Roofing in Developing Countries: Research for New Technologies

by: Special Advisory Committee of the Building Research Advisory Board, National Academy of Sciences

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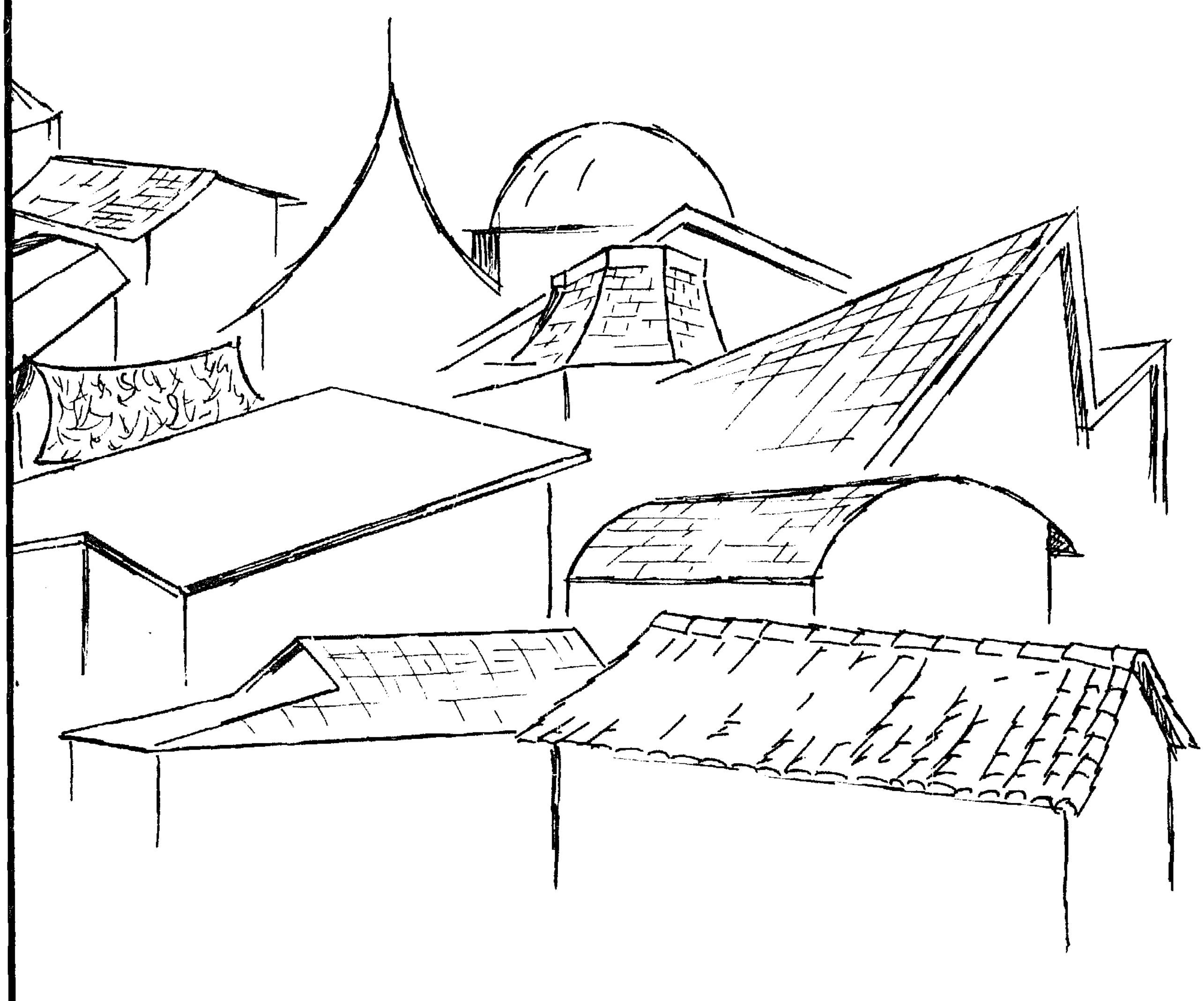

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Prepared by a Special Advisory Committee
of the
Building Research Advisory Board
Division of Engineering
National Research Council
for the
Board on Science and Technology for International Development
Commission on International Relations

Con Resumen en Español
Avec Résumé en Français

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Washington, D.C. 1974

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The members of the committee selected to undertake this project and prepare this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. Responsibility for the detailed aspects of this report rests with that committee.

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SPECIAL ADVISORY COMMITTEE ON NEW TECHNOLOGY SOLUTIONS TO ROOFING PROBLEMS IN DEVELOPING NATIONS

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THOMAS CALLAWAY, Director, Division of Technology and Documentation, Office of International Affairs, U.S. Department of Housing and Urban Development, Washington, D.C.

ERIC CARLSON, Chief, Housing Section, Centre for Housing, Building and Planning, Bureau of Social Affairs, United Nations, New York, New York

J. P. R. FALCONER, Associate Director, Center for Development Technology, Washington University, St. Louis, Missouri

RICHARD L. FRICKLAS, Johns-Manville Products Corporation, Denver, Colorado

ALBERTO GONZALEZ-GANDOLFI, Chief, Building Section, Centre for Housing, Building and Planning, United Nations, New York, New York

PHILIP HUBER, Senior Specialist, Housing and Urban Development, Department of Social Affairs, Organization of American States, Washington, D.C.

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ROBERT G. LINDNER, General Manager, Technical Center, H. H. Robertson Company, Ambridge, Pennsylvania

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ARNOLD ROSENBERG, Research Director, Construction Products Division, W. R. Grace and Company, Cambridge, Massachusetts

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WILLIAM R. TYLER, Manager, Technical Division, Building Industry Sales, Aluminum Company of America, Pittsburgh, Pennsylvania

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NOEL D. VIETMEYER, Staff Study Director for Board on Science and Technology for International Development, Commission on International Relations, National Academy of Sciences, Washington, D.C.

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Foreword

Shelter, a basic human need, is chronically and critically in short supply in many developing areas of the world. Of all the elements of shelter, the roof is perhaps the most important in providing protection from harsh environmental conditions, and it often meets cultural needs as well. Emphasis on roofing needs, and thus research on improved roofing technology, is fully justified at this time and, indeed, an essential first step in improving housing technology.

Historically, people solved their shelter problems by using native materials. They considered traditional roofs of local materials adequate until they came in contact with distant places and learned of different techniques and materials. In efforts to improve roofing, they imported new materials and new technology, sometimes combining the imports with local or readily available substances. When imports required a departure from tradition, many communities rejected innovations because of the accompanying changes in art forms, lifestyles, and technology. In other instances, where new materials and technology have been accepted, they have proved too costly to meet the demand, or they have increased hazard to life and health, even though they represent an improvement in the provision of shelter per se. In many developing areas, climatic conditions alone decrease the durability of even the best roofing materials used in more industrialized, temperate-zone countries. The task of achieving substantive improvements in roofing is formidable.

This report represents the voluntary efforts of an Advisory Committee of the Building Research Advisory Board appointed especially to consider feasible and practical new-technology solutions to roofing problems in developing countries. The committee included highly qualified individuals who, at the request of the National Academy of Sciences-National Research Council, gave freely of their time and expertise in behalf of advancing building technology in developing countries.

