs for low-cost structures by J.Eygelaar shows that if properly designed savings on the support structure for lighter-weight roofs can make them more cost competitive without reducing safety or proper performance.[6]

Comparison of costs for a modular bay of 2.0 m x 6.0 m for various covering materials, including rates for preservative treatment, nails and transportation:

Table 2 Cost of Support Structures

- corrugated galvanized iron sheeting 26 s.w.g., standard profile 2.40 m x 0.9 m	100 %
- corrugated galvanized iron sheeting 26 s.w.g., trough profile	85 %
- corrugated asbestos-cement sheeting 5 mm, standard profile	115 %
- low pitch concrete roofing tiles	196 %
- burnt clay tiles, Mangalore type	183 %

This comparison indicates that if a support system is properly designed, certain roofing systems could be made more cost competitive with the savings through optimal dimensioning, etc.*

* Costs for supporting structures are between 20 and 38 percent of the total roofing costs, labor not included.

3.2. THE ROOFING SUBSTRATE

A roofing substrate is mainly needed for built up roofing systems.

But built up roofing systems, like bituminous roofs used in North America, are very rare in the tropics and definitely not cost competitive in low-cost housing.

In low-cost housing in developing countries, roofing systems requiring a roofing substrate are earth roofs or roofing systems in which the covering material is subfunctional. Materials used as roofing substrate are:

- chipboard;
- boards made from agricultural waste (stramit);
- concrete panels (ferrocement);
- woven bamboo mats;

The roofing substrate can often serve as supporting structure at the same time or in the case of channel roofs serve all roofing functions in one.

3.3. THE ROOF COVERING

The roof covering or roof membrane is the major component of a roofing system, not only as far as its function is concerned but also with respect to cost. A great variety of materials can be considered for roofing purposes, most of them are composites.

A comprehensive list of potential roofing materials and components has been developed by the Special Advisory Committee on New Technology Solutions to Roofing Problems in Developing Countries, presented in an article written by Warren R. Nellis of the National Academy of Sciences, Building Research Advisory Board.[7]

Table 3

Roofing Materials

- Paper formed
- Metal sheets formed
  - Iron(galvanized and painted)
  - Aluminium
- Plastic
  - Sheet
  - Foamed
  - Formed
  - Fibres (artificial thatch)
- Bituminous
  - Formed
  - Built up
  - Shingles
- Cement asbestos
  - Formed
  - Shingles
- Wood/wood products
  - Shingles/Tiles
  - Plywood
  - Particle board
- Vegetable
  - Grass
  - Cones
  - Reeds
  - Bamboo
    - Thatch
    - Woven
- Concrete
  - Plain/reinforced
  - Ferrocement
  - Lightweight
    - Foamed
    - Lightweight aggregates
- Clay products
  - Formed
    - Tiles
    - Sheets
- Fabrics
- Animal products
- Minerals
  - Slate
  - Stone
  - Gypsum
- Earth materials
  - Stabilized
  - Non-stabilized
  - Foamed

Binders

Portland Cement
Other hydraulic-setting cements
From blast furnave slag
  Fly ash
  Calcinated clay
  Limestone
  Magnesium oxychloride sulfate
  Gypsum
  Lime
Sulfur (elemental)
Asphalts (pitches)
Coal tar derived
Petroleum derived
Tall oil pitch (coatings)
Natural asphalt
Vegetation derivatives
Pitches
  Tall oil pitch
  Cottonseed pitch
Resins
  Cashew nut shell liquid
  Soya bean oil residue
  Lignins
  Starches
    Grains
    Root Crops
Sugars
  Molasses
Slurry of Banana stalks&leaves
Gums
Oils (drying,with&without catalyst)
  Linseed
  Cashew nut shell liquid
Rubber
Natural latex
Protein
  Casein
  Animal and fish blood
  Legume protein
  Bone/hoof glue (animal glue)
  Tannery waste
Animal grease
Silicates
  Sodium silicate (water glass)
Resins (Enormous potential at local level - can be produced from agriculture faster than if an industry must be established.)
Thermosetting plastics
  Unsaturated polyesters
Urethanes
Urea-formaldehyde
Thermoplastics
  Polyolefins
Earths
  Clays
Shellac
Glass
  Blast furnace slag

Reinforcement

Metal
  Rod
  Fibre
  Mesh
  Woven
  Expanded
Mineral fibres
  Asbestos wallostonite
  Amphibole
  Chrysotile (long fibre)
  Rock wool (slag)
  Glass fibres
Vegetable waste
  Rice hulls
  Bagasae
  Cottonseed
  Peanut and other seed hulls
Textile fibre wastes (cotton, jute, sisal, etc.)
Coconut husks
Straw

Fibres/Aggregate

Inorganic
- Sand
- Earth
- Expanded (bloated) clays
- Verniculite
- Expanded shale
- Expanded perlite
- Expanded slag and glass
- Sintered fly ash
- Rock
- Shell
- Pozzolans
- Diatomaceous earth
- Clays
- Waste glass
- Air (in foams)

Organic
- Vegetation (processed&waste)
- Bark
- Wood (sawdust, chips)
- Cork

Carbonized and expanded vegetation
- Husks
- Cereal grains
- Hulks
- Plant products in general
- Paper
- Charcoal
- Processed garbage
- Coconut pith
  - Nut shells
- Animal products
  - Hair
  - Feathers

Synthetic materials
- Waste cans and other metals
- Rubber (tires)
- Plastic foam (styrene, etc.)
- Plastic fibres

Coatings

Materials
- Sulfur (elemental)
- Polymers/paints
  - Metallic
  - Silicones
- Cashew nut shell liquid
- Bituminous
- Organic wastes
- Mineral particulates
- White wash
- Galvanizing

From this list of materials, a number has been tested and used for roof coverings for low-cost housing. Many compositions, although untested yet, have high potentials to become low-cost materials with qualities required for this purpose. Others like aluminium and plastics, both materials with high energy values, are less likely to become potential low-cost roofing materials.

Aluminium is not discussed in the following chapters for this reason. Although it is probably the most durable of all roof coverings and most appropriate for the warm - humid tropics, the high foreign exchange requirements make it further less affordable for low-cost housing.

Plastics have with the increased costs of petroleum derivatives lost competitivness to non-petroleum based technologies.

In general, plastics raw material can be produced economically only on a large scale and due to the above fact, the main drawback to the development of plastics industries in developing countries is the lack of adequate markets for any materials that could not usefully be employed locally. Economists also are skeptical about the capacity of the market for plastics products themselves.[8] This is because plastics have not been much favoured for use in buildings since most people in these countries prefer "traditional" materials.*

With the housing deficit occuring mainly in urban and semi-urban areas of the developing world, the roofing criteria most critical to users, builders and authorities is flammability of the roofing system. Considering this and the fact that the housing problems in rural areas are less severe and of different nature, roofing systems with inflammable roof coverings are not discussed in this thesis.

In the following chapters, roofing systems are described under the title of the respective roofing materials:

- paper systems;
- metal roofs;
- bituminous roofing materials;
- cementitious composites;
- burnt clay;
- earth roofs;
- waste materials;
- sulfur composites;

* Traditional materials in this context shall mean those which have been used over longer periods of time than just a few years (CGI, asbestos, cementitious, bituminous, etc.).

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4. paper systems

The structural properties and potential uses of paper for building construction have been investigated for many years.*

Paper is a fairly cheap recyclable material made from a renewable resource, is light weight and easily manufactured.

Paper has often been used as a core material in structural panels with various other materials as facings.[1]

All paper panels appeared as an attractive alternative because of their lower cost and weight and because of the flexibility and simplicity of construction which it affords.

Two methods of making panels can be distinguished:[2] honey combed panels and multilayer corrugated cardboard panels.

Only few papers marketed can be considered suitable for structural applications; their names commonly used by the manufacturers are:[3]

- beaming paper
- liner board
- multiwall kraft
- super kraft
- cylinder liner
- newslined chip
- tag paper

* especially during the second world war in the US to find an adequate material for disaster shelter, and low-cost housing for war returnees.

4.1. HONEY COMBED PANELS

Honey combed panels are a structural sandwich layered construction, formed by bonding two thin facings to a thick core.[4] (Fig. 4.1)

The core is made of expanded kraft paper honey combs and the facing could be of a great variety of materials (cement boards, plywood, aluminium foil, plastic foil, bituminous felt or plaster board).

4.2. THE MULTILAYER CORRUGATED CARDBOARD PANELS

The multilayer corrugated cardboard panels are made of standard corrugated cardboard bonded together in several layers and facings of the same variety of materials as mentioned above.[5] (Fig. 4.2)

Quite a few all paper housing systems have been developed but not many found applications in the tropics.

Unimpregnated paper is, of course, far too weak and too water absorbing to be used externally. Resins which are known to impact good strength to paper are too costly or not enough fire retarding.

The paper industry and paper world in May 1948 wrote:[6]

> "On reviewing a number of possible fortifying agents, two materials, asphalt and sulfur, appeared to be outstanding with regard to cost and supply."

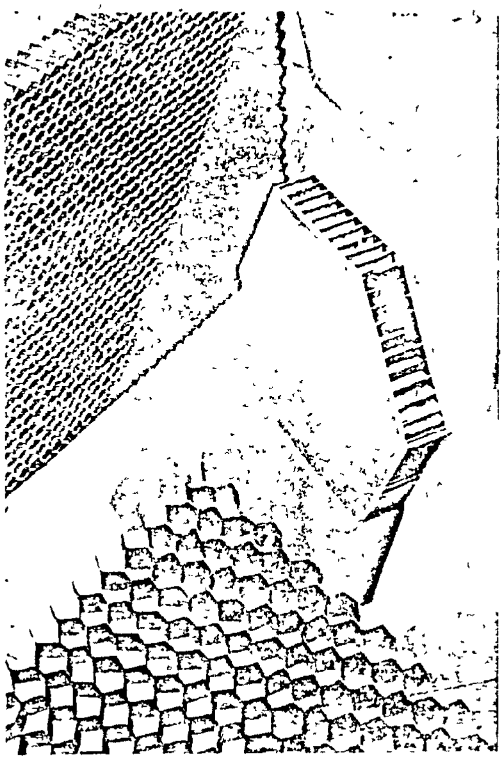


Fig. 4.1
Honeycombed panel

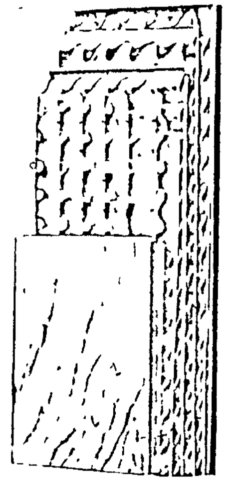
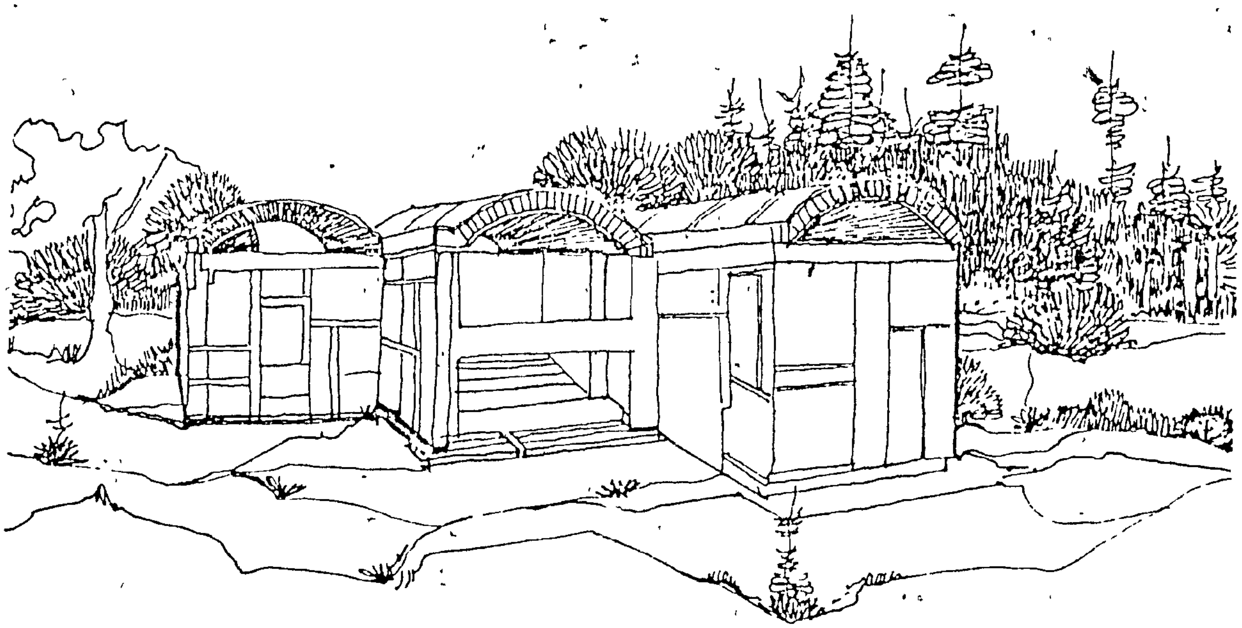


Fig. 4.2
Multilayer corrugated panel



Paperboard and Beverage Can Houses built at Cornell University, May 1973.

Fig. 4.3 A paper composite proposal

The latter was chosen in combination with an aluminium paint finish. The experimental structure has originally been designed for a one year life span but has lasted more than twenty five, its roofing finish frequently being renewed.[7] (Fig. 4.4)

The larger panels seem to be ideal to form a roofing substrate but need a roof covering to complete the roof. This eliminates all the competitivness of such a roof and indicates that paper boards may be the ideal low-cost ceiling, a necessary roofing element in the tropics for most roofing systems.[8]

In the course of my studies at McGill, I have made experiments with sulfur impregnated shingles which turned out rather promising and will be discussed in the chapter on sulfur in detail.

Climate Considerations

The light-weight paper roof covering and substrate would make it an adequate system for composite climates; the severe conditions of a warm humid climate make it a doubtful solution for those regions and in a hot dry climate it is difficult to substitute thermal mass by the average thermal insulation paperboard can offer.

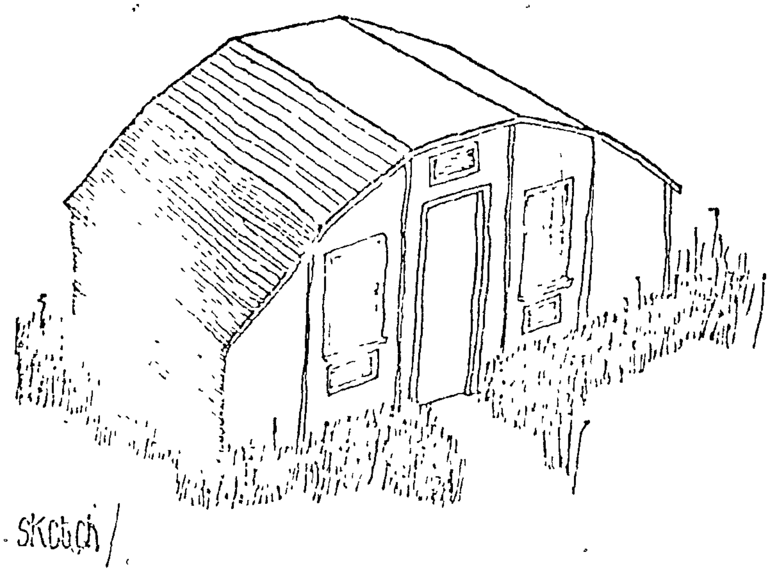


Fig. 4.4

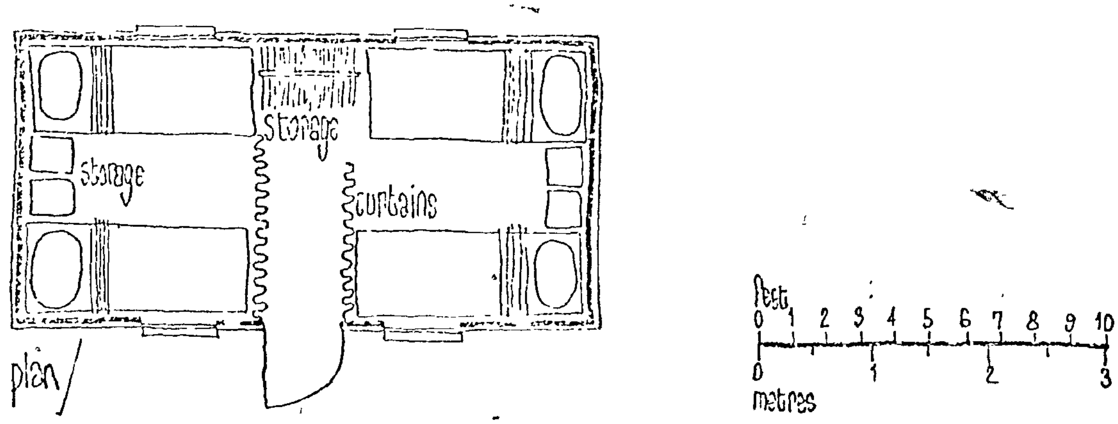
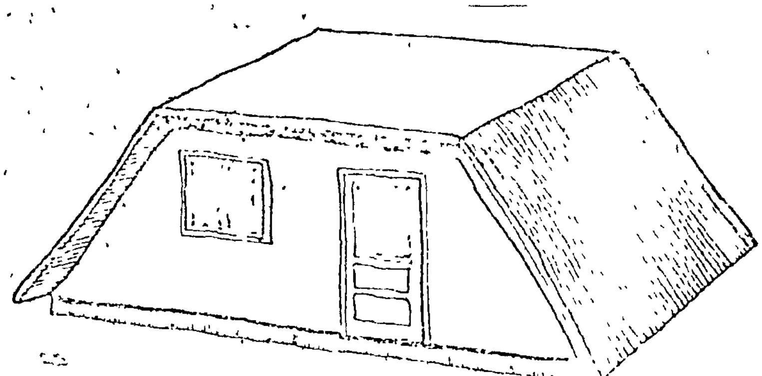


Figure 4.5 Shelter from waste paper and sulphur.

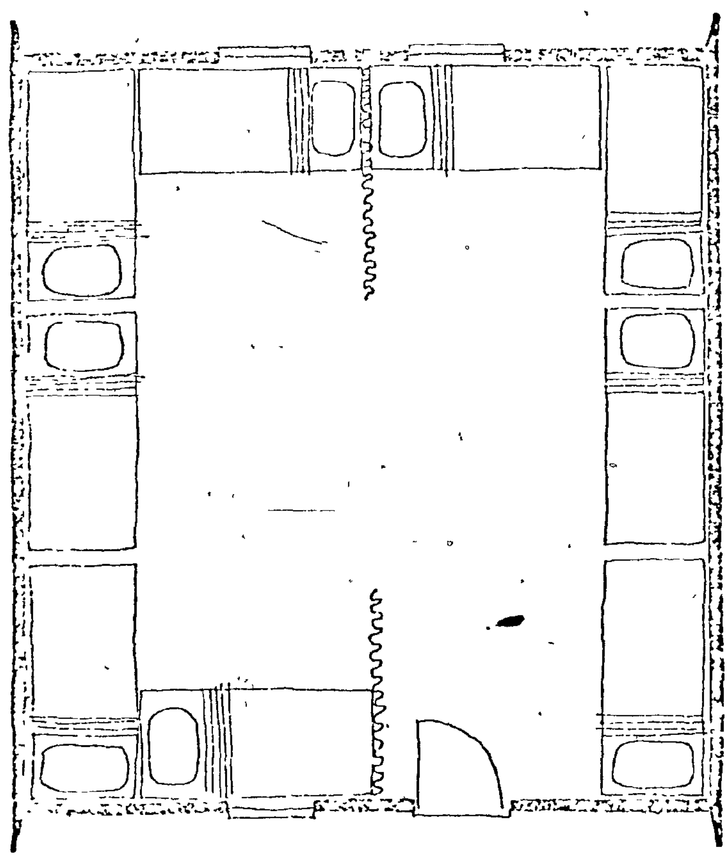
(Acheson, A.)

SHELTER FROM WASTE PAPER AND SULFUR	Developed in USA during the second world war, this structure uses paperboard made from waste paper impregnated by immersion in molten sulfur for ten minutes. (Figs. 4.4 amd 4.5)
DIMENSIONS	16' x8' x8' high (max.) (4.8m x2.4m x2.4m high)
AREA	128 sq ft (13 sq m) enclosed.
WEIGHT	1029lbs (465kg) inclusive.
VOLUME PACKED	100 cu ft (3 cu m).
ERECTION	2 people 3 hours.
PRODUCTION	Prototype was handmade on hardwood corrugators.
SUPPORT	Loadbearing panels without frame.
PORTABILITY	Vehicle (1/2 ton)/ship/aircraft/helicopter.
LIFE EXPECTANCY	1 year, but lasted more than twenty-five.
ENERGY SYSTEM	None required. Heated by oil or electricity.
REUSABILITY	Since panels are connected by metal strips, they could be easily dismantled and re-erected.
SITE PREPARATION	None required except clearing and rough work.
MAINTENANCE	Fire retardant paint needed attention.
FUTURE USE	Performed well enough to be permanent house.
EXAMPLES IN USE	Only the prototype has been made.
CAPACITY	4 people.
SUMMARY	WASTE PAPER/SULFUR/UNFOLDABLE/NOT EQUIPPED.
PRODUCER	Institute of Paper Chemistry, USA.
INFORMATION	From producer. Documented in magazine "The Paper Industry and Paper World" May 1948.



sketch / the basic unit (one like this was erected in Peru after the earthquake)

Fig. 4.6



plan

Fig. 4.7 Model 400 Universal Papertech home.

(Acheson, A.)

MODEL 400 UNIVERSAL PAPERTECH HOME Figs. 4.6 and 4.7	This is the smallest of a range of cardboard structures produced by Herbert Yates' company since 1959. Material is corrugated card with polythylene filler; structure is coated with ~~polyester resin & fibreglass mat when erect.~~
DIMENSIONS	20'0"x21'4"x8'8" high (6m x 6.4m x 2.6m high)
AREA	400 sq ft (40 sq m) enclosed.
WEIGHT	1000 lbs (450 kg) total.
VOLUME PACKED	600 cu ft (20 cu m).
ERECTION	8 hours for 4 people. (4 people lift one panel).
PRODUCTION	Factory produces 60 panels/hour. (5 panels/home).
SUPPORT	Panels are loadbearing. Span reduced by using sloped wall panels at 60^{o} to horizontal.
PORTABILITY	Vehicle/ship/aircraft/helicopter.
LIFE EXPECTANCY	20 years.
ENERGY SYSTEM	None required. Services not included with shell.
REUSABILITY	Not possible to dismantle and repack once built.
SITE PREPARATION	Necessary to have flat surface to act as floor.
MAINTENANCE	Requires painting every five years.
FUTURE USE	Can provide basis for permanent home; extendable.
EXAMPLES IN USE	Used as emergency shelter in Peru. Many others.
CAPACITY	8 - 10 people.
SUMMARY	CARDBOARD/UNFOLDABLE/NOT EQUIPPED.
PRODUCER	Universal Papertech Corp., Hatfield Industrial Park, Hatfield, Pennsylvania, 19440, USA.
INFORMATION	From producer.

Economic Considerations

Paper products today are exlusively produced in industrial processes and chiefly in industrial countries where consumer goods packaging is needed most. Paperbased roofing systems would have little or no local economic impact and use practically 100 percent foreign exchange. However, where kraft paper is nationally produced and an effective fortifying agent to weatherproof the product can locally be applied, this material could have a high potential for more extensive use for roofing in low-cost housing.

Technical Considerations

The lightweight material is easy and cheap to transport and easy to install. "Breakage" through rough handling could be higher due to the low impact resistance of the material. Durability can be high if design and maintenance of the roof are to normal standards.

The problem of satisfactory fire resistance may not easily be solved but can be reduced to acceptable levels with surface treatment or impregnation.

Social Considerations

Paper or materials on the basis of cellulose fibres are widely used in building materials but in its pure form paper is not easily associated with performance characteristics as outlined for a roof. This and safety considerations may make it difficult to find wide uses for paper roofing systems in developing countries.

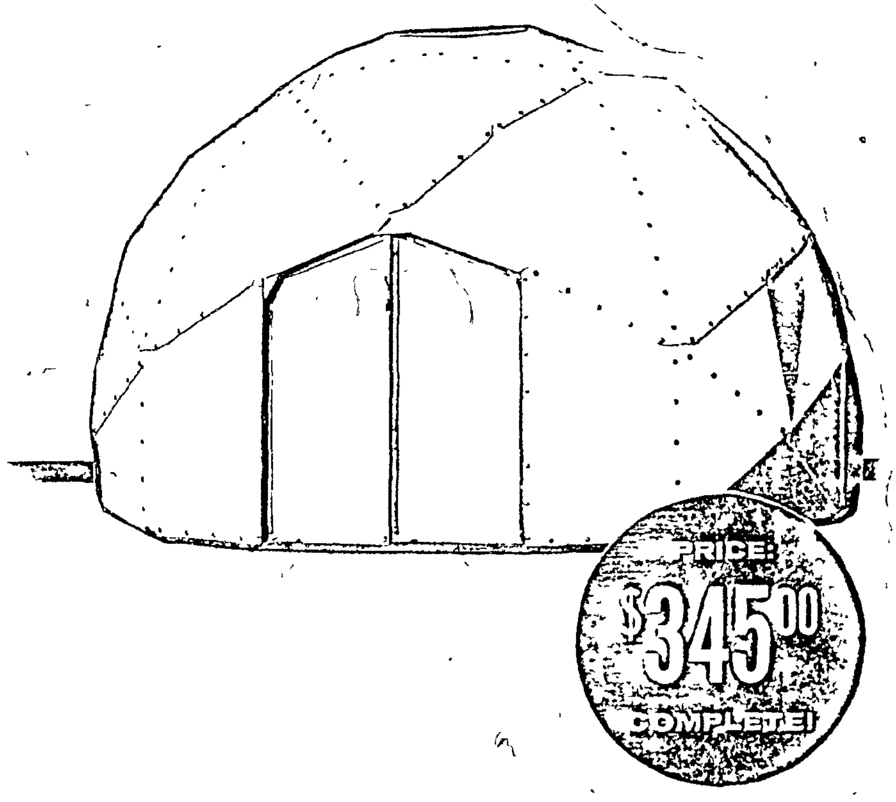


Fig. 4.8 A geodesic dome structure sold in the 50's and 60's in the US (Filtered Rosin Prod.Co.)

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5. metal roofs

Metal for roofing in the tropics is a "historical material."

Since the rolling of corrugated plates was patented in 1850,[1] corrugated galvanized iron (CGI) sheets have become the widest used modern roofing material in the tropics. (Fig. 5.3)

Metal roofs in low-cost housing in the tropics are almost exclusively made of CGI sheets of various sizes and quality.* Few owner builders are making use of flat metal sheets for roofing as they don't make a very watertight roof below 45^{0} slope. More recently, efforts have been made to find uses of thin metal sheets, galvanized or otherwise protected, for low-cost roofing systems as the one developed by Eckhard Schulze-Fielitz and discussed in this chapter.[2]

A very important consideration in selecting a roofing system is its long term performance. In the case of a metal roof this is closely related to its corrosion-resistance, and the compatibility of the metals used with their fixings, other building components and other materials in contact with the roof.[3]

The life of galvanized steel is dependent on the zinc thickness, the quality of the coating and the type of atmosphere it is exposed to.

* In many developing countries there is a local manufacturing industry producing CGI sheets using imported "black" steel sheet, which is flattened, cut to size, hot dip galvanized, and then formed into the required profiles.

According to Proskurkin and Gobunov, the different atmospheric conditions, such as the pressure of various impurities in the air (SO_2, CO_2, SO_3, etc.), are a further important factor in the behaviour of zinc.

Thus a CGI sheet galvanized in a hot dip process with a 0,6 kg/m^2 zinc coating in an industrial atmosphere, would have a life of about seven years until significant rusting occurs (corrosion rate of 0,006 mm per year).[4]

A tropical marine enivornment, with salt-laden winds and possibly sea-spray, can provide conditions which are extremely corrosive towards metals and reduce the life span of a "zinc" roof even more. Moreover, hygroscopic salts deposited on metal surfaces will act as a moisture trap and speed up the corrosion process.[6] (Fig. 5.3)

It is therefore not surprising that the life span of a CGI roof depending on location ranges from 3 to 30 years.

The corrosion process does not only have an influence on the life span of the roof but also its climatic performance. After the first year in use the reflectance of CGI roofs decreases considerably, thus increasing its

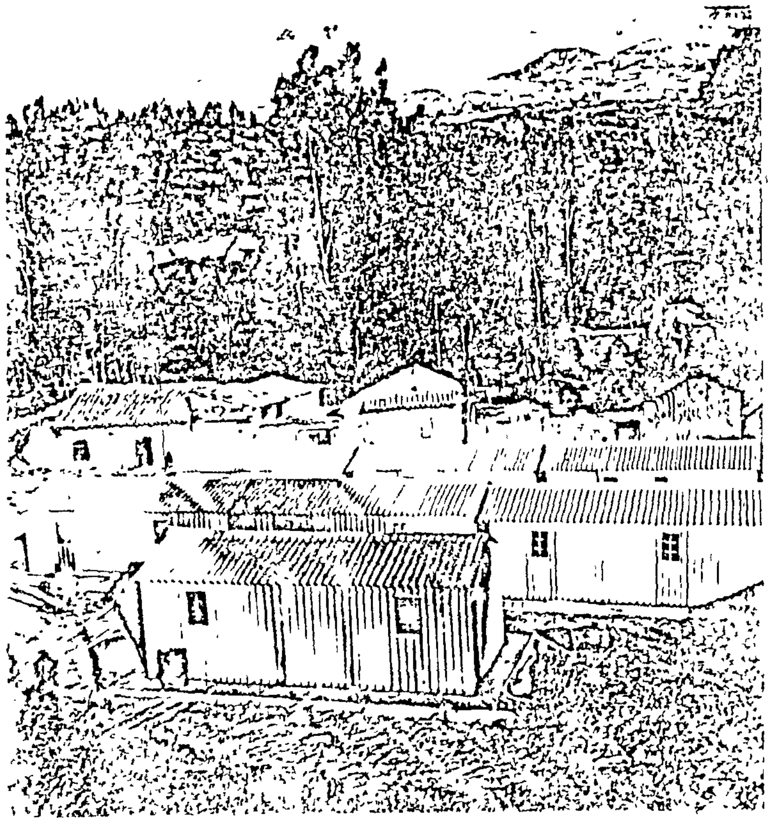


Fig. 5.1 Emergency Housing after the 1920 earthquake in Peru, CGI huts supplied by UN (Acheson, A.)

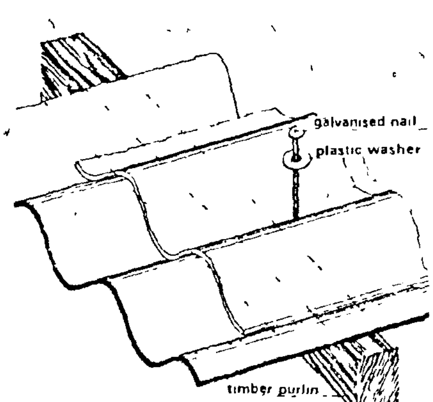


Fig. 5.2 The typical assembly

Fig. 5.3 The roof scape of Ibadan, Nigeria (Stern 1982)

absorptivity and heat transmission to the inside of the house. This fact should be of high consderation to the users of metal roofs as surface coating is necessary to maintain a reasonable climatic performance of the roof and increase its life span at the same time.

The cheapest and very effective coating is a white wash which has to be renewed after every rainy season. Oil paint lasts longer, but is subject to fungal or algal growth.[7]

Other surface coatings on the basis of polimeric materials are also subject to degradation by solar radiation, binders and plasticisers decompose and volatilise or are leached out by rain, leading to cracking of the film; pigments tend to fade and are generally expensive.[8]

Proper design and construction of a metal roof can extend the life span considerably.* Crevices and horizontal areas where water can remain stagnant should be avoided. Roof spaces should be designed to prevent condensation, either by ventilation or other means. (Fig. 5.2)

* CGI roofs for low-cost housing can be built without endlaps to a ratio of 1:5 (appr. 11^{0}) but the ridge has to be sealed well, the valleys of the CGI sheets are usually filled with bitumen-sand cement mortar.

5.1. SUPPORTED ROOFING SYSTEMS

The Corrugated Galvanized Iron Roof

The CGI sheet is often called the beginner's material for the roof builder in developing countries.

Two of the main reasons must be that this material is almost anywhere available in the tropics and that it is very easy to build with.

The sheets are of various sizes between 2.10 m x 0.60 m to 3.60 m x 0.90 m. A number of different gauged qualities* (26/28 0.5mm gauge) in circular or geometrical corrugations of between 3-5 cm rib height are distributed in bundles of ten, twelve or more sheets.[9] (Fig. 5.4)

More recently and for large scale projects rather than the individual builder, local manufacturers offer long span sheets of lengths of up to 12.0 m which eliminate some of the negative characteristics of CGI roofing (tendency to fly when lift off in storms, removability, smaller purlin spacing).

Supporting Structure

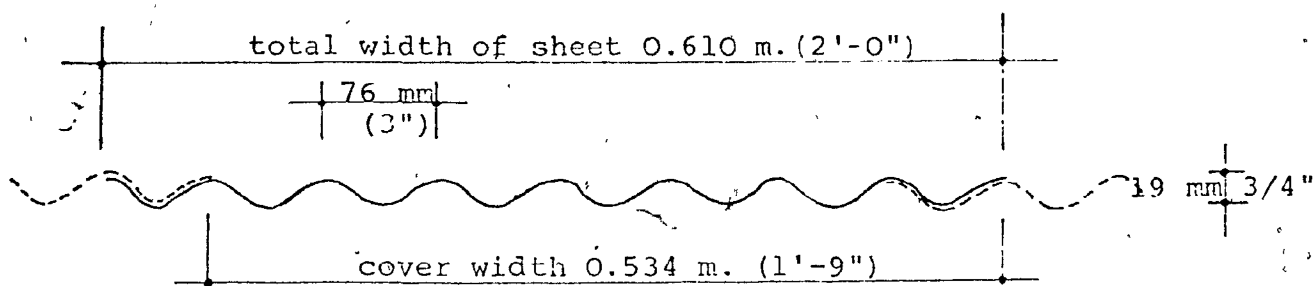
The minimal weight of this roof does not create many structural problems to the builder. However, it is important that the structure is well tied together so that

* It is not uncommon that sheets of lessor thickness (s.w.g. 37) 0.17mm are used, but it is not recommended for permanent structures.

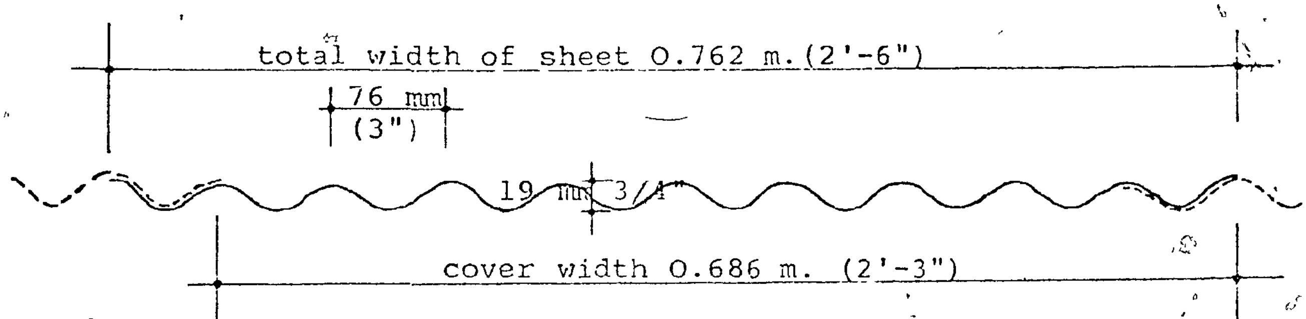
Fig. 5.4

METAL ROOF SHEETING

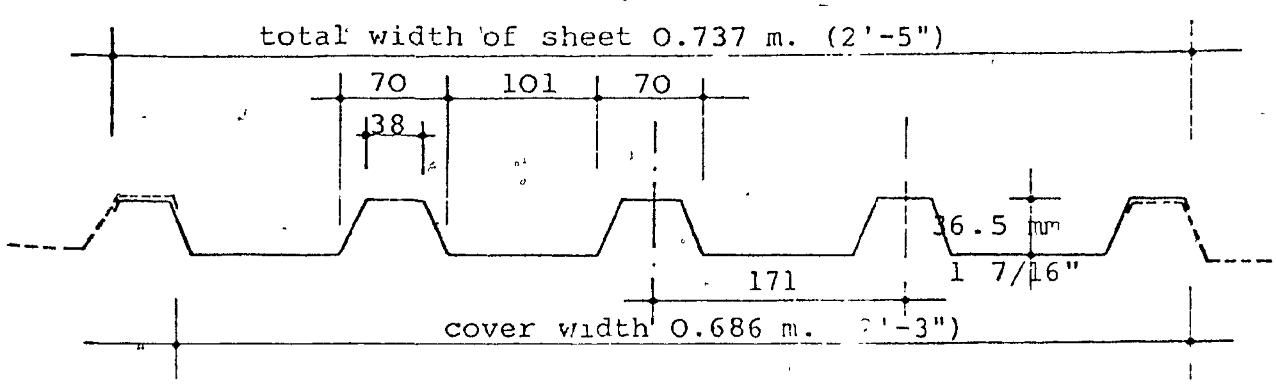
Types manufactured in Kenya



TYPE : standard corrugations 8 x 3"



TYPE : standard corrugations 10 x 3"



TYPE : trough sheeting I.T. 4

(Eygelaar, J.)

it can resist the uplift during storms. Flying CGI sheets are deadly objects.*

Depending on the architecture of the house, trusses can be eliminated and purlin can span from wall to wall.

General Criteria [10]

CGI is a very versatile material and its advantages outweigh the disadvantages clearly.

Advantages	Disadvantages
low-cost	high import costs
low-weight	low mass
low-volume (for shipping and joining)	poor thermal barrier
life up to 40 years	rusts
can be nailed and formed	needs to be maintained
paintable	range of quality
high reflectant	noisy in wind and rain
impermeable	contaminates water
wide availability	over-accepted
high status	dangerous if loose, tendendcy to fly
vapour barrier	
tough	
wind resistant	
fire resistant	
reusable	

* Under normal circumstances purlin spacing for 26 g sheeting will be 1.2 m to 1.5 m.

Climate Considerations

The well maintained CGI roof with a well ventilated ceiling space and a ceiling of low thermal capacity is the ideal low-cost roof for the warm humid tropics.[11]

Koenigsberger and Lynn say:

> "Our heat flow calculations have convinced us that a ceiling belongs to the minimum requirements to be insisted upon even in houses for the poorest of the poor."

A ceiling is required also for acoustic reasons. The drumming of tropical rain on an unprotected roof disturbs sleep and makes it impossible to understand normal speech.

In all other climatic regions the CGI roof cover cannot fulfill proper roofing functions as it will be necessary to add some thermal mass or thermal resistance insulation to the roof so that it would perform reasonably.

But it is obvious that in those climatic regions the CGI roof is less cost competitive.

Economic Considerations

Except for countries which have their own steel industry CGI roofing will not have a positive local impact on the economy as foreign exchange requirements are almost 100%. The negative aspect of foreign exchange seems to be outweighed by the material's performance characteristics and its social acceptance.

Technical Aspects

Structural and fire safety seem to be of main consideration after that of ease of installation. The argument that the material can be used maintenance free is somehow an accepted compromise to shorter life span due to the easy and cheap replacement possibility of individual sheets or entire roofs.

Social Aspects

The strongest social aspect is that of social prestige. For the dweller it is his first step towards modernism and a sign of progress.

It is hard to imagine that even if this material has to be imported that this well established market could disappear without reaction from the home builders.

5.2. SELF SUPPORTING STRUCTURES

Long span CGI sheets as mentioned in the preceeding paragraph are also available in stronger gauges and geometrical shapes with higher ribs. These sheets could span 3.0m to 4.0m easily but would not be cost competitive for low-cost housing as too much steel in weight would be used.

Dr. Eckhard Schulze-Fielitz (Cologne) has, together with Sitec Robert Lourdin in Paris, registered a patent for a metal roof system utilizing thin metal sheets formed into channels.[12]

The Channel Roof

The interesting aspect of this channel roof is the utilization of an industrial semi-product in the form of painted or galvanized coils.

These coils when shipped to the building site are unrolled from the truck with the two edges running through a tool which is forming the edge profile. (Fig. 5.5)

The profile on these edges is necessary for the fixing of the channels to the rails but does also force the sheet into its channel form. Depending on the gauge of the metal sheet, the span,dead and life load, a roof of this

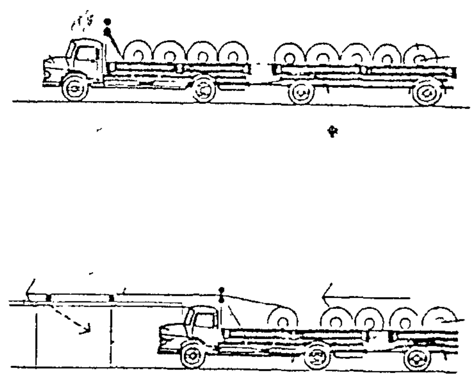


Fig. 5.5 Transport and installation.

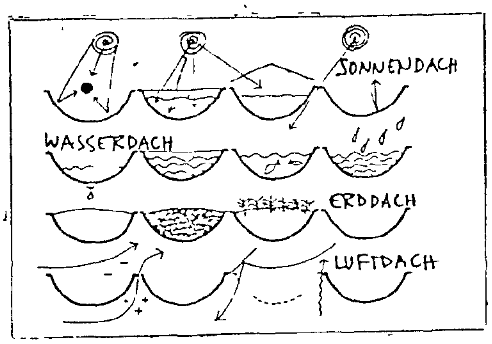


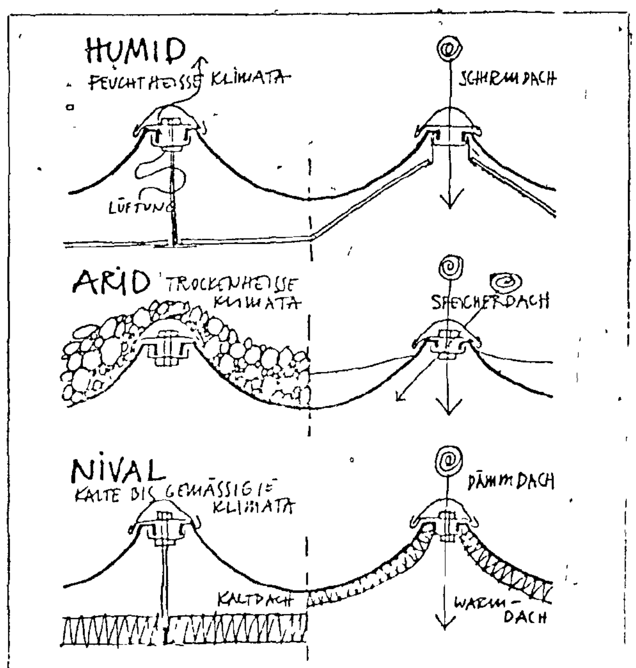
Fig. 5.6 The concept.

Fig. 5.7 Application in three tropical climate zones.

warm humid

hot dry

composite



(Schulze-Fielitz, E.)

kind can freely span up to 20.0 m and have a cantilever of up to 5.0 m!

The basic characteristics of this roof are the same as for all metal roofs but two distinct advantages make this system an interesting alternative:

- the adaptability to all tropical climates and (Fig. 5.7)
- the structural capacity.

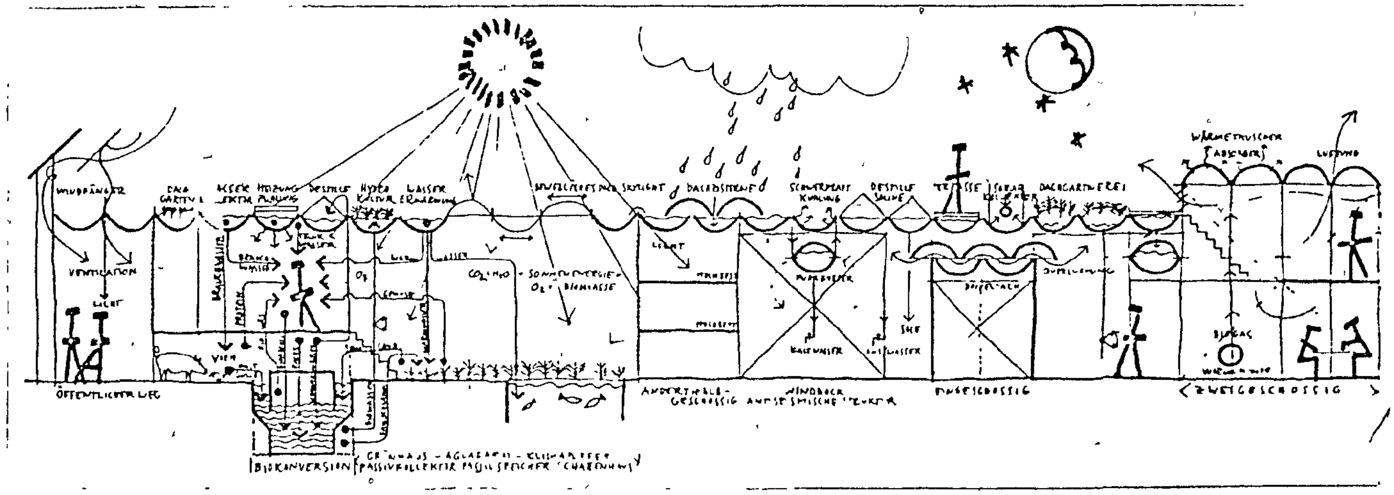


Fig. 5.8 The total roofing concept as seen by the inventor.

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12 Schulze-Fielitz, E., op. cit.

6. bituminous roofing materials

Bitumen, Tar or Pitch are terms often used interchangably.

Asphaltic substances have been used by man for thousands of years.[1] They offer excellent binding qualities with good water proofing properties. Asphalt is derived from many sources including the destillation of petroleum, naturally occuring deposits, and deposits of rock asphalt* mined out of the ground. (Table 4)

Asphalt or bituminous substances are available with a wide range of properties from soft and sticky to hard and brittle and is made by heat, solution or emulsification.

These substances are today mixed with a wide variety of materials to provide water proofing coatings, or to function as binders for fibrous felts, corrugated sheets, boards or shingles.

In the tropics, the material's behaviour should be of great concern as on roofs and other exposed places, the viscoelastic properties of bituminous materials are seriously affected by repeated wetting and drying, while heat brings about softening and blistering.[2]

* The bridge between the ancient and the present day use of bituminous substances was the discovery in 1712 of rock asphalt at Neuchâtel, Val de Travers.

The study on durability of "materials for tropical building" reveals further that ultraviolet radiation leads to embrittlement and the production of water-soluble materials which can be leached out by rain; felt fibres may rot or undergo deterioration due to mould, or even be attacked by termites. High winds cause felts to crack and tear, and they can be abraded by sand storms.[3]

Considering these aspects and the fact that bituminous roofing materials are expensive, it is highly unlikely that such materials will find broad applications.

Also, built up roofs are sophisticated systems demanding the work of skilled labor.

In spite of all negative facts bituminous roofing materials are used in developing countries in the form of corrugated sheets and namely roofing felts. (Fig. 6.1)

In low-cost housing roofing, felts find application in combination with traditional roofs such as Makuti roofs (Somalia) but also to watertighten flat earth roofs in hot dry climates. (Fig. 6.2)

J.P.R. Falconer, in his report from a Field Trip to Jamaica for USAID in June 1974, mentioned a composite material marketed there under the name of "Decormastic"[4] tile, a stamped galvanized iron sheet (appr. 28 ga.) coated with asphalt with a granular mineral surface, similar to that

VARIETIES OF BITUMEN

ASPHALTIC BITUMEN
(from natural sources)

DERIVED BITUMEN
(from refining of crude petroleum)

Natural Seepage
(mixed with wind-blown sands etc)

Natural Rock Asphalt
(calcareous rock, with about 20% bitumen)

Lake Asphalt
(with about 54% bitumen)

When combined in correct proportions these sources produce NATURAL MASTIC ASPHALT

When combined in correct proportions together with a mineral filler such as crushed limestone, these sources produce SYNTHETIC MASTIC ASPHALT

FLUX OIL may be added to either of these mixes, to reduce the viscosity of the resultant MASTIC ASPHALT

Table 4 (Kinniburgh, W.)

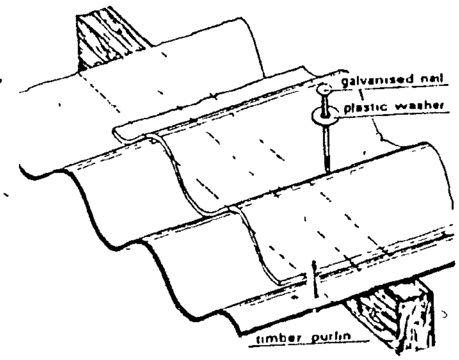


Fig. 6.1
typical assembly of
corrugated bituminous
roof (Ondulite Ltd.)

on asphalt roll roofing. This certainly represents a higher cost material than CGI but appears to increase life span without any need for maintenance. (Fig. 6.3)

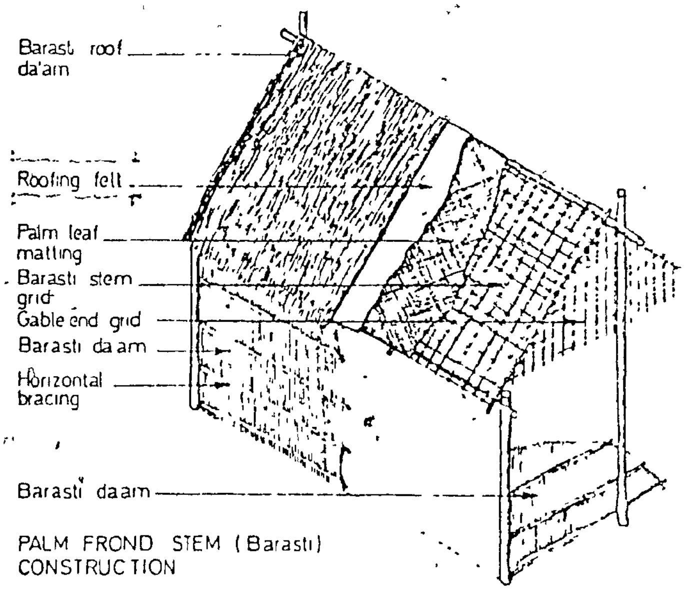
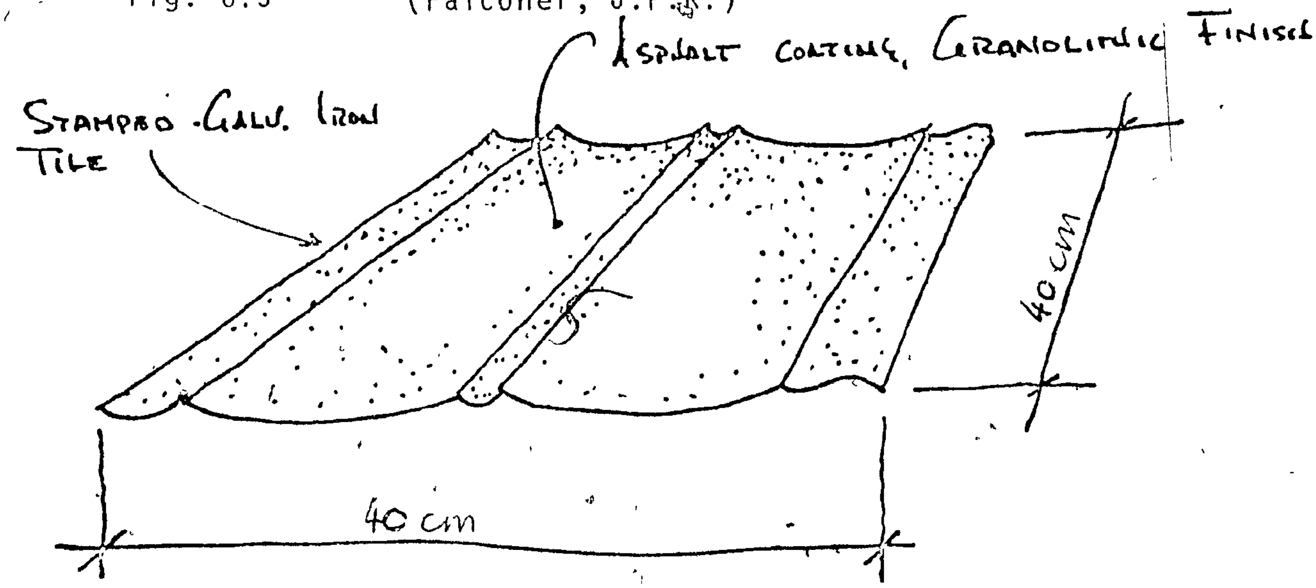


Fig. 6.2 Use of roofing felt in indigenous building (AD/4/75)

Fig. 6.3 (Falconer, J.P.R.)



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7. cement composites

7.1. INTRODUCTION

Before discussing the various types of systems falling under this group, it is necessary to make a few introductory remarks to the three main types of cement composites:

a) conventional steel reinforced concrete

b) ferrocement

c) fibre-cement

a) Conventional steel reinforced concrete (RC) widely known and used for all kinds of purposes for over hundred years now* is not the first composite material used for low-cost roofing in developing countries. And yet, concrete in some form is a fascinating material and can be used to make certain low-cost roofing components (joists).

Concrete technology, commonly known and not specially described in this thesis, is based on the chemical binding process called hydration and the structural complementation of steel and PCC.[1] The greater tolerances which can be accepted for quality and mixing proportions compared to ferrocement and fibre-cement make this process a less critical one for developing countries.

Portland cement (PC) is the most common hydraulic-setting binder, made of mainly limestone, consuming large

* The basis for wide application was given only with the exact description of the cement production process by J.C. Johnson in 1844.

quantities of energy for its production*. There are some other materials which have hydraulic setting properties or can be used as partial substitutes for the more and more expensive PC:[2]

- blast furnace slag
- fly ash
- limestone
- bauxite
- pozzolans
- magnesia
- ash of burned rice husks[3]

PCC and steel as reinforcement complement each other in an ideal way, but unfortunately steel is not a cheap material** and neither is the composition of the two.

Studies have been made to reinforce PCC with bamboo as a substitute for steel,[4] but for our purposes other criteria are making this composite a less competitive one: the comparison on a cost/strength ratio basis.

b) <u>Ferrocement</u>: The paradox associated with ferrocement, James P. Romualdi[5] says, is that it is both one of the oldest and yet one of the newest forms of reinforced concrete. Since the construction of a small row boat by Lambot in 1848,[6] ferrocement has been used for a wide range

* 1 ton of PC needs 6.300.000 kcal to produce.

** 1 ton of steel takes 7.225.000 kcal to produce.

of marine structures (such as cargo ships), storage bins and notably large span thin-shell structures such as Freyssinet's hangars at Orly, Nervi's numerous structures in Italy and Maillart's Cement Industries Hall at Zurich Expo 1939.[7] (Fig. 7.1)

Except for the early pioneers, there was a general realization only in the sixties that this material has a much broader application in building structures than its previous applications.[8]

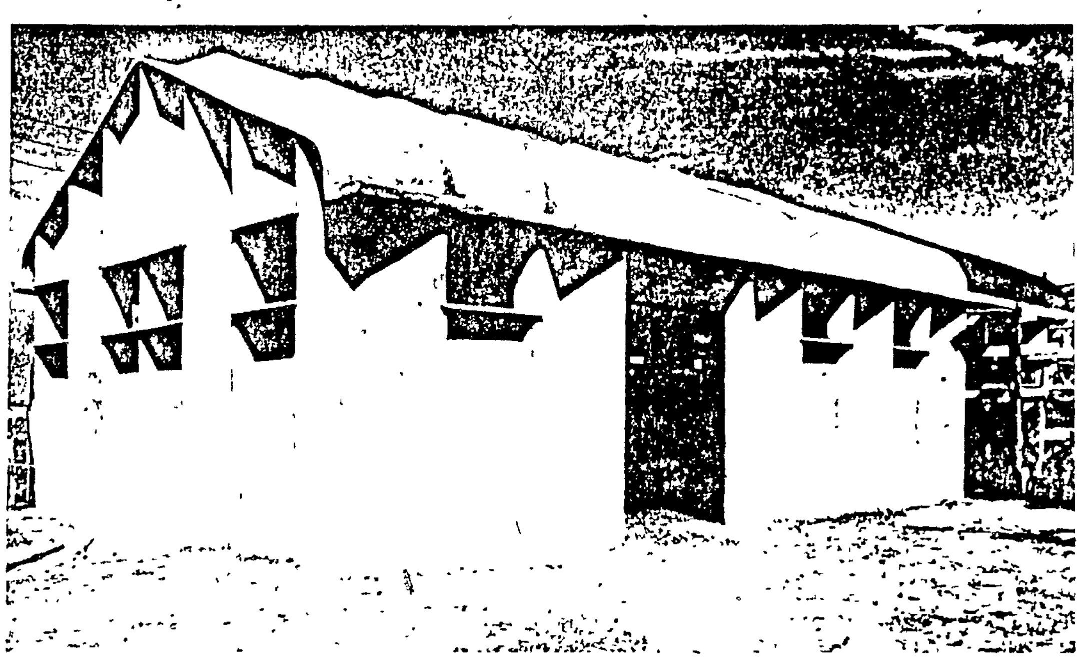
c) <u>Fibre-cement</u>, the youngest group of reinforced concretes, is in a more primitive form probably the oldest known technology of pseudo-ductile materials produced from fibres embedded in relatively brittle cement based matrices.[9]

A. Kelly refers to chapter 5, verse 6 in Exodus noting the impossibility of making bricks without straw as reinforcement at that time.[10]

There is, today, a wide range of fibres suitbale for use as reinforcement of concrete. They can be divided into two main groups, those with moduli lower than the cement matrix, such as cellulose fibres, coconut fibres, nylon and polypropylene and the second group with a higher moduli such as asbestos, glass, steel, carbon and Kevlar.[11]

Asbestos fibres are the only type of the second group being feasible for the use in building components and even this material is challenged today as it occurs in few places only and requires developing countries to import it in relative large quantities using scarse foreign currency.[12]

Fig. 7.1 Ferrocement warehouse built in 1947 by Nervi's firm; walls and roof were less than 3 cm thick (Abercrombie, S.)



7.2. CONVENTIONAL STEEL REINFORCED CONCRETE (RC)

In industrialized countries, few homes are roofed with RC-systems and it is therefore also reasonable to say that conventional steel reinforced concrete is usually not associated with low-cost roofing for developing countries.

But concrete technology is simple to apply with relatively little equipment needed, and cement is available in the remotest places around the world.

Furthermore, RC-systems are monolithic strong and durable structures and are therefore having positive shelter characteristics.

These facts, together with the frequent need or wish to build a roof which can be accessible or serve a floor ceiling function in the future, has led to the common flat RC roof as a certain roofing solution in many developing countries.

But flat RC floor/roof slabs for short spans in low-cost housing are uneconomical elements for the two following reasons: [13]

- unproportionate high quantity of steel and concrete (dead weight) needed compared to the capacity required;

- uneconomical system of redirecting forces in flat slabs;*

Considering spans of between 2.40 m and 5.00 m, the RC slab of appr. 10 cm thickness would not be cost competitive on a cost/strength ratio basis when compared with the other "hybrid" RC systems.**

These systems have been developed to minimize the use of steel and cement without limiting the user and shelter functions. (Fig. 7.2)

7.2.1. SELF SUPPORTING SYSTEMS

Self supporting RC roofing systems have been developed for prefabrication of large housing schemes or for self help processes in aided low-cost housing developments.

Vaults Prefabricated

Structurally, the vault is a less favourable configuration for a low-cost roof than a dome is as it will require or tie rod beam to absorb the horizontal forces except, of course, in a pure compression vault.

* Beams and slabs are bulk-active structure systems (bending structures) adequate for long continuous spans without the need to give up the advantage of rectangular geometry.

** For curved elements like the vaults and domes, the comparison is even less favourable; a ferrocement structure uses 3 to 4 times less steel and cement than a comparable RC-system.

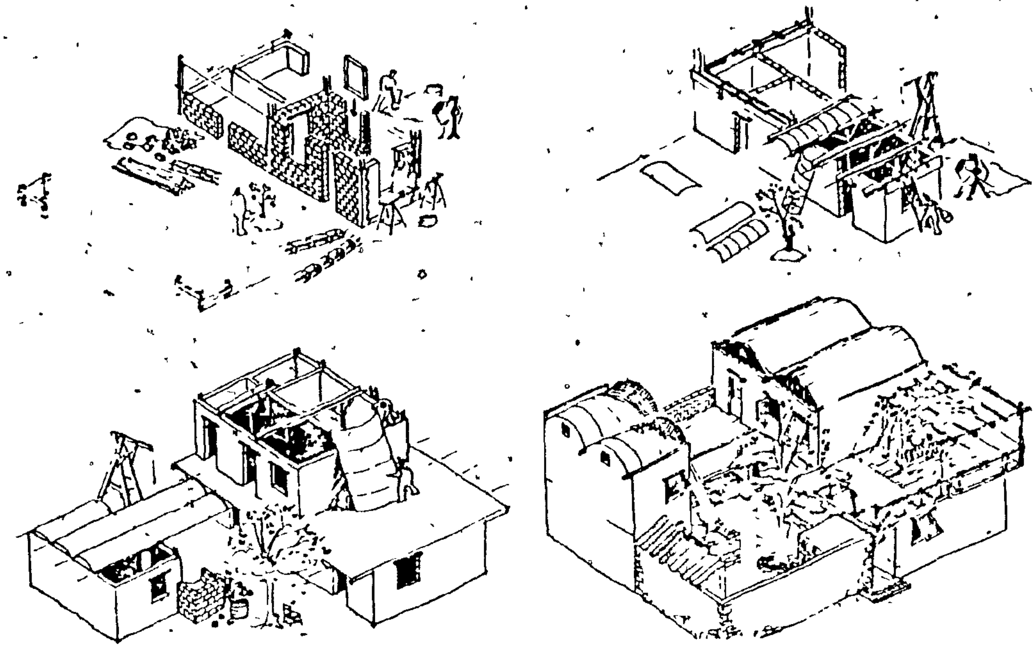


Fig. 7.2 This "hybrid" version has been designed for a refugee resettlement in Northern Cyprus. Thin on site produced asbestos cement shells are used as lost shuttering. Low strength concrete, with distribution reinforcement (mesh 10 x 10 cm), is poured a top. (Bauwelt, Heft 9, 1978)

An interesting but almost forgotten process had been applied by Alvaro Ortega, a Columbian architect, who has been teaching at Harvard and McGill amongst other institutions.

It is the method of prefabrication he is proposing which is of great interest for our purpose. He has developed a method of casting curved thin concrete sections on the ground in stacks of as many as forty-one a top the other, so that all the shells required for (in our case as many as ten houses - 60 m2 each) could be cast from a single form.[14] (Fig. 7.4)

The most interesting part of this method is the utilization of vacuum equipment that is used not only in pre-curing the thin precast elements, but in lifting them as well.* (Fig. 7.5)

After each element is poured, it is covered with pads connected by hoses to a vacuum pump which draws out the uncombined water in the mortar. Within half an hour, the newly-poured surface, though still moist, is strong enough to support the wet concrete of the next shell.

To prevent bonding between the stacked layers and to give a smooth undersurface, each shell is coated with a plastic foil, paper or lime paint, before the next element is poured. Using this vacuum drying system, it is possible to

* The vacuum concrete process has been invented by Bitner in Germany.

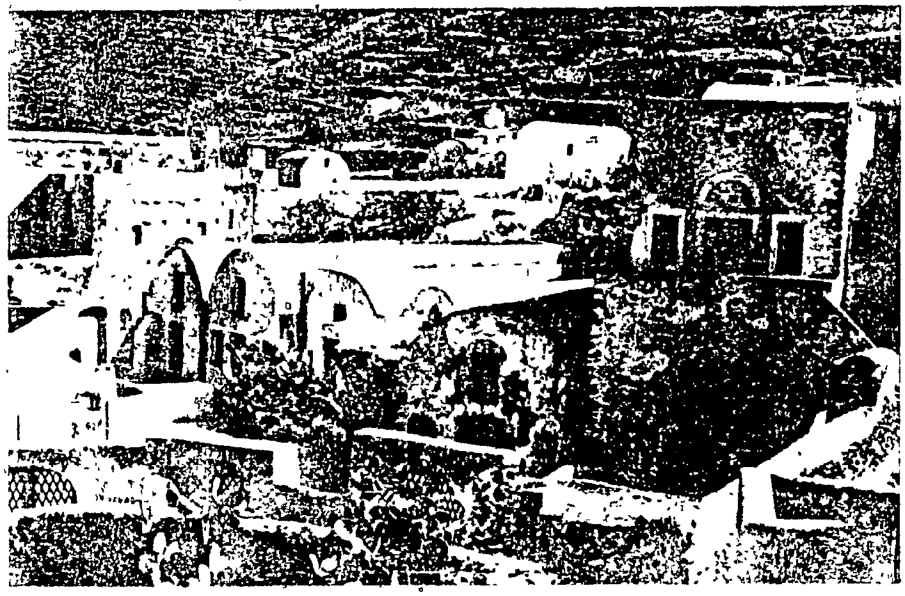


Fig. 7.3
Prehistoric dwelling forms can today be built economically with new techniques. (Rudofsky, the Prodigious Builders)

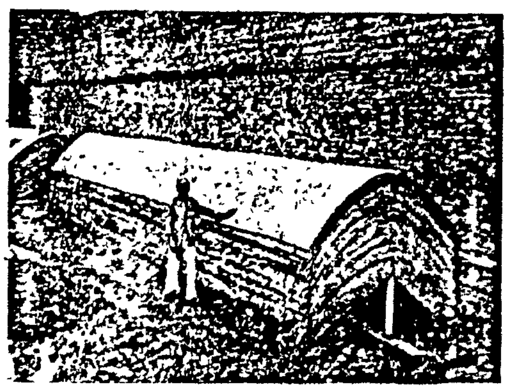


Fig. 7.4 Stacks
(Architectural Record)

Fig. 7.5
Lifting

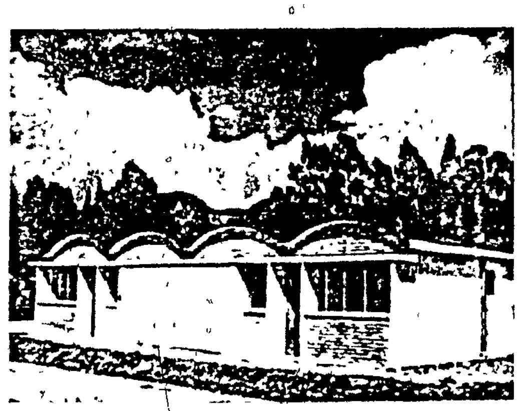


Fig. 7.6
The final structure.

cast eight layers in a normal working day in each stack. And, because each layer is sealed top to bottom, the stack becomes a ready-made curing room in which moisture and temperature are kept uniform until the shell reaches full strength.

This system has first been used in the USA on the Pentagon building and in the early fifties in a number of projects by Ortega in Columbia, notably for a 600 unit housing project in Bogota.[15]

Thin shell concrete roofs have characteristics similar to ferrocement ones, except that their production is more expensive due to the special equipment needed.

It also seems that for low-cost housing, the barrel vault with its structural disadvantages compared to a double curved structure should only be considered if aesthetical priorities require a roof of such shape. (Fig. 7.3)

The vacuum process, if considered at all, could also be used for double curved elements and then represent a feasible alternative for large scale projects where the ferrocement process is considered too slow.

<u>The Floor-Ceiling Vault</u>

Christopher Alexander et al write under flat roofs:[16] "Flat roofs, except roof gardens (or we could say if they have to serve a floor function) are already eliminated by the psychological arguments of sheltering roofs (Ibid. pp. 569-574) and, of course, by structural considerations. A flat roof is necessary where people are going to walk on it; but it is a very inefficient structural shape since it creates bending."

The floor-ceiling vault combines two interesting characteristics, a functional one serving as floor and an architectural one creating a ceiling height variety.

There are, of course, various ways of achieving this combination, one of which I will discuss with the ferrocement low height dome which can be filled with sand, mud or any other suitable filler for that matter to form a flat surface on top. (Fig. 7.7)

Alexander's vault is made in a simple way, first placing lattice strips at 30 cm centers, spanning in one direction, from one perimeter beam to the opposite perimeter beam, each strip bent to make a sensible vault shape.* Then strips are woven in the other direction, also at almost 30 cm centers, forming a basket. The strips can be nailed onto the form of the perimeter beam around the room. This basket is immensely strong and stable. (Figs. 7.8 and 7.9)

* From structural considerations we know that a circular shell dome will generate virtually no bending moments when its rise is at least 13 to 20 percent of its diameter.

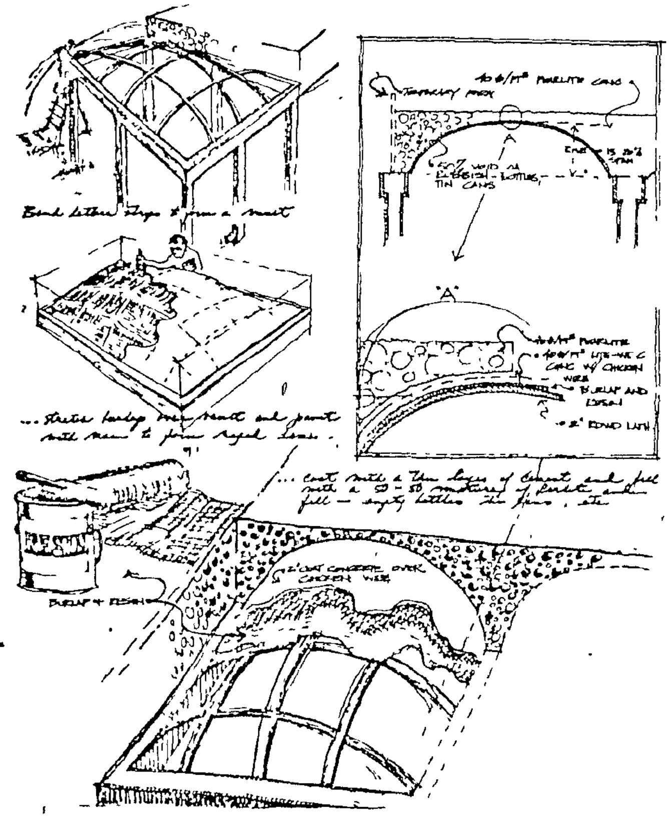


Fig. 7.7

Fig. 7.8
Lattice strips in position.

Fig. 7.9
Burlap over the lattice work.

Burlap is then stretched over these lattice strips, tacked onto the strips so that it fits tightly. The burlap is painted with a heavy coat of polyester resin to stiffen it.

This burlap-resin skin is strong enough to support 2.5 to 5 cm of lightweight concrete. One layer of chickenwire as shrinkage reinforcement is needed. The shell, which forms, is strong enough to support the rest of the vault and the floor above. In order to keep the weight of the vault down, it is important that the concrete forming the floor be lightened by mixing it with 50 percent voids and ducts. Any kind of voids can be used, empty beer cans, wine jugs, sono tubes, ducts, and other lightweight hollow materials. (Fig. 7.7)

Conclusion

Alexander's version is of interest as it utilizes a combination of structural and material characteristics to form a sound and architecturally appealing structure.

My own suggestion is to find another solution to stiffen the burlap as few people in developing countries would use resins effectively and moreover resins are expensive and have a short shelf life, especially in the tropics. It is also worth trying whether the initial ferro-cement-like thin shell is needed in the first place or if the burlap or similar form work, together with chickenwire, could not support the entire infill at once.

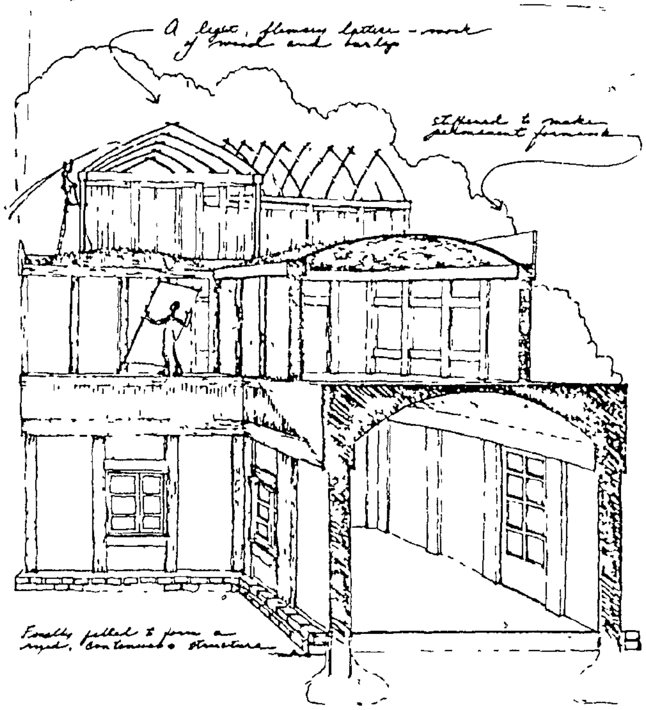


Fig. 7.10

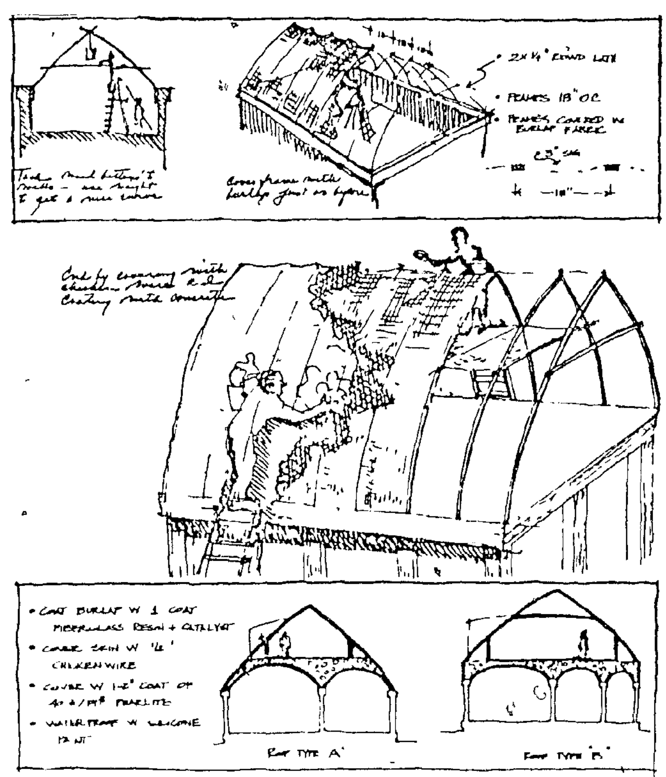


Fig 7.11
A type similar to the floor ceiling vault.
(Alexander et al)

7.2.2. SUPPORTED SYSTEMS

Supported RC roofing systems are known in industrialized countries in the form of planks, channels and rib slabs, usually used for larger spans and for industrial buildings.

In India, Central and South America, such systems have been developed for low-cost housing, taking advantage of rectangular geometry and economising on the use of cement and steel.

Joist and Infill Systems

Joist and infill systems are supported structural systems forming a flat structural element of small construction-height, capable of serving a floor-ceiling function in an economical way for spans in the range of 2.4 m to 5.0 m. This method is used around the world in developing countries for various purposes but mainly in housing and for short spans.

The components are joists usually in precast reinforced concrete; infill panels or bricks, spanning between the joists and a covering screed in concrete or mortar.[17] (Fig. 7.12)

A hybrid version is the "lost shuttering" type where hollow bricks forming a continuous ceiling are shaped with blockouts to form a rib slab by the concrete poured on top of them. (Fig. 7.13)

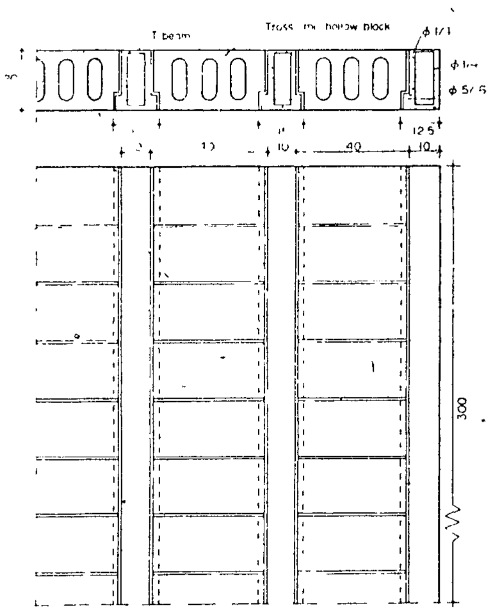
These methods are providing a saving of 40 to 60 percent in the consumption of both cement and steel against reinforced cement concrete floor slabs. It is not surprising to see that such a system in opposition to the situation in developed countries is cheaper than a conventional reinforced concrete slab would be. (Material cost versus labor cost.) However, in comparison to other systems described in this chapter, this method is still relatively expensive in the context of low-cost housing and should only be considered for housing where future vertical extensions are anticipated and possible.

In those cases the roof is a very expensive one for the period before the extension is undertaken as waterproofing has to be added on the surface.

For any other purpose, the joist and infill system will not be competitive as it is still structurally an uneconomical system and quite labor intensive to build, too.

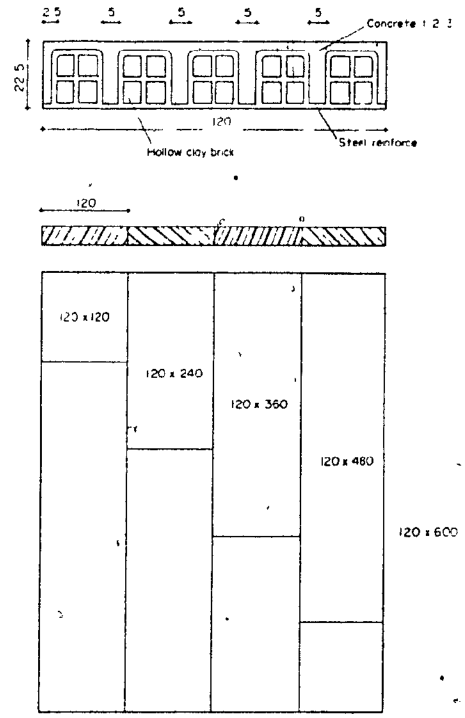
As far as its adabtability to climate is concerned it is to say that it would make a very poor roof for the warm humid tropics but as it is a recommended solution for a floor-ceiling type, temporary measures would have to be taken to improve the climatic performance of this temporary roof.

(East-West Center)



(d) Concrete beam and trass lime hollow block

Fig. 7.12



(e) Hollow clay brick slab

Fig. 7.13

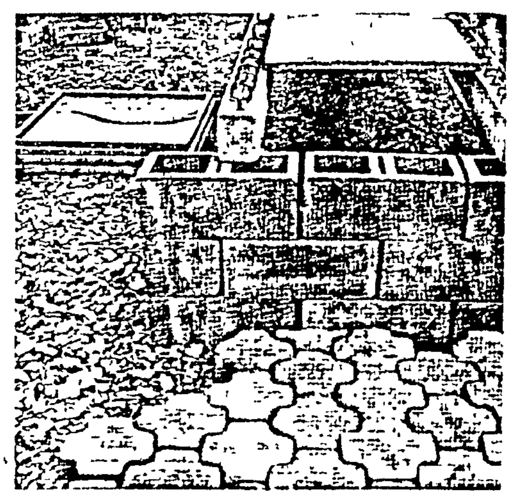


Fig. 7.14
The typical components.
(GATE)

The Joists

The prefabricated joists are reinforced according to the structural design and loading conditions.

In the case of the Indian "Concobrick" system [18] reinforcement is provided for final loading conditions while the precast concrete position is to take the dead and live loads during construction.

The Infill Panels or Bricks

Most conventional systems,namely those used in Central and South America,are using hollow tiles or bricks of the same type as sandcrete blocks are to span the gap between the joists. In industrialized countries, they are always made of burnt clay and much lighter in weight. (Figs. 7.15 and 7.16)

The jackarch principle uses burnt hollow bricks covering a larger span than the conventional system.

A jackarch panel (1200x500x75 mm) is formed by [19] laying 20 bricks in 1:4 cement: sand mortar upon a low ridge of soil of the required curvature. The height of the curve may vary from 50 to 100 mm, the former being preferable. No reinforcement is used. (Figs. 7.17)

Another popular system widely used in India is the "Zed-Tile" roof where the infill panels are made by stretching [20] burlap or hessian cloth over a wooden frame having inside

(Figs. 7.14 and 7.18

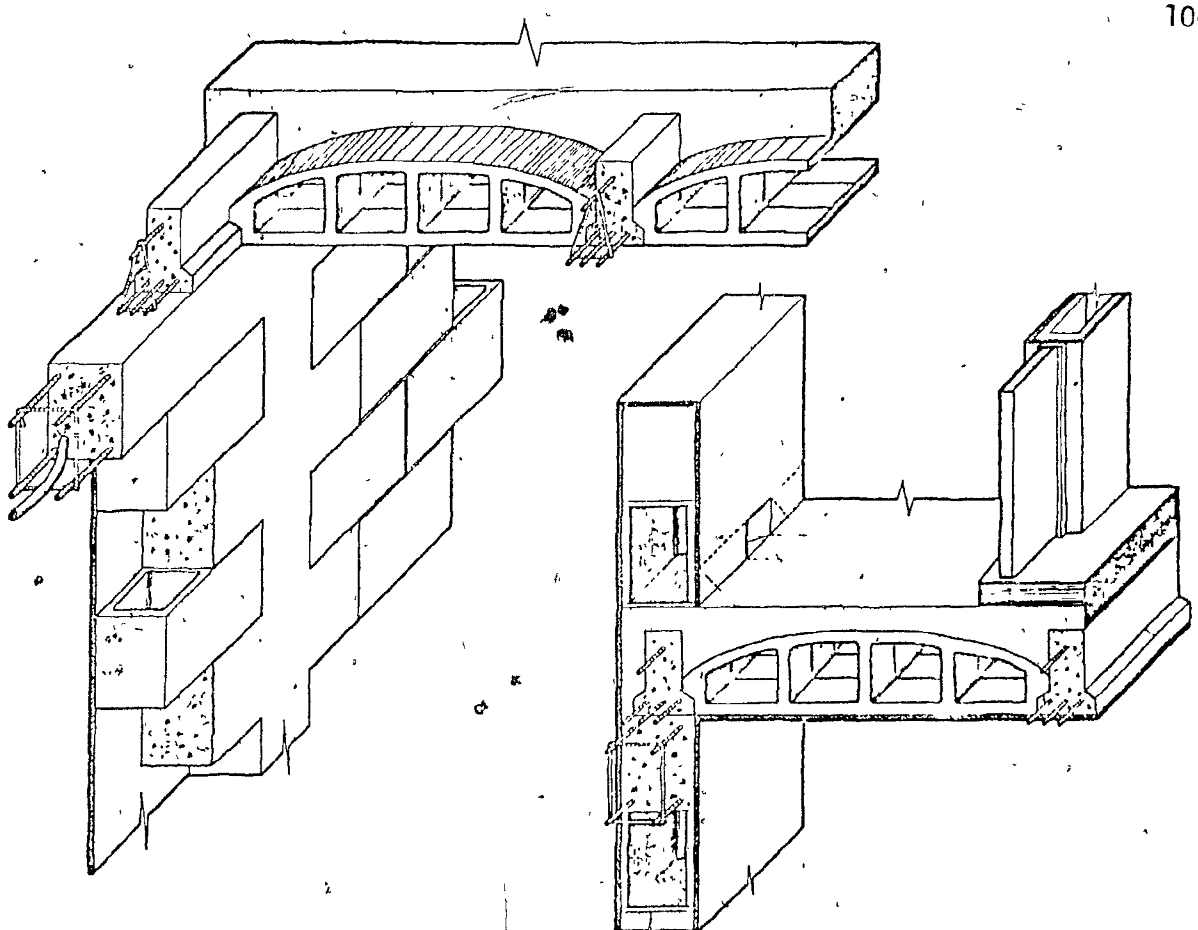
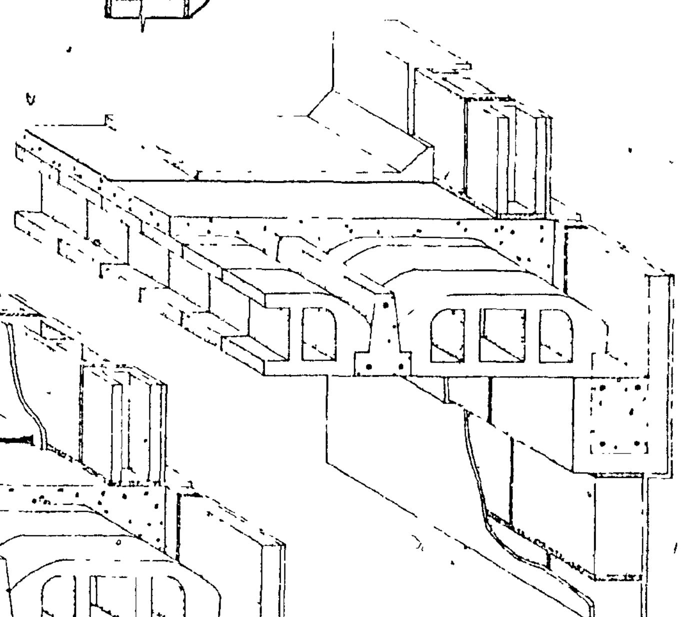
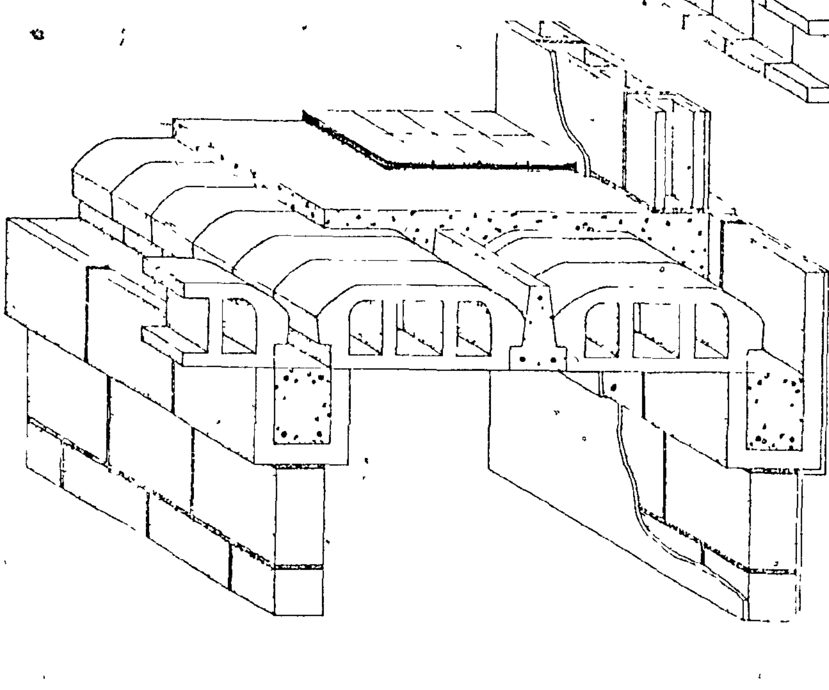


Fig. 7.15

Joist and Infill Systems as used in Mexico and South America (Université Laval)

Fig. 7.16





dimensions of appr. 80 cm x 80 cm. The cloth is fitted slightly loose over the frame so that the concrete (mortar) takes a normal sag under its own load. The natural curve formed by the concrete's load will let the slab act as a catenary, being completely in tension. This slab used as infill between the joists in an inverted position will wholly be in compression.