The Building Research Advisory Board appreciates the contributions committee members have made and takes this opportunity to acknowledge their effort. In addition, the board extends its appreciation to all others who assisted the committee, particularly William Reps, National Bureau of Standards; Frederick Krimgold, Doctoral Candidate, Stockholm, Sweden; Henry Sjaardama, CARE, Inc.; Robert J. Cowan, CARE, Inc.; W. Ludwig Ingram, Central American Research Institute for Industry (ICAITI), Guatemala; David DeSelm, U.S. Department of Housing and Urban Development; and Mario A. Piche Alfaro, U.N. Centre for Housing, Building and Planning.

Joseph H. Newman, *Chairman*
Building Research Advisory Board

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I. Introduction

THE ROOFING PROBLEM

The full impact and implication of the roofing problem currently experienced by developing countries cannot be realized without some familiarity with the overall housing problem. More than 80 developing countries suffer from an acute housing shortage, principally because of the ever-increasing need for new housing created by expanding populations and the periodic large-scale loss of housing from natural disasters. Each country must overcome serious social, economic, and technical obstacles if the most basic needs and demands for shelter are to be satisfied. For most developing countries, the housing deficit is the most complex problem and one that will become more serious as population growth continues.

The housing deficit is further compounded by the fact that population growth, and the demand for new and improved housing, is greatest in areas where social and technological impediments are the most difficult to address and personal income is lowest. Already enormous financial needs are continually aggravated by extremely limited purchasing power and the absence of a credit system. Much of the population has an income so low that it cannot afford even the most modest housing.

Needs, and thus the basic factors in reaching any solution to the overall housing problem, vary considerably according to location. Designs for new housing in urban areas should take into account the increased hazards to life and health created by population density; yet, doing so will increase costs.

At present the formation of new households and the migration of rural households, or heads of households, to places of employment frequently lead to uncontrolled new, and often population-dense construction surrounding major cities (e.g., Calcutta, Rio de Janeiro, Ibadan). Most such urban housing—and often rural housing as well—is uncontrolled, poorly constructed of scavenged materials, unsanitary, unsafe, and short-lived. Disaster-prone areas need housing that is both safe and capable of rapid and high-volume production. In planning housing for developing countries in tropical and subtropical regions, continuous attention must be given to the ever-present problems of the environment's deteriorating effects on materials.

The most serious obstacle to low-cost housing in the developing countires, regardless of setting or sophistication, is the lack of a low-cost roofing material that will provide satisfactory performance for a reasonable time under many adverse conditions. An essential component of a dwelling, the roof is critical to shelter, thermal comfort, privacy, and, in some localities, the satisfaction of other needs—for a status symbol, a refuge from floodwaters, a sleeping area, a water-collection system, a storage area, a food- and clothes-drying area.[1,2] In many developing countries roofing alone represents more than 50 percent of the total construction cost of a low-cost house.

Usually, roofing for low-cost housing in developing countries is not the product of any organized building industry or process. Instead, it is constructed with local self-help labor using rudimentary processes and materials. Most roofs made of low-cost, indigenous materials such as thatch or unfired clay lack durability and can be hazardous to health and safety. The materials often are subject to moisture-induced decay; they harbor vermin and insects and are particularly dangerous during fires, windstorms, earthquakes, and other disasters. To provide more permanent roof coverings, many developing countries expend scarce foreign exchange to import corrugated galvanized iron (CGI) and other metal roof-covering materials from industrialized countries in the temperate zone. These materials are often too costly for much of the population and, where they are used, do not solve the roofing problem. Metal products do offer the advantages of being relatively long lasting, salvageable after a disaster, self-supporting over short spans, easily maintainable, and simple to install. In hot climates, however, the heat absorbed by metal roofs converts homes into ovens. Where exposed to saltwater spray, ferrous metals corrode quickly.

OBJECTIVES OF THIS REPORT

In view of the magnitude and complexity of the roofing problem in developing countries, the Agency for International Development (AID) requested the Board on Science and Technology for International Development (BOSTID) of the National Academy of Sciences to review the practicality of a major research effort to develop new solutions to roofing problems in developing countries.

BOSTID invited the Academy's Building Research Advisory Board (BRAB) to conduct the review. In turn, BRAB appointed a special advisory committee of individuals with special knowledge of the technical, social, economic, and manufacturing aspects of roofing in developing countries. Two members of the committee were from developing countries; each directs his nation's housing research efforts.

The committee reviewed past and current research and development (R & D) activities directed at solving particular roofing problems of developing countries, as well as more general roofing R & D in other countries throughout the world. The committee found that most such R & D deals with the problems associated with roofing materials now in common use, or aims at improving a specific material or product, or seeks better uses of materials or products already available but used for purposes other than roofing. The committee further determined that although none of the current R & D activities reviewed demonstrates immediate solutions to the roofing problem, limited work is being, and has been, conducted on materials currently used for roofing (such as thatch, CGI, aluminum, and clay) and an extensive literature exists.[1] The committee decided, therefore, to explore the feasibility of developing new low-cost products and processes with potential for providing roofing materials that offer better performance than those most commonly used today.

This report presents the 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 solution to the particular problems of developing countries. Ten appendices address various technical aspects of potential new roofing technologies.

CHAPTER I REFERENCES

1. For example, see Koenigsberger, Otto. 1965. *Roofs in the Warm Humid Tropics.* Architectural Association Paper Number 1. London: Architectural Association.

2. For further information, see

Dietz, A. G. H.; Koth, M. N.; Silva, J. A. 1968. *Housing in Latin America.* Cambridge, Massachusetts: MIT Press. p. 197.

Abrams, Charles. 1964. *Man's Struggle for Shelter in an Urbanizing World.* Cambridge, Massachusetts: MIT Press. p. 182.

II. Conclusions

Conditions in the developing world vary greatly among countries, and even within countries, making it virtually impossible for the committee to address all problems associated with specific locations. During the conduct of its study, however, the committee did consider such regional conditions as the economic, social, and political acceptability of various materials, the availability (or lack) of credit facilities, climate, biological agents, and transportation problems.

On the basis of its study and its own knowledge, the committee arrived at the following conclusions:

1. The introduction of high-performance roofing systems that are low in cost and capable of adaptation to satisfy local social-acceptance requirements, could, of itself, significantly accelerate production of more and better housing. Furthermore, research directed toward development of fresh approaches to roofing problems in developing countries is likely to be productive at this time; in polymer science, in innovative applications of cement and asphalt, and in the improved use of indigenous vegetable, animal, and mineral products, the committee members found sufficient unrealized potential to convince them that, given adequate research funding, new solutions can be found.

2. The roofing problems of developing countries are such that proposed solutions must be conceived, analyzed, and evaluated in terms of a system comprised of the following three principal elements, singly or in combination:

- the supporting structure (e.g., trusses, beams);
- the roofing substrate (e.g., concrete slabs, wood boarding); and
- the roof covering (e.g., tiles, built-up roofing materials, waterproof coatings).