Other methods could be used like ferrocement arches or flat elements, even the possibility of using fibre boards or stramit panels should be studied.

The Covering Screed

The covering layer of concrete or mortar bonds the elements together to form a composite roof/floor.

It is necessary to give the roof/floor impact strength and to distribute the loads.

In the "Concobrick" system the roof/floor is constructed by putting the jackarch panels on partially precast I-beams. Concrete of reasonable strength is laid over to fill the haunches and form an integral structure with the I-beam and the panels.[21] (Fig. 7.17)

The roof is often finished after placing a 50 mm thick layer of mud and wheat straw mix and/or lime concrete for some thermal capacity and waterproofing.

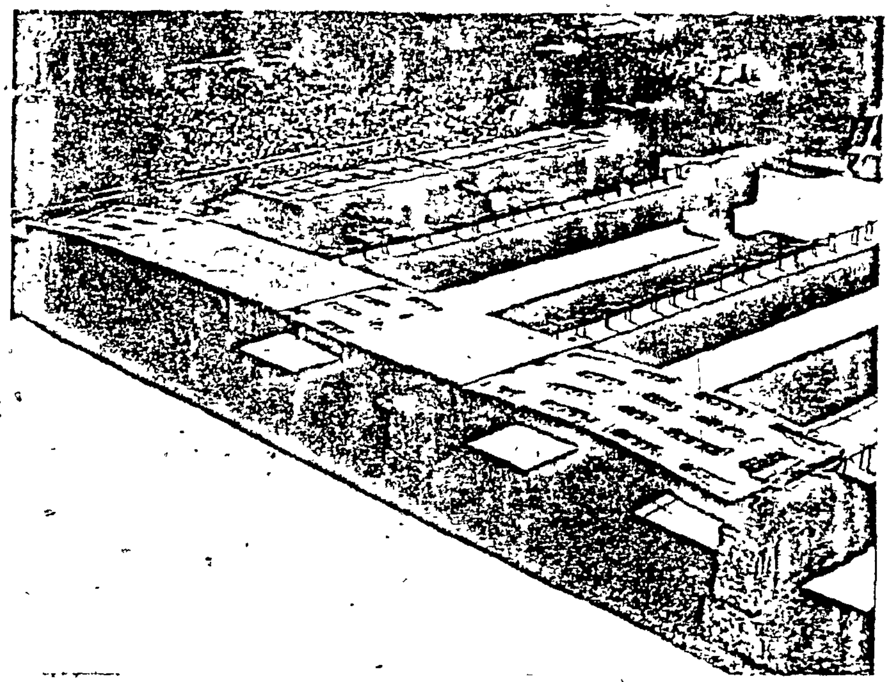


Fig. 7.17
The conco-brick system. (Surya Kant Mistra)

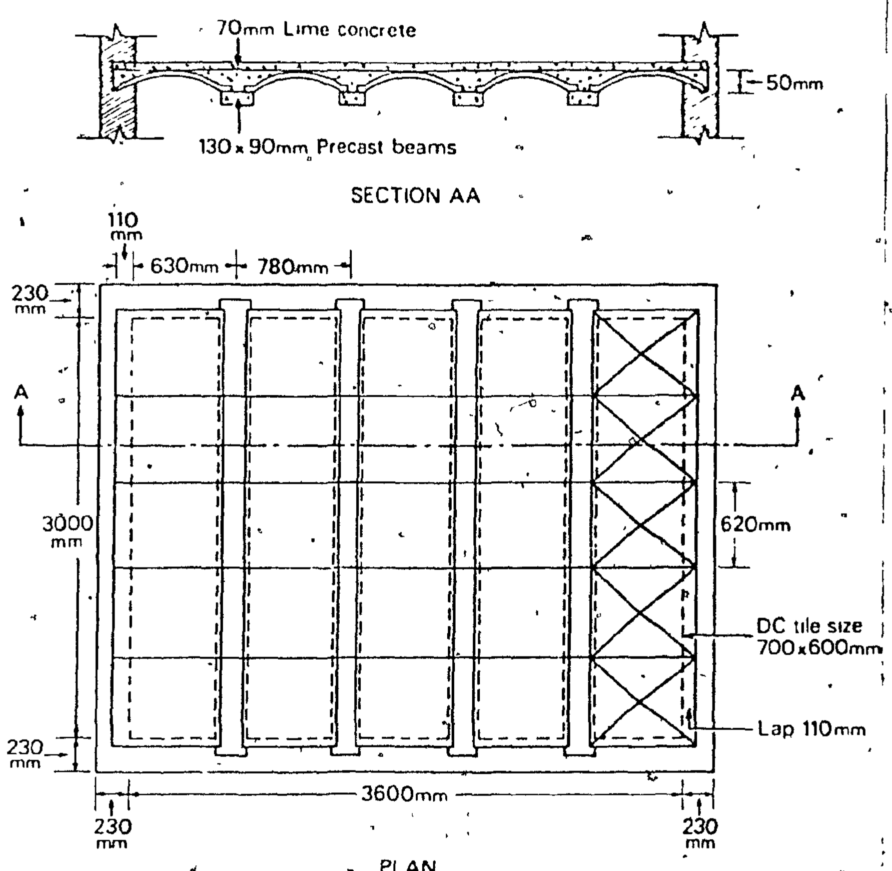


Fig. 7.18
The zed-tile system. (Ashfag Hasan)

Prefabricated Panels

Similar to the joist and infill systems, there are partial precast floor systems which can be considered for the purposes of roofing (floor, ceiling or accessible roof). These systems (Fig.7.19) are either forming a true rib slab when finished (a structurally economical solution for larger spans), or a less economical discontinuous channel system. (Fig. 7.20)[22]

All of these systems, if compared with the joist and infill principle, will be less competitive in developing countries and they should only be considered if cement and steel are relatively cheaper and prefabrication is an economical, positive factor.

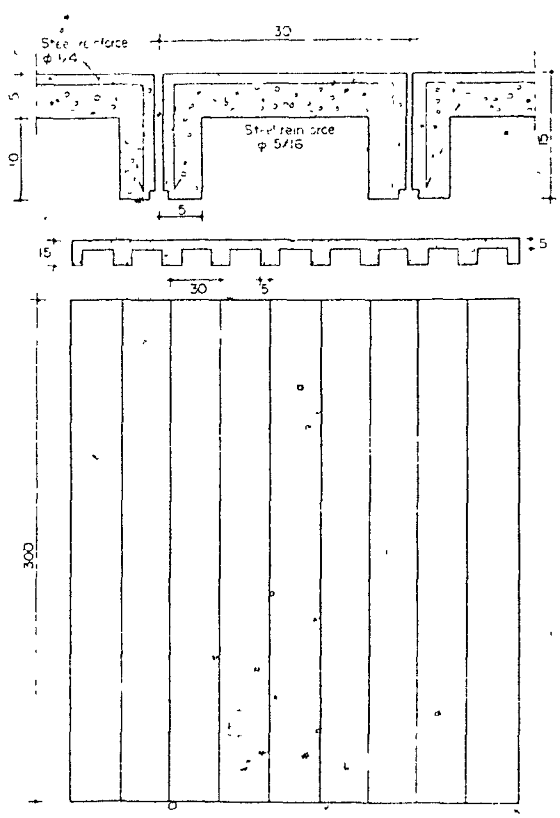


Fig. 7.19. Prefabricated Panels (East-West Center)

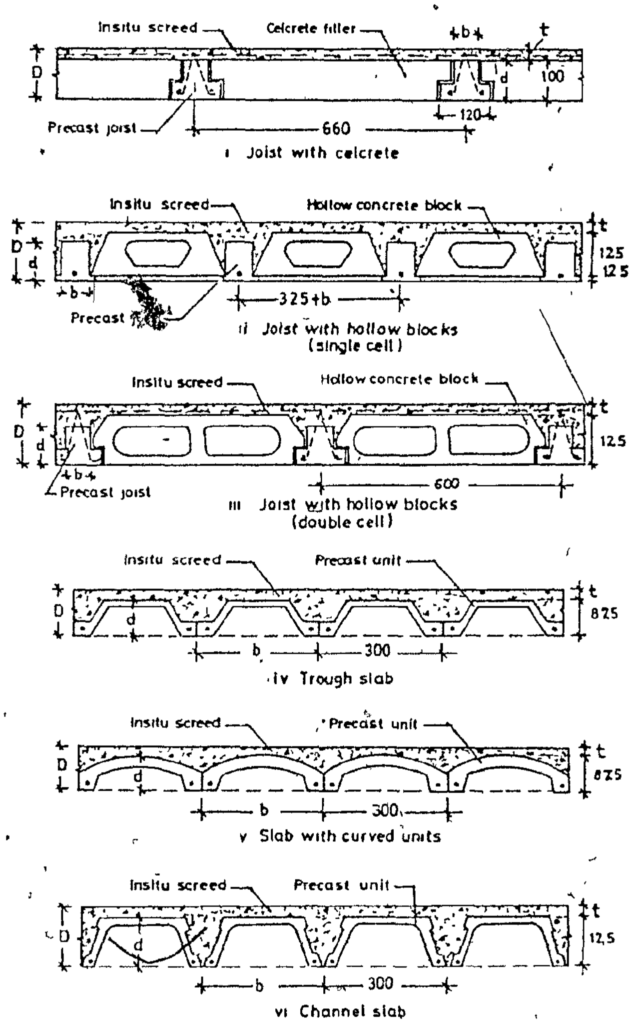


Fig. 7.20 Partial precast floor systems (Ramamurthy and Ganesan)

7.3. FERROCEMENT ROOFING SYSTEMS

Ferrocement exhibits behaviour so different from conventional reinforced concrete in strength, deformation and potential application that it is classified as a separate and distinct material.

The American Concrete Institute Committee on Ferrocement defined it as construction material as follows:

> "Ferrocement is a type of thin wall reinforced concrete construction, where usually a hydraulic cement is reinforced with layers of continuous and relatively small diameter mesh. Mesh may be made of metallic materials or other suitable materials."[23]

The mechanics of ferrocement and the mechanical properties are very complex because of the almost infinite variation of size, geometry, fabrication method, orientation, yield and ultimate stress of steel wire mesh that could be used as reinforcement.[23]

Consequently, designing a ferrocement structure is a sophisticated engineering matter which for our purposes has to be simplified to a trial and test method of the roofing elements as they are manufactured.

There are rules of thumb for the proportioning of ingredients by Abercrombie which will produce a mix quite strong enough for most small projects:[24]

- Use slightly more than half as much mesh as cement, measuring by weight.
- Use the minimum amount of mortar needed to cover the mesh.
- Use slightly more than half as much cement as sand, measuring by weight or volume.
- Use slightly less than half as much water as cement, measuring by volume.

The materials have to be of good quality and shall conform to the locally used standards for concrete construction.

Cement

The cement can be ordinary portland cement but should be fresh and of uniform consistency.

Fine Aggregates (Sand)

Sand shall be obtained from a reliable supplier and should be clean, hard strong, free of organic impurities and deleterious substances.

The following table gives some guideline on desirable gradings:

Table 5 (ACI)

Sieve Size U.S. Standard Square Mesh	Percent Passing by Weight
No. 8	100
No. 16	50 - 85
No. 30	25 - 60
No. 50	40 - 30
No 100	2 - 10

Water

Water used in the mixing is to be free of any organic and harmful solutions which will lead to a deterioration in the properties of the mortar. Salt water is not to be used.

Steel Reinforcement

The reinforcement should be clean and free of all loose mill scale, dust and loose rust, and coatings such as paint, oil or anything that might reduce bond.

Welded wire mesh, hexagonal woven mesh or chicken wire, and expanded metal lath can be untreated or galvanized with a wire diameter of not more than 1.5mm. The type of mesh recommended is the 15mm x 15mm gage 19 with a yield strength at 0.2% offset strain, in excess of 4500kg/cm2. Rods, wires and strands if used shall have a diameter smaller than 10mm. (Figs. 7.21 and 7.22)

It is the fabrication of the reinforcing cage, the mortar-plastering and the curing which are furthermore crucial for the quality of the product.[25]

Fabrication of the reinforcing cage

The wire mesh and/or mesh fabric or rods are to be placed and shaped to the roof form such that the production

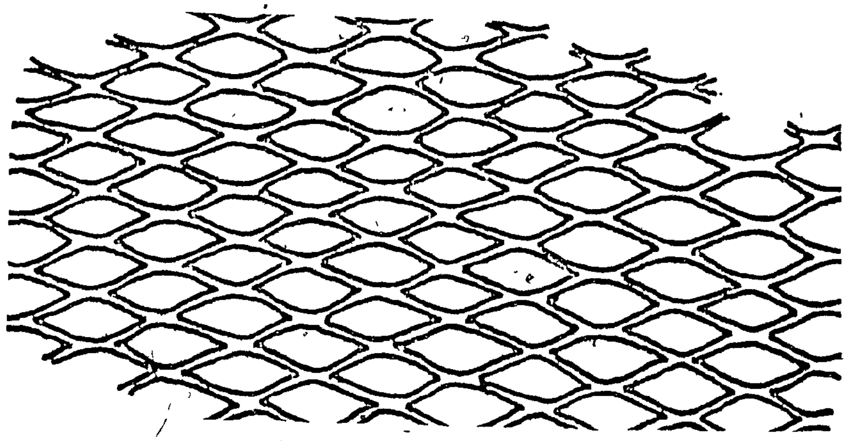


Fig. 7.21 Expanded metal lath.

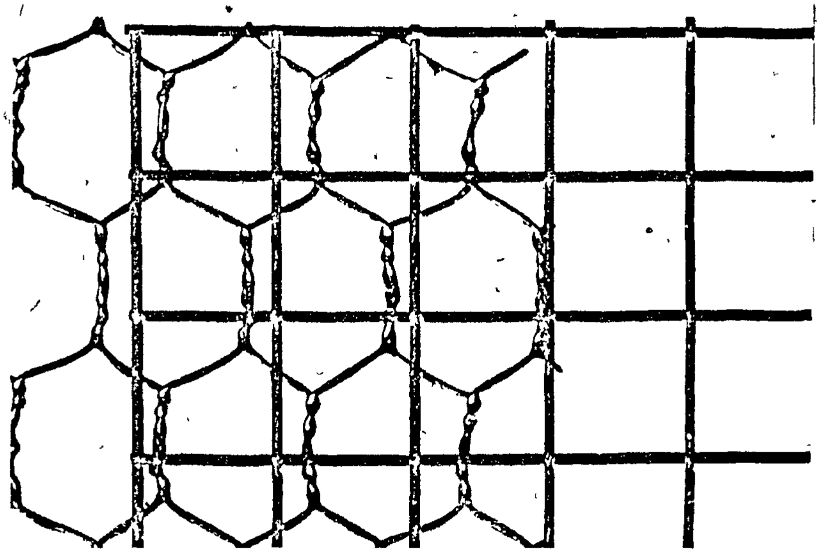


Fig. 7.22 Common chicken and welded wire mesh 15 mm.

of a void-free material may be obtained. Adequate reinforcements are to be placed locally where higher stresses are expected.

The different layers of wire mesh should be carefully and securely tied together and to the central layer of coarser reinforcement, if needed, in order to provide an as much even thickness as possible and to avoid movement during the placing of the mortar.

Any discontinuities in the strength of the reinforcement are to be avoided and an overlap of 10 cm is recommended to assure continuity between the ends of a layer of mesh. (Fig. 7.23)

Mortar - Plastering

Mixing, handling and compaction of the mortar should be considered and closely supervised to ensure high quality material.

The mortar must be thoroughly compacted during placing to ensure the absence of voids around reinforcement and in the corner of any frame work.

Under no circumstances should the mortar be compacted simultaneously from both sides of the reinforcement in one operation. Vibrators and handrodding can be used if necessary to achieve better penetration and distribution.

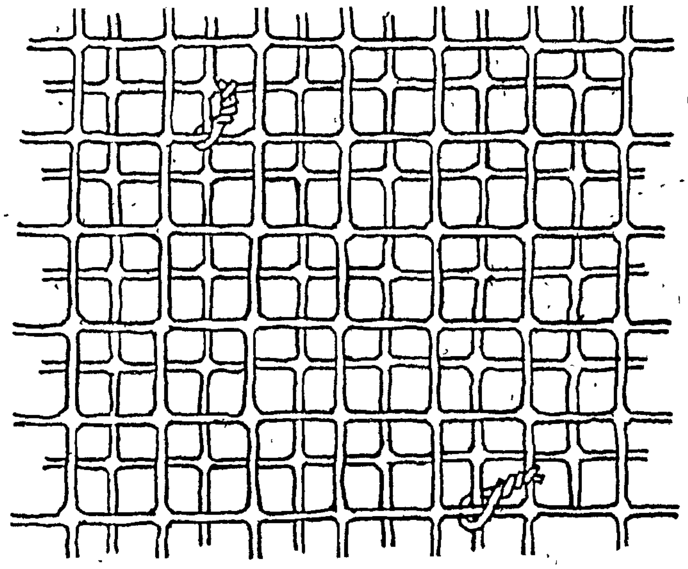


Fig. 7.23 Properly tied reinforcement.

Fig. 7.24 Mortar plastering.
(National Academy of Sciences)

The mortar should be placed within a reasonably short period of adding the mixing water and with continual agitation during the waiting period. During handling and placing of the mortar, care shall be taken to avoid segregation of the mix. (Fig. 7.24)

Curing

Curing, a very important stage of ferrocement making, Abercrombie says, is simply taking care that after the mortar has been applied proper conditions prevail whilst the earliest and most critical part of the hydration process automatically takes place.[26]

The set mortar is to be kept wet for a period dependent on the type of cement used and the ambient conditions.

The method of curing should normally be by water spray but other proven methods are acceptable, such as steam curing and membrane curing. The temperature of curing must be above 10^oC.

Painting

White wash or paint to improve thermal performance should only be applied after completion of curing and after the surfaces have been dried.

Conclusion

Ferrocement combines almost ideally the most desirable characteristics for low-cost roofing.

It is made of materials that are easy to find almost anywhere in the world, easy to buy on almost any budget and easy to use with the most meager amount of skill or training; no elaborate tools are needed; and, because the basic mesh can be bent by hand into shapes that are naturally structural, supporting framework can often be eliminated. It is also relatively lightweight, impressively watertight, rotproof, and bugproof, and it shares with all concrete work the enviable quality of improving its strength as it ages.[27]

Abercrombie mentions as disadvantages the work, which in our case could hardly be rated negative.

The other argument, its rarity, is probably a greater obstacle. Use encourages further use; disuse, further disuse.

Therefore a great body of scientifically conducted tests of the material's strength and of all the pecularities of its behaviour should be started. Without these tests, no reliable guidelines for still missing proper building standards nor approval from the building codes which enforce those standards can be established.[28]

7.3.1. SELF SUPPORTING SYSTEMS

Considering ferrocement as a construction material in all its applications, it must be in the form of a self supporting roof where it performs at its best.

The characteristics of ferrocement. free formability and thin structural thickness, demand a shape of the roof surface with a bearing mechanism of surface-active structural systems* (single or double curved surfaces).[29]

It is quite obvious that with this technic, ferrocement will not be ideal for constructing flat self supporting accessible roofs where the redirection of forces is most uneconomical anyway.

With a little more construction height, a ferrocement structure can serve a floor ceiling function in certain circumstances.

Modular Panels

Modular panels for self supporting low-cost roofs combine some highly desirable characteristics.

But considering that they will in most cases be used for flat roofs, ferrocement panels as mentioned in the preceeding paragraph will not be able to perform the most

* These are structure systems in surface stress condition.

desired functions a flat roof usually should: being accessible or serving a floor ceiling function for future extensions. In spite of this fact and as a comparison to the "canaleta" panel, I think that for certain cases the following system could be feasible for low-cost roofing.

Jose Castro[30] describes a panel in his paper[31] which has been successfully used in Mexico as roof and wall elements in different projects. One of them was a group of 350 houses built by the prisoners of the Tabasco Jail, using only these elements to form the structure. (Figs.7.25, 7.26 and 7.27).

"Mexican" Channel

The U-shaped channels of various dimensions are prefabricated individually. The reinforcement, consisting of two steel rods 6.0mm placed in the corners and two or more layers of wire mesh or the more and more used cheaper but also effective expanded metal (E-600, 600gr/m), is shaped with the help of a template.

The channels are then plastered manually on a smooth surface floor with a wooden form to the sides.

The finished and cured channels, weighing appr. 75kgs for 4m spans, can easily be installed by two men.

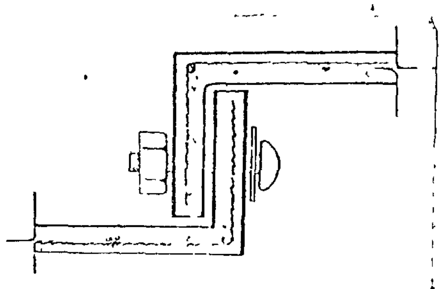


Fig. 7.25 Joint detail of ferrocement roofing channel.

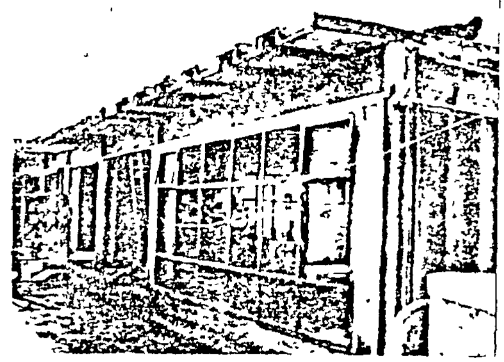
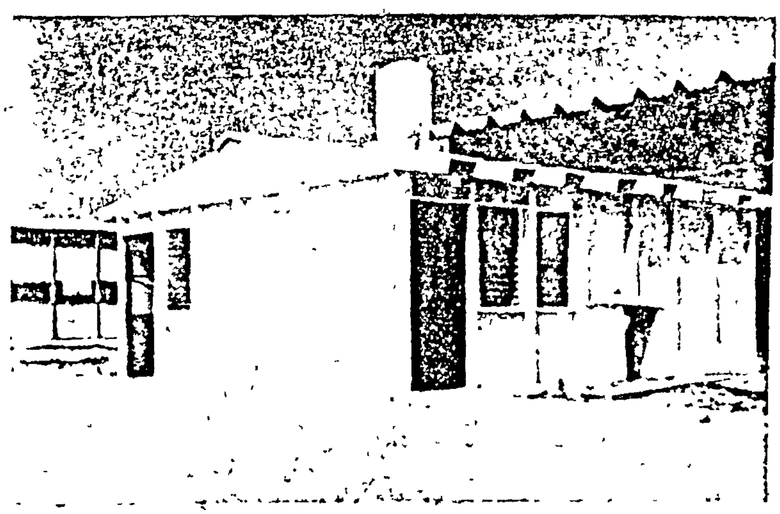


Fig. 7.26 Flat roof application. (ACI, Castro)



Pitched roof version. (ACI, Castro)

Dimensions:	0.50m to 1.0m wide 3.00m to 6.0m long appr. 2cm thick 8 - 20cm webs
Production:	on site manual prefabrication or local industrial manufacture;
Application:	flat or shed roofs, pitched roofs with ridge beam support;
Climatic Performance:	warm humid climates, preferably with a ceiling and well ventilated between roof and ceiling; composite climates, with a ceiling of some thermal capacity (fibreboard, stramit);
Economic Impact:	is positive as process is labor intensive, local materials can be used (except for the wire mesh which is usually imported; in China, it is reported, workers also weave mesh from wire on site);
Technical Aspects:	except for a trained supervisor, no skilled labor nor any special and expensive equipment is needed; the panels are easy to install and very durable;

Maintenance: annual cleaning will improve climatic performance which could further be improved with the application of a white wash;

Social needs: can be satisfied as discussed in the first part of this thesis (pp34-37) except that it is not accessible for other purposes than maintenance;

Free Formed Precast Panels

The three advantages of single fold structures over rib-slab structures are the main reasons for advocating use of ferrocement for roofing:

'A single fold ferrocement roof structure allows:[32]

- reduction of slab span to about half because each fold acts as rigid support;
- elimination of ribs because each plane acts also as beam in longitudinal direction;
- increase of spanning capacity through increase of construction height;

It is therefore only logical to use the ferrocement technique to these advantages. Apart from the U-shaped channel elements, the following two systems could be traced:

- folded plate roofs;
- folded curved panels;

The folded plate roof elements are precast in a mold of compacted soil protected by a mortar cover.

Each U-shaped plate is cast individually and then joint together by overlapping the wire rods and meshes left at the edges. Finally the union is plastered with mortar trying to keep the shape and good consolidation to guarantee the watertightness of the system.[33] (Fig. 7.27)

The folded curved panels (Fig. 7.28) are manufactured the same way as folded plate roof elements, utilizing the ferrocement process described in this chapter. But other than the system described in the preceeding paragraph, these elements, when cured and put in place, are simply joint together with mortar applied to the high joints.[34]

Domes Prefabricated

The use of prefabricated ferrocement domes is recommended for the construction of strictly modular projects, thereby allowing repeated use of the molds.

J. Castro, in his summary of the practical experiences resulting from the research work carried on by two Mexican education institutions, demonstrated the advantages of such a roof.[35] (Figs. 7.29, 7.30 and 7.31).

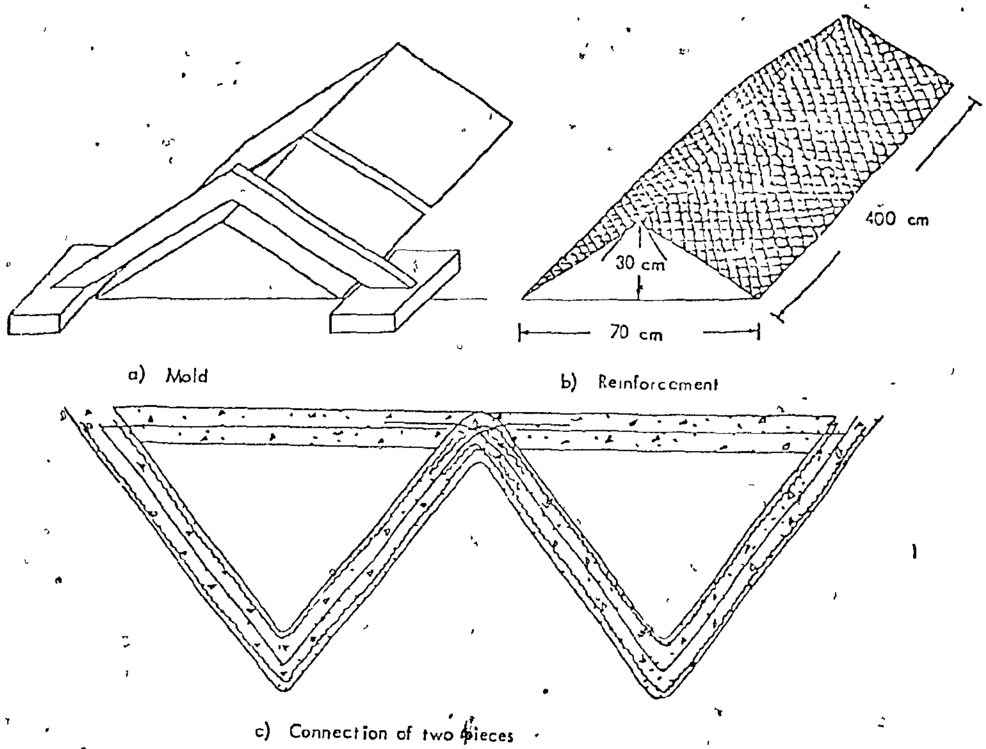


Fig. 7.27 The folded plate system (Castro)

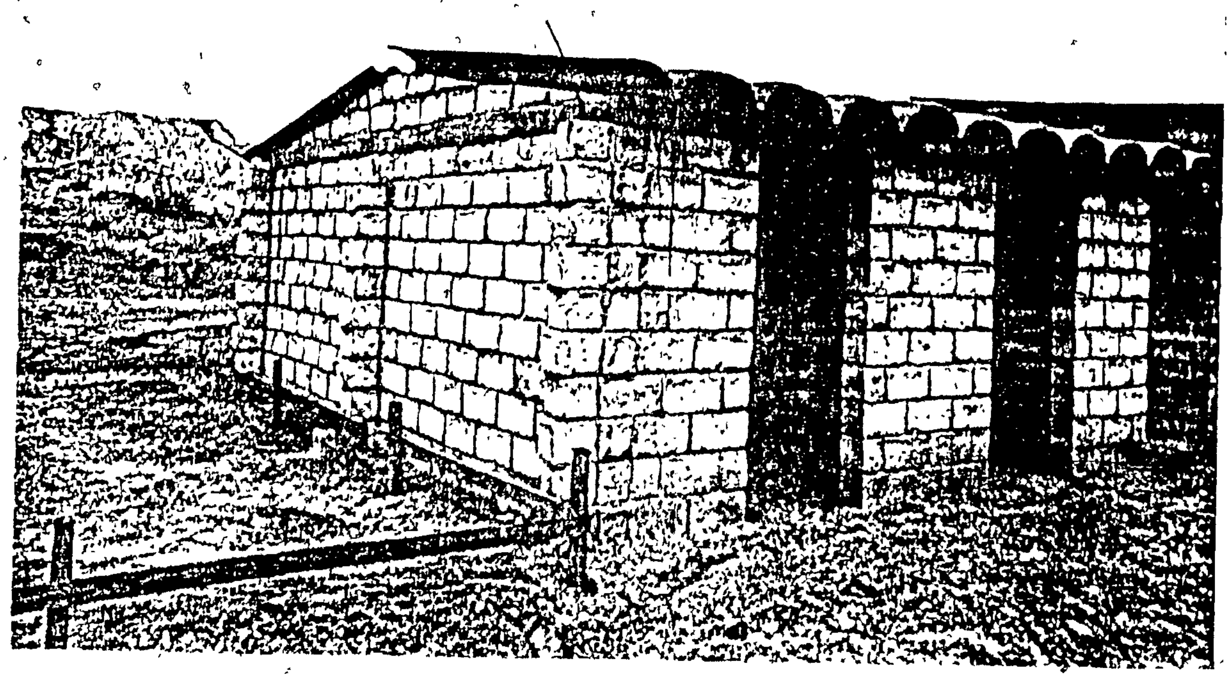


Fig. 7.28 Ferrocement panels developed by GATE in El Salvador.

The construction of precast ferrocement domes entails the following stages:[36]

- manufacture of mold;
- reinforcement of precast domes;
- pouring and curing;
- form-stripping and storage;
- erecting and joining;

In the manufacture of the mold, four interconnected wooden trusses are used which must have shapes corresponding to the cross-sections of the shell at the locations shown in Fig. 7.29.

The construction of the mold simply consists of making a dome of well compacted earth, covered by a layer of well-finished concrete having a thickness of appr. 8cm, with the shape defined by the trusses.

Before the reinforcement is put in place, the mold needs to be cleaned and greased to facilitate withdrawal of the mold. The reinforcement consists of two no. 2 bars along the edges, one of them straight and the other one with the necessary bends to provide the handles to lift and fix the dome to the structure. These handles should be placed at the corners of the edge and on the sides at a maximum spacing of 1m. Furthermore, two layers of chickenwire mesh or expanded metal lath attached to the bars are directly mounted over the mold.

After the pouring and curing of the prefab domes the mold is removed with the help of a wooden tripol (Fig. 7.30) or any structure able to withstand the weight of the shell (appr. 23kg/m2), plus a pulley and a rope. With this equipment, two or three people can lift the shell from the mold.

Once the form has been stripped, the dome can be carried to the storage site or to its final position by not more than eight people.

"Mexican" Dome [37]

Dimensions	3.00m to 6.00m and more span; 0.50m to 1.10m and more depth; appr. 1.00cm thick; (2.00cm edges)
Production:	very easily prefabricated on site and to any desired shape;
Structural Performance:	it was demonstrated with several experiments that resistance to uniform loads increases with increasing slopes at the edges. The domes with eliptical shapes have higher resistance when subjected to distributed loads than those with sinusoidal shapes; their resistance to concentrated loads was increased;

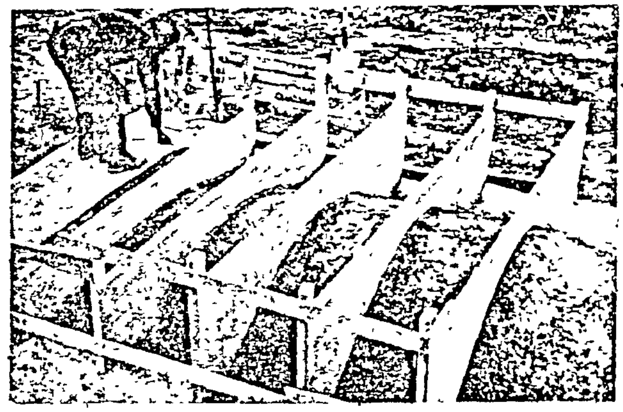


Fig. 7.29
Shaping the form.
(ACI, Castro)

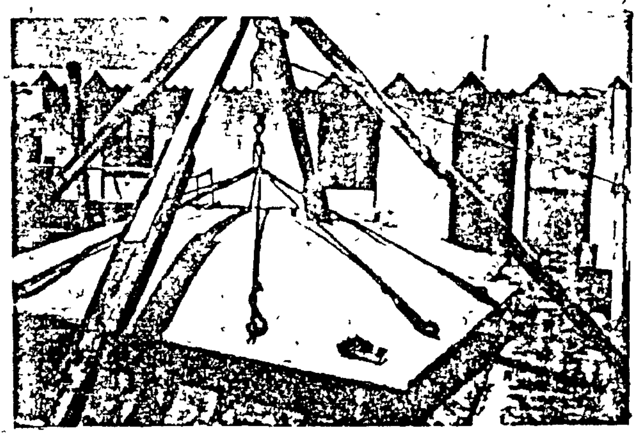


Fig. 7.30
Lifting the cast
dome. (ACI, Castro)

Fig. 7.31
Carrying the dome.
(ACI, Castro)

Climatic Performance:	this roofing system can be modified to perform in every climate; warm humid climates: a minimum of a kraft paper ceiling with aluminium foil lining on the upper side could make indoor conditions bearable during the day if ventilation is sufficient; hot dry desert climate: as this roof can support heavier loads than 100kg/m2 with a still good safety factor, it is actually ideal for this climate with an earth-cover or sand added to give the roof enough thermal mass for a time lag big enough; composite climates: in this climate with modular houses built, one dome could have more, the other less thermal mass and as such be adequate for different seasons;
Economic Impact:	is positive as unskilled labor can produce these domes with locally available materials;
Technical Aspects:	for domes not exceeding 4.0m span no special equipment is required to handle the domes; as they weigh about 22kg/m2 only, they can be handled by eight people in the dismolding which is acceptable in self-help construction methods;

Maintenance: no maintenance needed except for cleaning out roof water drainage;

Social Needs: can all be satisfied but the shape may not appeal to societies in the warm humid tropics and non-moslem ones as this roof is often described as a symbol of Islamic Architecture;

Cast Insitu Domes

This version is equally cheap and also simple to build as the prefabricated version is. Its advantage over the prefabricated one is that it can be built with greater span, does not have to be moved with the risks of being damaged and that it can be fitted to any room shape, without difficulty. (Figs. 7.32 and 7.33)

The only disadvantage is that the plastering of the dome is more difficult and has to be done most likely from the inside or with elaborate scaffolding otherwise.

Insitu built domes have the same characteristics for the user as prefabricated domes have and will perform the same way, too.

The construction method for this type of ferrocement roofing differs from the afor-mentioned insofar that more reinforcement is needed and that the vertical structure has to be connected with a tie beam at its top.

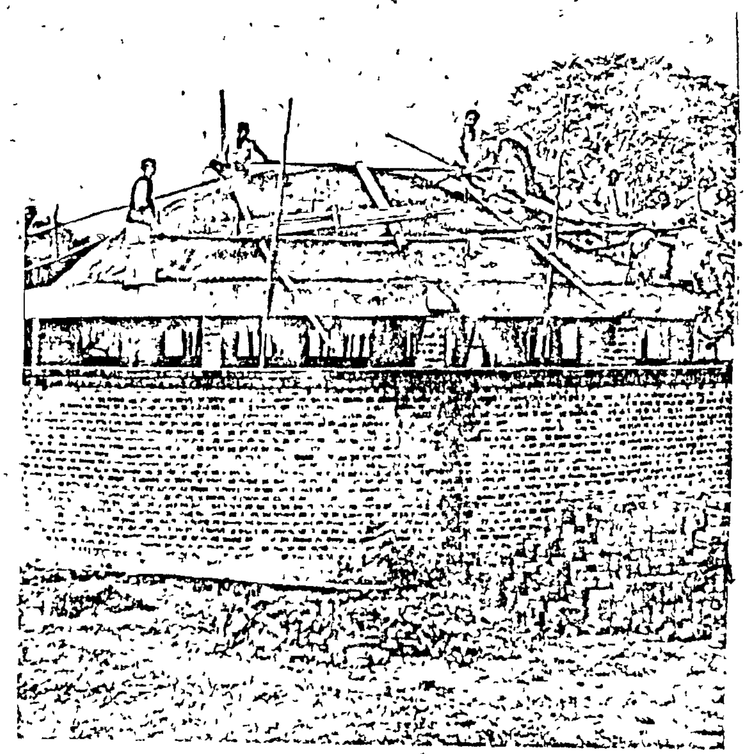


Fig. 7.32 Insitu cast dome (Ferro-cement Journal)

Fig. 7.33 Placing of mortar. (Ferro-cement Journal)

To form a double curvature surface, 6mm or 8mm bars well tied to the concrete ties are first placed in the center and should have a camber of 15% of their span. Other bars are then placed perpendicular to the first one with one meter distance between them. (Fig. 7.34)

The reinforcement is then completed as described in the preceeding paragraph.

The pouring operation in this case can be performed in one or two stages according to the size of the roof.

For this operation, two people are needed. One worker on one of the supports and either manually or with a trowel he distributes the mortar over the chicken wire as far up the dome as he can reach (1.2m to 1.5m) thus forming a ring. Simultaneously, another worker from within the room to be roofed, holds the mortar which is applied from the outside with a metal float or trowel in order that the mortar does not fall.

The central part remains uncovered and will be completed after 72 hours. In this case, the worker can climb on the previously cast portion, carrying out the same process as for the lower one.[38]

It is advisable, in all cases, to support the dome until the mortar has cured in order to avoid deformations caused by the weight of the mortar and to guarantee curvature of the shell at all points.

Vaults Cast Insitu

For the relatively small spans needed in low-cost housing, it is usually easier to build a double curved insitu ferrocement roof than making the expense of building ribs into a single curved vault (Fig. 7.35). Further, the skill and effort required to build a compression vault conventionally is more than for doing the same in ferrocement. Therefore, in countries like those around the Mediterranean Sea, where the pure compression long barrel vault is a traditional form, the method of ferrocementing could substitute the traditional way of building and produce an earthquake proof low-cost roofing system.

Free Formed Cast Insitu Roofs

It is the free formability of ferrocement demonstrated in a great diversity of structure from Dinosaurs to organic shaped houses[39] which give this technique such a high potential for roofing. The superb characteristics of ferrocement do not normally make an owner built freely formed ferrocement roof more expensive than a prefabricated or in simple geometric form insitu built one. (Fig. 7.36)

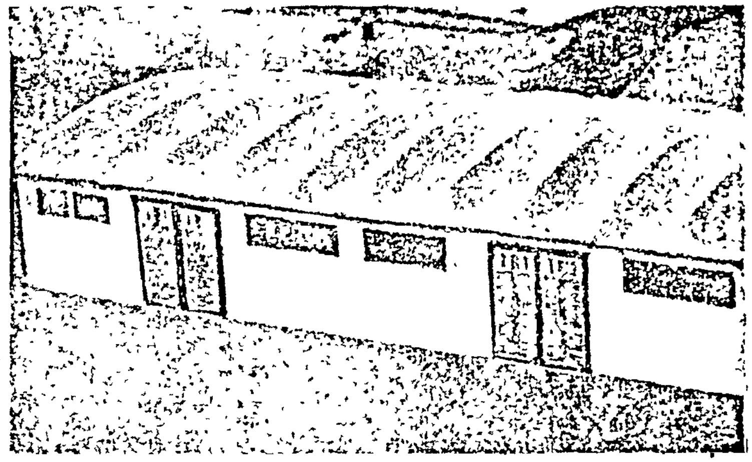


Fig. 7.34
Example of ferro-cement roof in USSR. (National Academy of Sciences)

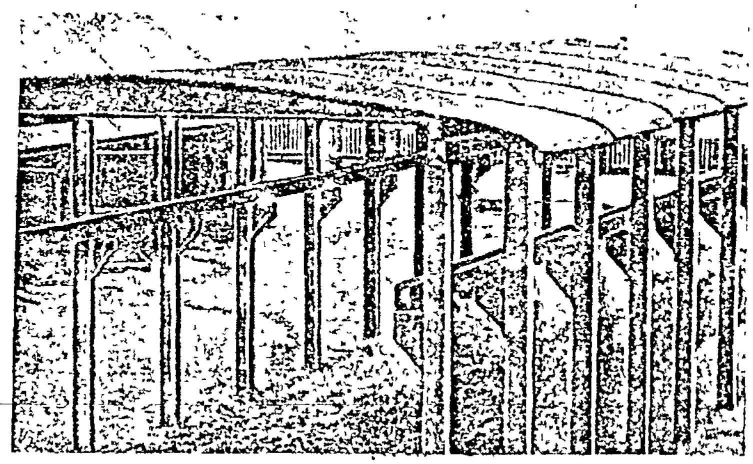


Fig. 7.35

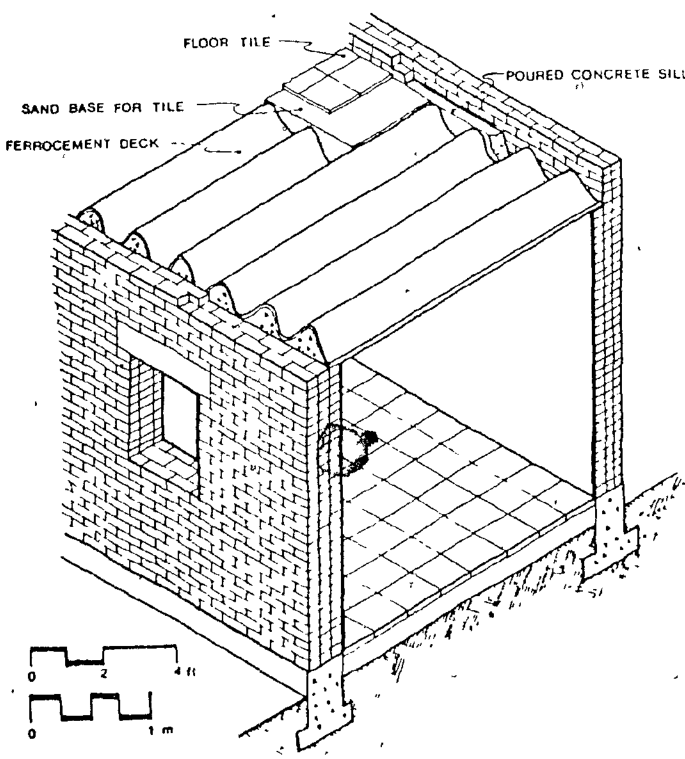


Fig. 7.36 Selfhelp housing in Egypt: a student design competition, second prize: Paul de Court, a suggestion for an economical flat roof with thermal mass.

Akin, Oe., Selfhelp Housing in Egypt: A student design competition, Carnegie Mellon University 1980.

7.3.2. SUPPORTED SYSTEMS

The advantages of supported ferrocement roofing systems are that the components can be manufactured in "blind production" to an optimal cost/strength ratio.

The disadvantage, of course, is that such a system needs a support structure usually wooden trusses and purlins which, considering the characteristics of ferrocement, make such a roof usually more expensive than a self supporting ferrocement roofing system of the same size.

Ferrocement roofing sheets can be produced industrially and large purlin spacing is possible.

For pitched roofs, ferrocement sheets of various shapes could be a feasible alternative to the more expensive asbestos roofing materials.

Ferrocement has a higher flexural strength than asbestos cement but performs, otherwise, not as favourable as asbestos cement sheets of comparable size do.

Corrugated Sheets

P. Srinivasa Rao and M.S. Mathews in their paper,[40] report about the development and testing of ferrocement corrugated sheets. They conclude that such sheets can be cast with a minimum of equipment and supervision. They further note that while the strength of the ferrocement sheets they had tested is half that of asbestos sheets, the strength to cost ratio approaches about the same value. (Table 9)

TABLE 6 DETAILS OF SHEETS

Material	Notation	Size Length	Size Width	Average thickness	Total Weight	Weight per unit area.
Ferrocement sheet	FS1	59 in. (150 cm)	37.5 in. (95 cm.)	0.434 in. (1.1 cm)	86 lb. (39 kg)	0.039 lb/in.^{2} (0.0027 kg/cm^2)
Ferrocement Sheet	FS2	59 in. (150 cm)	39.5 in. (100 cm)	0.275 in. (0.7 cm)	58 lbs. (26.5 kg)	0.025 lb/in.^{2} (0.0018 kg/cm^2)
Asbestos Cement Sheet	AC S	59 in. (150 cm)	19.75 in. (50 cm)	0.236 in. (0.6 cm)	26.4 lb. (12 kg)	0.023 lb/in.^{2} (0.0016 kg/cm^2)

TABLE 7 DETAILS OF MIX PROPORTIONS

Sheet	W/C ratio	Mix ratio	Cube strength 3.95 in x 3.95 in x 3.95 in (10 cm x 10 cm x 10 cm.)
FS 1	0.45	1 : 1.75	*3200 lb/in.^{2}(224 kg/cm^2)
FS 2	0.35	1 : 1.75	*3130 lb/in.^{2}(220 kg/cm^2)

*Strength on the day of testing; average of 3 cubes.

TABLE 8 DETAILS OF REINFORCEMENT

Description	Diameter	Gauge	Ultimate tensile stress
Hexagonal Chicken mesh	.0181 in. (0.046 cm)	26	124212 lb/in.^{2} (8735 kg/cm^2)
Hexagonal Chicken mesh	.0318 in. (0.081 cm)	20	37825 lb./in.^{2} (4660 kg/cm^2)
Mild steel rod	.1106 in. (0.281 cm)	-	47850 lb./in.^{2} (3365 kg/cm^2)

TABLE 9 FAILURE LOADS

Description	Width of Sheet	Ultimate Load	Load taken per unit width
FS1	37.5 in. (95 cm)	550 lbs.(250 kg)	14.7 lb/in.' (0.264 kg/mm)
FS2	39.5 in. (100cm)	560 lbs.(255 kg)	14.2 lb./in. (0.255 kg/mm)
ACS	19.75 in.(50 cm)	615 lbs.(280 kg)	31.2 lb/in. (0.56 kg/mm)

TABLE 10 COST OF FERROCEMENT AND ASBESTOS SHEETS

Item	FS1 Rs.	FS2 Rs.	ACS[1] Rs.[2]
Cement mortar	0.15	0.10	-
Mesh	0.45(26g)	0.70(20g)	-
Rods	0.20	-	-
Cost of Mould (20 reuses)	0.20	0.20	-
Oil	0.05	0.05	-
Vibrator	0.05	0.05	-
Labour	0.40	0.40	-
Curing	0.10	0.10	
	1.60	1.60	
Handling, breakages @ 10%	0.16	0.16	-
Profits, overheads.	0 24	0.24	-
	2.00	2.00	3.50[3]
Strength/cost ratio.	0.132	0.127	0.16

1 Cost is given for sq. ft area of the sheet

2 1 U.S. $ = Rs. 8.50

3 Cost as per prevailing market rates

(ACI, Ferrocement)

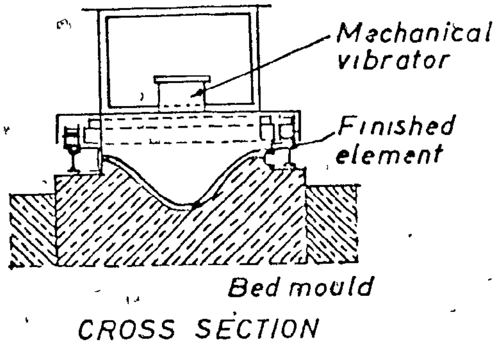


Fig. 7.37

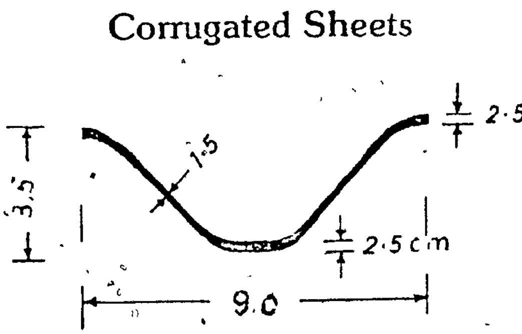


Fig. 7.38

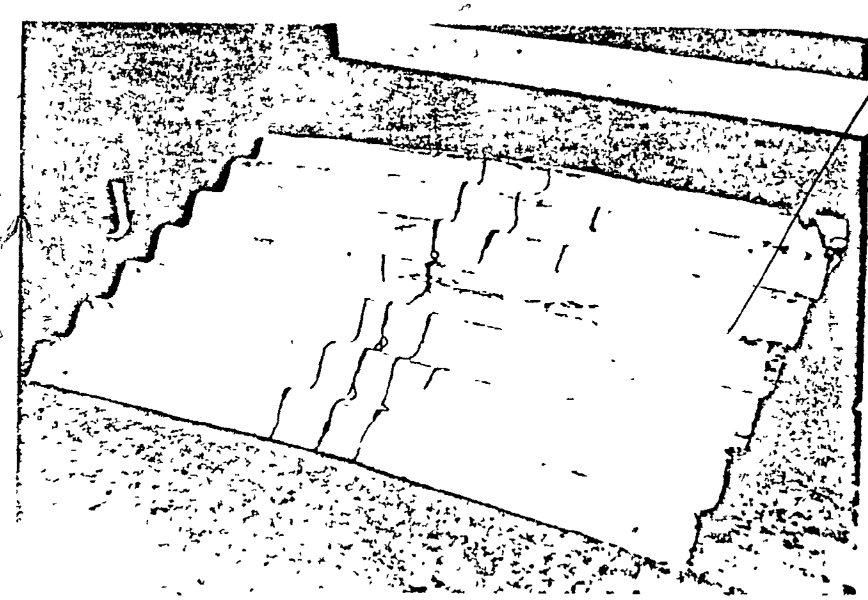


Fig. 7.39
Crack pattern.

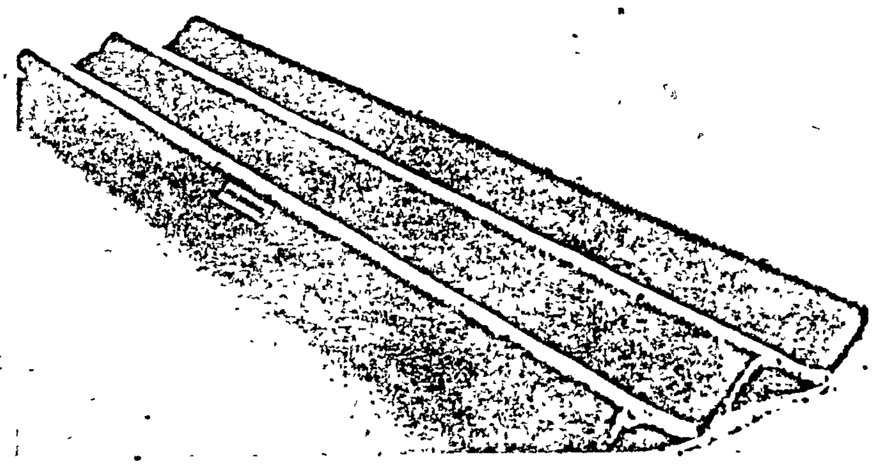


Fig. 7.40
Machinability of ferrocement sheets.

(ACI, Ferrocement)

Flat Sheets

Using flat ferrocement sheets in form of roofing tiles or bigger sheets does not really make sense as the material would not be used to its advantages and it would therefore never be competitive. The plank system as suggested for mass housing in Indonesia by Hasan Poerbo and Albert Kartahardja demonstrates such an application but leaves many questions open.[41] (Fig. 7.41)

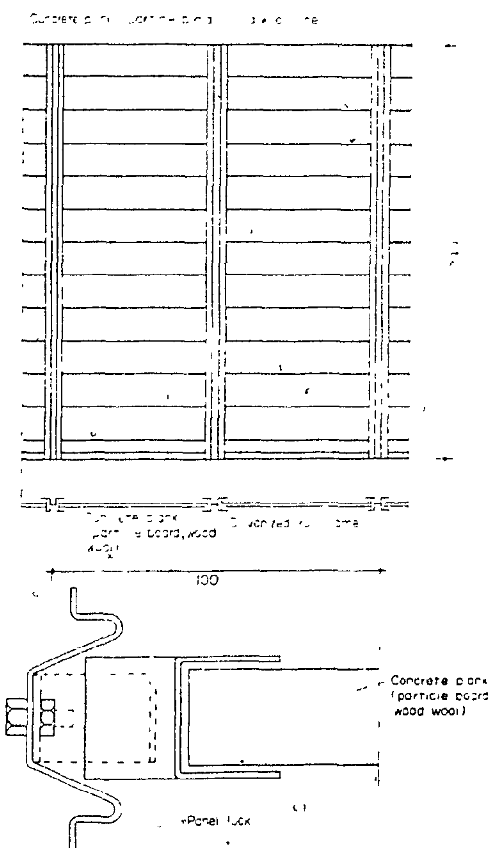


Fig. 7.41
(East-West Center)

7.4. FIBRE-CEMENT ROOFING SYSTEMS

Similar to ferrocement, fibre-cements exhibit behaviour quite different from conventional reinforced concrete and the scientific principles behind the understanding of how fibres incorporated into brittle things prevent these breaking, has only recently been explored, undertood and rationally applied.[42]

Since 1900, the most important example of a fibre-cement composite has been asbestos cement and this fibre material still reigns almost supreme, even though, particularly within the last few years, intensive research has been aimed at finding suitable substitute fibres.[43]

In the State-of-the-Art-Report on fibre reinforced concrete by the ACI, published in 1973, the definition of fibre reinforced concrete reeds as follows:

> "Fibre reinforced concrete is concrete made of hydraulic cements containing fine or fine and coarse aggregate and discontinuous discrete fibres. Continuous meshes, woven fabrics and long rods are not considered to be discrete fibre type reinforcing elements in this report."[44]

It is the non industrial process which is of interest to the producer of a fibre-cement low-cost roofing system, and its design will naturally be based on pratical experience and some basic principles as stated hereinafter.

As mentioned in the introductory part of this chapter, we can distinguish between two basic groups of fibres, the one with fibres of a lower moduli than the cement matrix and the other with fibres of a moduli higher than the matrix.

For the purpose of low-cost roofing, the highly complicated and scientific field of study of fibre material properties can be simplified to a few basic aspects.[45] This especially as a part from asbestos fibres, mainly those of the first group, will find use for low-cost components.

Properties of Materials

The main factors controlling the theoretical performance of the composite material are the physical properties of the fibres, the matrix and the strength of the bond between the two.[46]

Asbestos Cement

Asbestos cement, the widest used fibre-cement composite around the world, has excellent physical properties for a roofing material but has in recent years lost its cost competitiveness in many developing countries due to shifting economic conditions.

A study of alternative roofing systems for a pilot project in Somalia, by Florida A&M University School of Architecture,[47] reveals that in Somalia and possibly most other poor countries in that "bracket", asbestos cement roofing is the most expensive roofing system amongst common roofing materials used in the tropics.

This shift is due to the fact that asbestos is in relative rare occurence and, therefore, requires foreign exchange for most buyers of this raw material.

Furthermore, asbestos cement products are mainly produced in industrial processes and in few locations so that transportation becomes an important cost factor, too.

The known hazards to health are also largely responsible for the current interest in finding asbestos substitutes for cement reinforcement.[48]

Why is it then that asbestos cement has been used so widely and has been unchallenged by other fibre-cement materials until today?

After its discovery, asbestos, which is the only known naturally occuring fibrous mineral, performed so well in bond with cement and was relatively cheap to produce that there was no reason to look for alternative materials.

* The extremely heavy consumption of this raw material (appr. 20 million tons a year) represents a burden of several million dollars of scarse foreign exchange for each developing country. Thailand imports US-$8 million worth of asbestos fibres a year.

The use over decades led to further use and the formation of a strong industry.

Standard specifications were established which are an important basis for the wide use of any product.

Asbestos Fibres

By far the most abundant of asbestos minerals is chrysotile or white asbestos. Chrysotile constitutes more than 90 percent of the world asbestos reserves and is used in the manufacture of asbestos cement.[49]

Before the asbestos fibres can be combined with cement, heavy pretreatment is required to break up the blocks of fibres, mined from the seems in the rock bed, into thin fibre units of an effective diameter of 1 um or less and lengths of 2 mm average.* [50]

A practical range for tensile strength of white asbestos after Klos, is 560-750 MN/m2. Fibre strengths of this order are easily obtained with several fibres other than asbestos and this consideration is also responsible for the current interest in asbestos substitutes for cement reinforcement.[51]

The inorganic asbestos fibres have, apart from their good mechanical properties, a high chemical resistance.

* Longer fibres can be as long as 100mm.

And although the asbestos cement material becomes under natural weathering conditions progressively more brittle and suffers a certain amount of corrosion, it is known to be very durable.

Organic Fibres

The low modulus organic fibres are generally subject to high creep which means that if they are used to support permanent high stresses in a cracked composite, considerable elongations or deflections may occur over a period of time. They are therefore more likely to be used in situations where the matrix is expected to be uncracked, but where transitory overloads such as handling stresses, impacts or windloads, all relevant factors for roofing, are significant.[52]

On the basis that locally available organic fibres to be used in simple manufacturing processes should be considered for low-cost roofing, the following fibre materials seem to me appropriate for consideration:

Akwara Fibres

In many parts of the world, manufactured fibres are not readily available and studies have therefore been made of natural vegetable fibres. Akwara (piassave fibre) is a natural vegetable stem fibre which is readily available in

Nigeria and has been studied by Urzomaka[53] with regard to its use in concrete. The modulus of the fibre is low (1 to 4 GW/m2) but it is stated to be dimensionally stable in water and durable in a cement matrix. However, at fibre volumes up to 5%, there is no improvement in modulus of rupture of the concrete although the resistance to impact is increased.

Cellulose Fibres

Cellulose fibres have a considerably lower tensile strength and modulus of elasticity than asbestos. They are, as Krenchel[54] further explains, hygroscopic and their strength is reduced by the absorption of water.

The dimensions of the fibres are not stable under varying moisture content, and the fibres rot if kept moist for longer periods. Finally, cellulose fibres cannot tolerate heating to beyond 100-120°C.

In view of this, cellulose fibres do not immediately seem to lend themselves as a suitable substitute for asbestos in this context, but Krenchel reasons that they must be mentioned because they are presumably the only fibre material that has so far been used to any reasonable extent as reinforcing material for Portland cement in accordance with the same principles as asbestos.

The paper industry has worked on the improvement of this fibre material, primarily by impregnating and coating the fibres with polimeric materials such as melamine and phenol-formaldehyde, to produce a water resistant paper with greater dimensional stability than is normally achieved without impregnation.[55]

By utilizing the experience gained in the paper industry, it is not improbable that a competitive fibre-cement material with valuable mechanical properties could soon be developed, benefitting such countries as Brasil and Nigeria with vast Mangrove swamp areas, potential cellulose fibre resources.

Bamboo Pulp and Fibre

Seng-Lip Lee, in his paper on low-cost housing in Thailand,[56] describes the utilization of indigenous materials with an emphasis on the potential uses of bamboo. Amongst the many structural qualities bamboo has to offer, Seng-Lip Lee also notes that his investigations revealed that bamboo fibres appeared more promising than other natural organic fibres on account of its superior strength and surface texture. Moreover he states that it possesses good buoyancy characteristics which help prevent bundling fibres during the mixing process.

Two types of bamboo reinforcements were used; bamboo fibres and bamboo pulp. The term bambo fibres refers to those fibres which were obtained by mechanically hammering dried short bamboo sticks of specified length. The fibre length varies from 38 mm to 63.5 mm with a mean diameter of 0.4 mm.

Pulp in this context refers to those fibres which were obtained by cooking bamboo chips in a 20% NaOH solution at appr. 170°C under a steam pressure of 8.5 kg/cm2 for 6 hours.

A detailed investigation by Pakotipraoha, Pama and Lee[57] showed that bamboo pulp and fibre boards are suitable substitutes for asbestos fibres. With cement paste binder, the resulting composite yields building boards which can be used for walls, ceilings and roofs.

The cost analysis also showed that bamboo pulp and fibre boards are competitive in cost compared with asbestos cement boards. Moreover, the production process is such that existing plants can be used with minor modification. It is hoped, Seng-Lip Lee concludes, that the use of natural organic fibres such as bamboo will save much needed foreign exchange and at the same time reduce the basic cost of the material.

Coconut Fibres

Coconut fibres are very durable under natural weathering conditions and attempts have therefore been made to include them in cement based materials. Published data is sparse but they are likely to suffer from the usual disadvantages of vegetable fibres in that the modulus is very low and they are sensitive to moisture changes. However, the results might turn out, these fibres have a potential in the production of low-cost roofing materials.[58]

Jute Fibres (Kenaf)

No data was available about its use in fibre-cements but similar to other natural fibres not specially mentioned in this report, like cotton or linen, all of these fibres could be considered for use as reinforcement of fibre-cement sheets.

Polyethylene

Polyethylene has not been used to any extent in cement composites because of its low modulus but the development of high modulus polyethylene has enabled the production of relatively cheap fibres with considerable potential in the field of cement based composites.[59]

Polyethylene Fibres

This material in form of fibres, monofilament and continuous opened film has been used in various types of cement bonded materials and with its high impact strength it may prove to be economical as direct replacement for asbestos cement sheeting.[60]

Sisal Fibres

A small study program on the use of sisal fibres in concrete has been carried out at the Building Research Station.[61] The fibres tended to clump in the mix and setting was retarded by leaching or organic impurities from the presoaked cuttings, but satisfactory pressed concrete beams were produced with up to 5% of sisal by weight of cement. However, no additional strength was obtained by the addition of sisal reinforcement. More promising results have been obtained by Swift, at Kenyatta University College, Kenya, who has produced effective corrugated sheeting using combinations of long and short fibres.[62]

The Matrix

The maximum particle size of the matrix is important because it affects the fibre distribution and the quality of fibres which can be included in the composite. The mortar should not contain aggregate particles of more than 5mm maximum size.[63]

Strength of the matrix is mainly affected by the free water/cement ratio which should be between 0.35 - 0.45.[64]

The Bonding Strength

A problem with the low modulus fibres is that they generally have large values of Poisson's ratio and this, combined with their low moduli, means that if stretched along their axis, they contract sideways much more than other fibres.[65]

This, D.J. Hannant further describes, leads to a high lateral tensile stress at the fibre-matrix interface which is likely to cause a short aligned fibre to debond and pull out. For our purpose, devices such as woven meshes or networks of fibrillated fibres may therefore be necessary to give efficient composites.

Preparation of Fibre Reinforced Concrete

Above all other aspects which might differ from the mixing of ordinary concrete, it is necessary to have a uniform dispersion of the fibres and prevent the segregation of balling of the fibres during mixing. Because of absorption, the water requirement will vary with the type and nature of fibre but for our pratical purpose the following proportions can be used with the exception that the fibre content when using natural fibres should be increased up to 5 percent by volume of mix.[66]

TABLE 11—TYPICAL PROPORTIONS FOR NORMAL WEIGHT FIBER REINFORCED CONCRETE

Cement	550-950 lb/cu yd
W/C ratio	0 4 to 0 6
Percentage of sand to aggregate	50 to 100 percent
Maximum aggregate	¾ in.
Air content	6 to 9 percent
Fiber content	0.5 to 2 5 percent by volume of mix (steel-1 percent = 132 lb/cu yd glass-1 percent = 42 lb/cu yd nylon-1 percent = 19 lb/cu yd)

1 lb per cu yd = 0.5933 kg/m³
1 in = 2.54 cm

TABLE 12—TYPICAL FLY ASH FIBROUS CONCRETE MIX

Cement	490 lb/cu yd
Fly ash	225 lb/cu yd
W/C ratio	0 54
Percentage of sand to aggregate	50 percent
Maximum size coarse aggregate	⅜ in
Steel fiber content (0 010 x 0 022 x 1 0 in)	1.5 percent by volume
Air-entraining agent	Manufacture's recom
Water-reducing agent	Manufacture's recom
Slump	5 to 6 in.

1 lb per cu yd = 0 5933 kg/m³
1 in = 2 54 cm

In case of asbestos cement, changes in mixing techniques, selection of appropriate fibre sources and blending have occured through the natural progress and development within the industry. Techniques like the one of fibre deposition onto a preformed shape and compression profile rolling with vacuum extraction employed at the same time can be applied as well as the hand forming over a template of the thin sheet green state asbestos mix with a wet life of appr. one and a half hours.

7.4.1. SELF SUPPORTING SYSTEMS

The characteristics of fibre-cement composites similar to those of ferrocement require the form of a folded structure to serve this function economically. This fact has led to the single most successful application of a cementitious roofing channel around the world and also some other interesting self supporting systems made of fibre cement.

The Roofing Channel (Canaleta)

In February 1961, Architectural Record reported on how Alvaro Ortega, who was then on the staff of the United Nations' Technical Assistance Commission, had taken asbestos cement pipe directly from a Guatemala factory,[67] sliced it in halves and while it was still fresh, pressed it into galvanized metal forms to make channel-shaped roof members. When dry, these channels, 6.40 m long, 20 cm deep, 38 cm wide at the bottom and 66 cm wide at the top, were rigid enough to span 6.10 m without intermediate support.

Later, the channel profile has undergone a "face-lifting", two small bends at the edges for overlapping joints. (Fig. 7.42)

The later modified curved shape was developed to permit stacking of units to greater heights for storage and shipping. The first housing project was in Guatemala City, where the process was first tried out.[68] (Fig. 7.43)

Since its invention, the "canaleta" has made the tour around the world and is today manufactured in all continents and up to lengths of 10.5 m, but is unfortunately not a very low-cost roofing system anymore.

All user aspects are similar to those mentioned under ferrocement channels, except for cost considerations. Should it be possible to substitute asbestos fibres with cheaper and locally available ones, fibre-cement roofing channels could certainly become a cost competitive self supporting roofing system again.

Domes and Vaults

Where aesthetical considerations are given high priority and the shape of the roof is an important element for tribal identity, like in the Kainji resettlement scheme in Nigeria, a fibre-cement roof can be a convincing solution.[69] (Fig. 7.44)

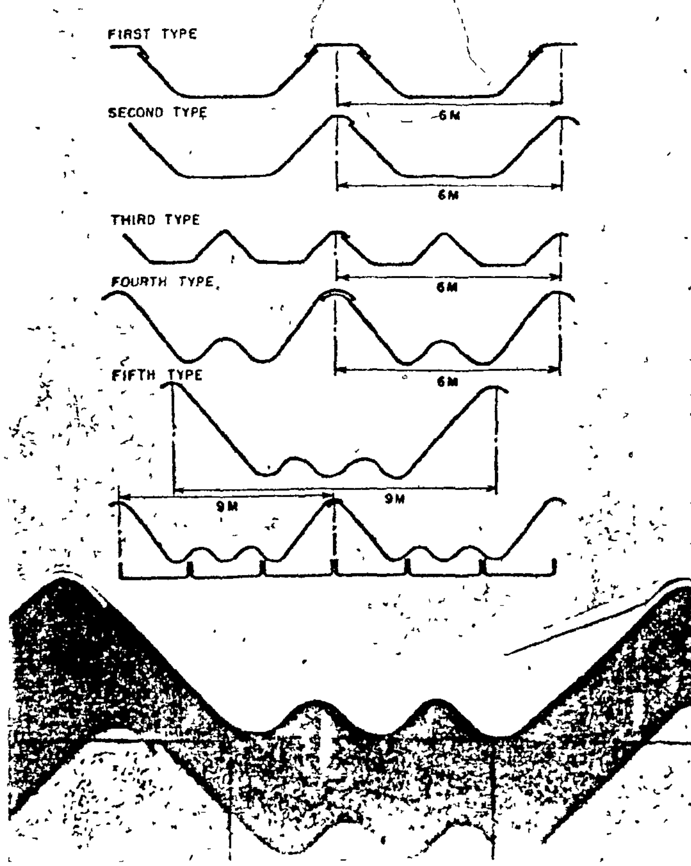


Fig. 7.42 The evolutionary process of the "caneleta". (Architectural Record)

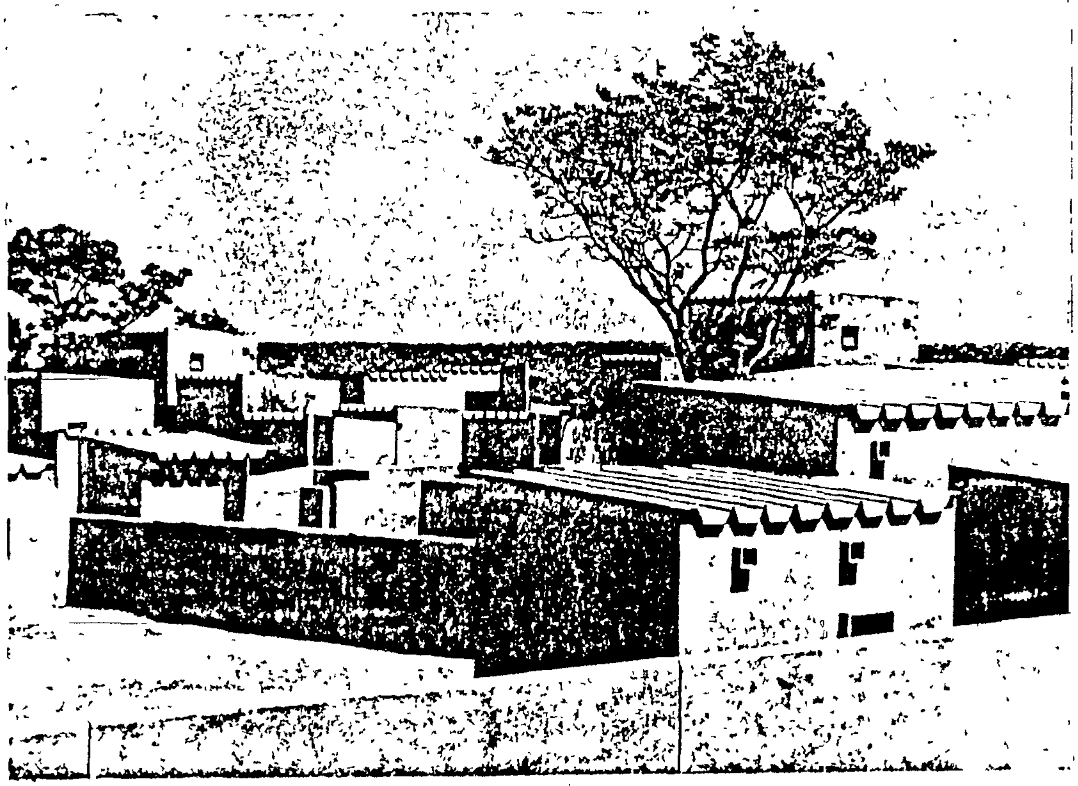
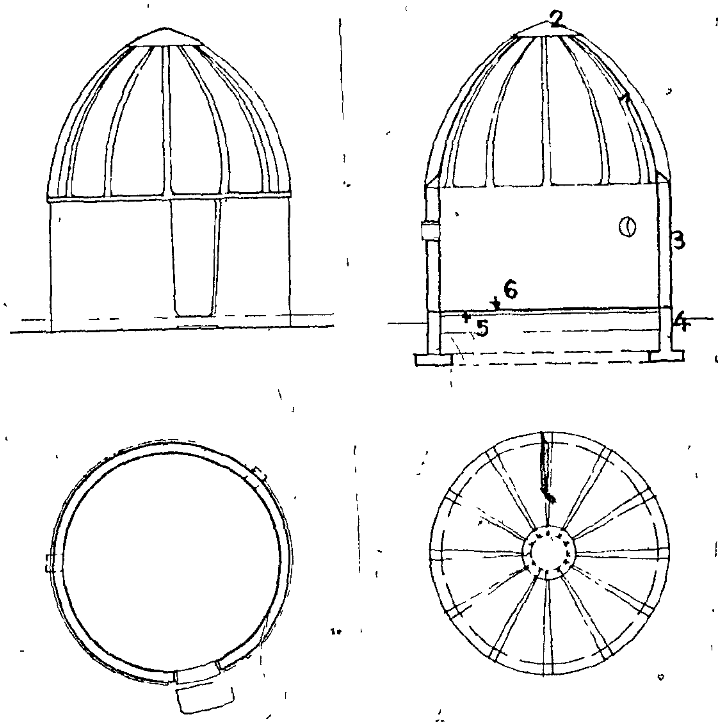


Fig. 7.43 (Asbestos Cement Revue, AC58)



1 Asbestos-cement round, domed roofing segments.
2 Asbestos-cement roofing cap.
3 15 cm hollow block wall.
4 15 cm sandcrete block wall filled with concrete.
5 7,5 cm sand on rammed laterite.
6 2,5 cm cement screed.

Fig. 7.44 Section evaluations, floor plan, roof plan.

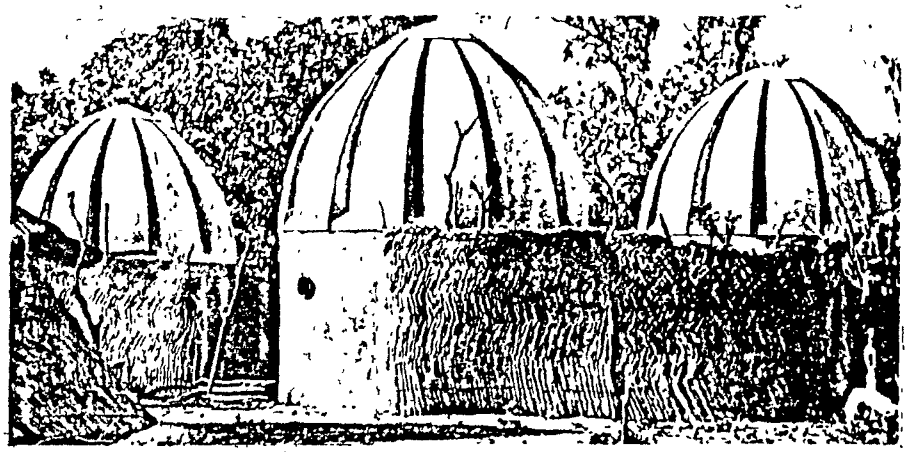


Fig. 7.45 Cluster.

(Asbestos Cement Revue, AC58)

For large scale projects like the above mentioned one involving the resettlement of 42,000 people, an industrially produced system will probably be necessary for reasons of time and scale. But otherwise the same system could be applied, made of fibre-cement (with any suitable fibre) locally manufactured and lower in cost than the same elements would be manufactured industrially in asbestos cement in a far distant place.

The Kainji Dome and Vaults

Introducing this unique application of fibre-cement roofing, it is best to quote the architect's own report on the design of roofing for this development:[70]

> "It was decided that a self supporting roof would be used if this could proove economically viable, structural possible, weather and storm proof. One of the advantages for this choice would be the elimination of wooden structural supporting members. It was realized that if a standard roof structure for sheeting support was used, this would be liable to warp and crack due to the extreme heat and extremes of relative humidity. In turn such warping or cracking would adversely affect any sheeting it supported, causing it to crack or admit rainwater. Another possible hazard in the use of timber in Northern Nigeria is

attack by termites, which is difficult to resist even by pressure impregnation or preservative application by hand. It was not certain that even if wood was specified to be impregnated that all cut ends would be treated on site.

Set against this was the argument that the inhabitants, whose traditional roof covering is thatch, if provided with a self supporting asbestos-cement roof covering, could neither repair nor replace damaged roofing, should this occur, under abnormal circumstances. Economies in reducing the erection period and security in fixings outweighed these latter arguments in favour of the self supporting roof.

The span was the first design consideration. From this evolved the three basic shapes of the buildings. Oblongs in juxtaposition covered with "canal" roofing sheets, squares covered with curved corrugated sheets and circles covered with segmental domes. The size of the sheet coming from the machine determined the span in relation to the stiffness necessary to resist the design loading of 160 kg/m2. The stiffness was obtained by shaping the sheets either in troughs, curves or arches.

The roofing is carried on the sandcrete block walling and is held down by long bent bars built into the courses of the blockwork. The end of the bar terminating in a clothes hanging hook within the rooms, incorporated to ensure easy checking of the proper fixing of all fastenings. In the case of the curved roofing sheets the gutter fastenings are similarly taken down into the walls and the sheeting is then bolted to the gutter. The asbestos roofing sheets as fixed have stood up to tropical storms and localized tornadoes.

Throughout the development of the design of the roofing, a local asbestos-cement manufacturer worked with the architects to ensure that every aspect of the problem: span, support, strength, fixings and waterproofing, was satisfactorily solved." (Figs. 7.46 and 7.47)

I have visited some of the 119 new settlements in April of 1979, almost ten years after its completion, and was impressed by the good conditions the roofs were in.

It must be said that the climatic performance of these roofs with no ceiling and in the case of the domes and vaults inadequate ventilation is not at all that satisfactory. These villages and towns are situated in the composite climatic zone.

Roofs in this climate should be adequate for the different seasons and should therefore have some thermal capacity. The dwellers have made some modifications themselves and the unshaded walls with a reasonable time-lag reradiate some heat during the cooler nights so that the negative diurnal

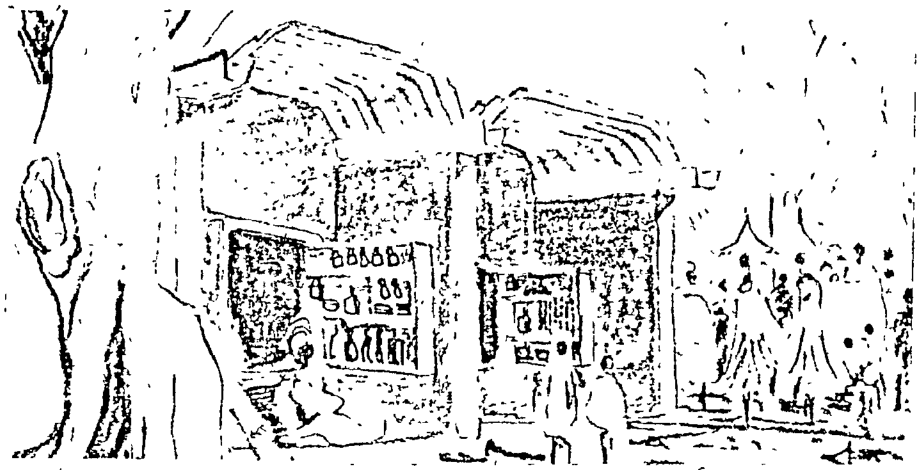


Fig. 7.46 The architects' impression.

(Asbestos Cement Revue, AC58)

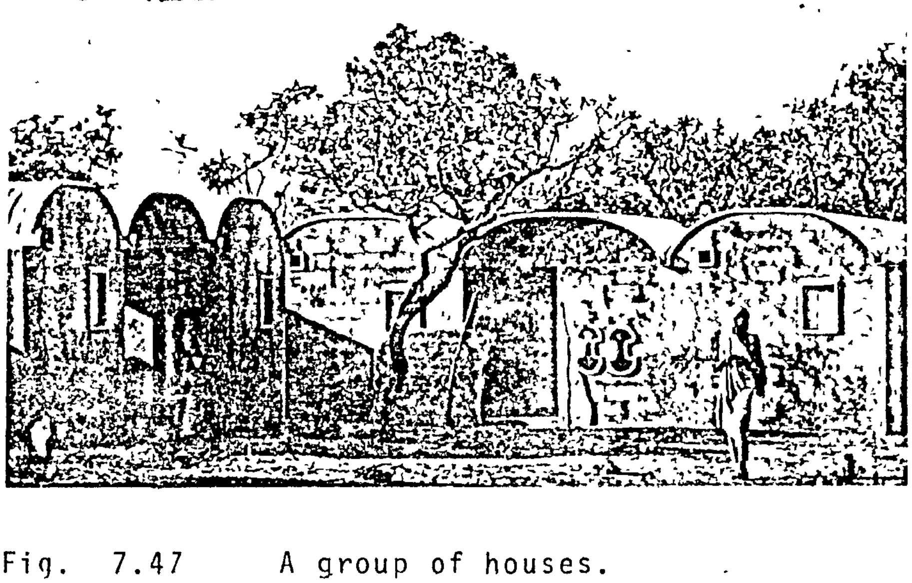


Fig. 7.47 A group of houses.

peaks have been reduced and thus the solution responds to the different climatic conditions of the various seasons.