3. For each of these three elements, consideration must be given to

- Availability of materials in or close to the locale in which they are proposed for use. Proposed roofing systems should maximize the use of materials either obtainable from, or manufactured in, the country for which the systems are intended. Wherever possible, the systems should make use of materials that can be obtained from, or produced near, the point of use, to decrease dependance on local transportation systems. Furthermore, materials requiring local material resources should be selected only after investigation determines that those resources are available. (For example, high-quality concrete requires a supply of clean, fresh water, which may not be available.)
- Availability of labor required for production, transportation, and erection or construction. Domestic production would generate employment and stimulate the growth of supporting industries and services, as well as provide opportunity for improving worker skills.
- Skills and skill levels required for production, transportation, and erection or construction. Most developing countries have an abundant supply of unskilled labor, especially in urban areas. Insofar as possible, roof systems should be of simple design and easy to install, to provide employment and skill-training opportunities for local labor.
- Potential hazards to the health and safety of housing occupants and the community. Health and safety are, of course, of paramount importance. If synthetic materials, particularly plastics, are to be utilized, the flammability, smoke generation, and toxic characteristics should be given special attention. For locations known to be subject to earthquakes, floods, and high winds, the roofing system should be designed and constructed both to provide occupant protection against such hazards and to ensure that even if structural failure occurs, the threat to the community from falling or flying debris will be minimized.
- First cost, durability, maintenance costs, and the effect of each on the total roofing system. A durable but inexpensive roof covering that requires a costly or complex structure for support can lead to a total roofing system that is so uneconomical that it is completely unacceptable. The durability of the structural support and the roof substrate material should be considered, as well as that of the roof covering. Each should employ materials that can be maintained easily by the occupants or by local labor.
- Environmental conditions of the locale in which the material is proposed for use, particularly if it will be subjected to tropical and subtropical

climates. Special attention should be given to the possibility of degradation by ultraviolet light, moisture, biological agents, and damage by rain, wind, and earth movement. The roof covering or substrate should have a thermal insulating value sufficient to protect the interior from the heat of the sun during the day and, if enclosed or enclosable, to preserve interior-produced heat during the night. In hot climates, the roofing system should be designed and oriented to reduce the effect of the sun's heat and to take maximum advantage of prevailing breezes.

4. Searches for low-cost materials or systems embodying the above-mentioned characteristics should include composites containing a reinforcement, a filler, and a coating, all of which are held together by a "binder."* Research into composite materials could lead to the development of roofing materials capable of utilizing a vast array of indigenous products. (For a discussion of some composites and related ingredients, see the appendices.)

5. Insofar as possible, local products should be utilized for each component of a composite. For example, vegetable fibers, rock wool, glass fiber, and wire mesh ought to be considered for reinforcement; soil, waste glass, rock, and sawdust ought to be considered for fillers; and paint, whitewash, and sand sprinklings ought to be considered for coatings. (See appendix J for a more extensive list of possible component materials.)

6. Although potential reinforcement, filler, and coating materials are available in each of the developing countries, suitable binders to hold them together generally are not. If suitable binders can be developed and simple, low-cost methods can be devised to use them in the manufacture of composites, such composites might well provide the versatility required to meet local needs in widely differing developing regions.

7. To the fullest extent possible, R & D in roofing technology ought to be conducted within the developing countries, even if the cooperation of public, private, or academic institutions of more developed countries must be sought. Research and design specialists living in developing countries will be more cognizant of available resources and the design requirements peculiar to their specific localities. Furthermore, new roofing technologies generated by a developing country will probably be more easily diffused among, and accepted by, the local population.

*In some composite materials one component may serve more than one function; in others, one function may be unnecessary. For example, a separate coating to protect the surface or a filler to give bulk and weight may not be required.

III. Recommendations

During its investigation, the committee identified a wide variety of materials that researchers could consider in a search for new roofing systems for developing countries (see appendix J). Since developing countries differ so widely in their needs, climates, and available materials and resources, each must determine independently which avenues of research are most promising. The committee believes, however, that an organized, systematic approach to the establishment and direction of R & D programs within the developing countries could lead to early results of immediate use for most, if not all, countries. Thus, the committee offers the following recommendations:*

1. AN INTERNATIONAL ADVISORY COMMITTEE

A standing advisory committee should be established under appropriate international auspices. Its efforts should be directed specifically to accelerate, enlarge, and consolidate the dispersed low-cost roofing research programs for developing countries that now exist. The committee should give emphasis to regional rather than global approaches.

*This report was completed before the recent rise in crude oil prices. Substantially increased costs of petroleum derivatives will adversely affect the competitiveness of polymeric binders and foamed plastics (recommendations 2 and 3) and will increase the attractiveness of the nonpetroleum-based technologies discussed in recommendations 4–10.

Typical of the needs such a committee could address is a systematic inventory of roofing materials and the design and construction practices currently utilized in developing countries, as well as roofing problems now being studied by those countries and other research organizations. Such an inventory would make possible the identification of research gaps and areas calling for more attention.

Most committee members should be housing experts from developing regions; others should be drawn from the most appropriate research and academic facilities worldwide and from technical assistance organizations that have substantial interest in, and considerable resources committed to, housing in developing countries (such as AID; World Bank; United Nations Development Programme; United Nations Centre for Housing, Building and Planning; Inter-American Development Bank; Organization of American States; CARE).

2. POLYMERIC BINDERS

Roof-covering research, development, and demonstration programs should be directed toward the use of existing, commercially available unsaturated polyester and related polymers for binding combinations of indigenous materials (such as vegetable fibers, earths, and fabrics) of selected developing countries.

Such effort could be productive now because the technology of fabricating building products using thermosetting (e.g., unsaturated polyesters) and thermoplastic resins and related polymers in combination with other materials is highly developed and well documented (see appendix A). If such products are compatible and blend with locally available raw materials, they could be made in almost limitless shapes and sizes to meet designs required by a variety of customs and traditions. The committee believes that a concerted program of pilot-level development and testing could produce composite materials suitable for low-cost roofing systems in most developing countries.

The major challenge will be to develop inexpensive composites that will resist deleterious elements such as moisture, ultraviolet light, insects, and fungi. Special emphasis should be placed on identifying potential hazards associated with products utilizing plastic materials. For example, if open-fire cooking is done indoors, certain plastic roofing elements may ignite and produce injurious smoke or toxic gases. Polymers can be treated by fairly simple techniques to perform well when directly exposed to fire. But, to date, applications of such treated polymers have been relatively expensive.

If materials that perform adequately can be developed at reasonable cost, the manufacturing technology and application probably could be transferred throughout developing countries with little difficulty; the simplicity of producing synthetic-resin roofing materials would permit easy diffusion of the technology and ready commercialization by small-scale entrepreneurs. The finished building products are likely to be economically competitive with, or have a price advantage over, CGI. The materials also may be used for applications other than roofing.

The costs of manufacturing the roofing composite could be very small. The system would be versatile and lend itself to labor-intensive production.

In their raw state, basic resins and polymers are stable and can be stored for some time, but, to maintain their specified characteristics, they must be kept in a cool, shaded location. Since they are concentrated, they require little shipping and storage space and have little intrinsic value until processed into a building material. If the basic resins and polymers are not available in developing countries, they would have to be imported but would probably represent only a minor portion of the cost of the finished roof. No significant logistical problems need to be overcome in importing bulk resins and polymers—abundant supplies and numerous manufacturers exist, and end-point handling, storage, and transportation are not difficult.