7.4.2. SUPPORTED SYSTEMS

Supported fibre-cement systems consist of flat sheets, tiles or corrugated sheets of various spans and sizes mounted on a support structure usually made of wooden or bamboo trusses and purlins.

The most common of them all to date is the corrugated asbestos cement sheet roofing, of course. But there have been other shapes developed with the aim to find a structurally optimal solution using minimal quantity of material.

The Corrugated Asbestos Sheet Roofing

Similar to CGI sheeting, corrugated asbestos cement roofing sheets are manufactured in various circular shapes and sizes; the most common being 2.00 m x 0.6 m (0.9 m) and 5 mm thick with an average density if appr. 1400 kg/m3.

The pitched roof with corrugated asbestos cement sheets with endlaps should have a slope of at least 18^{o}.

The support structure or purlins need to be well levelled with purlins at 0.95 m centers on rafters at 2.00 m centers. Installation of asbestos cement roofs is not as easy as with CGI sheets as this material is quite fragile and not easy nailable. A ladder or plank should be used to distribute the load of the person working on the roof.

The "Chapa Modulada"[71].

The chapa modulada is an example of a free formed (curved) asbestos roofing sheet from Brasil.

The interesting feature of this system is the combination of aesthetic qualities with structural and economic ones. These 8 mm thick sheets are in various lengths of up to 3.70 m and width of 0.60 m on the market. This means that a roof can be built with trusses, just a ridge beam, and relative small dimensions of rafters. And as the roof covering is made with no endlaps such a roof can have as low a pitch as 8^0 or 10^0. (Figs. 7.48 and 7.49)

Organic Fibre Cement Sheets

Supported roofing systems are cost competitive if the needed support structure reduces the cost of the entire roof below that of a comparable self supporting system. The roof covering material, in this chapter being fibre-cement, should therefore have a strength appropriate to the design.

Supported asbestos cement roofing systems are after the considerable economic changes in most developing countries not competitive anymore if compared with other fibre-cement.

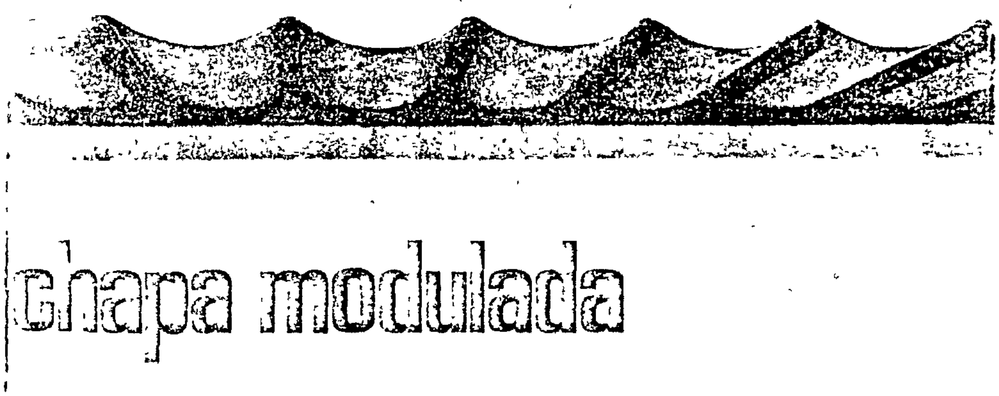


Fig. 7.48

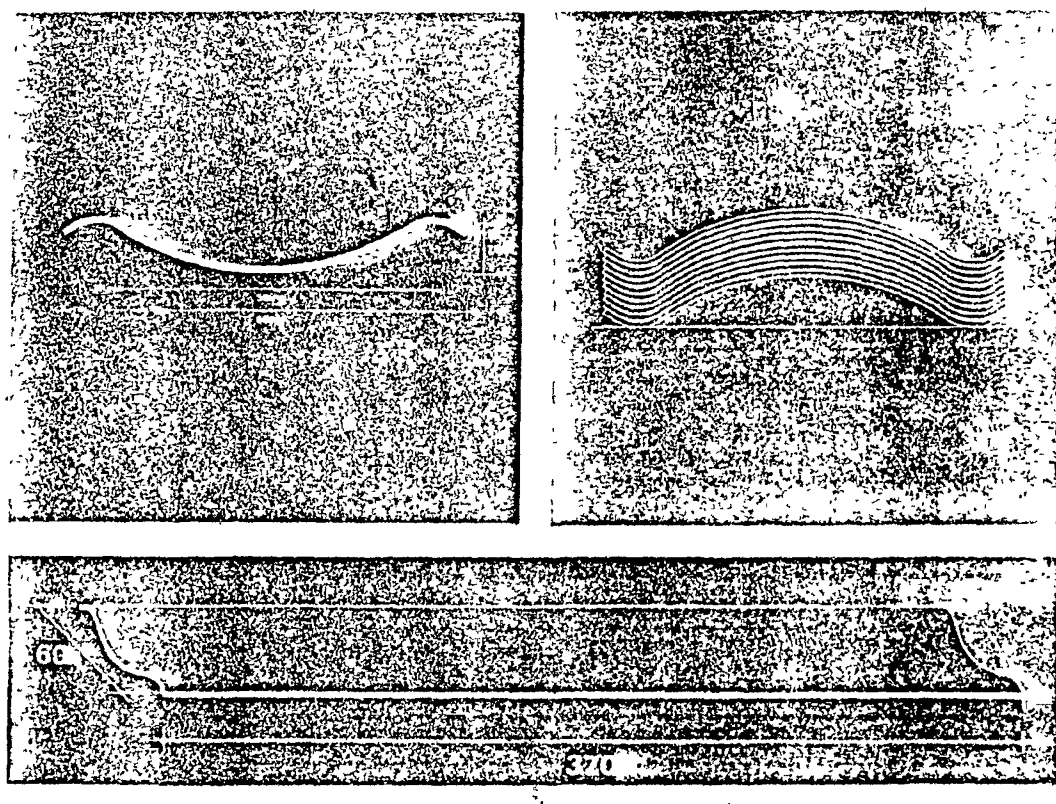


Fig. 7.49 (eternit do Brasil)

systems on a cost/strength ratio basis.

Two of those alternative systems[72] are the one developed at the Central Building Research Institute in Roorkee, U.P. India, under the title of "corrugated roofing sheet from coir waste/wood wool" and the one developed at I.T. workshops, by J.P.M. Parry & Associates Ltd.,[73] in Warley, West Midlands, U.K., being a low-cost handmade roof sheet of fibre reinforced cement.

The Corrugated Roofing Sheet from Coir Waste/Wood Wool

The light, fire resistant sheets are made from wood wool from soft wood which is mixed with coir waste fibres and cement.

The mixture is formed to a mat of suitable thickness and pressed on a corrugated mold. After demolding the sheet is cured and dried.

Although the mixing proportions were not stated, the data sheet revealed that this product would need appr. 30% less cement than asbestos cement sheets of comparable size would.[74]

They can be used like asbestos cement sheets and do not require any further finishing or water proofing. The 1.5 m by 0.85 m and 8 mm thick sheets weigh appr. 11 kg/m2 and have a capacity of 160 kg/m2. (Fig. 7.50)

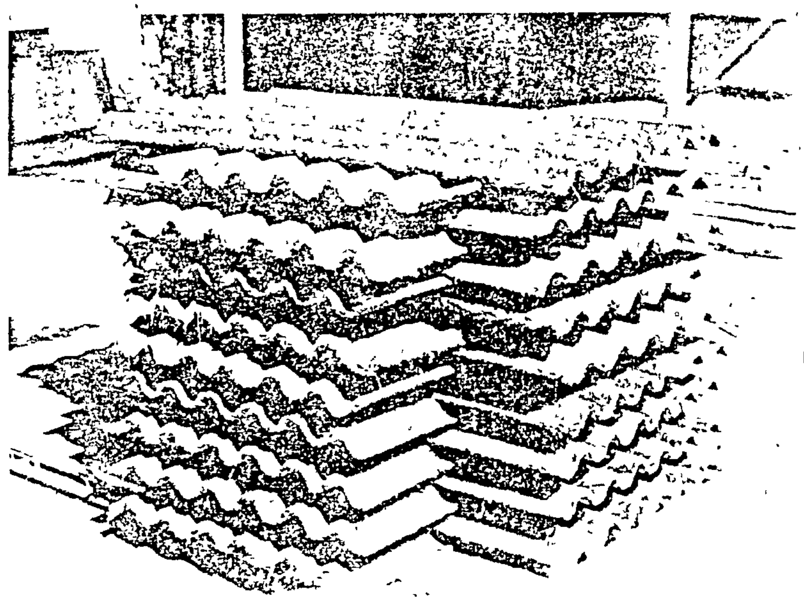


Fig. 7.50 Corrugated roofing sheet from coir waste/wood wool (Stulz, B.)

The I.T. Workshop Roofing Sheet (Fig. 7.51)

Roof sheets: Work on evolving the best application for the fibre-cement roofing technology has resulted in the development of a sheet or panel designed to fit on a variety of roof structures.[75]

The sheets can be made in two alternative forms; smooth side upwards with a highly reflective top surface, or with the trowelled face upward, so that the strengthening cross ribs provide an attractive tile-like effect.

Most fibre-cement sheets are now made in short lengths of one metre to accommodate irregularities which occur in many roof structures.

Purlins out of line would break a single long sheet. But two short sheets can adjust at the overlap and avoid breaking.

Ridge tiles: A second component which can be made in the same plant is the fibre-cement ridge tile. In its simplest form this is just a plain capping which provides a strong ventilating ridge to the roof.

All the products are made of a simple formula of Portland cement, sand, chopped fibre and water. A wide range of artificial and natural fibres can be used to make the FRC products, including sisal, coir and polypropylene.

The technology: The process is simple but involves some subtleties of skill and technique which take a few days training to learn from an experienced, certificated sheetmaker. The work begins with the operator trowelling a thin scread of cement. This is then corrugated by pulling it onto the mold using a selflubricating interface sheet.

The apparatus can be made out of steel or wooden components and is easily transported in a standard van. It can be constructed and put into operation within a few days by an experienced team, producing sheets at a fraction of the cost of similar materials.

Strength: The sheets can be made to a specification. Where needed, greater strength can be achieved by increasing their thickness or the depth of the corrugations and cross ribs, or by using a higher cement sand ratio. For normal climates it is considered that a load carrying capacity of 100 kg at a point midway between the purlins will be adequate. In hurricane-prone areas it might be necessary to increase this minimum to 150 kg. Typical FRC roof sheets weigh 18 kg per sq.m.

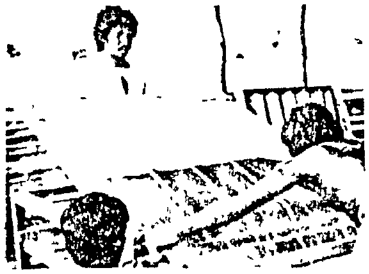
Durability: As the production process was first developed in 1977, roof sheets made with I.T. Workshop method have only so far been under exposure test since then until the time of preparation of this leaflet in 1980. None of the many thousand sheets put under test or in to practical use on buildings in different countries over the last 3 years has shown any sign of physical deterioration due to age. So durability could be a feature of this new product as well as low initial cost.

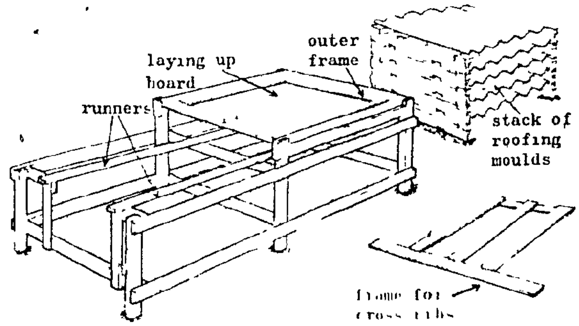
Structures: Although up to a third heavier than asbestos, FRC sheets do not demand any difference in roof structure as the main factor determining the design of these is not weight, but wind pressure which could amount to ten times any load put on the roof by the weight of the sheets themselves. Builders should use trusses made on a template to ensure that purlins are accurately positioned. FRC sheets are not flexible and will crack if fixed irregularly.

Fixings: The majority of FRC sheets in use are nailed, but where possible the use of hookbolts is preferable providing a more secure fixing. Development work is in progress on a system of built-in fixing ties to further reduce the cost of bought-in components.

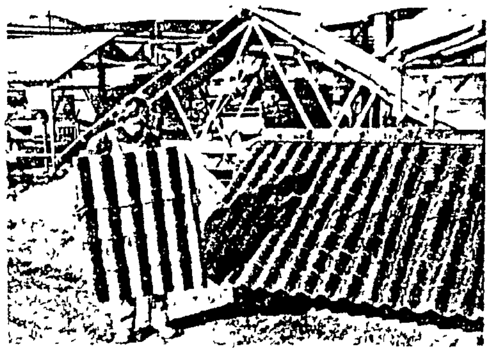
Maintenance: The sheets are not especially resistant to impact from heavy falling or flying objects and where this occurs repairs will be needed for holes and cracks. This can be done insitu without actually removing the sheet, and it is even possible to undertake the repair from below, thereby avoiding having to climb on the roof. The repair is simple to carry out, the sheet surface around the crack is painted with

Fig. 7.51

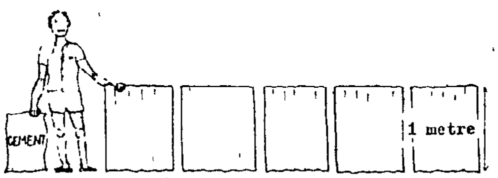




Manufacturing of sheets.



Testing.



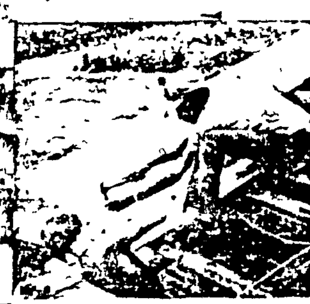
IN TYPICAL APPLICATIONS ONE BAG OF CEMENT AND ONE MAN'S LABOUR NOW MAKE FIVE ROOF SHEETS IN A DAY

I.T. ROOF SHEETS WORLDWIDE

Honduras; catchment tank roof

Fiji; demonstration ro

U.K.. maintenance workshop



The Gambia; demonstration roof

Sri Lanka; material sto

PVA (white wood glue) and then a patch of fresh fibre-cement patted on by hand and left to set.

Economics: The most important cost in producing the sheets is cement. For normal applications with good sand it is often possible to produce standard duty sheets with as little as 8 kg of cement. One bag of cement will therefore produce roofing cover up to 6 sq.m. Where heavy duty sheets are required, cement used may be as much as 12 kg so that one bag will produce 4 sq.m. Labor needed to run roof sheet plants is usually 4 men to make 20 items a day. For costing, allow about 1.5 manhours wages per sheet. Sand and fibre are not usually regarded as a significant cost factor. One kg of fibre will normally produce 5 sheets and a ton of sand over 100 sheets.

Climate

Like the other fibre-cement roofing systems, this roof can perform as well in warm humid climate as in composite climatic zones if other arrangements such as for ventilation and adequate ceilings are made.

Economics

If cement is produced locally, foreign currency requirements are eliminated. The process is relative labor intensive and the sheets can be manufactured in blind production. The cost factors appear to be well balanced.

Technical Criteria

Installation can be defined as being easy and transportation problems do not occur. Durability is high and maintenance is minimal.

Social Criteria

All social criteria as described (pp. 34-37) earlier can be measured positively with this roofing system in the two climatic zones where it is suitable.

General

It appears that this type of supported roofing system represents a well balanced solution with the promis of a wide application offering an alternative for the CGI roof replacement.

7.4.3. CONCLUSIONS

Applications of fibre-cement will depend on the ingenuity of designer and builder taking advantage of the static and dynamic tensile strength and other characteristics of the material.

Comparing the characteristics with those of ferrocement it appears to me that they could complement each other in the form of fibrous ferrocement elements. Fibre-cement embodies qualities which make the material a potential roofing material for supported roofing systems in the form of corrugated sheets. But it should also be possible to produce elements for self supporting roofs such as the asbestos domes and vaults specially designed and manufactured for the Kainji resettlement in Western Nigeria in the 1960's,[76] but utilizing cheaper locally available fibres.

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8. burnt clay

Burnt clay materials have been used for building since history has been recorded. These products are made from a material found in abundance almost anywhere around the world.

The clays used for roofing tiles are quite variable in composition but produce a hard, infusible, insoluble mass, resistant to weathering and fire.

The quality and color of the finished product depends on the type and mix of clay used and on how well the wet formed tiles are dried and burned.[1]

Three different processes for producing burnt clay products are known:[2]

- soft mud process
- stiff mud process
- and dry pressed process

In the soft mud process clay is mixed with water to a soft consistency and pressed into molds. If the mold walls are wet with water to prevent sticking, the tiles are called water struck; if the mold walls are sanded, the tiles are sand struck.

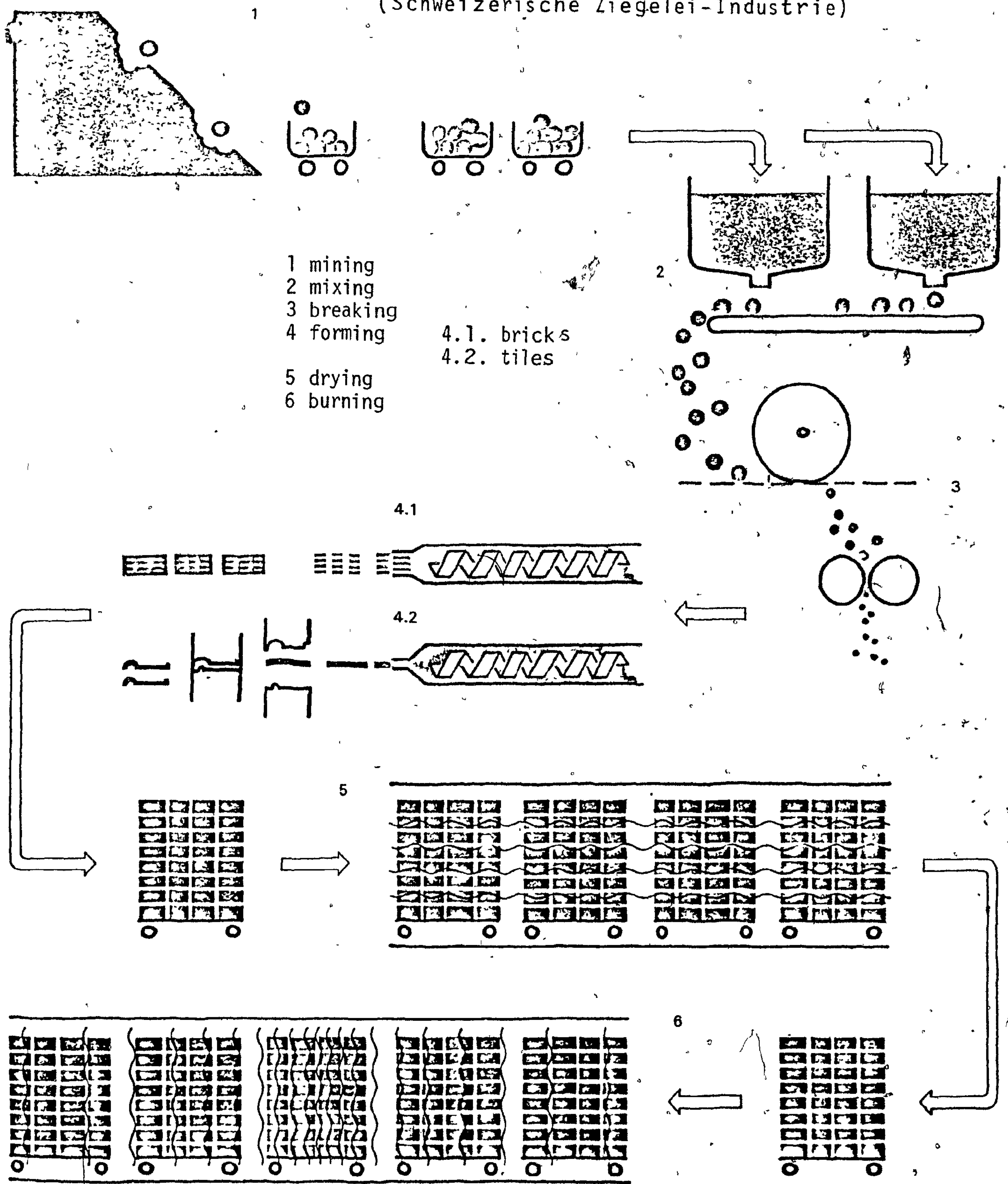
In the stiff mud process (for bricks mainly), high consistency clay is forced through a die as a continious ribbon whose cross section is equal to either the end or the flat side (bed) of the unit. It is cut by taut wires into individual end-cut or side-cut units.

In the dry-pressed process "dry" consistency clay is forced under heavy pressure into multiple or gang molds. This process produces the greatest accuracy. (Fig. 8.1)

After forming, bricks and tiles have to dry either naturally or in special dryunits. The final process of burning takes place in kilns under temperatures between 900°C and 1000°C.[3]

The durability of the tiles depends upon the degree of burning achieved. Tiles nearest to fire are burned the hardest and may be overburned, those farthest from the fire may be too lightly burned and only good enough for mild conditions.[4]

Fig. 8.1
The fabrication of burnt clay products
(Schweizerische Ziegelei-Industrie)



8.1. SELF SUPPORTING "CLAY ROOF"

An interesting but today little or no more used technic of building jack arches or vaults with clay elements is the method of using the ceramic fusée. The fusée has the shape of a bottomless bottle made of ordinary drawn and stamped clay.[5]

The total length is 30 cm with a useful length of appr. 25 cm, an external diameter of 8.0 cm, an internal one of 6.0 cm and an approximate weight of 1 kg. (Fig. 8.2)

The neck ensures the proper overlapping of the fusées in one and the same line by fitting them one into the other which makes them adaptable to extremely pronounced curvatures.

Structurally it appears that this method would not be cost competitive with ferrocement, as a mortar coating to bond the rows of fusées together is necessary, which together with the recommended distribution reinforcement would make up a ferrocement structure alone. (Fig. 8.3)

However, there is an interesting aspect which is the second important property of the "Ceramic Fusée", its isothermy. Depending on the method they are laid. this isothermy may reveal two different aspects:

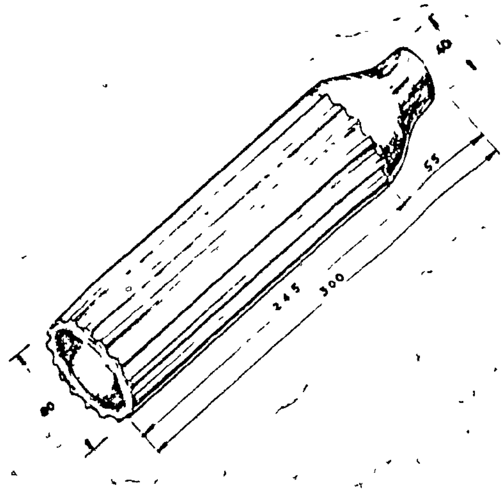


Fig. 8.2 The Ceramic Fusée (C.S.T.B. France)

Fig. 8.3 Laying the fusées.

- classical isothermy common to all hollow structures;
- dynamic isothermy; (Fig. 8.4)

Although many m^2 of roofs have been constructed in France (310,000 m^2 to 1969), Netherlands (appr. 750,000 m^2) and other European countries, I could only trace one low-cost housing scheme in a developing country, 508 houses in the new town of Medina de Fedala in Morocco. (Fig. 8.5)

The necessity for an industrial process to economically manufacture these hollow "fusées" make it a difficult choice for a roofing system. However, it seems that if a brick factory would have the tools to manufacture them cheaply, this system could make a good roof for composite and hot dry maritime climates.

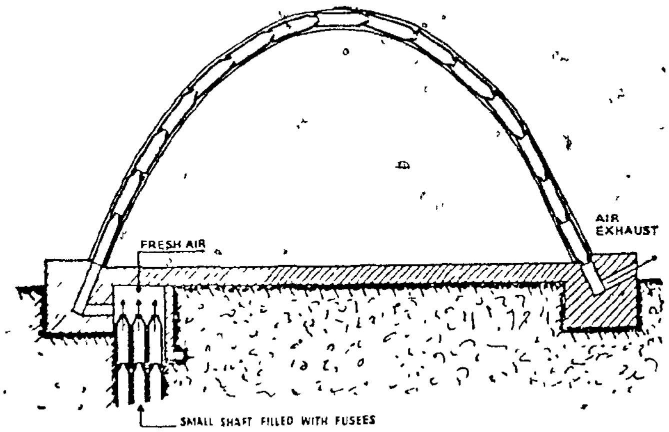


Fig. 8.4 Diagram, showing the air circulation in an arch.

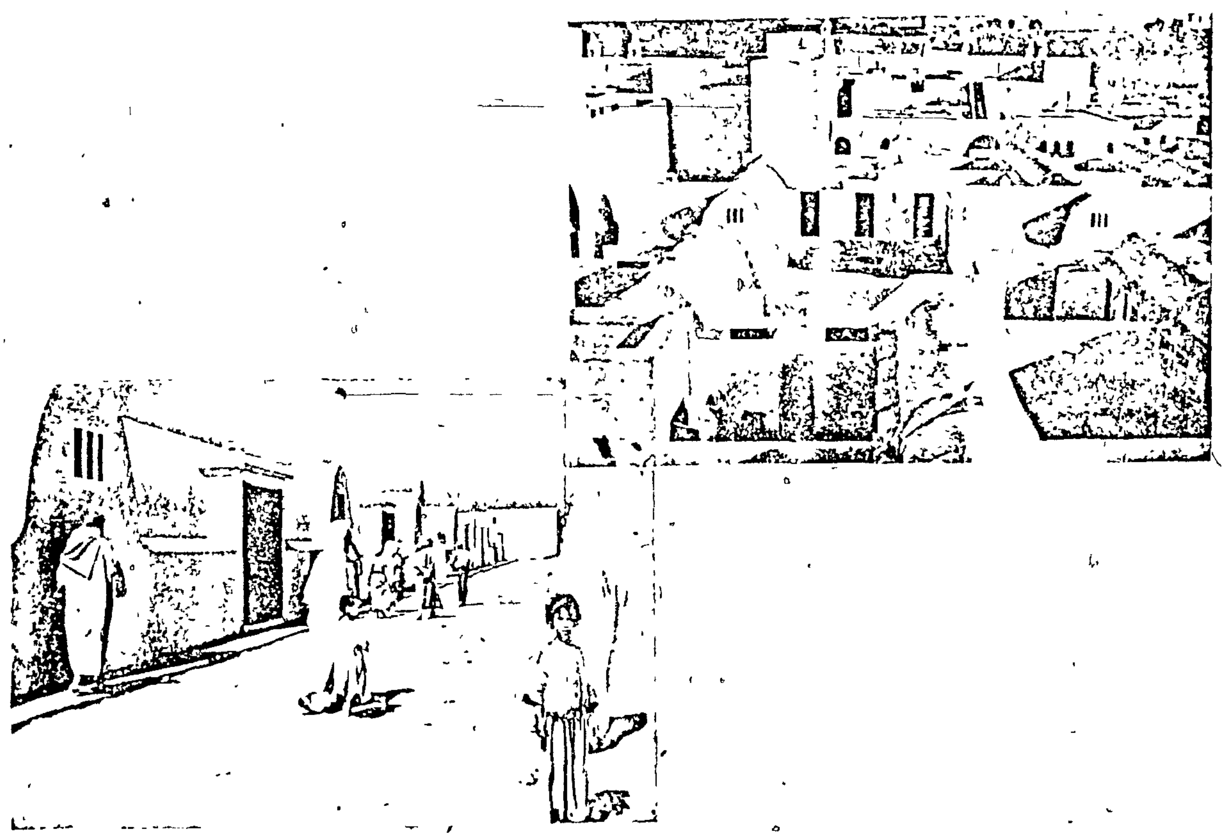


Fig. 8.5 The new town of Medina de Fedala (Morocco)

8.2. SUPPORTED CLAY TILE ROOFS

Simple kilns have been used in many developing countries to produce pottery for everyday's use, in many cases they have been reintroduced to manufacture bricks and tiles.

Clay tiled roofs did not have a tradition in most developing countries. But with colonisation in South America clay tile roofs became very popular and were dominant in urban areas until CGI roofs were introduced later.

Tiles

Various shaped tiles have been developed all over the world. The most common of them all is the single curved roman tile. (Fig. 8.6)

Roman and plain tiles are so common as they need little precision in manufacturing and still make a weather-tight roof. Naturally a roman tiled roof would be heavier than one made with overlapping or interlocking tiles. But it is the use of a simple soft mud process to manufacture plain, roman or overlapping tiles which makes these types the most widely used ones. Interlocking ones are usually manufactured in industrial processes with modern machinery and in continous kilns.[6] (Fig. 8.7)

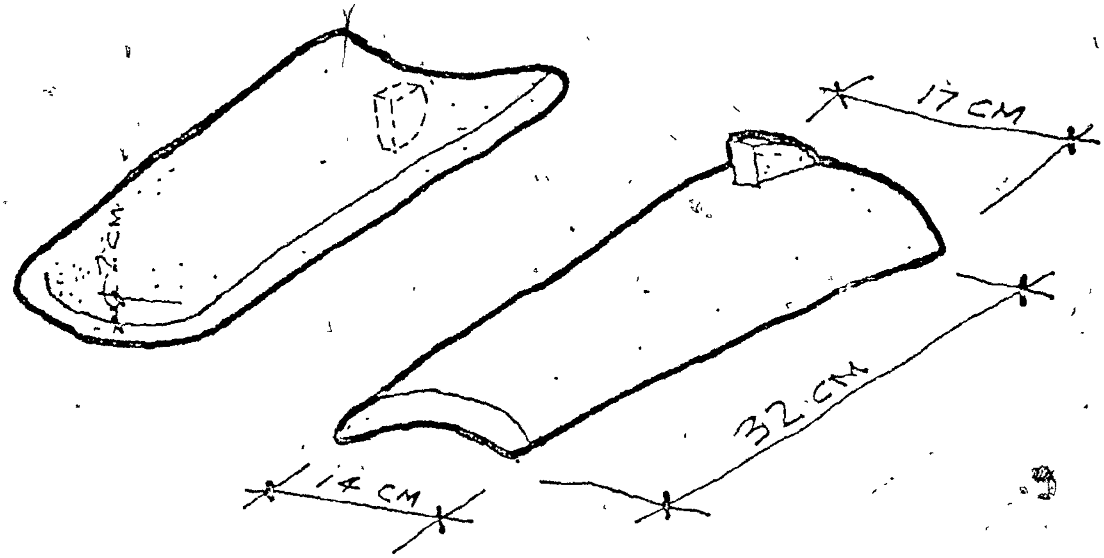
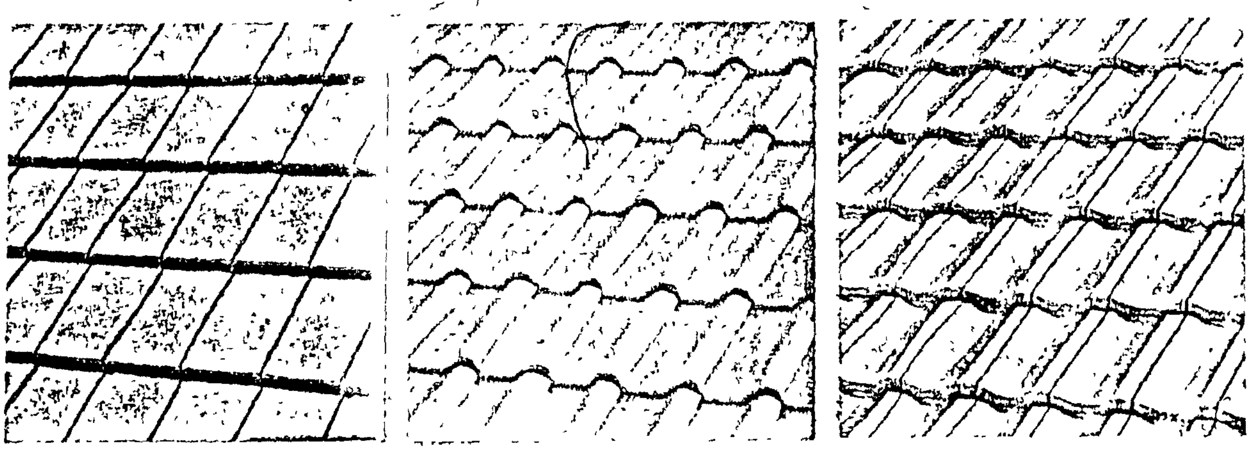


Fig. 8.6
The roman type fixed clay tile.
(Florida A&M University)



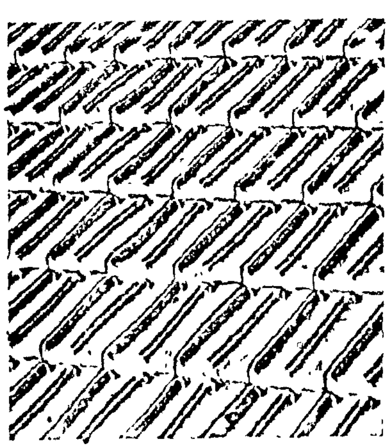
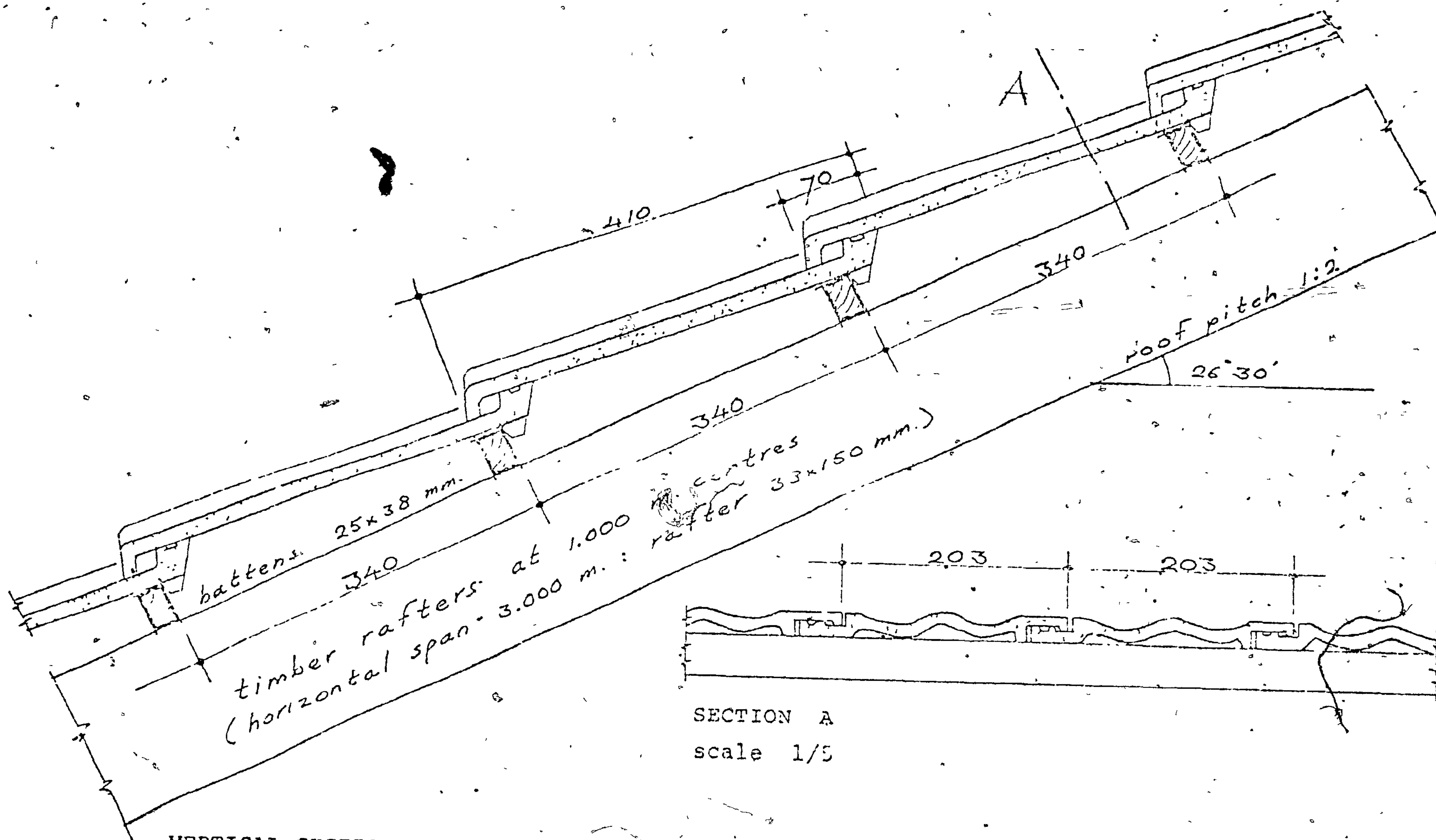


Fig. 8.7 Flat overlapping and interlocking machine made clay tiles.
(Schweizerische Ziegelei-Industrie)

Roofs made of burnt clay tiles require a minimal slope of 1:2 (appr. 26^{0}) without sarking* but could have a ratio of 1:3 (appr. 18^{0}) with sarking.

However, steeper slopes are recommended for structural as well as shelter reasons. In most cases a higher pitch is chosen for aesthetic reasons anyway.

* Sarking is an impervious membrane under the roof covering to prevent penetration of occasional drops of water during driving rain, made of either bituminous roofing felt or polythene sheeting.



VERTICAL SECTION
scale 1/5

SECTION A
scale 1/5

Fig. 8.8 (Eygelaar, J.)

Burnt clay roofing tiles - Mangalore type

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Support

The relative heavy roofing material (appr. 30-35 kgs/m^2) requires a support structure usually made of sawn timber, capable to carry this dead weight plus super imposed loading and the weight of the ceiling structure.

Corrugated Clay Roofing Sheets

"In Appendix 1. Low-cost roofing research in India of roofing in developing countries", an interesting product has been described:[7]

A process has been developed for producing corrugated clay roofing sheets (105 cm x 60 cm x 0.1 cm) from specially processed clay mix. These sheets do not warp or crack during drying and firing, and the process is simple enough to be implemented with hand labour in "village industries". The tensile strength of these sheets lies in the range between 100-105 kgs/cm^2, and water absorption is below 2 percent. Each sheet weighes about 15 kgs.

But room dimensions in low-cost housing lead to roof spans which do not require trusses for supporting the roof purlins (used for CGI roofs) or the roof battens used for tiled roofs. The roof purlins or battens can rest either directly on walls or partitions or on simple rafters.

Climate Considerations

Koenigsberger's and Lynn's study on roofs in the warm humid tropics show that this roofing system even if used with some insulation and a ceiling does not perform as well as a CGI roof or fibre-cement roof would.

The thermal mass of this roof has a negative effect in this climate.

In hot dry climates the clay-tile roof has too little thermal capacity to make a comfortable roof. Furthermore this is the least airtight roof discussed and would be uncomfortable during frequent dust and sand storms occuring in this climate zone.

In all other climate zones (maritime desert climate, composite climate and tropical upland climates) this roof appears to be a good compromise for the changing seasons' conditions. However, a ceiling with resistive insulation should be installed with this roof, if possible.

Economic Considerations

If the clay tiled roof has been one of the more expensive roofs during the fifties and sixties this has gradually changed during the last decade.

The relative cost of the various low-cost materials has changed considerably due to international movement of raw material prices, increased cost of energy and the introduction of local industries utilizing local materials and labor in many developing countries now.

A very strong advantage of burnt clay products is that they can be competitively produced with local materials in blind production, either in the most primitive labor intensive way and small quantities or in a highly industrialised process and large quantities.[8]

It is possible to find the right size and type of manufacturing process between labor intensive and capital intensiye technologies for every region and thus foreign currency requirements will be minimized.

In areas where fuel is exhorbitantly expensive, this material may not be cost competitive.

Social Considerations

A tiled roof is safe and pleasant in shape and color; it has a permanent and modern status and reflects a natural transition from traditional roofs made of organic materials.

In some areas colonial heritage may be a negative aspect against this otherwise very acceptable roof.

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9. earth roofs

Earth is probably still the single most important building material in developing countries around the world.

Earth means the entire spectrum from topsoil to colloids, clay, silt and sand with little or no organic matter.[1] For building purposes clay and sand are used with water in various ways to form building components or elements. Foundations, floors and walls made of rammed earth, adobe blocks or cob and wattle and daub are the oldest methods of building construction and with time and labour being a less critical factor a cost competitive way of building houses.

Heavy rainfalls are a destructive force, eroding earth structures very quickly.

To increase its resistance to deterioration and water and in some instances, to increase the strength, attempts have been made to stabilize soil by admixtures.[2]

The following indigenous materials have been employed, usually on a completely empirical basis: cattle dung and urine, grass, flax, straw, oat straw, jute fibre, sawdust, wood shavings, tannic acid, molasses, various plant juices, pulverized claybrick and tile, gum arabic, and hard wood ashes.[3]

But the most extensive work in stabilizing earth has been done with "modern" agents like portland cement, lime and lime admixtures and emulsified asphalt.

Surface coatings are another way of protecting earth structures from erosion and general weathering. Many different plasters and stuccoes or other thick coatings are commonly applied to limit water absorption. Where cost is of overriding importance and better materials are either too expensive or unavailable, mud plaster is widely employed.

In Northern Sudan, the earth finish used for walls and roofs is called Zibala, a mix of animal dung, straw and mud.[4] (Fig. 9.1)

Lime and Portland Cement, if available and not too costly, can provide a hard and durable protective plaster or stucco when properly formulated with a good grade of clean sand, using standard mixes.[5]

The extreme exposure to weather makes the earth roof the critical element of the mud house.

Earth roofs are heavy structures and if not structurally sound great hazards to the dwellers.

After heavy rains they sometimes collapse under the weight of wet mud or of the pond which is formed as the result of the roof deflection. Earth roofs should not be considered in seismic areas as they are the first to be destroyed during even minor shocks.

9.1. SUPPORTED ROOFING SYSTEMS

Traditional roofs are still the most common in rural areas of the hot dry tropics where the materials and the skill are still available.