Field-research efforts on this type of application should include a cost-benefit analysis of imported resins as opposed to alternatives such as imported CGI.

3. FOAMED-PLASTICS PROCESSING

A pilot project should be undertaken to process foamed plastics suitable for roof-covering materials and to develop a mobile, small-scale, foaming-equipment system that developing countries could produce economically.

Foamed plastics—lightweight cellular substances produced by introducing gas bubbles into plastic compounds during manufacture—offer significant potential as versatile, lightweight roofing materials with high insulating values that could be produced on site in a variety of shapes and sizes (see appendix B). To date, the use of foamed plastics has been severely limited by the lack of simple, low-cost, reliable foaming equipment capable of producing a high-quality, uniform product.

The customary foamed-plastic processing equipment generates the foam chemically and then sprays the stabilized, frothy mass of fine bubbles into the desired position. In the past, the processing equipment used in field demonstration projects in developing countries was quite complex and sensitive and required costly maintenance; recent advances in equipment design, however, have eliminated many of the problems experienced earlier. Therefore, it would seem most appropriate and timely to incorporate these advances in the development of a mobile, small-scale foaming system that could be mass-produced by the developing countries. Such a system, coupled with a demonstration that foamed plastics can be used in conjunction with indigenous reinforcing fillers and coatings as roof-covering and substrate materials, could lead to the formation of profitable local business enterprises that would produce both the equipment and a variety of foamed-plastic products.

The recommended pilot project should be organized clearly as an experiment to assess and document the performance of the equipment, as well as the economics, consumer acceptance, use, longevity, and durability of the prototype roofs produced. The project might well be conducted as a cooperative effort between U.S. and developing-country enterprises, with participation of academic institutions, building-oriented professional and trade organizations, and technical assistance agencies in the housing field.

It should be noted that recently the U.S. Federal Trade Commission charged that polyurethane and polystyrene foams subjected to fire can be hazardous to life and health in certain housing applications. This fact is well known by building technologists; however, foams with reported low flame-spread and smoke development are available today and its is likely that further improvements will appear in the near future. Nonetheless, those researchers developing foamed plastics for roofing materials in developing countries should be cognizant of the potential fire-related hazards and keep abreast of technical developments in this area.

4. SULFUR

Sulfur should be given serious consideration as a material for binding mixtures of other indigenous materials, as a valuable coating and joint-grouting material, and as a material from which small-size roofing products, such as tiles, can be made.

Although sulfur has not been widely used as a building material, its full potential as a binder for use in low-cost roofing for developing countries (see appendix C) should be explored. Only in the last decade has the use of this material for construction purposes been subjected to comprehensive scientific investigation. Its use in developing countries is particularly worth consideration because many have abundant supplies of sulfur as a result of volcanic activity and as a by-product of oil refining. Sulfur also could prove to be an inexpensive import item for countries lacking an indigenous supply.

Previous research and testing have been directed primarily toward the use of sulfur in sulfur-concrete and as a surface bonding agent. Elemental sulfur is a bonding agent with unique properties: It becomes molten at 240 °F, only slightly higher than the boiling point of water; it is insoluble in water and demonstrates qualities of water impermeability; it is odorless, nontoxic in normal use, and a poor conductor of heat; it has an indefinite storage life; and it can be reprocessed. All these features indicate excellent potential for use in developing countries as a roofing material.

Elemental sulfur is particularly suitable for labor-intensive construction methods, but does have certain limitations: It is highly flammable, and it must be converted to a liquid state before aggregates or fillers can be added. Product developers and users must also be aware of the possible release of sulfuric acid in the presence of moisture and the potentially harmful effects of ingestion. Advantages seem to outweigh the disadvantages, however, and a concerted R & D effort is warranted at this time.

5. CARBONIZED PLANT MATERIALS

A laboratory-research and field-demonstration program should be conducted on the transformation into low-cost, lightweight roofing sheets of carbonized and expanded, nonfood, high-starch plant products that have been combined with unsaturated polyester resins and related polymers (see appendix G). Research should include local field surveys to identify types, quantities, and availability within the developing countries of plant products suitable for this purpose.

6. AGRICULTURAL AND WOOD WASTES

An intensive program should be initiated to develop economical processes for manufacturing resins from native agricultural products (e.g., natural vegetation, bagasse) for use primarily as binders.

As noted in appendix G,[1] the lignin and furfural in vegetation can be used as *in situ* binders if heat and pressure are applied. This technology is well known in industrialized nations; it is probable that simplified processing methods would permit developing countries to produce an abundant supply of satisfactory building panels.

7. WASTES FROM PRIMARY INDUSTRIES

Wastes such as fly ash and blast-furnace slag from the steel industry have properties that make them suitable as cementitious binders (see appendix E) and should be investigated. These wastes could prove of particular value in countries lacking adequate limestone and portland cement resources.

Red mud, a copious by-product from bauxite refining that gluts many developing countries, also merits serious consideration, as do metallic wastes from the production of iron and steel. Disposal of these and similar waste products is an ever-increasing worldwide burden to heavy industry; their conversion to useful products would serve a two-fold purpose. Research in such alternative uses may be so attractive to the affected industries that they might be induced to contribute funds or materials.

8. CONCRETE

An analytical and laboratory testing program should be undertaken to develop more appropriate and economical reinforced concrete products. (See appendix H on ferrocement.) The research effort should focus on the use of reinforcing materials such as wire mesh, locally available chopped wire, glass fibers, rock wool, and various vegetable products such as bamboo,[2] bark, and wood fiber (wood-fiber concrete is known as "wood wool" in some parts of the world[3]). Consideration also should be given to substitutes for portland cement, some of which are suggested in appendix E.

9. CLAY-BASED MATERIALS

A research program should be undertaken to develop methods for improving the general performance and range of applications of clay-based roofing materials. (See appendix I.)

10. FIBER PRODUCTS

The suitability and effectiveness of waste raw materials from textile and other fiber industries (based on such fibers as jute, sisal, hemp, kenaf, and cotton) common in developing countries as a blend in a composite material for roofing components should be explored.

In summary, there are numerous promising avenues of exploration, and it is the opinion of the advisory committee that full advantage should be taken of them at this time.

CHAPTER III REFERENCES

1. See also *Production of Panels from Agricultural Residues.* December 1970. Report No. ID/79 (WG.83/15/Rev. 1). Geneva: United Nations Industrial Development Organization.
2. For further information, see F. B. Cox and H. G. Geymayer. 1969. *Expedient Reinforcement for Concrete for Use in Southeast Asia.* Technical Report C-69-3. Vicksburg, Mississippi: U.S. Corps of Engineers.
3. For further information, contact Dr. J. W. S. De Graft-Johnson, Director, Building and Road Research Insitute, CSIR, Kumasi, Ghana.

Appendix A. Plastics

By chemical definiton, plastics (also known as polymers) are synthetic, chainlike molecules of high molecular weight that are the end result of the chemical binding of large numbers of smaller molecules known as monomers. Today there are approximately 40 families of plastics.

Each plastic has a well-defined combination of properties, processing requirements, and economics that make it uniquely applicable in certain situations and unusable in others.

In developing countries, plastic resins containing monomers could, in principle, be combined with locally available reinforcement and fillers by local labor using low-cost equipment to form roofing sheets that could substitute for currently used corrugated metal sheets. The widespread availability of the chemicals, the relative ease of training local labor to make such roofing, and the low cost of equipment all strongly suggest that a project should be initiated to develop such roofing.

A development program for using plastic resins in this manner would have these advantages:

- A local industry might result, to manufacture roofing materials.
- The use of indigenous materials and local labor would contribute to the economic growth of less developed nations.

Contributed by Trayon Onett, Marketing Manager, Research Department, Koppers Company, Inc., Monroeville, Pennsylvania.

• The reinforced plastic sheets would be lightweight, weather resistant, translucent, verminproof, corrosion resistant, and potentially low cost.

• The use of this type of material would relate roofing solutions to the general housing problems of developing countries.

• The use of indigenous materials would help overcome the problem of local acceptance of shapes, styles, and aesthetics usually associated with the introduction of new materials. Though a new material is used, the house could be constructed in a traditional architectural form.

• The development program would establish the extent of training necessary to use existing talent and skills.

• Walls and floors could later be made from different proportions of the same ingredients.

To utilize these advantages and implement such a development program, it is recommended that

1. A complete program for evaluating indigenous reinforcing, fillers, various resins, additives, and stabilizers be initiated. The results of this program could be incorporated into pilot development plans for larger-scale construction, testing, and field evaluation.
2. As the physical testing and evaluation program are initiated, a market acceptance and economic feasibility program be started in a developing country.

SELECTION OF A PLASTIC

With over 40 families of plastics available and hundreds of variables possible within each, determining the balance of properties required in the end use becomes most important. Today, polymers can be tailored to produce bulk fiber, foam, film, coating, and adhesive plastics that may be hard or soft, rigid or flexible, rubbery or leathery, and porous or nonporous.

Some of the physical considerations that must be considered are the end-product requirements for the following characteristics:

Stiffness or flexibility
Temperature range
Tensile, flexural, and impact strengths
Intensity, frequency, and duration of loads
Color retention under environmental conditions
Electrical properties
Moisture resistance
Chemical resistances

Weather and sunlight resistance
Odor and taste
Production requirements (quantity and speed)
Material costs

The ratings of physical requirements will be assigned ranges (e.g., tensile strength: 4,218,600 kg/m^2 or 6,000 psi, essential; above 5,624,800 kg/m^2 or 8,000 psi, desirable; above 8,437,200 kg/m^2 or 12,000 psi, unimportant). Choosing the best plastic for a specific job then becomes a matter of finding the one material that best combines the necessary and desirable properties per unit cost.

Plastics are differentiated as either thermoplastic or thermosetting. Thermoplastic resins require heat to form plastics, and the final plastic can be remolded a number of times without loss of properties simply by applying more heat. Thermoplastic scrap can be reclaimed and reprocessed without difficulty. Chemically, the plastics they produce are linear molecular chains that fuse and solidify without serious chain breakage and without much cross-linking. Polyethylene, polystyrene, polyvinyl chloride, cellulosics, and nylon are examples of thermoplastic resins.

A thermosetting resin forms a plastic with a permanent shape that cannot be altered reversibly when heated. The final plastic after setting is a cross-linked, intractable, nonflowing material. Applying additional or higher heat only destroys it. Thermoset scrap cannot be reprocessed and can only be reused as filler material. Typical plastics in this family are polyesters, phenolics, and ureas.

Certain thermosetting resins require no heat and little or no pressure to form their final shape. They achieve cure by reacting with other chemicals at room temperature to create their tightly cross-linked chain structures. These reactions occur in relatively short times, and the final cure and set are permanent. Among these are some specific polyesters, epoxies, silicones, and polyurethanes.

THERMOPLASTIC RESINS

The descriptions of thermoplastics presented below will serve as a quick introduction to this branch of the plastics industry.

ACRYLONITRILE-BUTADIENE-SYTRENE (ABS)

Very tough; has an unusual combination of a high rigidity and impact strength; readily accepts decorating or plating; possesses excellent embossing properties; has fair chemical resistance, very low water absorption, good dimensional stability, and high abrasion resistance; formulation can be varied to obtain different combinations of flexibility, heat resistance, and toughness.

ACETAL

An engineering plastic with very high tensile strength, stiffness, and exceptional dimensional stability; has high chemical resistance, high abrasion resistance, low moisture absorption, excellent resistance to creep under load, and low tendency to stress cracking; is nontracking electrically; has low coefficient of friction and superior retention of physical properties if immersed in hot water. Two types are available–homopolymeric acetals that have higher strengths, and copolymeric ones that are easier to process.

ACRYLICS

Widely used for their high optical clarity and brilliant transparent colors; best of the transparent plastics in resistance to outdoor weathering; excellent electrical strengths; hard, glossy surface; fair chemical resistance. Available for fabrication as acrylic sheets or standard and high-impact molding powders.

CELLULOSICS

Among the toughest of plastics; five basic cellulose families–nitrate, acetate, propionate, butyrate, and ethyl celluloses. Nitrate, the toughest, is highly inflammable and explosive and embrittles with age. Acetate is easier to process and not explosive but has poor solvent resistance and embrittles with age. Propionate and butyrate are chemical and weather resistant.

FLUOROPLASTICS

Four general types–polytetrafluoroethylene (TFE), chlorotrifluoroethylene (CTFE), fluorinated ethylene (FEP), and polyvinylidene fluoride (PVF_2). TFE is nonburning and has very high heat and chemical resistance (up to 550 °F), excellent resistance to heat aging, the lowest coefficient of riction of any plastic, very high dimensional stability, and zero moisture absorption, but is very difficult to process. CTFE has most of the outstanding properties of TFE but is somewhat easier to mold. FEP is very easy to mold but is the most expensive of the fluoroplastics. PVF_2 has heat resistance to 300 °F, is the easiest to mold, and has higher tensile strength* and lower cold flow† than the other fluoroplastics.

**Tensile strength*: the pulling stress in pounds per square inch required to break a given specimen.

†*Cold flow*: the tendency to change dimensionally with time under load (e.g., creep at room temperature.

IONOMER

A generic name for polymers in which ionized carboxyl groups create ionic cross-links in the intermolecular structure. They offer excellent toughness and high optical clarity, superior resistance to oils, greases, and solvents, and high abrasion resistance. Their high melt strength permits very deep draws in thermoforming, and they are very resistant to stress cracking. Films have outstanding flexibility and are hard to tear but have easy tear propagation.

METHYL PENTENES

Offer excellent transparency; short heat resistance to 430 °F, good chemical resistance, and low water absorption. Have the lowest specific gravity (0.083) of any commercial plastic, superior electrical strengths at high temperatures, sharp melting point at 464 °F, and poor resistance to outdoor weathering. Are easier to process than most high-heat plastics.

NYLONS (POLYAMIDES)

Are self-extinguishing if ignited and offer outstanding toughness and wear resistance, a very low coefficient of friction, excellent chemical resistance, high electrical strengths, poor dimensional stability due to hygroscopy* and cold flow.

PHENOXIES

Offer outstanding chemical resistance except for organic solvents; are tough, hard, and ductile; show low shrinkage during molding. Compared to other thermoplastics, they have the lowest creep resistance, permeability to gases, and coefficient of thermal expansion.