Materials are basically timber from the palm tree and earth finished with "Zibala". The palm tree provides the main beam "mirig", the joints "sharig", the matting bearers "jarid" and the matting "birish" which receives the mud layer.[6] * (Fig. 9.1)

Sometimes dry leaves of the palm tree or dry grass are placed under the mud layer. The initial cost is normally small but good experience and a certain skill is needed to build this heavy roof. (Fig. 9.2)

* Zibala, mirig, sharig, jarid and birish are designations used in Northern Sudan and are different in other places.

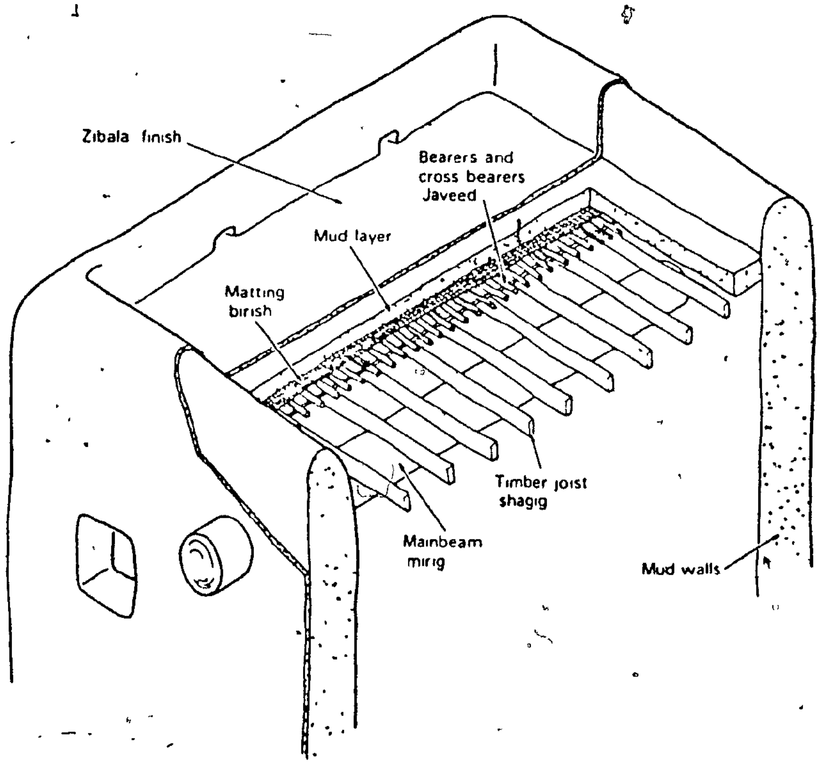


Fig. 9.1
typical mud roof
in upper Sudan
(OBN no. 182)

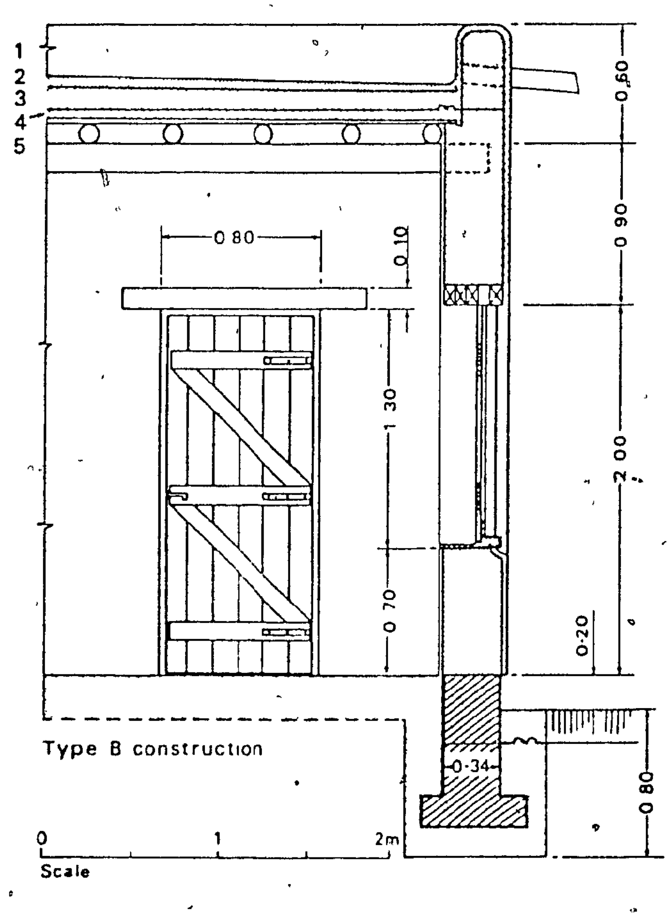


Fig. 9.2 Typical section through mud roof (OBN no. 165)

1 Mud-brick parapet
2 Roof finish
3 Earth layer
4 Polythene or roof felt
5 Bamboo matting, joints and beams

Climatic Considerations

This roof, combined with customary mud walls and minimum openings, provides a satisfactory internal climatic condition in hot dry and composite climates. If built properly, the roof can also sustain the infrequent heavy rainfalls. *

Economic Considerations

This roof has a positive local impact on the economy; it can be built almost entirely of locally available materials in a labour intensive process with little equipment needed.

The need of heavy main beams and numerous timber joints makes it more and more expensive but modern solutions have shown that this traditional method of building can be improved with modern low-cost materials.

Technical Considerations

The cost factors of this roofing system indicate that there are two problems to consider: the support structure and maintenance.

* Kano in Northern Nigeria counts appr. 20 rainfalls during the rainy season, other places in the Sahara Desert from zero to four or five.

The support structure can be made of precast concrete joists similar to the false slab system and then covered with CGI sheets or traditional materials. More recent proposals suggest to use ferrocement structures as they could carry the earth material and make the roof watertight at the same time.

Annual maintenance is absolutely necessary as most earth roofs leak after heavy rains and roofs gradually deflect. Even, if made watertight with the help of plastic foils or roofing felts laid on the subroof before adding the mud, a protecting coat of plaster or some sort of tiles is necessary to prevent excessive erosion.

Social Considerations

After having visited places like Kano in Northern Nigeria, Agadez in Niger or Beni Isguen in Algeria where the mud house is predominant, it is hard to imagine that there could be a better way of building houses in this climate than the traditional way. The flat roofs, forming an outdoor extension offering privacy, are an integral and extremely important part of the Islamic house.[7]

The roof in this climate is used for sleeping and various domestic activities such as drying linen or food staples.

Although the application of this type of roof in urban areas is becoming impracticable due to its weight and difficulty of construction and maintenance in multi-storey buildings, its social importance and acceptance has probably never been in question.

9.2. SELF SUPPORTING ROOFING SYSTEM

Mud brick domes and vaults had a tradition in the oriental architecture as far back as 4000 B.C. or even farther.[8] It can be assumed that wherever roofs did not have to be accessible that this method would be more economical and architecturally satisfactory as no scarce timber is needed and weathering would be less severe than on a flat roof. (Fig. 9.3)

The only recent example of these types of roofing I have found are the famous mud brick dome and vault houses and community buildings of the village of New Gourna in Upper Egypt, designed by architect Hassan Fathy.[9]

Initially there were a 1-50 one and two storey houses built including communal facilities such as market place, shops and craft works, an open air theatre, a large recreation area, an administration building and townhall, two large 12 classroom schools, a craft school and workshops, a community building, and a very fine Mosque, all in sun-dried mud bricks.[10]

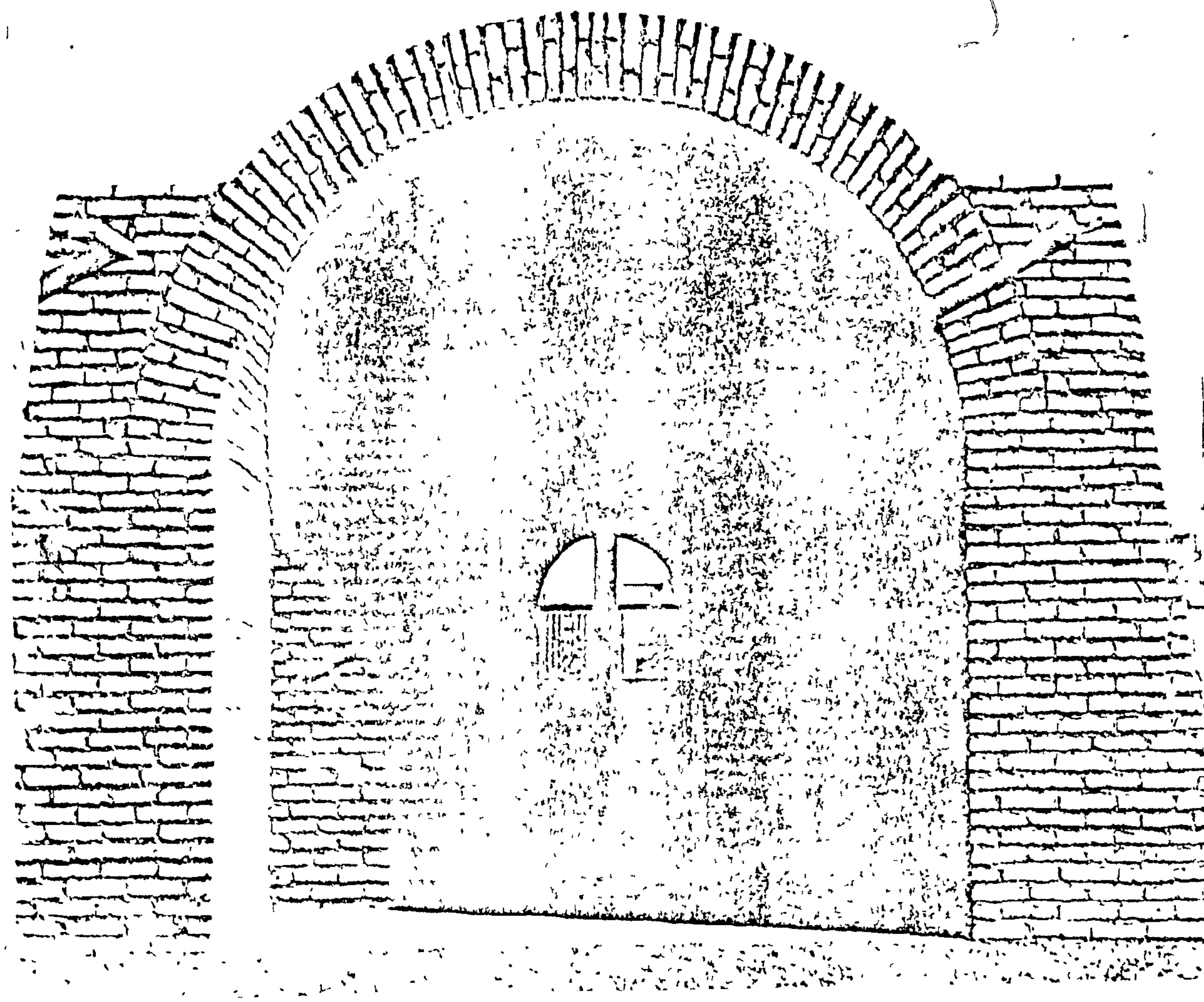


Fig. 9.3 Experimental earth structure built at the International Institute of Housing Technology, Fresno State College, Fresno, California.

These mud bricks, containing good clay soil (one cubic meter), white calciferous sand (1/3 cubic meter) and fresh straw chaff (about 22 kgs), were manufactured in the traditional way with no stabilizing agents.[11]

For practical purposes, spans for mud brick vaults are about 3.50 m. Construction is usually started against end walls and built towards the center. One mason can lay about one linear meter of parabolic shaped vault per day.[12] (Fig. 9.5)

Low and high domes are built in the "igloo" manner, and similar to the high vault, are built in pure compression as mud roofs would not stand up to forces of bending or tension. (Fig. 9.4)

The low domes similar to Christopher Alexander's suggestion (p. 96) is suitable for two-storey construction or where, by filling in above the domes, a flat roof is to be obtained.

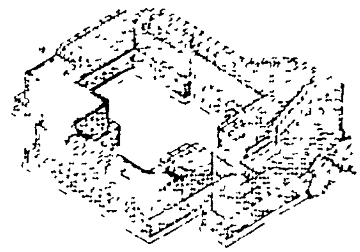
Climatic Considerations

They are direct comparable to those of the flat supported earth roof.

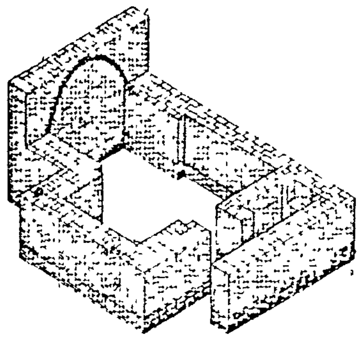
Economic Considerations

With the severe shortage of structural timber in many hot dry regions, this method offers a feasible alternative to the supported flat roof version. It is,

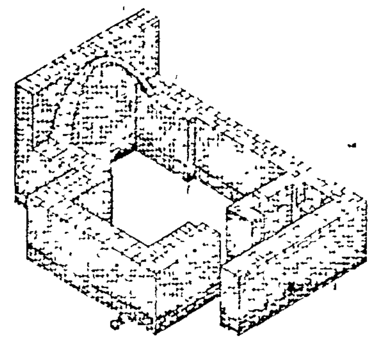
Fig. 9.4 The process of building earth domes and vaults as built by H. Fathy in New Gourna, Egypt.



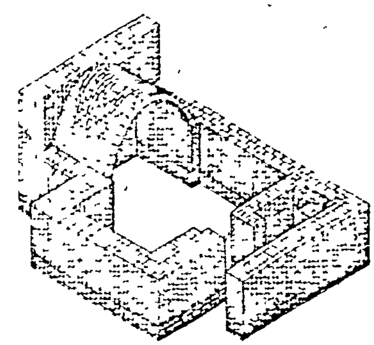
Foundations



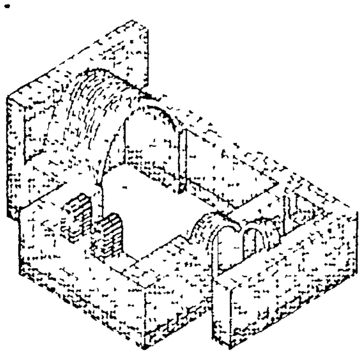
Walls built up to the level of the spring points of the vaults. End wall built up for vault to lean on. Inverted catenary form traced on end wall.



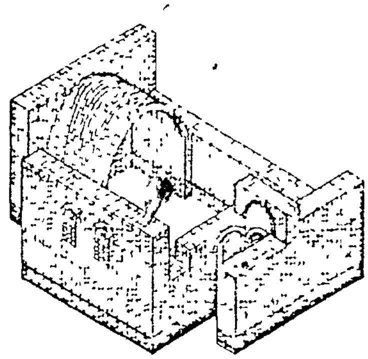
Vault building with courses leaning towards end wall so that no form work or shuttering is needed



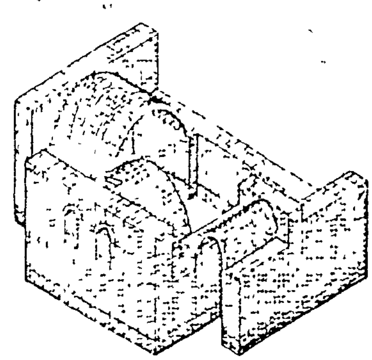
Vault completed



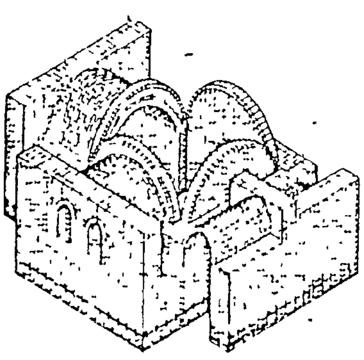
Window openings built up with dry brick – no mortar.



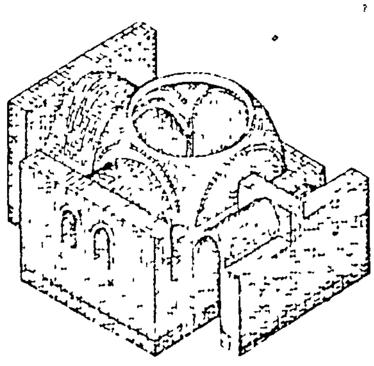
Walls built up. Arches built over dry brick in windows



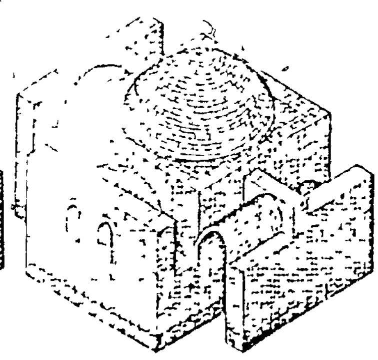
Small vault built in same way as large ones. Loose bricks removed from window openings



Circular arches built over vaults to form a base for the dome



Pendentives completed, forming continuous course from which dome can be completed



Brick courses of dome incline increasingly until dome is finished.

however, much more labour intensive and with the even higher use of earth material more problematic for urban areas in bigger cities.

Maintenance is absolutely essential.

Technical Considerations

More than any other traditional roofing system this method of building requires skilled/and experienced labour no longer found everywhere.

Social Considerations

More than probably any other culture today, Moslem societies are traditionalists, rejecting many Western methods which are often inappropriate to local conditions and needs. As John Turner[13] is saying, the idea of housing as a "product" is unworkable; I believe that in the hot dry regions where Islam is prevailing, mud brick constructions are allowing housing to be a "process" and therefore this indigenous system will always have a future.

Fig. 9.5
(HUD, mud brick roofs)

Two masons are seen applying the mud guide ring which will tie the vault to the end wall. The end wall has been built above the limits of the ptoposed vault and has had sufficient time to dry and reach its maximum stability. It is now ready to receive the thrust of the vault. Before Gourna Village was started the masons would make this mud ring guide by guess work and by eye. Dr. Hassan Fathy speeded up construction time by making a wood template in the shape of the under side of the vault and using this template as a guide for this mud ring. A more uniform vault was the result, plus a saving in time, In addition, at New Gourna, two masons, rather than one, work on the vault. One helper can supply material for both masons.

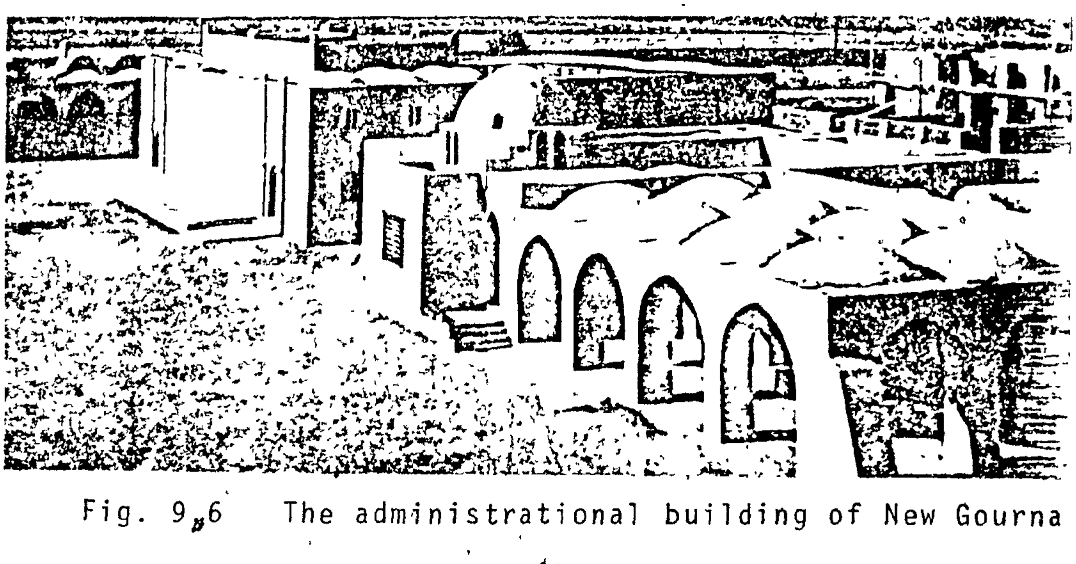


Fig. 9.6 The administrational building of New Gourna

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10. waste materials

10.1 INTRODUCTION

The sheer volume of waste output derived from packaging and agricultural as well as industrial production processes is clearly sufficient argument to justify research into re-use and recycling of waste materials for building purposes. Unfortunately, the population of industrialized countries does not see much value in waste materials. (Fig. 10.1)

The kind of value we see in what we waste and how this is looked at by native populations of developing countries has been written to the point by Martin Pawley in his book, "Garbage Housing"[1]:

> "We in the West have come to identify the termination of one use with the termination of all usefulness, and we carry this simple idea through ruthlessly, in our treatment of the old as much as our treatment of the waste products our society generates in such profusion."

Martin Pawley further quoted Frances Fitzgerald who wrote in her book, "The fire in the lake"[2], that enormous differences in culture and perceptions separated the Americans from the native populations of South East Asia:

"For the Americans in Vietnam", she pointed out, "it would be difficult to make this leap of perspective, difficult to understand that while they saw themselves as building world order, many Vietnamese saw them merely as the producers of garbage from which they could build houses."

It must be the use of terms like waste, refuse, garbage, junk and litter, bearing an unmistaken negative connotation, which created this perception of: once used is equal to termination of all usefulness. Forrest Wilson[3], in his article on the First International Conference of "Garbage Architects", made a very strong statement for the quality and value of waste materials used for building purposes, and he probably used for the ~~above~~ reason a positive term in the title: "Building with <u>Byproducts</u> of Society".

If the term byproduct is used for all those materials usually described under waste, <u>secondary use</u> of these materials for building purposes would have a much more positive meaning.

There is, of course, a wide variety of byproducts used already for building and other purposes. These "waste" materials are usually grouped into <u>consumer waste</u> and <u>industrial waste</u>.

Consumer waste is less significant as a planetary poison. Nonetheless, the fact that it is to be found everywhere (but in lesser quantities in developing countries) presents unique problems of retrieval which are not generally faced where industrial waste is concerned.[4]

Industrial wastes are in general concentrated and are also relatively localised and will therefore, according to Pawley[5], most likely remain the most realistic target for recycling programmes.

Recycling, in the strict sense of the term, is not a very efficient and is certainly a very expensive way of tackling most of the problems posed by consumer waste disposal.[6] But even if recycling of industrial and agricultural wastes appears to be realistic today, it would make more sense if they could be adapted to secondary or alternative uses.

Secondary use is most often associated with low-cost construction. This is also true in developing countries, though to a lesser degree. Martin Pawley argues that secondary or alternative use of waste materials is the only means by which an adequate amount of housing materials can be supplied in a fast developing society without total disruption of existing production processes.[7] As long as we find these ideas remote from our mind or reference, it will be impossible to venture into this new world of possibilities which also offers a unique design challenge.

10.2 CONSUMER WASTE AND BYPRODUCTS

Consumer waste consists of various components, the most important of them being: paper, metals, glass and organic matters. Separation of these components is very difficult and most garbage is therefore indiscriminately dumped.

Different ways have been tried by introducing means of recovery of resources contained in garbage. Magnetic and flotation separation, air classifying, pyrolysis and use of some substances for production of building blocks, boards and panels are the latest accomplishments in this field.[8]

In principle, processes converting consumer waste into building materials consist in its decomposition into workable mass, grinding into fine granular material and compressing it under heat with the use of chemicals. End products are boards, panels, blocks, roofing tiles and shingles* which have apparently good physical and mechanical properties.[9]

Other than recycled consumer waste roofing materials are those with a long and honorable history. The secondary use of bottles for building has in fact been recorded as far back as the fourth century. The Roman tomb on the Via Apia was dubbed "pigna terra" in honor of its dome built of clay pots.

* Neither a product reference nor any project application could be traced by the author.

Similar to the above, it is not known what the pots were serving for before they were used for the dome of the orthodox baptistry built around the same period in Ravenna, but they might well have been former wine jugs.[10]

In more recent pioneering history, buildings were built of whisky bottles, some of them still standing in Nevada, Alaska and Australia.[11] (Fig. 10.2)

In developing countries, bottles hardly find their way to become roofing materials as they are making good containers for palmoil or other household liquids.

A secondary-use consumer waste material for roofing are thin metal containers. When cut open and flattened, they make good roofing sheets or shingles. Such an application had been seen by the author in some of the squatter settlements in West Africa.

Waste-Paper Corrugated Roofing Sheets

The Central Building Research Institute in Roorkee, jointly with the Regional Research Laboratory in Jorhat, India, has developed a corrugated paper roofing sheet with remarkable properties.[12]

These sheets are made out of "road sweeping paper", grass or straw. The process of making these sheets involves

Fig. 10.1 Waste from packaging (Pawley, M.)

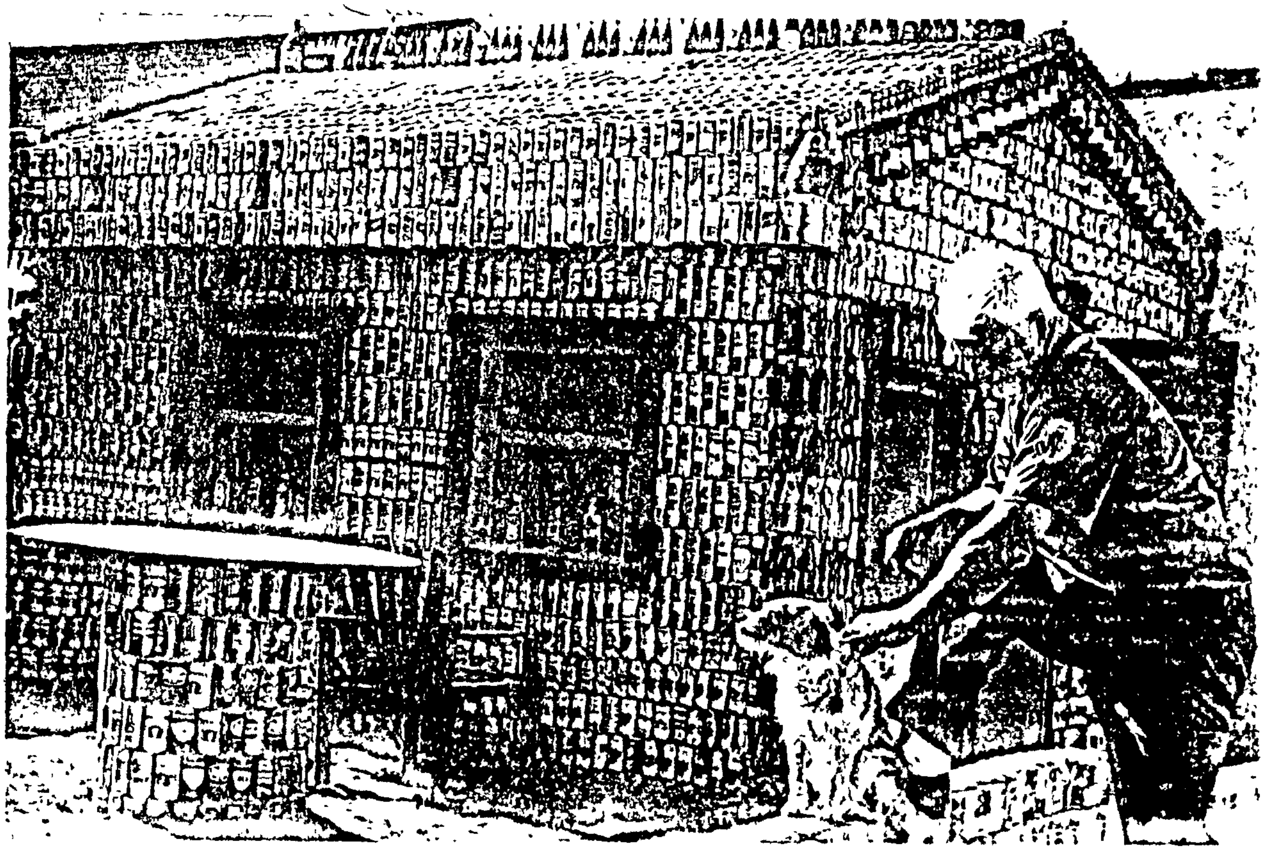

Fig. 10.2 Walter Sizemore built his house from cans and bottles with a steel frame (Pawley, M.)

mechanical beating of the waste paper or other cellulose wastes and mixing it into pulp. The pulp is then fed into a continuous sheet-forming machine, producing wet sheets of various thickness.

10.3 AGRICULTURAL BYPRODUCTS

Agricultural byproducts, husks, stalks and grasses are available in many countries of the developing world in abundance and represent, like forest wastes, a remarkable resource.

The major agricultural byproducts with possibilities for pressboard and concrete manufacturing are:[13]

- abaca
- alphagrass
- bagasse
- barley husks
- cassava stalks
- cocoa shells
- coconut shells
- coconut outer husks
- coffee husks
- corn stalks
- corn cobs
- cotton stalks
- cotton seeds and hulls
- flax shives
- grass seeds
- hemp shives
- jute fibres
- kenaf sticks and coir
- linseed residues
- oat straw
- palm fronds
- peanut shells
- rape straw
- rice straw
- rice husks
- rosella
- seed flax
- sisal fibres
- sunflower husks

Forest byproducts for similar uses are:

bark

wood chips

wood shavings

saw dust

No specific roofing material has been developed from these materials so far, but several products can be considered as partial roofing materials, serving as ceiling boards or roofing substrate.

There are several problems involved in the manufacture of a roofing material from the above residues, such as:[14]

a) Storage, seasonal harvesting, risk of decay and fire hazard;

b) Transport costs, especially when the plant is not located near waste resources;

c) High expenses may arise from import of synthetic resins in the absence of locally produced or natural adhesives;

d) The size of the industry plays an important role in developing countries. Experience shows that up-to-date fibreboard production should be in the order of about 15,000 tons yearly and that of particle boards can be slightly lower in order to justify the investment. This might be too high for markets in smaller developing countries. In addition, there is a lack of know-how which cannot be easily overcome by developing countries without international assistance.

Three typical and well known products under this group are:*

"<u>Stramit</u>" straw panels, produced semi-automatically by compressing, with cardboard glued to both surfaces.

"<u>Duripanel</u>", an incombustible, weather-proof, resistant to rot, fungus and termites, product made of wood strands and portland cement.

"<u>Lignex Board</u>", a resin catalyst, rice husk bonded and hot pressed board with qualities good for building purposes.

10.4 <u>INDUSTRIAL REFUSE AND BYPRODUCTS</u>

There is a great variety of inorganic industrial wastes which can be used in construction. Some of them found as residues of byproducts are suitable as component for composite materials. Others in form of production byproducts or production rejects can be used as they are or somehow modified.

* Producer information.

The following examples are worth mentioning:

Asphalt

Paper Products

Sulfur

is discussed in more detail in separate chapters of this thesis.

Blast furnace slag has hydraulic properties and can substitute up to 80% of cement clinker, thus yielding considerable economy in fuel and energy consumption.[15]

Fly ash, formed by small solid particles generated in coal-burning power-generating plants, exhibits pozzolanic activity and is also a practical extender for portland cement.[16]

Burnt clay-bricks breakage is very good light-weight concrete aggregate and if finely ground, its pozzolanic properties can be utilized in substituting cement in mortars.[17]

Car body elements. The idea of economic integration as envisioned by Martin Pawley was carried farthest with respect to roofing in the "Citroen House", designed by Jeff Skorneck 1973 at Cornell University. (Fig. 10.3) With the collapse of Chile's foreign credits in 1971, the Citroen Chilena SA factory in Santiago, which had for several years built 2.3 and 4 CV vehicles using only imported engines and transmissions, was obliged to virtually cease production. Using manufacturer's data, J. Skorneck developed a design for the adaptation of

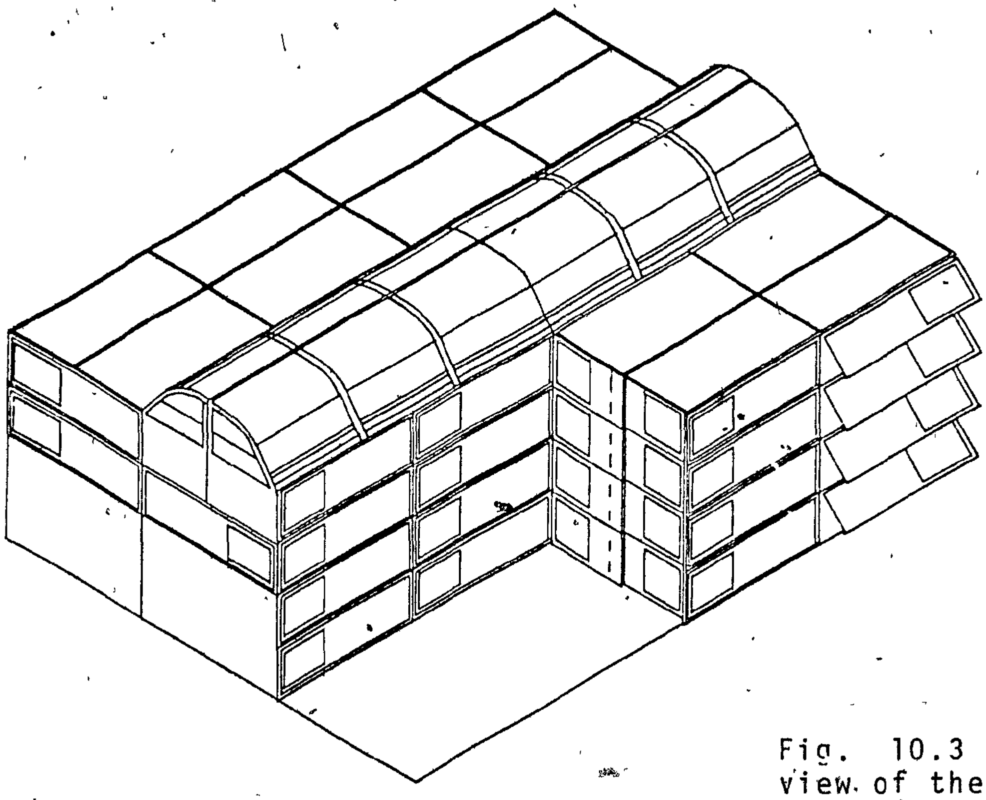

Fig. 10.3 Isometric view of the Citroen House (Pawley, M.)

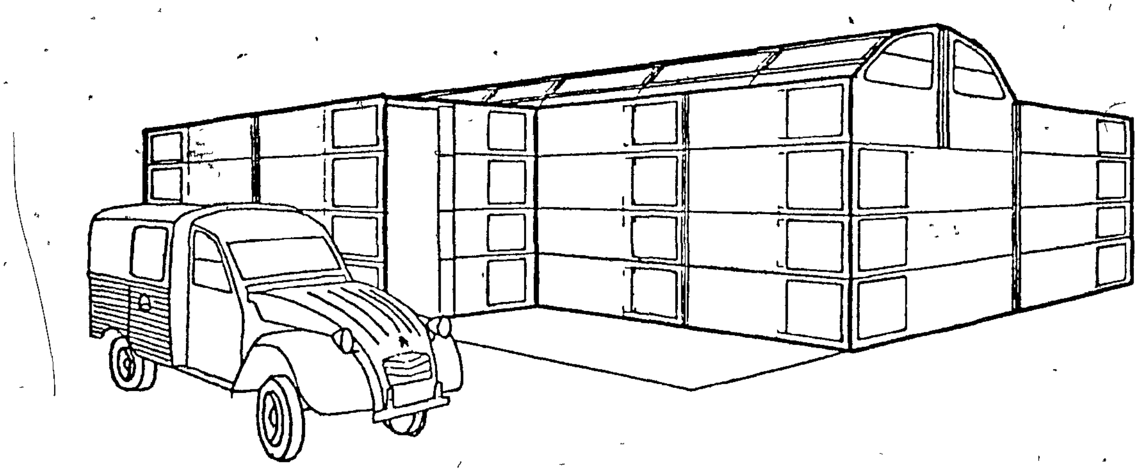

Fig. 10.4 Citroen House with Fourgonette in front (Pawley, M.)

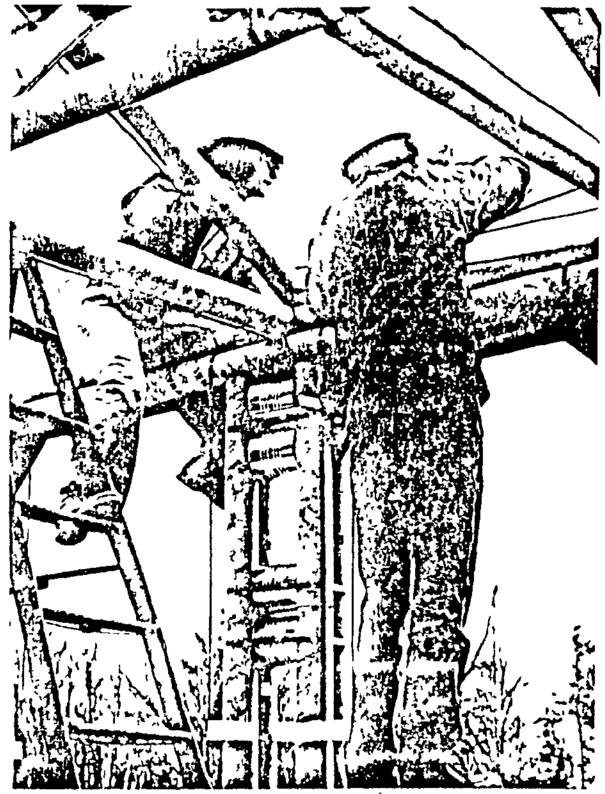

Fig. 10.5 Work on the Crouch House structure (AIA Journal)

Fig. 10.6 The roof covering of the Crouch House

Chilean produced body parts for the 2CV Fourgonette into a housing system. The vehicle (Fig. 10.4) proved surprisingly suitable for the conversion, which could have yielded a production of 5000 housing units per year.[18]

Butyl rubber cutoffs from extrusion processes were used as roofing tiles in the Crouch house, built in Troy, N.Y. (Fig. 10.5) The structural frame, trusses and columns of this house, are made from cardboard newsprint cores. The cores are joined with no. 5 steel cans, pinned with galvanized roofing nails and the trusses and columns are secured with steel strapping. The exterior walls of the Crouch house are no. 10 steel cans in mortar, except for a bottle wall at the living room and bedroom.

The roof covering consists of a triple layer of packaging cardboard, laminated with scrap polyethylene sheet and bonded with cold tar roofing cement. Over this are rubber tiles derived from butyl rubber cutoffs.[19] (Fig. 10.6)

10.5 CONCLUSIONS

Agricultural and industrial wastes are not sufficiently utilized mainly because there is inadequate current research and development to provide confidence to manufacturers and consumers in new products based on waste materials.

Tradition and prejudice supported by insufficient experience with such materials are leading to mistrust on the part of users.

Lack of support from the public sector and a limited market vis-à-vis investments and often scarcity of foreign exchange for import of sometimes sophisticated equipment for processing[21] are further limiting introduction or wider use of waste materials in developing countries.

But the waste resource utilization period of the future will be rich in innovations and the ingenuity of the designers the only limits.

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11. sulfur composites

11.1. INTRODUCTION

The Minimum Cost Housing Group (MCHG) at McGill University, School of Architecture, has with the initiative of Prof. Alvaro Ortega and today Prof. Witold Rybczynski conducted research and experiments into uses of sulfur for building for the last decade.

Much has been published and a great deal has been learned since the MCHG built the first sulfur house ever in 1972.

Several other projects followed but relatively little has been done to find applications of sulfur composites for roofing.

I was attracted by the potentials of this bonding material and the fact that some original work could be done.

The only limitations were time and the fact that I was working alone. The work I am describing hereafter has been continued by Prof. Rybczynski in spring 1981 during a course he was giving at Florida A&M University in Tallahassee, Florida; some of the results are mentioned in this chapter.

Sulfur is one of the four basic raw materials of the chemical industry (the other three being coal, lime stone, and salt).[1]

Sulfur, a yellow nonmetallic element, occurs in sedimentary and volcanic deposits and exists in several different forms, the most stable being orthorhombic sulfur, a crystalline form that melts at about 116°C.[2] (Fig. 11.1)

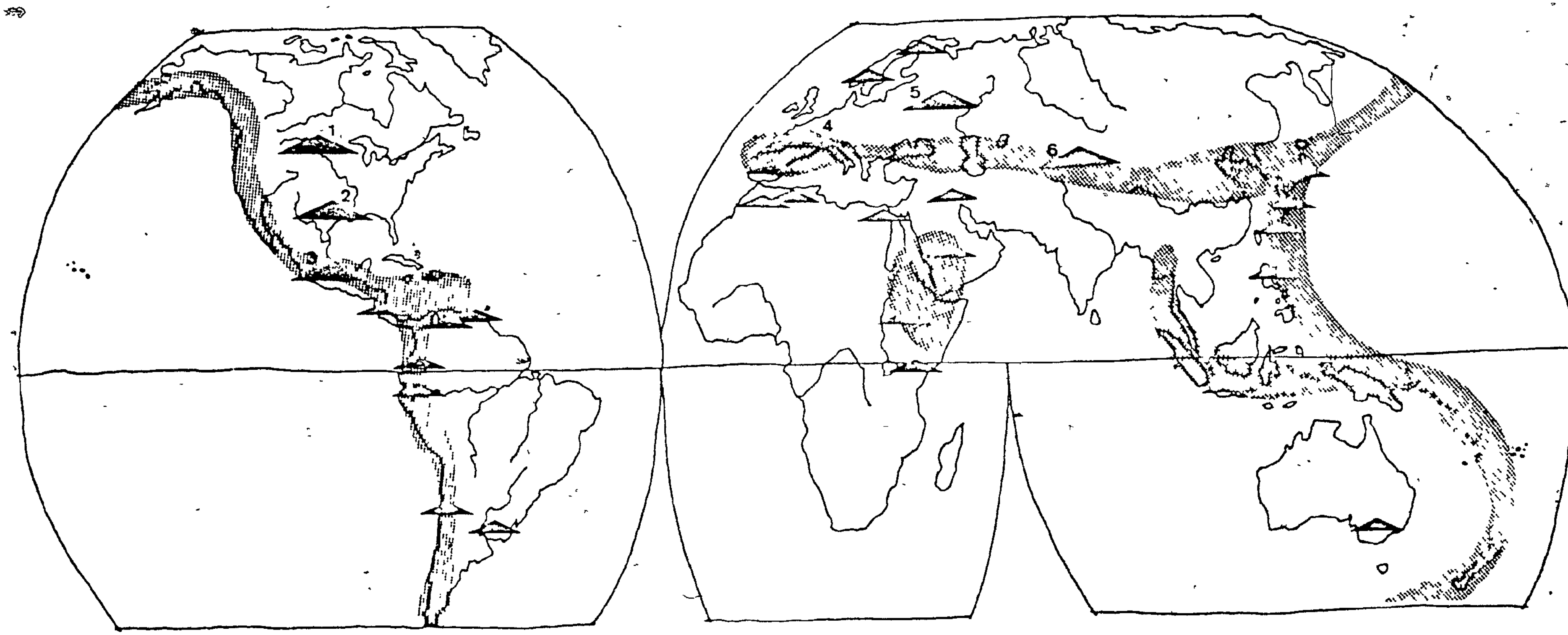
Today, an important source of sulfur lies in the large volume of sulfur dioxide recovered from filters in coal-fired steam power plants and other large industrial processes* namely petroleum and natural gas production.[3]

If economically and politically furthermore feasible, the recovery of sulfur as by-product in industrial processes through the sulfur abatement program could double sulfur production in the United States** alone and provide numerous small sulfur sources throughout the world forming the basis for the production of low-cost sulfur bonded building materials.[4]

The use of sulfur in building has been known since the Middle Ages, and examples still exist in Latin America from the 17th century, when sulfur was used to anchor metal in stone.[5]

* The main smoke stack of Inco Ltd. in Sudbury, Ont., emitts appr. 2500 t of sulfur dioxide every day. 4500-5000 t are retained in filters.