POLYALLOMERS

Similar to polyethylene and polypropylene, but with high abrasion resistance, broader processing conditions, and better stress/crack resistance. Offer excellent embossing properties, low specific gravity, and short molding cycles.

POLYCARBONATES

Rigid, transparent, tough engineering thermoplastics offering excellent outdoor dimensional stability, very low creep under load, fair chemical resistance,

**Hygroscopy*: the tendency to absorb moisture.

and excellent impact resistance. Are self-extinguishing if ignited, physiologically inert, and ductile enough to yield rather than shatter under load.

POLYETHYLENE

An excellent combination of electrical and physical strength; lightweight, easy to process, and low cost; offers good toughness, flexibility, and chemical resistance; easily heat sealed, but heat resistance limited to 180 °F; has poor stress/crack resistance and is difficult to hold to tolerances in molding. Available as low-, medium-, and high-density polyethylene. The stiffness and physical strengths increase toward the higher density.

POLYAMIDES

Maintain heat resistance to 500 °F continuously and up to 900 °F for short periods; offer very low coefficient of expansion, outstanding resistance to heat aging, high impact strengths, and excellent wear resistance; are the most difficult to process so they must be sintered or solution coated; are very expensive.

PHENYLENE OXIDE

Engineering plastic, very tough over a temperature range of 275 °F to 375 °F; offers superior dimensional stability, low moisture absorption; highest resistance to creep under load, and excellent chemical resistance. Modifications available at lower cost but with lower heat resistance.

POLYPROPYLENE

Offers excellent resistance to stress or flex cracking, very low specific gravity, excellent impact strength, good chemical resistance; floats on water; forms films and fibers having superior strength, optical qualities, grease resistance, and moisture-barrier properties.

POLYSTYRENE

General-purpose grade very rigid; shows low moisture absorption, low shrinkage during molding, high optical clarity, and poor outdoor stability; many solvents attack polystyrene; easy to process. Many modifications of polystyrene are possible (e.g., adding butadiene for impact resistance, making copolymers of styrene-acrylonitrile for high strengths, or adding blowing agents for foamed parts).

POLYSULFONE

An engineering plastic showing good transparency, high mechanical strengths, high heat resistance, superior electrical strengths at high temperatures, unusual resistance to strong mineral acids and alkalis, and superior retention of properties on heat aging.

POLYVINYL CHLORIDES (PVC)

Of two basic types—rigid and flexible; tough, hard, and difficult to process; offer good outdoor stability, superior electrical properties, excellent resistance to moisture and chemicals; are self-extinguishing if ignited. Many copolymers and formulae variations are available for special applications.

THERMOSETTING RESINS

ALKYDS

Offer excellent dimensional stability, arc resistance, and high heat resistance; cure without creating volatile by-products; have very fast, low-pressure molding cycles making them easier to mold than most thermosetting resins; surfaces are hard, stiff, and tough. Various fillers and reinforcing fibers may be added to the resin to produce a wide variety of compounds, each offering a different combination of properties.

AMINOS (UREA AND MELAMINES)

Hard, rigid, and abrasion resistant; have excellent dimensional stability under load, good solvent resistance and chip resistance, and are self-extinguishing if ignited. Urea molds faster and costs less; melamine has higher surface hardness and heat resistance. Both are static-free and have excellent electrical properties. Fillers and reinforcing fibers are added for economy, better dimensional stability, and higher strengths.

DIALLYL PHTHALLATE (DAP)

Offers most exceptional dimensional stability of all the plastics as well as superior electrical properties and excellent heat and chemical resistance; surfaces are hard, tough, and have very low moisture absorption; is easy to mold at low pressures without forming volatile by-products; offers low postmolding shrinkage when glass-filled.

EPOXIES

Has outstanding physical and electrical properties and excellent adhesive properties; offers unusually low shrinkage during molding and superior dimensional stability under a wide variety of adverse environments; resins are normally liquids even without solvents or dilutants; some formulations can be cured without heat or pressure; many formulae variations.

PHENOLIC

Low-cost molding material with excellent combination of high physical strengths, high temperature resistance, good dimensional stability, and superior electrical properties; color limitation of black or brown; mineral, glass, and cotton flock materials commonly used as fillers.

POLYESTERS

Two types–saturated or unsaturated. Films and fibers are formed from the saturated polyesters; the unsaturated polyester resins, when reinforced, give products with excellent resistance to high temperatures and chemicals. Superior electrical properties and one of the most economic of all resin systems. Reinforced parts have high physical strengths and can be molded with little or no heat and pressure. Finished parts can be cast, molded, pultruded–or the opposite–laminated, foamed, or sprayed.

POLYURETHANE

Available as film, as well as rigid or flexible foam. Thermosetting types can be flexible and rigid, depending upon formulation. Good abrasion and wear resistance, superior impact resistance, and good electrical properties and chemical resistance. Thermoplastic forms are also available and are used to produce tough films and wear-resistant parts.

SILICONE

Offers excellent property retentions over wide temperature range, -100 to 500 °F; nonstick surface. Can be cured without heat or pressure; molding compounds can be rigid or flexible, depending on the type of silicone. Reinforcement with fillers yields extra strength. Silicone fluids are used to make mold releases, antifoaming agents, and water-repellent coatings. Physiologically inert.

REINFORCEMENT MATERIALS FOR PLASTICS

The addition of reinforcing materials to these families of resins can dramatically improve the strength, toughness, dimensional stability, and properties of electrical, thermal, and chemical resistance of the plastic formed from them. An initial screening of a resin and reinforcement system must include measurements of tensile strength, flexural modulus, impact resistance, heat deflection temperatures, flame retardance, and volumetric materials costs. The reinforcing material in greatest use in the United States is fiberglass, supplied as mat, cloth, roving (twisted strands of fiberglass), or continuous glass filaments. In addition, inert fillers of minerals, clays, and silicas are used to impart weather resistance and flame or chemical retardance. Final fabrication is accomplished by the addition of a catalyst for casting or ambient-temperature curing. If high production is required, the finished parts are usually pultruded, compression-die molded, bag molded, or vacuum formed. The addition of initiators, catalysts, fillers, and additives enables the processor to tailor a chemical system to the availability of materials, and the volumetric material costs.

Among the indigenous materials that can be used in reinforced manufacturing are asbestos fibers, fly ash, hemp, coconut fibers, jute, and groundnut shells (see also appendix J).

Appendix B. Foam Composites

The thermal characteristics and light weight of foamed materials suggest their potential for use in roofing if combined with reinforcement for increased structural strength.[1]

A major advantage of reinforced-foam roofs is that they incorporate in one unit the roof surface, insulation, supporting structure, and ceiling. The separate substructure and ceiling that must be used with other types of roofing materials is eliminated. As a result of the savings gained by eliminating the substructure, the cost of a bamboo-reinforced polyurethane composite roofing material, for example, is approximately one-third to one-half that of conventional materials. At present polyurethane is the most available of the matrix materials. Poor physical properties, high cost, or processing problems eliminate many other foams from further consideration for this application at this time.

Work on several different urethane foam formulations[2,3] indicates that rats, mice, and termites will not attack it. Rodents will chew and claw through only if it is placed between them and their regular food source. Work by Wessel[4] indicates that the urethanes have (on a scale of good, moderate, and poor) good resistance to attack by fungi and bacteria.

For use in residential structures, roofs must not pose a potential fire

Contributed by J. P. R. Falconer; adapted from a paper by D. J. Stubblefield, Falconer, and T. B. Moore, presented at the Third International Cellular Plastics Conference, Montreal, Canada, September 1972.

hazard to the occupants. This is a particularly important consideration when a foamed roof is used on a low-cost dwelling in a developing country since with no ceiling the foam is exposed to the interior where oil lamps, cooking fires, etc., could ignite it. Foams with low flame-spread and smoke-development ratings are available, and certain foams are nonburning. However, polyurethane and polystyrene formulations have recently come under question by the U.S. Federal Trade Commission as possibly representing a serious fire hazard. Furthermore, during combustion and even before ignition, some foamed materials have been shown to give off toxic fumes.

Aromatic polyurethanes and some other plastics undergo degradation when exposed to sunlight. This is particularly troublesome in tropical countries. Ultraviolet rays in sunlight produce free radicals that react with oxygen to produce a discolored, highly cross-linked, friable surface, which is sloughed off. This may be prevented by coating the foam with an elastomeric weather barrier.[5,6]

The long-term stability of a foam matrix in a hot, humid environment depends strongly on the molecular structure of the polymer. Work by Frisch et al.[7] indicates that polyurethane foam stability under hot, humid conditions is inversely related to the cross-link density. That is, foams with the lowest molecular weight between cross-links were the most stable. An extensive dis-

TABLE B-1. Cost of 500-sq ft Sprayed Bamboo/Foam Roof

Item	Cost (U.S.$)
Polyurethane foam	110
Bamboo	
700 culms @ 5¢	35
Mold cost	
200 2 × 10 ft panels/mold @ $40/mold	0
Release agent	0
Weather barrier @ 20¢/sq ft	100
Labor (fabrication and erection or spraying)	
125 hrs. @ 60¢/hr	75
Equipment*	+6
	326
30% overhead and miscellaneous	98
	424
Total cost, $/sq ft	$ 0.85

*500 houses per year for 5 years, $15,000 for spray. A foam cost of $0.50/lb and a labor rate of $0.60/hr are assumed.

cussion of the effects of a foam's chemical structure on thermal degradation is presented by Tilley et al.[8]

The theory of fiber-reinforced foam composites is covered in a recent paper by Rinde.[9] This paper also discusses the preparation and testing of several different types of foam/fiber composites. Since the mode of failure usually associated with roofing materials is excessive deflection rather than fracture, the major mechanical property of interest in evaluating potential materials is the modulus of elasticity. Once the modulus is known, the roof thickness may be adjusted to limit the maximum midspan deflection under a given loading condition, and roof costs can be determined.

For developing countries, vegetable fibers are attractive to consider as potential reinforcement for foams. These fibers typically have a modulus of elasticity of 1×10^6 to 4×10^6 psi, and tensile strengths of 1×10^5 to 2×10^5 psi. As reinforcing they have the distinct advantage of being relatively inexpensive (compared with typical fiber reinforcements such as steel or fiberglass) and are available where the roof will be produced and used. Bamboo is a particularly attractive reinforcement, and an extensive program of research into bamboo-reinforced polyurethane foam sheets for developing-country roofing is now under way at Washington University.* Table B-1 lists a typical cost breakdown for such roofing.

MAKING THE FOAM

Since a multicomponent chemical system must be blended in accurate proportions in foam making, the equipment is complex, specialized, and expensive.

The development of foam-processing machinery has accelerated rapidly during the past 10 years and should continue as applications of foams increase. Recent developments, centered around the use of positive-displacement piston pumps vs. rotary-gear pumps, will reduce the requirement for temperature-conditioning equipment and the physical size of the machinery. Current work indicates that this will also simplify operational procedures considerably and give a higher degree of portability for on-site work.

Today, equipment manufacturers must also constantly upgrade, redesign, and innovate to keep pace with the improving urethane chemical systems. We can look forward to improved machinery performance with fewer maintenance problems, and perhaps most importantly, simpler operating pro-

*For further information, contact J. P. R. Falconer, Center for Development Technology, Washington University, St. Louis, Missouri, U.S.A.

cedures. All these factors will contribute to increased acceptance of roofing made of urethane foam systems.

Because of the complexity of the equipment, it is mandatory that operators be given intensive training. Those who are eventually assigned the responsibility of operating the equipment should possess a relatively high mechanical aptitude, and have previous experience in mechanical-equipment repair or operation. Some basic training to familiarize personnel with the chemical system may be desirable but from a functional standpoint is not required. Particular emphasis should be placed on developing troubleshooting ability and proper machine-maintenance procedures. A thorough study of the machinery manufacturer's manual should be required.

The foam can be made rapidly. For example, a 3-in. thick, 10-ft long, 10-in. wide roofing element may be foam filled in 20 seconds with a machine having a throughput rating of 30 lb/min. (This includes the time needed to assemble reinforcing in the molds.) It is feasible to produce one such roofing element per minute with equipment of this size.

SPRAY-IN-PLACE BAMBOO/FOAM COMPOSITES

Through the centuries, techniques have been developed for working with bamboo. Various types of woven mats, and poles wired together, are used for many purposes. In developing countries bamboo mats are often used as structural wall elements and as the base for roofing such as thatch.

Foam can be sprayed on both sides of a bamboo mat to provide thermal insulation and to give a unitized, sealed roof. The underside becomes the ceiling. After the exterior side is coated with a weather coating, it becomes durable and weather resistant.

This type of roof construction is ideally suited to self-help housing, since the homeowner can contribute a large part of the work. Also, with the spray-in-place technique, the builder has a great deal of architectural latitude in the final roof design, because almost any configuration can be set up before it is sprayed. This helps to eliminate a sometimes undesirable situation in which each house looks just like its neighbors.

Urethane spray machinery must, of course, be highly portable. Good design dictates a lightweight spray gun equipped with a suitable method for purging mixed material if an internal mixing chamber is used. The entire system is designed into an equipment package as small and lightweight as practical. The proportioning pumps should be adaptable to a variety of material volume ratios. Suitable provision for temperature control should be incorporated throughout the pumping system and through the flexible hose assemblies to the gun. Power, if electricity is unavailable in the field, may be provided by a gasoline- or diesel-powered generator.

Using a system commercially available in the United States, a two-man crew can spray from 7000 to 9000 sq ft per 8-hour day, including adequate time for start-up and shutdown procedures. Complex structures or forms and the need to use ascending-descending ladders, platforms, and scaffolds reduce this.

For large projects truck-mounted bulk tanks are desirable. Properly designed and built, mobile foam-spray units are efficient and economical.

To use the foam-spray approach, considerable training of spray personnel is required. Training programs have to develop a thorough understanding of all component parts of the spray-foam machine. This extends to a complete discussion of each component part, its purpose, and the possible causes for its failure. The trainee must be capable of disassembling and rebuilding the machinery, and he should be placed in situations in which he must diagnose a failure or improper function of the machine. His ability to recognize the problem, select the proper solution, and then carry out the repair properly is invaluable in the field.