** and exceed the forecast consumer demand.



MAP SHOWING WORLD SOURCES OF ELEMENTAL SULPHUR NOW BEING MINED

SULPHUR PRODUCER   MAJOR PRODUCER
Canada, USA, Mexico, France, Poland, USSR

Volcanic region (Sulphur ores)

Fig. 11.1

In the middle of the 19th century interest in finding new utilizations for sulfur as cements and concretes led to the first patent registrations, the very first one in 1859 under the title: "Composition of Matter for Ornamental Purposes" by Wright, A.H.[6]

More recently research in sulfur concrete and impregnation, as well as the development of fire-retardant additives, have encouraged already a fair use of applications in road construction, special pavements, containers, pipe lining and components for building. Various low-cost housing pilot projects have been undertaken after the first sulfur concrete structure was built in 1972 in Montreal*[7] But no particular roofing material or roofing system based on sulfur had been then developed. Many other institutes have conducted research into finding wide uses for sulfur in building and engineering; a successful product as a result of this research is sulfur foam for insulations of roads in the Arctic and other insulation purposes.[8] Many of these institutes have also determined properties of sulfur composites, namely sulfur concrete (SC). This research will eventually lead to the formulation of legal standards which in return will form the basis for wider application and acceptance of the sulfur composites.

* One or more buildings have been built in Canada, United States, Western Germany, Mexico, Columbia, Guatemala and the United Arab Emirates.

The characteristics of sulfur concrete (SC) are in many ways favourable to those of Portland Cement Concrete (PCC) except for the flamability of sulfur. The characteristics of SC are the following:[9]

- impermeability
- low thermal conductivity
- low electrical conductivity
- no shrinkage
- extremely smooth finish
- high compressive strength
- quick setting
- no curing
- recycleable
- no water needed
- corrosion resistant
- can tolerate chloride and sulfate containing aggregates
- bonding properties are not affected by salt
- components can be produced of high precision
- flamable
- melting at 116^{o}C
- thermal contraction as the fresh concrete cools
- thermal expansion above steel and PC concrete

- reacts to copper
- "high" rate of creep
- placed in ground bacterial degradation possible
- possible formation of acid under action of water and sunlight
- unpleasant odor when melted
- energy needed for process

11.2. SULFUR APPLICATION

The problem of flamability of sulfur composites has been studied extensively and the fact that it has a low fuel value, burns slowly and can be rendered self extinguishing by the addition of plasticizers, does allow applications in housing.

The fact that the preparation of sulfur concrete or other sulfur composites involves melting and handling of the material at temperatures above 100°C is not a major problem as other processes in building construction have proven.*

Prof. Rybczynski, in his paper for the "Symposium on new uses for sulfur and pyrites" in Madrid 1976, addressed a more important aspect with regard to the

* Bituminous roofing and asphalt paving are both hot processes.

arguments in favour or against the use of sulfur in building:[10]

"The environmental impact of building materials, both with respect to their production and use, is extremely complex and difficult to measure. With the exception of traditional materials such as wood, stone or earth, most modern materials require substantial energy inputs. Sulfur concrete, on the other hand, does demonstrate four characteristics that could form the basis for reassessing materials in the light of emerging ecological concerns and needs for energy conservation, which are both relevant in low-cost construction."

The first of these characteristics is that sulfur for building represents a zero opportunity cost, since this material is either involuntarily produced as industrial by-product or is locally available as a valueless volcanic ore.

Secondly, that the use of industrial by-products, or wastes, for building represents a more effective use of resources is demonstrated by the fact that it takes 33 times more energy to produce portland cement than it takes for the same quantity of sulfur.*

* 1 ton of portland cement produced takes 6,300,000 kcal
1 ton of sulfur appr. 190,000 kcal.

The implication, particularly for the petroleumless countries of the industrialized as well as the third world, could be enormous.

The third characteristic that sulfur concrete can be recycled without excessive energy input will also be important in helping to reduce the amount of wastes.*

Finally, in assessing the energy requirements of a building material, Rybczynski says, maintenance must be considered. Sulfur concrete seems to be very durable and if poured in a smooth form does not require painting and, being a non-porous material, it is also self cleaning.

There are many indications that sulfur as a binder has high potentials in applications not investigated so far. Until 1979 one of them was roofing. The three sulfur technologies, sulfur concrete, sulfur impregnation and sulfur coating present a wide range of potential applications for low-cost roofing. After I had acquainted myself with this for me new material and the basics of the three technologies, it was necessary to make a choice as to in which direction I should lead my experiments. I was interested in finding a solution for a self supporting roofing system and then if there was more time left also for a supported one.

* To recycle one ton of sulfur concrete, appr. 30,000 kcal are needed.

The information of the numerous projects carried out by the MCHG over the past ten years and the experience of my Project Advisors, Prof. Witold Rybczynski and Vickram Bhatt, were of valuable help, saving me a lot of time and making me quickly feel at home with this sometimes rather smelly substance.

11.3. SELF SUPPORTING ROOFING SYSTEMS

Two technologies were promissing to lead to a solution: Sulfur concrete and sulfur impregnation.

The latter has been tried with cardboard formwork tubes but several problems arising with the handling and the material itself made me decide to persue a solution with sulfur concrete.[11]

The main difference between the making of a SC structure and one of PCC is the mixing and placing of the composites.

The mixing of SC for smaller quantities has so far been done in a concrete mixer, heated at the bottom by an open gas flame. After elemental or recycled sulfur has melted, sand and gravel in small quantities are added so that the mix stays liquid until the proportions are right and the hot composite can be poured into place. (Fig. 11.2)

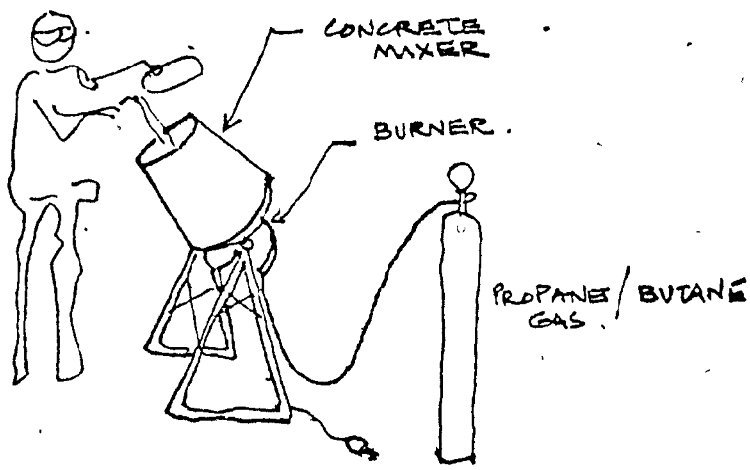


Fig. 11.2 Mixing of sulfur concrete (MCHG)

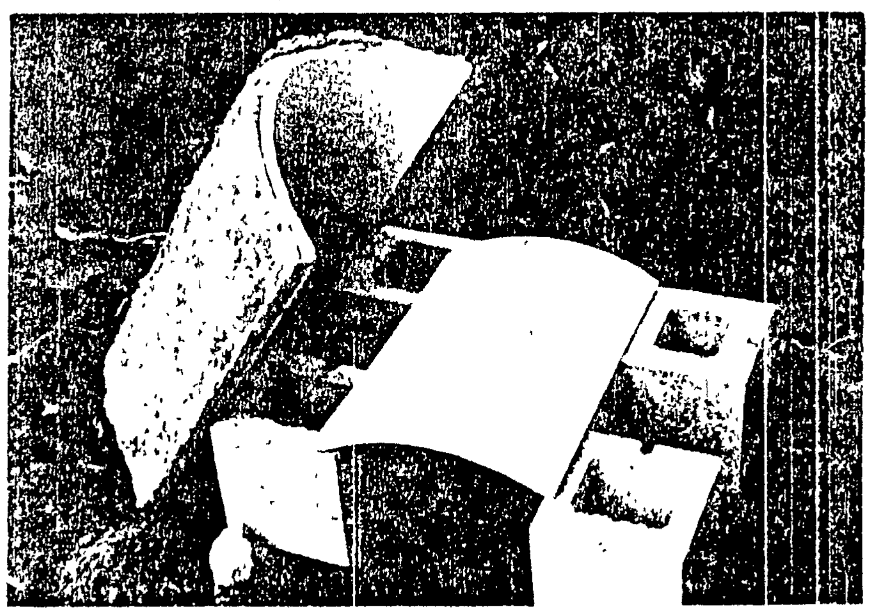


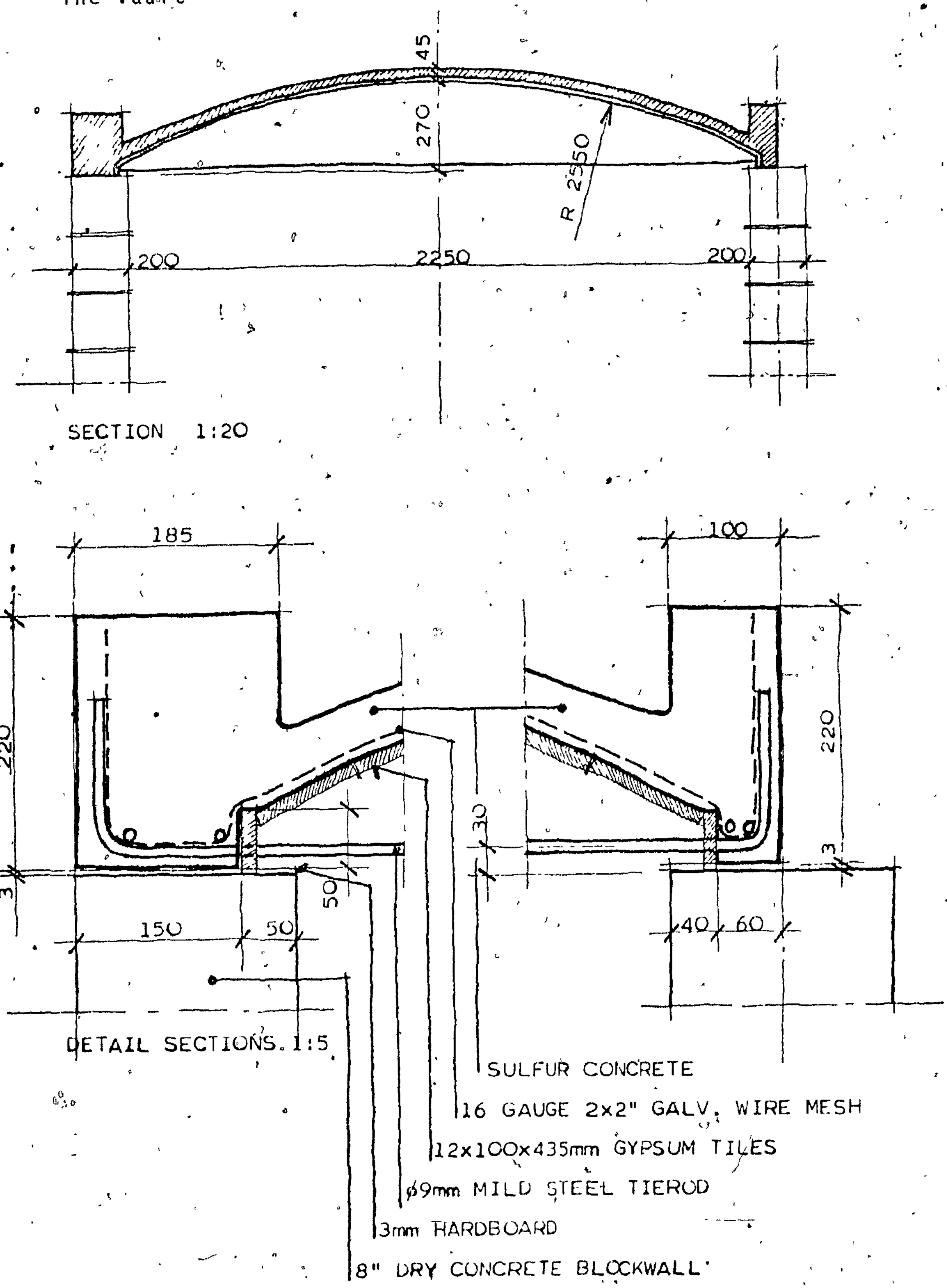
Fig. 11.3 The first test vault with gypsum tile

Other methods have been tried like preheating the aggregate and melting of the sulfur separately, but special equipment would have to be designed until larger quantities could be processed within a shorter period of time.[12]

The proportions of the mix are similar to PCC but more research is needed to make qualified statements about effects of changing proportions. The mix used by weight was appr. 25% sulfur, 37-44% sand and 30-35% coarse aggregate (stone chippings 10mm). In comparison, PCC would be made of appr. 15% water, 12% cement, 25% sand and 45% coarser aggregate. The remaining 1% in SC and the 3% in PCC represent enclosed air.[13]

The placing of SC creates some different problems. The hot mixed composite has to be placed fast into the form-work, cannot be vibrated and will start to solidify immediately. As sulfur is not a hydraulic binder, no curing time other than the cooling down of the material is needed and a SC element will reach 90% of its ultimate strength within the first six hours (depending on its mass and dimensions). These facts make it difficult to manufacture thin shell structures as it is almost impossible to trowel

Fig. 11.4
The Vault



SC poured into place for more than a minute. Furthermore, the rather liquid state of the mix makes it difficult to place it on sloping formwork at equal thickness and to get a smooth surface. The formwork can be of similar type and quality as for PCC construction.

The Roof Vault

Although I am convinced today that it would be possible to build double curved thin shell structures in SC similar to ferrocement, a shell vault with a height of a tenth of its span and a spherical curvature appeared to be the ideal shape at the time. (Fig. 11.4)

The preliminary experiments had proven that gypsum was bonding well with SC and that it could be otherwise possible to cast a thin vault with a span of 2.40 m (chosen for practical reasons, workshop, formwork, etc.).

As a fire protective coating, gypsum is a very effective, cheap and everywhere available material.(Fig. 11.3)

The vault was cast without any major problem; care had to be taken that no weak cold joints occured. The day after casting, the formwork was stripped with all gypsum tiles,previously placed in the formwork, sticking well to the undersight of the vault (à la Space Shuttle).(Fig. 11.5)

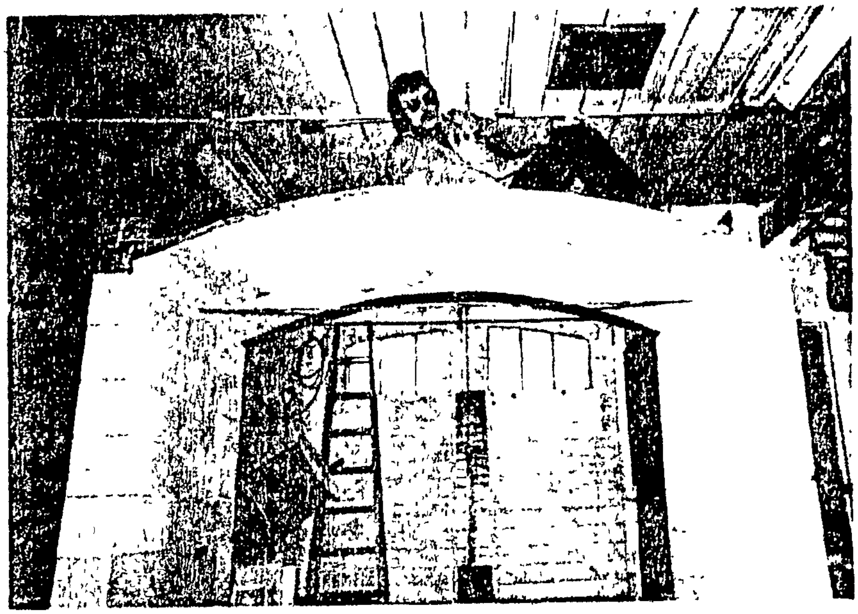


Fig. 11.5 The vault, one day after casting (MCHG)

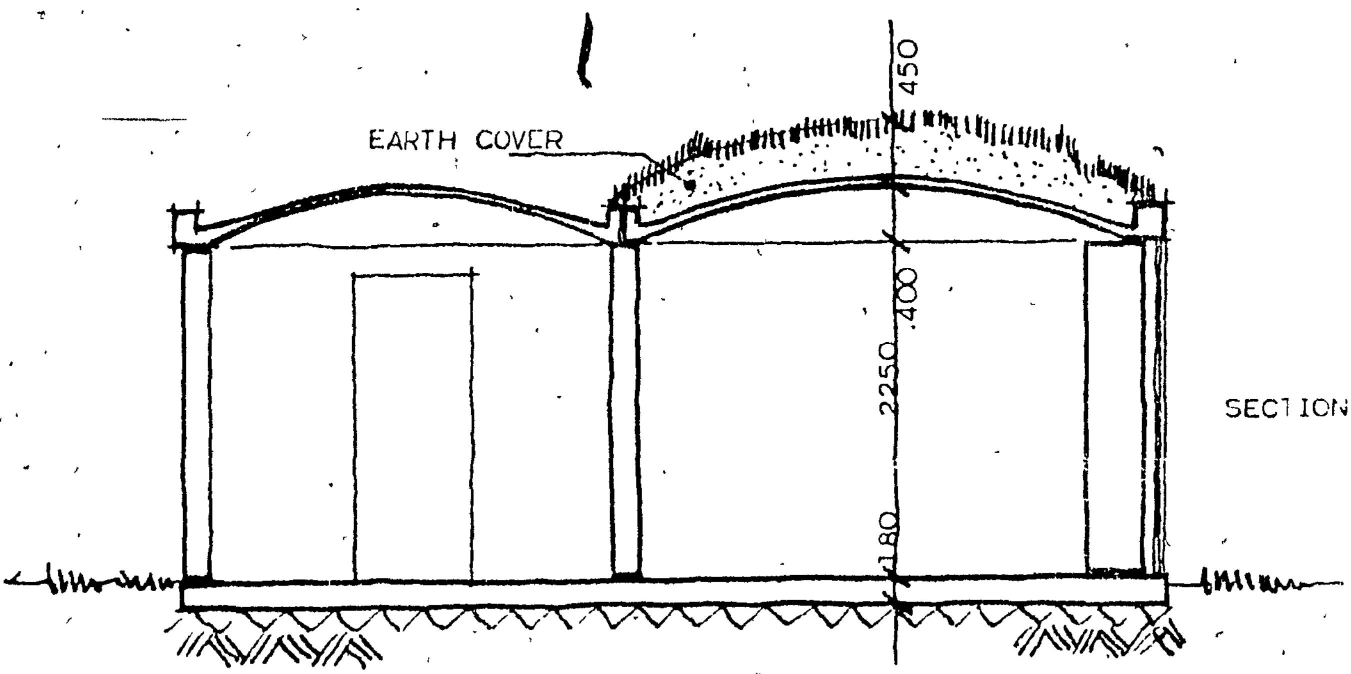
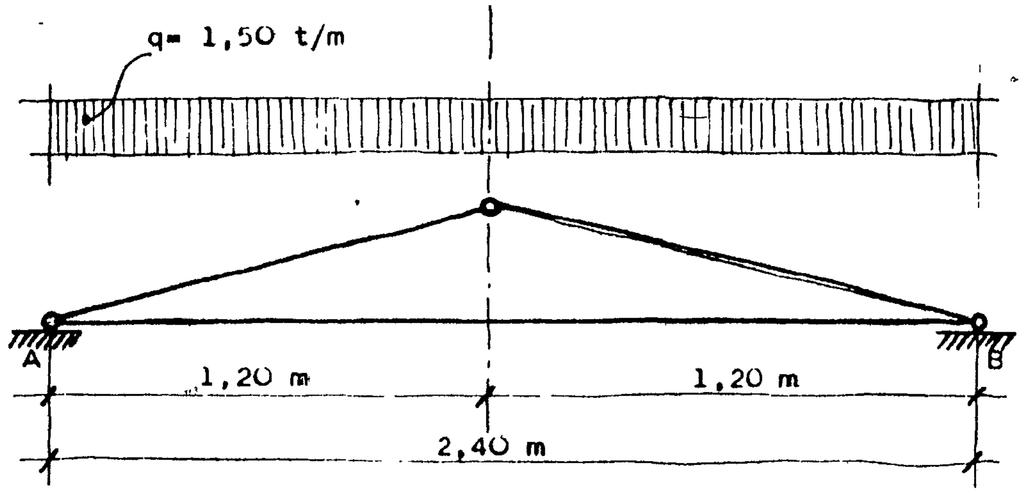
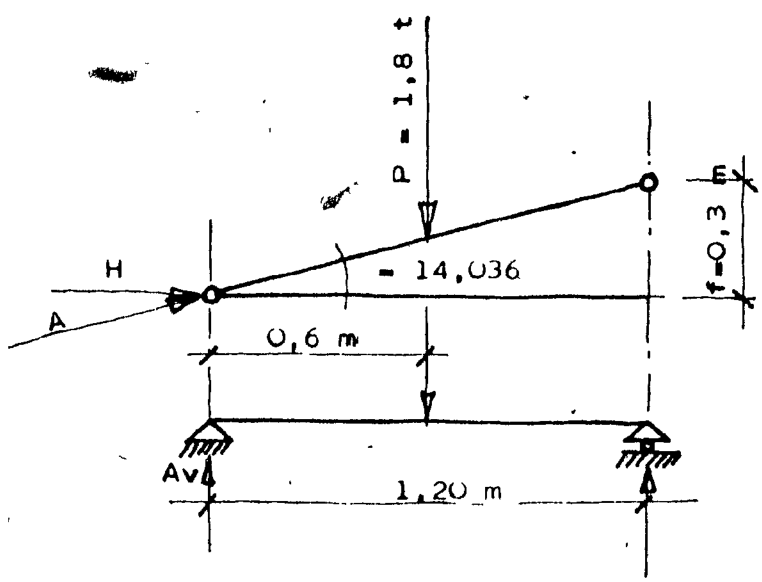


Fig. 11.6 Thin shell SC roofs do not need any additional protection if earth is added.



Because of the complexity of the calculation of this statically indeterminate structure, I had to simplify the calculation as a feel of magnitude, to a three hinged arch.



SC Properties as chosen

compr. strength	B_{sc}	=	200 kg/cm2
tensile "	B_t	=	18 kg/cm2
flexural "	B_{fl}	=	35 kg/cm2
Mod. of elasticity	E	=	70300 kg/cm2

$Av = 1,80\ t$

$H = \frac{Av \frac{1}{2} - P \cdot f'}{f} = \frac{1,8 \cdot 1,2 - 1,8 \cdot 0,6}{0,3} = 3,6\ t$

$A = B = \sqrt{P^2 + 1^2} = \sqrt{1,8^2 + 3,6^2} = 4,025\ t$

$M_m = \frac{P \cdot 1}{4} = \frac{1,8 \cdot 1,2}{4} = 0,54\ tm$

$Q_p = P \cdot \cos\varphi - H \sin\varphi$

$= 1,8 \cdot 0,97014 - 3,6 \cdot 0,24254 = 0,8731\ t$

$k = \frac{Mm}{100 \cdot h^2} = \frac{54000}{100 \cdot 25} = 21,6\ kg/cm2$

$c_e = \frac{\sigma e\ max}{k} = \frac{2400}{21,60} = 111,11$

$\mu\% = 1,02 \quad ; \quad c_b = 6,3$

$\sigma actual = cb \cdot k = 6,3 \cdot 21,6 = 136,08 \quad 120\ !$

The above edge stress appears to be high but as there are no standards for SC yet, this would have to be further investigated.

Reinforcement

FE req. $\frac{\mu\% \cdot b \cdot h}{100} = 1,02 \cdot 5 = 5.10\ cm2$

Code requirement for pure distribution reinforcement for PCC

101.6mm2/m (0.048 in2/ft)

16 gauge wiremesh 19 sections 34 mm2

It would be necessary to use a bigger gauge wiremesh for future constructions, but it does not necessarily reduce the strength of this vault except that it could have some influence on cracking due to shrinkage and temperature effects.

Tie Rod

mild steel bar ø 9mm 0,6362 cm2

max - 3700 kg/cm2

H - 3,6 t ; b - 1.2 m H . b - 4.32 t - H'

Section required for H' - 1,1676 cm2 0,6362 cm2

The above calculation shows that with an assumed load of 1.5 t/m2 the tie rod would fail first.

The tie rod used would only allow for a load of 812 kg/m2 (166.3 lb/sqft). H also indicates that it will be necessary to fix an additional tie to be able to establish the actual strength of the shell in future testing.

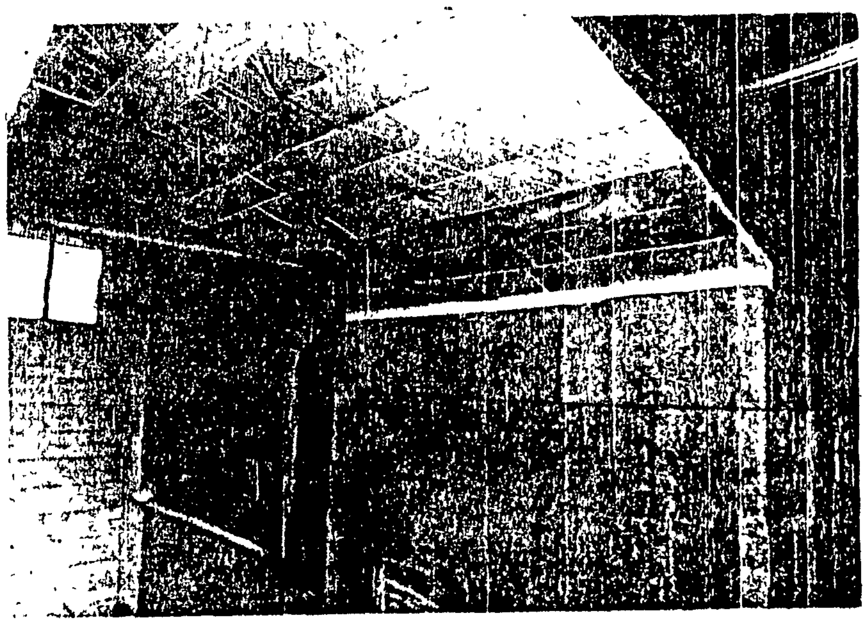


Fig. 11.7 The undersight of the precast gypsum tiles placed in the framework before casting the vault.

From the result of preliminary test loading (appr. 400 kg/m2), my calculations and the fact that this vault has withstood severe weather conditions outside our workshop for over 2 years, the following can be concluded:

- the capacity of such a shell vault is more than what is needed in low-cost housing;
- a compressive strength of appr. 200 kg/cm2, tensile strength in the range of 18 kg/cm2, and and average flexural strength of 35 kg/cm2, are very low properties for any reasonably well prepared and placed SC mixture.

Climate Considerations

Similar to ferrocement roofs, SC roofing systems will not be ideal for warm humid climates unless the roof is planned to serve a floor ceiling function later. In all other climate zones, roofs made of SC can be combined with an earth or sand cover to reach the thermal mass needed.(Fig. 11.6)

Economic Considerations

In a country or region where sulfur occurs naturally or as by-product as it does in many developing countries, small scale sulfur operations could already be feasible today.

However, to introduce this technology, some training and preferably repeated demonstration are needed as has been shown in the case of the Phillipines where much had been done but little is happening today.

Technical Considerations

On a small scale, SC can be prepared almost everywhere; for larger scale operations, more appropriate equipment, like the one existing for blending sulfur with asphalt, would have to be developed.

Social Considerations

Safety from fire may be of some concern but possible odor at times of high solar radiation and humidity in the air may be a negative factor weighing against the use of this material. All other social criteria can be plotted positively against this material, depending on the way it is going to be introduced.

11.4. SUPPORTED ROOFING SYSTEMS

A wide scope of sulfur based materials could be considered for a supported roofing system. Naturally, a supported roof should be as light as possible to serve its functions cost effectively.*

Therefore, in my second project during the summer of 1980, I concentrated on the following two technologies: impregnation and coating to find a suitable composition with the desirable characteristics for a low-cost roof in developing countries.

Sulfur coating as I had suspected earlier, did not produce satisfactory results as the coating material is subjected to bending and tensile stresses beyond the material's capacity. Coating could be successful in combination with fibres or sand as reinforcement if applied on rigid materials.[14] But in an almost pure state, even if plastisizers are added, sulfur coats on fabrics, barasti, thatch or even chipboard will crack after a very short time.[15] (Fig. 11.8)

Sulfur impregnation had been tried earlier and produced some promising results. The MCHG has conducted experiements with wood and also other more or less porous materials which resulted in surprising improvements of the materials' properties.[16]

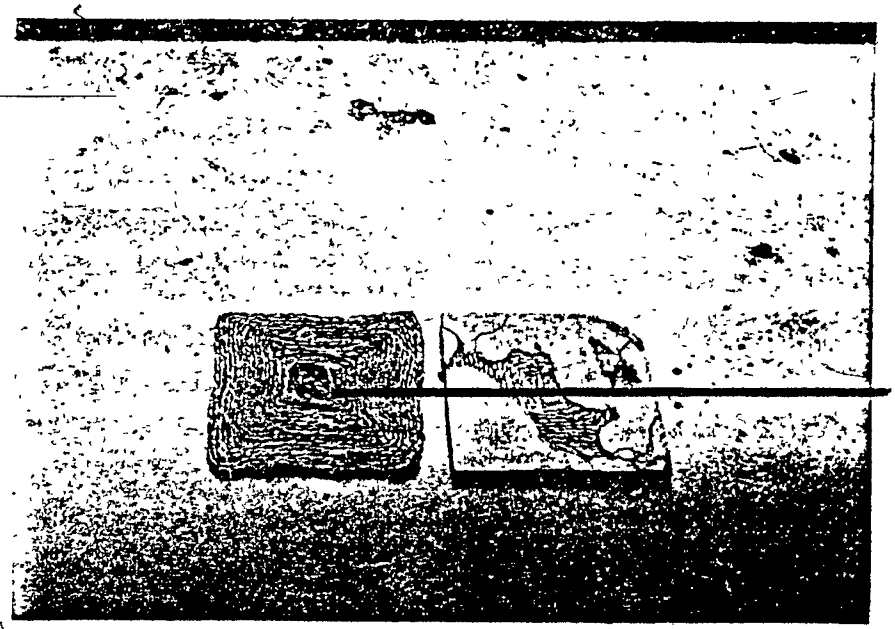


Fig. 11.8 (Seyam, R.)

Fig. 11.9 Sulfur spray coating of block wall (new uses of sulfur)

Earlier projects have shown that for continous working and experimenting with impregnation, suitable and lasting equipment is absolutely necessary. If the heating system of a sulfur bath breaks down, the liquid solidifies quickly and could spoil the equipment and experiment all-together.

Kitchen melting pots have been successfully used in laboratory experiments but they are both expensive and not very adequate in size.

The Equipment

As no adequate and affordable equipment could be found, I designed and built my own melting basin. (Fig.11.10)

The petroleum and chemical industry is keeping sulfur liquid in large steel holding tanks, heated with high pressure steam, the pipes running in bundles submerged in the liquid sulfur.

The main problems with sulfur impregnation are corrosion of the equipment, fire hazard when overheating occurs and the need to constantly maintain the temperature level of the bath.

Corrosion turned out to be a minor problem in our case. For fire protection, the basin was packed in 8 cm of glass wool and covered with asbestos cement panels. The temperature was monitored with a pyrometer connected to a probe.

The temperature could be controlled with four rheostatic step-up switches connected to four heating plates, mounted in pairs to the long side of the basin. (Fig.11.10)

The Test Materials

It was my intention to test a wide range of materials, including some which would normally not be considered low-cost but could, when impregnated with sulfur, have improved properties which could in return make them more cost competitive.

I selected the following materials for testing:

- kraft paper
- card-board
- corrugated card-board
- hard-board
- soft-board, low quality
- soft-board, high quality
- papier maché (egg cartons)
- stramit panels (straw composite)

- asbestos fibre-board
- plaster-board (gyprock)
- cement block
- plywood 6 mm
- pine (2"x4") 5cm x 10 cm
- softwood shingles
- coconut fibre bundles
- jute fabric
- canvas (good quality)
- foam rubber

The first tests were conducted to see how the equipment was functioning and whether other unforeseen problems would develop.

As the basin was relatively small, every time a new material was submerged the temperature dropped and the escaping vapour created "smelly" fumes. After the vapours had escaped, the temperature sometimes rose quickly and the heaters had to be readjusted; disasters could be avoided but burning sulfur emitts toxic fumes and around 160°C sulfur burns very well, and more than once it was close to that situation.

The next step was to find out the time of impregnation needed until the various materials were saturated. This is dependent on the following three criteria: <u>structure of</u>

material, dimension of material and surface tension of liquid.

The sulfur bath contained appr. 5% DCPD (dicyclopentadine) plastisizer, increasing the viscosity of the mix and reducing combustibility of the impregnated material.

A small quantity of iron oxide was also added to change the color from sulfur yellow to a warmer red shade.

A short dip in the bath would give a relative thick coat to the finer structured materials. Hair cracking developed during the cooling process and no improvement of the base materials' properties could be noticed, (similar to coating).

It is quite obvious that complete series of tests including the finding of saturation time and major properties of all 18 materials was too big a scope for a one man "show" in just a couple of months. And as I was trying to find a roof covering material for a supported roof, weather resistance was of more importance than structural properties. For a later stage, structural properties would be important to know so that optimal spans and product sizes could be established.

All 18 materials were impregnated for various periods of time and the absorption rates were calculated on percentage of weight. The saturated samples were then submerged in water for at least 6 hours at a time and the water absorption was measured again by weight.

Table 13 Sulfur impregnation of various materials

	dry weight gr.	impregnation minutes 30	180	300	500	weight after 6hrs in water gr.	water absorption in percent
kraft paper	5.0	22	18	20	19	23	17
card-board	34.5	105	85	90	82	99	17
corrugated	34.5	99	73	89	105	110	5
hard-board	188	311	275	276	261	279	6
soft-board 1st qlty. 2nd qlty.	403	995	1383	1656	---	1675	1
asbestos fibre board	192	321	390	416	425	425	-
"egg carton"	20	135	132	155	---	160	3
plywood 6mm	237	305	318	---	375	375	-
pine shingle	146	186	172	256	280	311	10
softwood 2x4	942	---	910	910	910	951	4
gypsum board	600	---	962	1050	broken up	1120	6
canvas	40	100	101	---	---	109	7
jute	44	235	239	---	---	268	11

Considering all aspects of low-cost roofing and the results of the impregnation tests as per table , corrugated sulfur impregnated card-board in form of shingles, sheets or tiles promised to be the most feasible roofing material amongst those tested.

Stramit panels cannot be improved through impregnation as they are absorbing too much sulfur and therefore are loosing their insulation qualities and also structural strength.

Fibre-boards (soft and asbestos) are comparable to any fibre cement board after impregnation and it would be worthwile conducting tests with this material to compare it with "can letas" or corrugated sheets.

Plaster-board (gyproc) created several problems; in the process, the material became more brittle and the surface cover separated after some time. When saturated or if left in the molten sulfur for too long, the gypsum tiles started to break up in smaller pieces.

Soft wood, after impregnation, has properties similar to hardwood and appears to be dimensionally very stable when exposed to changing weather conditions. This very interesting result could lead to the use of low quality timber for structural purposes where much more expensive materials are used today.

Organic fibres, if not woven tightly, do not make a useable composite with pure sulfur as their moduli of elasticity is too different so that the matrix will break from surface tensions alone.

Fabrics like burlap have shown promising results but good quality tightly woven material is needed and that is not everywhere a low-cost material.

An interesting and positive result of impregnating combustible materials with sulfur is that the flamability of the composite is reduced considerably as all pores are filled and no air is entrapped anymore.

Conclusions

The impregnation project I conducted during the summer of 1980 proved that this process could produce a low-cost roofing material with characteristics as outlined in this thesis but that further testing is needed, like weather exposure, design of a system, structural properties and as many more others as possible.

From ready available materials, corrugated card-board produced the best results but "egg cartons", if manufactured as corrugated sheets similar to CGI sheets, could make an even better lightweight, low-cost, maintenance free and durable roofing material.

Corrugated sulfur impregnated card-board shingles were mounted to the West wall of the MCHG workshop in summer 1980 and have performed very well since.

The Fall Project in 1980

The Arboretum, belonging to McGill University and located at McDonald Campus on the West Island of Montreal, needed urgently some toilet facilities for their visitors. Some small funding was available but only enough for a very low-cost solution.

The concept of an improved pit latrine was chosen. The improvements included ventilation of the pit and passive solar heating. As construction materials, sulfur improved or composited materials were chosen.

The support frame was made of sulfur impregnated timber and the floor of sulfur concrete tiles. One side wall was made of sulfur impregnated chipboard, the other with a black painted metal sheet and a vandal proof acrylic transparent sheet; the metal sheet was mounted appr. 20 cm above floor level, reaching 1.80 m high and 10cm inside the acrylic sheet to allow the air to circulate but provide privacy at the same time. (Fig.11.11)

The two toilets were designed back to back with a dividing double wall forming the ventilation duct.

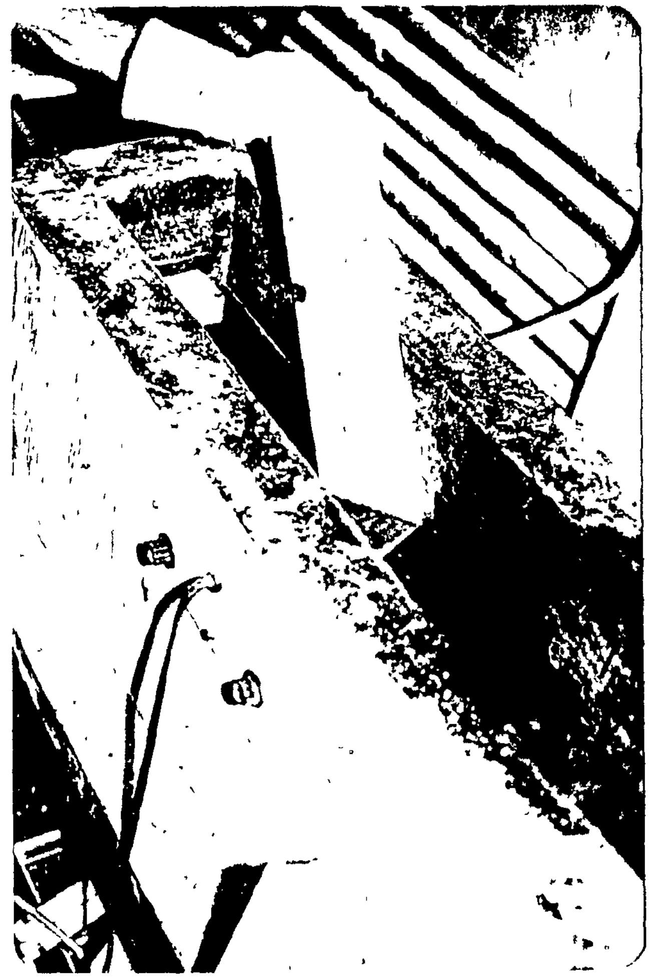


Fig. 11.10 The sulfur bath equipment used for testing.

Fig. 11.11 Assembly of solar heated and sulfur impregnated toilet house.

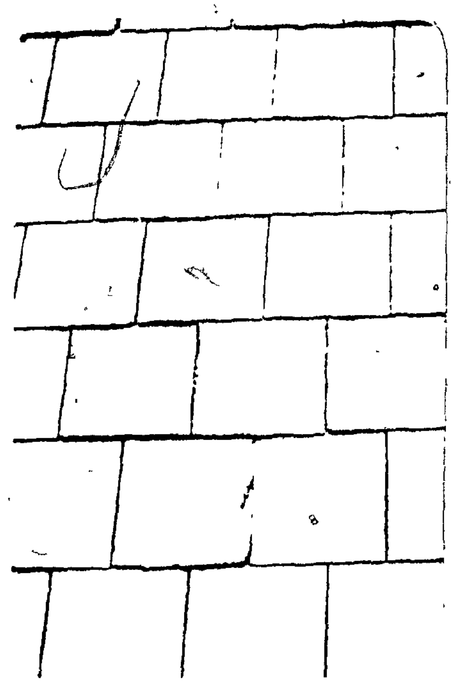


Fig. 11.12 Sulfur impregnated cardboard shingle roof.

For the door, we wanted to use impregnated soft-board which we could impregnate at Laurentide Chemicals & Sulfur Ltd. in Montreal. The large holding tanks at their premises were ideal to immerse components as big as needed, but the handling of the wet state sulfur impregnated soft-boards turned out to be impossible with the equipment available. The only way of impregnating soft materials of bigger sizes is with the help of a support grill on which the material can be dipped into the liquid and lifted out of it again. Once dry, impregnated soft-boards , also heavy, are comparable to fibre cement composites.

The roof finally, we decided to build with a support and substrate made of plywood and a cover of sulfur impregnated corrugated card-board shingles. (Fig.11.12)

The entire structure was basically prefabricated in transportable elements and was erected in one day on site.

Conclusions

After two winters in use, two major deficiences could be observed.

The roofing has been badly damaged by weather due to the fact that the pitch designed was too low.

Winds were bending the tiles up and in some cases they were broken. Driving rain penetrated into the grooves from the headends and disolved the bond between the surface liner and core. But on a steeper roof or with a tile or sheet of different design, this material could perform very well.

Other Recent Projects

The experimental low-cost construction workshop of Florida A&M University, School of Architecture, in Tallahasse, Florida, has, under the guidance of Prof. Larry Birch and Prof. Witold Rybczynski conducted further experiments with materials and sulfur impregnation for low-cost roofing in 1981.

Their findings partly correspond with those of the MCHG but complement them in many fields.

Sulfur Impregnated Cotton Fabric Sheets[17]

Ramadan Seyam, after discouraging results with coating and impregnating other organic fabrics, produced 48 cm x 75 cm shingles (sheets) made of woven cotton fabric which he rolled on a steel pipe and immersed the package into a sulfur bath for two hours. Although his findings were not wholly satisfactory as far as water resistance is concerned, it appears to me that if the right fabric is used this could be a very feasible solution. (Fig.11.14)

Sulfur Impregnated Double Curved Cloth Roofing Shingle[18]

Jim Ervin, after testing different fabrics for strength, texture and workability, designed a shingle with a minimal need for overlap. This double curved shingle was formed in a wooden frame restricting or containing the four sides of the shingle while allowing the middle section to sag due to gravity.

An interesting modification to the preceeding system is his proposed "second dip" which could improve watertightness of the material. (Fig.11.15)

Sulfur Impregnated Folded Card-Board Tile[19]

This tile, designed and tested by Chaovalit Poonphol, has some very interesting qualities.

Poonphol found that the card-board when taken out of the sulfur bath could be formed for about 45 seconds which would be enough to fit the wet sheets into any mould. (Fig.11.13)

The results of his testings indicated that such a tile would fail in shear at the uniform load of 1277kg/m2 which was 8 times higher than for an unimpregnated one. He concluded that with a uniform load the tile would withstand 855kg/m2.

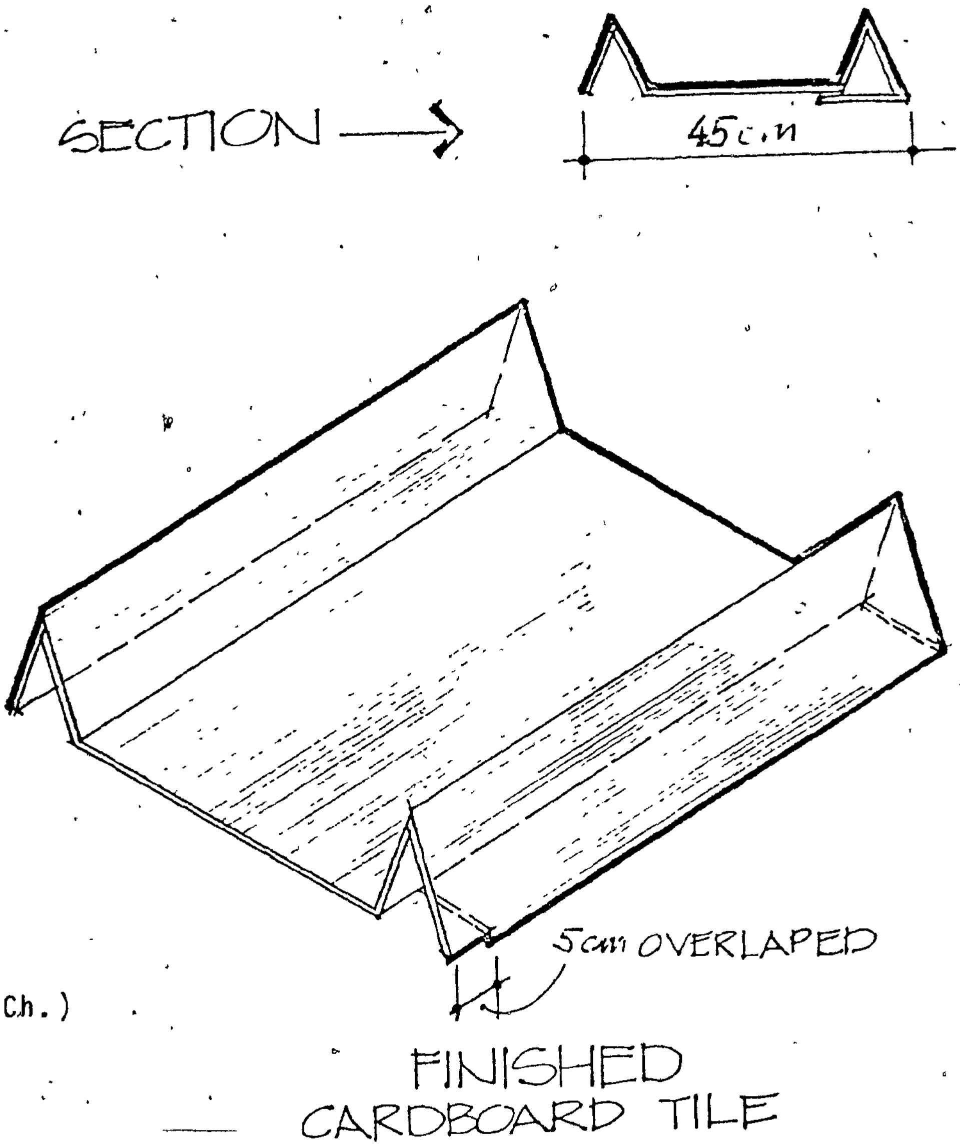


Fig. 11.13
(Poonphol, Ch.)

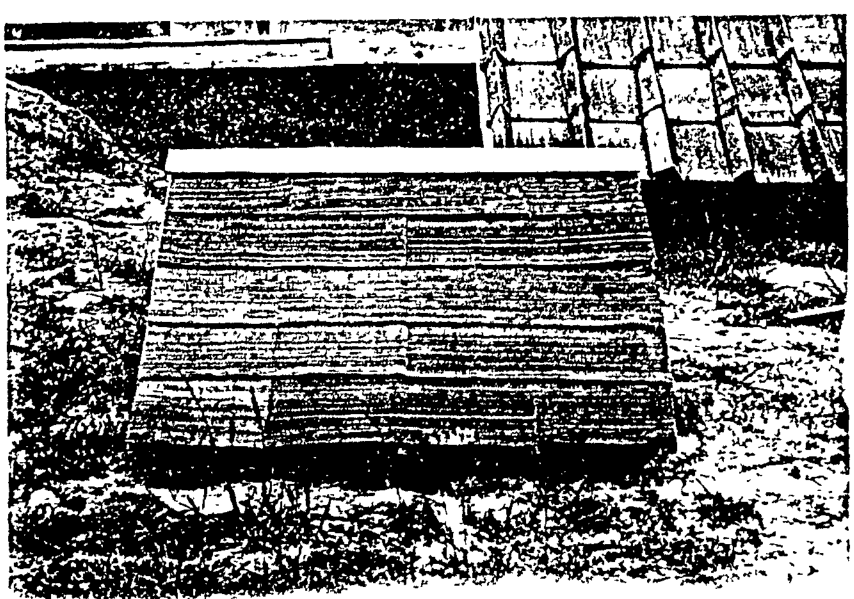


Fig. 11.14
Seyam's test roof
with Poonphol's in
the background

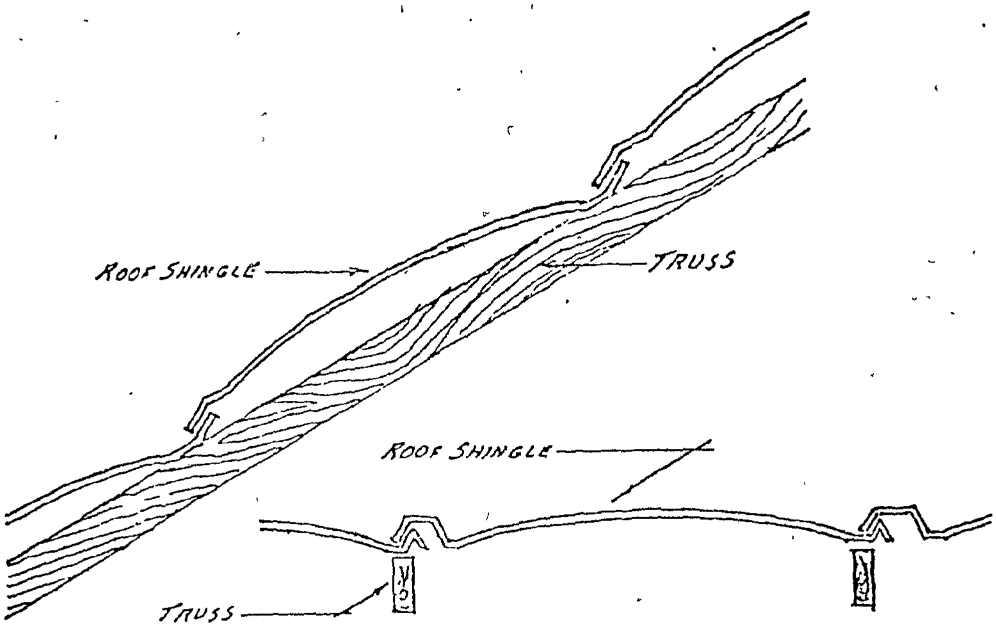


Fig. 11.15 The proposed assembly of Erwin's shingle

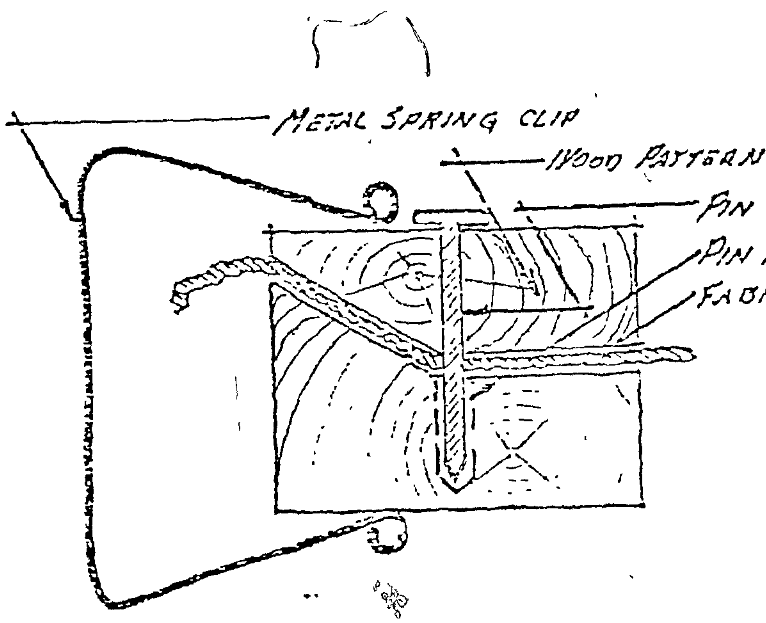


Fig. 11.16 Detail of overlap joint form. The second dip was also necessary to close the pin hole.

Climate Considerations

Sulfur impregnated roofing materials being lightweight would be adequate for the warm humid tropics, but in conjunction with an insulating roofing substrate such as stramit or similar material it could be considered for composite climates as well.

Economic Considerations

If sulfur is not locally available or nationally as cheap by-product on the market, sulfur composites will probably not be feasible for low-cost roofing.

But impregnation uses relatively little sulfur compared to SC. The technology is simple and can be applied at almost any scale with no skilled labor needed. That sulfur composites generally would be cost competitive is almost certain as sulfur is basically a cheap material in many developing countries and very durable in storage and as final product.

Technical Considerations

The major problem with sulfur impregnation certainly is the need for special equipment and a constant heating source. On a larger scale, a scrap tanker truck could provide an ideal holding tank; on a smaller scale, the melting pot, for example, could be an oil drum. The bigger the holding tank and subsequently the thermal mass of liquid sulfur, the less critical the heat loss would be.

Social Criteria

The flamability of most impregnated sulfur materials may not qualify them for use in high density urban environments but future inventions may improve on this aspect.

This roofing material, if well introduced, could create an image as any other modern roofing material does today.

Pilot projects using sulfur blocks for walls in developing countries have shown that new materials, if they serve their functions well, will generally be accepted.

NOTE

The most recent conclusion drawn by Prof. L.E. Birch of Florida A&M University on the results of card-board impregnation is that it is probably not feasible to use commercially available corrugated paper material for roofing shingles, as the impregnation process does not prevent the bond between the layers from disolving under humid weather conditions.

Consequently, the manufacturing process for corrugated paper material would have to be changed, using a water resistant glue. This is not very realistic, considering the secondary-use principle.

The "experimental low-cost construction unit" of the School of Architecture at Florida A&M University has therefore conducted further experiments in finding a paper based sulfur impregnated roofing material.

Tests have been carried out with newspaper clipped together in several layers; immersed in sulfur, these sheets have shown promising results, but before further conclusions can be drawn, this material will have to be exposed to the elements for some time.

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12. CONCLUSIONS

Low-cost roofing in developing countries is often thought of as hardware, or part of the physical entity of a house and nothing more. Although this is the final product, concentration on the hardware alone, we have seen, does not of itself lead to a useful solution, supposing a useful solution is to be found at all.

The term useful indicates that there is no single scale against which all aspects of low-cost roofing could be plotted and as Witold Rybczynski points out in his book, Paper Heroes, when comparing two "appropriate" building technologies:[1]

> "Usefulness" must be measured by a consideration of over-all benefits, not by some narrow measure of "appropriatness".

This statement reflects the complexity of evaluation and further underlines that the hardware, even if it serves its function, can have a positive or negative social and economic impact.

Amongst all the criteria discussed in this thesis (climatic, economic, technical and social), the climatic criteria are most critical for the dweller's comfort and are therefore forming the base for the selection of a roofing system.

From the climatic data* collected for a specific location of a project, a climatic pattern will emerge, which in this case, will inevitably correspond to one of the three major tropical climate types or their related subgroups as described in chapter 2: a) warm-humid equatorial climate, warm-humid or tradewind climate; b) hot-dry desert, or semi desert climate, hot-dry maritime desert climate; c) composite or monsoon climate, tropical upland climate. It is then relatively easy to arrive at performance specifications for a roof, taking all other criteria into consideration.

Amongst these "other" criteria, we find some which don't clearly fit into one of these four groups: "climate, economic, technical, or social", but rather deal with aspects related to local and operational problems and conditions. Four distinct questions dealing with these aspects can be identified:

* For the diagnosis of a tropical climate, C. Mahoney has devised a series of tables. The system was first published by United Nations Centre for Housing, Building and Planning, in "Climate and House Design" as part of the series "Trends in House Design". Table 1 is used to record the most essential climatic data, directing and defining the extent of data search. Table 2 facilitates a diagnosis of the climate and develops a series of climatic indicators. Table 3 translates these into performance specifications or sketch design recommendations.

How much is going to be built?

The answer to this question will determin what type of operation would be appropriate under the specific local conditions. The number of units to be built, whether one or several hundred, is an important factor in the decision making process. It will influence the type and size of operation and often limits choice considerably.

Who builds the project?

This will depend on the former question and certain local conditions. In most developing countries today, we find two broad sectors, modern and traditional, and each of these can be further subdivided into two subsections: a) international modern, b) national modern, c) transitional-traditional, and d) traditional-rural.[2]

How will the project be built?

This will be determined by the technology, quality and quantity or labor and equipment available or feasible to use for a particular project.

Furthermore, the time of completion will be an important factor under this question.

How is the project financed?

It makes a difference whether a project is solemnly financed and built by a family, mainly active in the informal sector, or through the World Bank and/or a national organization. Depending on the situation, this question influences the decision making with respect to higher or lower first cost and durability and maintenance considerations.

In the following three paragraphs, I will summarize and rank, in order of preference, roofing systems discussed in chapters 4 to 11, as they compare to one another under each of the three climate types. However, these recommendations can only be regarded as being very general. It is difficult to select a roofing system on a general basis as local conditions differ widely from one to another.

My selection is based mainly on the general climatic performance and those economic, technical and social criteria which are crucial and of importance universally. On this basis, I judge the following roofing systems to be useful in these climate zones.

ROOFS FOR WARM-HUMID EQUATORIAL CLIMATE

Due to the very small diurnal variations of temperature in this climate, roofs in this zone should have a very low thermal capacity, preventing the indoor temperature from increasing above the outdoor one. A ceiling with a well ventilated roof space should be considered as a minimal requirement.

1. The corrugated galvanized iron roof, CGI roof (p. 70)

Based on pure climate considerations, this roof is certainly a leader as it has the lowest thermal mass amongst all low-cost roofs considered.

The CGI roof is generally low-cost but the covering material requires usually up to 100% foreign exchange. This negative aspect, though, is today often improved by importation of black metal sheets which are formed and finished locally in a simple process. The fact that this material is available almost anywhere in the tropics, that transportation is not difficult and installation very easy, is making this system a very useful one.

The need for maintenance and relative short life span are balanced by the possibility of easy replacement and low-cost.

2. Fibre-cement roofing sheets (p. 163)

This system follows after the CGI roof, not so much for its thermal performance than for the good compromise of most other factors. The on site manufactured process is inexpensive, simple, and labor intensive. Apart from the need of cement, cheap organic fibres and aggregates can be used.

Compared to the asbestos cement roofing materials, this system performs equally well but needs less foreign exchange.

If this technology is properly and widely introduced, this roofing system has all the potentials to become a feasible substitute of CGI roofing.

3. Burnt clay tile roofs (p. 183)

Similar to fibre-cement roofs, this roof is in a balanced relationship to most criteria. Although its thermal performance is not as favourable as that of the CGI or fibre-cement roof, a ceiling with some insulation capacity could make this system even in this climate zone a feasible one.

The cost comparison of low-cost roofing systems in Somalia (Table 14) leads to an interesting conclusion as far as traditional versus modern roofing systems are concerned. Life cycle costing does not only place traditional roofs behind some modern ones, but it also shows that appropriatness cannot easily be made explicit on the basis of construction cost and the evaluation of the general criteria.

Comparing the Somalia study and the cost comparison of low-cost roofing systems in Nairobi (Table 15), it further indicates that appropriatness can differ in different places depending on local economic conditions.

Where as CGI roofing was the absolute leader in Nairobi, local fired clay tiles were lowest in cost in Somalia. But the authors of the Somalia study did not consider this

Table 14 Cost comparison of low-cost roofing systems in Somalia (Experimental Low-Cost Construction Unit)

ROOF TYPES	FIRST COST Materials $/SM	Labor $/SM	Totals $/SM	$/ROOF	FOREIGN CURRENCY REQD. (%)	MAINT. COST 15 YR $/ROOF	TOTAL LIFE CYCLE COST 15 YR $/ROOF	$/ROOF/YR
Traditional Makuti	$ 3.25	$0.08	$3.33	$185.81	51%	$199.84	$ 385.65	$25.71
As Built Makuti Type 1	5.86	0.10	5.96	332.57	54%	224.23	556.80	37.12
As Built Makuti Type 2	5.07	0.10	5.17	288.49	61%	265.01	553.50	36.90
30 cm Porlin, Makuti Alternate Type 3	4.07	0.08	4.15	231.57	65%	237.78	469.35	31.29
Preservative Treated Makuti-Alternate Type 4	8.57	0.11	8.68	484.34	83%	—[a]	484.20	32.28
Local Fired Clay Tiles	3.41	0.31	3.72	207.58	82%	—[a]	207.58	13.83
I.T. Workshop Corr. Fiber Cement Tiles	4.83	0.17	5.00	279.00	100%	—[a]	279.00	18.60
Corr. Galvanized Iron	9.13	0.04	9.17	511.69	100%	—[a]	511.69	34.11
Corr. Aluminim	16.26	0.04	16.30	909.54	100%	—[a]	909.54	60.64
Corr. Asbestos Cement	24.25	0.07	24.32	1357.06	100%	—[a]	1357.06	90.47
Sulphur Impregnated Corrugated Cardboard	7.06	0.07	7.13	397.85	100%	—[a]	397.85	26.52
Reinforced Concrete Slab	11.09	0.80	11.89	513.65	100%	—[a]	513.65	34.24

THREE LOWEST FIRST COST:

- Traditional Makuti $3.33
- Local Fired Clay Tiles . . . 3.72
- 30 cm Purlin Alternate Type 3 . . . . . . 4.15

THREE LOWEST COST PER YEAR:

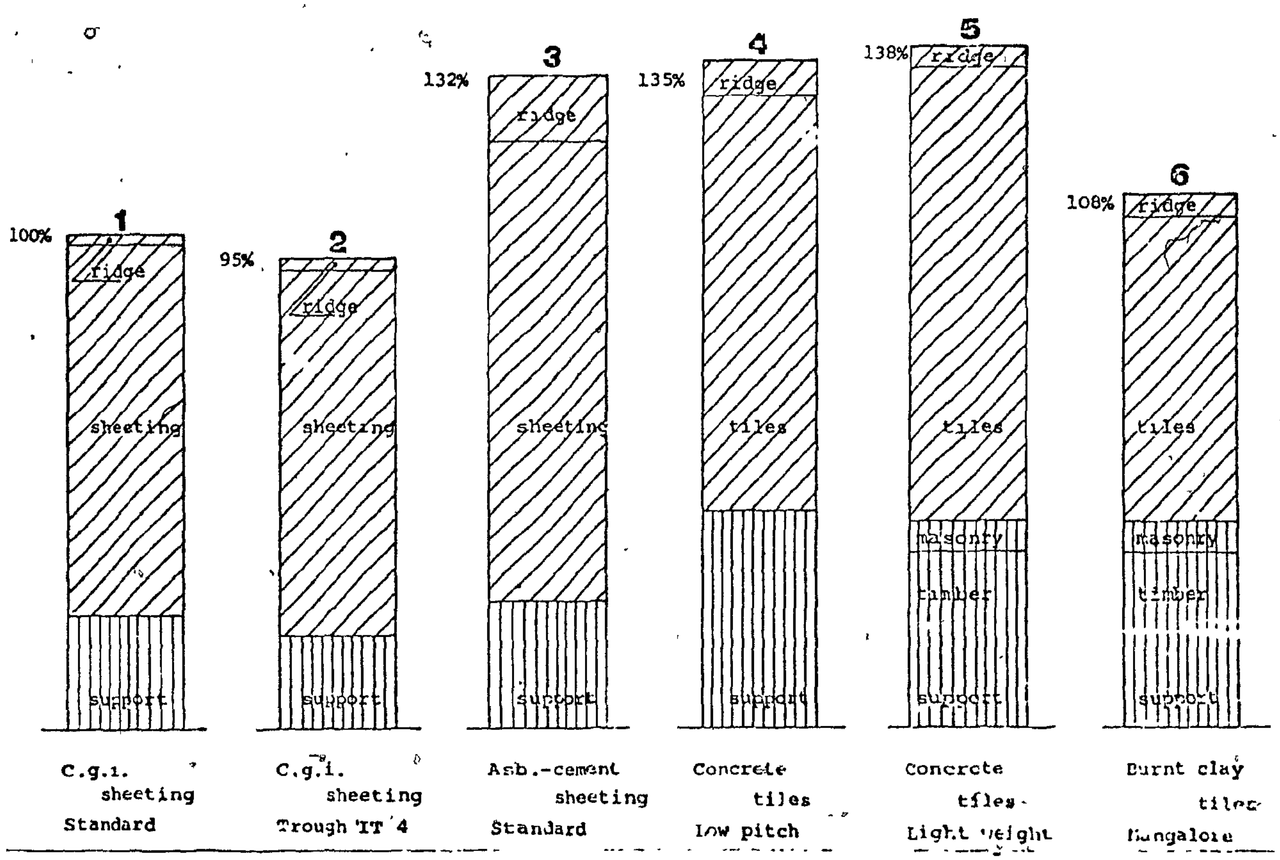
- Local Fired Clay Tiles $13.83
- I.T. Workshop-Corrugated Fiber Cement Tiles . . . 18.60
- Traditional Makuti 25.71

[a]Indicates no major replacement of any system or sub-system of the roof resulting in a negligible maintainence cost.

Table 15 Cost comparison of low-cost roofing system in Nairobi (Eygelaar)

ROOF STRUCTURES FOR LOW-COST HOUSING

COST COMPARISON FOR VARIOUS ROOFING MATERIALS



system to be appropriate as local firewood would have been depleted by building up a clay tile industry, which would apply in other countries with similar arid climates.

These facts indicate that the selection of a roofing system not only for this climate zone but in general, is a very dynamic process depending on local conditions mainly.

ROOFS FOR HOT-DRY OR SEMI DESERT CLIMATE

The large diurnal temperature variations necessitate roofs of large thermal capacities, storing heat during the day and dissipating it during the night. Residential structures need to have a time-lag of 9 to 12 hours.

Considering that wood is always in short supply in this climate zone and precipitation small; I have arrived at the following rank in order of preference of appropriate roofs for this climate:

1. Ferrocement structure with earth cover (p. 127, p. 132)

The excellent structural and economic qualities of ferrocement are making this material the ideal support structure, serving as roofing substrate and water barrier at the same time. All aspects as further summarized on page 276 apply and the earth or sand cover can be tailored to serve the thermal capacity needed. This roofing system has the further advantage that no scarce wood is needed and the roof can serve all traditional requirements and can also have an indigenous appearance.

2. The Conco-brick, Zed-tile and joist and infill systems pp. 100-108)

In densely populated cities like Cairo, where the mud-brick technology is not feasible anymore, these roof-floor systems are offering a good compromise, leaving the possibility of future upward extensions open.

The cost comparison of test roofs in Table 16 and 17 indicate that after the thermal performance has been evaluated, local economic conditions are influencing the situation a great deal. Roof. no. 6 appears to be the best compromise as cement seems to be imported but not the clay tiles and with the minimal use of cement for this roof, the system offers the best choice in that case.

If roof no. 10 had been built with a ferrocement support structure and thus reduced the high proportion of cost for imported materials, this roofing system would appear ahead of roof no. 6.

3. Mud brick dome and vault (p. 198)

This roofing system combines a great number of aspects positively and will always have a future. Especially the economic aspects like low-cost, no foreign currency required, use of local available materials, high labor input, and low investment technology, together with positive social aspects are outweighing the need for annual maintenance and skilled labor.

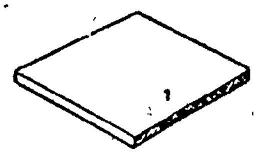
The major drawback of this otherwise very convincing, often with stabilizers improved material, is its low resistance to Earthquakes. Had this roof been included in the comparison of Table 17, it may not have turned out to be the cheapest one, but certainly the one with zero cost for imported materials.

ROOFS FOR COMPOSITE CLIMATE

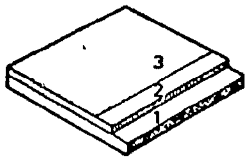
The changing seasons in this climate are demanding more of a compromise with regard to thermal performance of the roof. Ideally, a house in this climate zone would have a high-weight structure for the warm-humid period and one with a high thermal capacity for the colder season.

The compromise often is a structure with a time-lag of 5 to 6 hours or less.

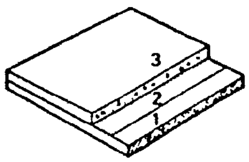
Table 16 Typical roofs for hot-dry climates (OBN 182)



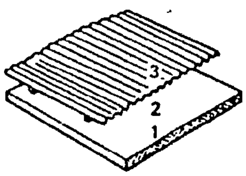
Roof no 1 & 2
1 100mm reinforced concrete slab



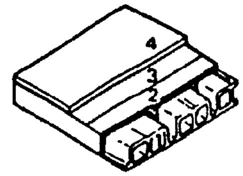
Roof no 3
1 100mm reinforced concrete slab
2 50mm expanded polystyrene
3 Two layers roofing felt



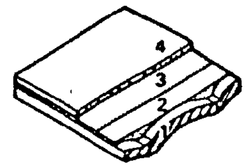
Roof no 4
1 100mm reinforced concrete slab
2 Two layers roofing felt
3 Khafgi (mix of cement sand lime and small chippings of red bricks)



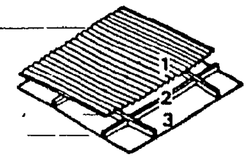
Roof no 5
1 100mm reinforced concrete slab
2 Ventilated air space
3 Corrugated galvanized steel



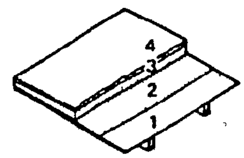
Roof no 6
1 300 x 250 x 180mm hollow tiles
2 50mm reinforced concrete
3 Two layers roofing felt
4 70-50mm cement sand screed



Roof no 7
1 Brick on edge jack arch
2 Cement sand screed
3 Two layers roofing felt
4 'Khafgi'

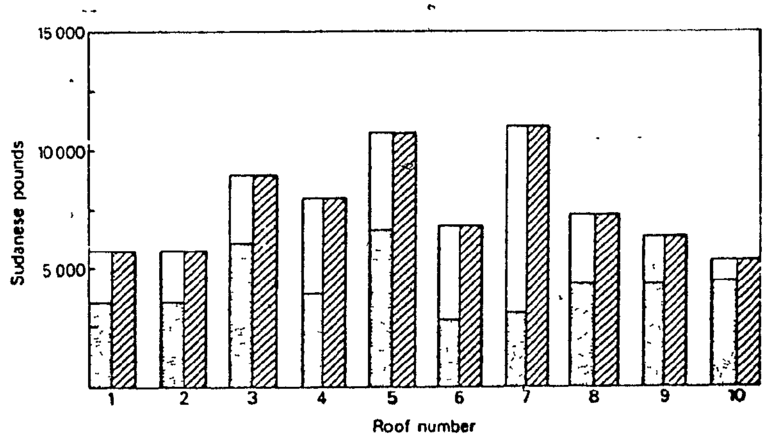


Roof no 8 & 9
1 Corrugated galvanized steel
2 Air space
3 15mm fibre board ceiling



Roof no 10
1 15mm T & G timber boarding
2 Two layers roofing felt
3 100mm mud layer
4 Zibala' layer (mix of animal dung straw and mud)

Table 17 Cost of roof construction for the above roofing types (OBN 182)



Cost of local materials ☐ Cost of imported materials ☐ Total cost ▨

1. Burnt clay tile roof (p. 183)

Whether the roof is made of ceramic fusées or conventional clay tiles, this material combines excellently all roofing criteria and appears to be closest to the ideal for low-cost housing in composite and tropical upland climates.

Nevertheless, there can be no absolute hierarchy of costs of different roofing systems and the following tables with cost comparisons of common roofing materials indicate only that indigenous, low energy consuming materials with excellent roofing characteristics, such as burnt clay tiles, are actually very cost effective.

The cost effectiveness of a clay tile roof is not only documented by these cost comparisons, but more so by the fact that burnt clay tiles have a longer, maintenance free life than CGI roofs for example do.

Considering over-all benefits, it is this kind of a roofing material which fits best in the prevailing transitional-traditional segment* of construction industry in developing countries.[3] But it would be wrong to assume that this is the ideal roofing material which could be applied anywhere in the developing world without further research in this field.

* In this segment are found small firms characterized by labor-intensive methods of construction, with attendant lowered productivity and labor skills and capabilities among the entrepreneurs and work force than is true of the modern segments.

Table 18 Roofing costs in Madhya Pradesh (ISOHP-74)

	ITEM	RATE WITHOUT WOOD WORK & OTHER ACCESSORIES	TOTAL COST OF ROOF
a.	Single wheel tile	Rs. 40.68 per 10 sq.m.	+Rs. 880.00
b.	Double wheel tile	Rs. 86.14 "	+Rs. 1,175.00
c.	Allahabad tile	Rs. 85.05 "	+Rs. 1,200.00
d.	Mangalore tile	Rs. 75.74 "	+Rs. 1,205.00
e.	Asbestos cement sheet	Rs. 126.79 "	+Rs. 1,470.00
f.	Galvanized Corrugated Iron sheet (22 BWG. sheets)	Rs 138.79 "	+Rs. 1,690.00
g.	Asphaltic sheet	Rs. 19.30 "	+Rs. 1,300.00
h.	Asbestos cement curved sheet	Rs. 174.60 "	+Rs. 1,315.00

Table 19 Roof construction cost comparison in Indonesia (Habitat International)

– roof with clay tile	Rp. 700–1,250
– roof with 28 BWG galvanised iron sheet	Rp.1,400
– roof with wooden single	Rp.1,800
– roof with asbestos sheet	Rp.2,000

2. Ferrocement roofing systems (p. 109)

Ferrocement, a "modern" material, has high potentials for roofing in this climate. The higher cost for this roof and possible foreign currency requirements for cement are well balanced by the fact that all other criteria can be satisfied in a very positive way. Machinability and the general structural capacity are making this roof further adaptable to various local and economic conditions.

For large scale developments, machine made panels like described on pp. 118-122 will most likely be more appropriate than insitu "cast" roofs". Transportation of roofing elements would make this material less competitive, on site or local production is desirable.

Ferrocement needs to be further promoted; wider use is then almost certain.

3. Waste material and paper systems (pp. 205 & 53)

It appears that these materials would be most appropriate in this climate zone as sun radiation, temperature and precipitation are less extreme than in the other two zones discussed.

The increasing interest in resource recovering projects, the scarcity of foreign currency, the increasing production of waste materials, like packaging, and also industrial and agricultural by-products, indicate that there is a potential for genuine application in low-cost housing. The major problem connected with the use of waste materials is a management problem, that means if Mr. Heineken had final doubts and the Chilean Government no courage to introduce or implement a by-product project, wide spread use and especially efforts into this direction will be limited.

Finally, the performance standards and general criteria discussed at length in this thesis provide specifications of the qualities which ideal roofing systems for the tropics should possess. These specifications may appear to be, as Koenigsberger[4] said, "a tall order". Yet, modern industry has coped with more difficult and complex tasks.

The enormous housing deficit and the roofing problem, especially when the housing is to be provided by self-help or mutual aid, utilizing unskilled or low-skilled labor, are therefore calling for research, development, implementation and finally application of new useful low-cost roofing systems. There are, however, barriers to innovation, especially in building because of its huge and diffuse nature and its intimate relationship to all of the social, economic, political and other influences that must be considered.[5]

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GLOSSARY OF TERMS

Abaca	Second in importance among the group called leaf fibre.
Adobe	Mud or soil used for building in form of bricks, poured or rammed.
Atap	Leaves used for thatching in Malaysia.
Azaras	Split palm trunks used as earth mix reinforcement in the construction of floors and flat or domed roofs in the arid zones of West Africa (they are appr. 2.40m long).
Bagasse	Fibre remaining after the extraction of the sugar-bearing juice from sugar cane (also called megass).
Barasti	Palm frond stem construction.
Barriadas	Squatter settlements (Peru).
Bidonvilles	Squatter settlements, slum areas (French Africa).
Birish	Roofing substrate (matting) on earth roofs in Sudan.
Burlap	Coarse fabric made usually from jute or hemp.
Bustee	Slum settlement (India).
Canaletta	Folded asbestos cement roofing channel.
CGI	Corrugated galvanized iron sheets.
Chapa modulada	Curved asbestos roofing sheet, made in Brasil.
Cinva-ram	Soil cement block hand-machine.
Cob	Soil lump in form of a football used as soil brick.
Coir	Fibre, covering coconuts.

Favela	Squatter settlements (South America).
Harapan	Roof extension of typical rural Philippine house.
Javeed	Bearers and cross bearers of an earth roof.
Kenaf	A fibre of the group called bast fibres used as jute substitute.
Khafgi	Mix of cement,sand and lime with a small chipping of ordinary brick, used in North Africa as screed.
Makuti	Thatch shingle (East Africa).
Mangalore	Hand pressed, curved roof clay tile.
Mirig	Main beam (palm trunk) supporting earth roofs.
PC	Portland cement.
PCC	Portland cement concrete.
Pisé	Rammed earth.
Rattan	Climbing vine, used for construction in Indonesia.
Rammed Earth	Clay mix, used for insitu construction.
RC	Reinforced concrete.
Rosella	Plant fibre.
Sawali	Bamboo matting in tropical Asia.
SC	Sulfur concrete.
Shagig	Timber joists on earth roofs.
Shanty	Slum type structures in Asia.
Soil Cement	Cement stabalized soil for making blocks, tiles or plastering walls and waterproofing earth roofs.
Stramit	Compressed straw panel (product name).
Swish	Cob in Ghana.

Thatch	Common term, used for roof coverings made of straw, leaves or grasses.
Torchis	A mixture, consisting of clay soil and cow hair, used for building daub walls and roofs (French).
Tubali	A West African term for hand made, pear shaped "bricks", made from a mix consisting of clay soil, water and short pieces of grass.
Vigas	Poles, used as rafters for earth roof construction.
Wattle and Daub	Framework of posts and poles, supporting a matting or other assemblage of woven or otherwise interwined reeds or sticks. Soil mixed with water is then plastered on both sides.
Zed-Tile	Fibre-reinforced, double curved infill element, used for floor joist and infill systems (India).
Zibala	Mix of animal dung, straw and mud for rendering mud walls and roofs in Sudan.
Zinc	A common African expression for CGI roofing sheets.

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Birch, E.L., Bruce, J.B., Hollister, D.T., Wright, M.M., Florida A&M University, School of Architecture, Tallahassee, Florida, USA, "Investigation of alternative roofing systems available for use in the Kurtunwaare Pilot Housing Project".
Experimental low-cost construction unit, publication No. 5, 75 p., June 1981, 24 refernces.

This report was prepared as a result of the USAID and Government of Somalia funded Construction Training Program for the Pilot Housing Project in Kurtunwaare, Somalia.
Following project specific notes, a comprehensive list of available roofing materials together with a detailed description of the twelve considered roofing types are shown. These roofing types are finally plotted against criteria like material and labor cost, foreign currency requirements, maintenance cost and the total life cycle cost for a 15 year period.

Eygelaar, J., "Roofs for Low-Cost Structures".
Housing Research and Development Unit, University of Nairobi, appr. 30p., 1978.

Erkelens, A., "Low-Cost Timber Rooftruss".
Housing Research and Development Unit, University of Nairobi, appr. 25 p, 1980.

These two, as well as further publications by the Housing Research and Development Unit on the topics of low-cost housing and low-cost roofing in particular are very practice related standard works.

Koenigsberger, O., Lynn, R., Architectural Association, London, U.K., "Roofs in the warm humid tropics". Architectural Association, Paper Nomber 1, London, U.K., 55 p., 1965. 17 tables and 26 references.

This paper discusses performance standards on roofing for the warm humid tropics. The results of heat-flow calculations of roofing and ceiling materials are analysed with reference to these performance standards. The main elements of cost are compared for those roofs which satisfy the tentative performance standards. Results are discussed and conclusions drawn for further research, present practice and future development.

National Academy of Sciences, National Research Council, USA, "Roofing in Developing Countries", Research for New Technologies.
Washington, D.C., 74 p., 1974.

This report presents the National Academy's Building Research Advisory Board's (BRAB) special committee's conclusions and recommendations concerning areas of research and kinds of materials indicating significant potential for the development of new roofing technologies that could provide early solutions to the particular problems of developing countries. Ten appendices address various technical aspects of potential new roofing technologies.

C. Technological Topics

Overseas building notes. Information on housing and construction in tropical and sub-tropical countries.

No. 145 "Durability of Materials for Tropical Building", 12 p, August 1972.

No. 148 "The Durability of Metals in Building", 8 p, February 1973.

No. 155 "On Ceiling Heights and Human Comfort", 6 p, April 1974.

No. 158 "Building for Comfort", 9 p, October 1974.

No. 160 "Low-Cost Housing in Urban and Peri-Urban Areas", 6 p, February 1975.

No. 164 "The Thermal Performance of Concrete Roofs and Reed Shading Panels under Arid Summer Conditions", 8 p, October 1975.

No. 165 "Buildings and the Environment", 10 p, December 1975.

No. 180 "Bitumen Coverings for Flat Roofs", 14 p, June 1978.

No. 182 "Roofs in Hot Dry Climates, With Special Reference to Northern Sudan", 17 p, October 1978.

Prognos AG, "Economical Housing for Developing Countries", Basel, Switzerland, appr. 1200p, in 4 volumes, 1979.

Vol. I General Survey Results, requirements, technological options, forecasts, trends of development, (appr. 100 p).

Vol. II Technological Survey, Raw materials and semi-finished products, (appr. 460 p).

Vol. III Technological Survey, Building systems and prefabrication, (appr. 410 p).

Vol. IV Macro-Economic Survey, Housing needs and markets, (appr. 200 p).

This very comprehensive collection of technological and economic data was unfortunately not available for my research for this thesis.

Other consulted, less comprehensive but nevertheless valuable and partly comparable works consulted were:

Goodman, L.J., Pama, R.P., Tabujara, E.G., Razani, R., Burian, F.J., East-West Center, Hawaii, USA, "Low-Cost Housing Technology", New York, Pergamon Press, 345 p., 1979.

Stutz, R., "Appropriate building materials", a catalogue of potential solutions, Swiss Center for Appropriate Technology, St. Gallen, Switzerland, 321 p., 1981.

Salyer, I.O., Ball, G.L., Uzmani, A.M., Werkmeister, D.W., Monsanto Research Corp., Dayton, Ohio, "Development of Low-Cost Roofing from Indigenous Materials in Developing Nations", annual report no. 2, Washington, D.C., AID, 349 p., December 1975.

D. Further Annotated Bibliographies on Low-Cost Housing for Developing Countries

East-West Center, Honolulu, Hawaii, USA, "Annotated bibliography on housing and settlements for low income people", East-West Center, 37 p., 1976.

This annotated bibliography has been put together from revised, edited and selected documents from HABITAT Forum, UN Conference on Human Settlements (HABITAT), 30st May - 11th June, 1976, and the TRIAD Operation Workshop, 24th May - 2nd July, 1976.

Slate, F.O., Acton, M.A., Chinamora, T., Cornell University, Ithaca, N.Y., USA, "Low-cost housing for developing countries": an annotated bibliography, 1950-1972, Cornell University, 214 p., 1974.

Bibliography/costs/housing/developing countries.