Considerable attention must also be given to proper spray technique. To develop a smooth arm motion requires muscular coordination and extensive practice. In spraying a roof, arm motion must take place while the worker moves, particularly when he walks backward. Personnel experienced in using paint spray guns will find the arm motion quite similar. However, coupling this arm movement with walking backward on a roof deck usually must be thoroughly practiced before an acceptable finished surface can be consistently applied.

A complete spray-foam-operator training program, including printed manuals and visual aid training films, is now being developed in the United States.

APPENDIX B REFERENCES

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Appendix C. Sulfur

Investigations of the past 10 years show that sulfur with plasticizers, aggregates, and fibers can be used in low-cost construction instead of, or in addition to, traditional materials.

Simple techniques and primitive equipment can be employed for melting and applying sulfur in small quantities (e.g., when it is used as a binder to cover joints in blocks, bricks, and slabs). However, to use large amounts of sulfur or for continuous production, practical techniques have yet to be developed.

Continued research is warranted and is justified by the following considerations:

- Sulfur is abundant in many parts of the developing world, particularly in volcanic regions. Oil refineries also produce sulfur in large quantities as a by-product.
- Sulfur can be used as a building material in low-cost construction, and its application requires relatively simple handicraft techniques.
- Sulfur is waterproof, adheres strongly to a wide range of materials, has no taste or smell, does not act on the skin, and is a poor heat and electricity conductor.
- Sulfur, when mixed with fibers, gains in tensile and flexural strength;

Contributed by A. Gonzalez-Gandolfi, Chief, Building Section, Centre for Housing, Building and Planning, United Nations, New York.

when mixed with natural and artificial aggregates, it produces a concrete of a quality acceptable for low-cost construction.

- Sulfur cures in minutes and can be cast in, and removed from, molds in a fraction of the time required for portland-cement concrete.
- Sulfur has high resistance to salt and acid solutions, and can be stored indefinitely.
- Sulfur can be reused.

However, sulfur has some drawbacks. One disadvantage—flammability—has prevented, until recently, its use as a building material. Today, a number of low-cost additives have been developed that reduce fire danger to levels meeting American Society for Testing and Materials (ASTM) performance requirements.[1] However, systems incorporating these have not yet been used widely enough to determine their cost-effectiveness.

Sulfur has been used in a minor way in housing for many years, for example, as grouting to fasten metal railings to masonry. Since about 1960, a systematic and wider investigation of this material has been undertaken. The Department of Chemistry and Chemical Engineering of the Southwest Research Institute, San Antonio, Texas, has built experimental buildings using sulfur and has investigated ways to spray sulfur and to make it more plastic and less flammable. The Texas institute has also developed methods to apply sulfur and to reinforce it with synthetic fibers.[1,2]

Further studies and experiments have been conducted in Guatemala,[3] Iraq, the United States (Columbia University),[4] Togo (sponsored by the United Nations), and Canada, by McGill University.[5]

SULFUR AS A COATING

If inexpensive sulfur spraying equipment can be developed, many building materials traditionally used for roofing (as well as some new ones) could be coated with sulfur to give increased strength and waterproofing. For example, even thatch roofs might be made more durable and waterproof.

A report of an exploratory study made by Columbia University under U.N. auspices states:

> A panel of reeds, a woven mat and a coarse cloth stretched on a wooden frame were impregnated and painted with sulfur. The resulting panels are quite stiff and completely waterproof even after cracks are induced by flexing the panels. Because of the low viscosity of the sulfur, the procedure is simplest with relatively dense fiber panels and tightly woven fabrics.
>
> Paper panels: the use of paper panels for low-cost, lightweight construction offering flexibility of form was considered in another project. The problem of waterproofing such panels can be solved with the use of sulfur coatings which adhered very well to

sample panels tested during the present study and also added to their strength in flexure.[4]

Some demonstrations in Guatemala proved that sulfur-sand and sulfur-pumice mixtures can be troweled onto wood-wool panels (wood fibers set in concrete). Further investigations have been recommended on roofing made of wood-wool panels with a waterproof coating of sulfur.[3] For coatings and some other uses, the brittleness of sulfur is a drawback but there are indications that this can be overcome.

Dr. B. R. Currell, Department of Chemistry, North London Polytechnic, reported in August 1971, that he had developed methods for plasticizing sulfur by adding unsaturated hydrocarbons to make it flexible.

SULFUR AS A BINDER

Sulfur-containing composite materials could provide strong, waterproof roofing membranes and high performance supporting structures. Experiments in the United States[1,2,4] and Guatemala[3] indicate the possibility of using sulfur as a binder with other materials, such as cement blocks and bricks, to make beams and slabs spanning 1.8288–2.4304 m (6–8 ft). Asbestos-cement is increased greatly in strength when impregnated with sulfur, and larger spans than those used in current asbestos-cement roofing practice might be possible.[5]

McGill University has produced very thin cast tiles. If they are cast in glass molds, a smooth 15 cm X 30 cm X 6 cm (6 X 12 X ¼ in.) rectangular roofing tiles are obtained. These could be used instead of clay or asbestos-cement tiles.

Slabs and tiles of different sizes, sulfur mixes, and finishes have also been made. A mix of sulfur, sand, and basalt aggregates, for example, was cast in a 60 cm^2 mold, 2 cm deep (24 X 24 X ¾ in.). The resulting slab can be used for flooring or roofing. Another demonstration was made using 50 percent of a local sulfur concentrate and 50 percent of pumice with which slabs 5 cm X 7 cm X 1 m (2 X 28 X 40 in.) were cast. Since the slabs are waterproof, they can be used as a roof plane without a roof cover on top, except for the joints. Techniques for grouting the joints should be investigated.[3]

Using sulfur in sulfur-concrete shells has been limited so far by difficulties in melting and pouring large quantities of sulfur. Sulfur-concrete composed of 70 percent sulfur, 25 percent sand, and 5 percent carbon black is reported to reach a tensile strength 47 kg/cm^2 (670 psi).[5] Demonstrations in Guatemala were successful with the following mix: 38.5 percent sulfur, 38.5 percent quartzite sand, and 23 percent pumice. Its compressive strength was 245 kg/cm^2 (3,500 psi).[3]

In 1969 a promising demonstration of sulfur's properties was made:

mineral resources indicates that future building material should, if possible, be produced from renewable resources such as vegetation. For example, in Europe mineral aggregates have become so scarce that roads now must be designed to eliminate the deep layers of gravel traditionally used as roadbeds.

To carbonize plant materials, kernels of common cereal grains–wheat, rice, corn–are expanded by applying heat and pressure, and the expanded kernels are converted to carbon by slow burning. The resulting product has a fine cellular structure containing entrapped air, which makes it an excellent lightweight insulator. The carbonization process renders the materials biologically inert, fire resistant (stable up to about 2000 °C or 3632 °F), and highly resistant to water and chemicals. Further development of this process will undoubtedly affect both the agricultural and construction industries.

To date, work in North America has centered on the use of edible cereal grains to produce the carbonized product; however, this can hardly be recommended for countries where food shortages exist. For these areas, research should focus initially on identifying locally available, nonedible grains or plant materials other than grains suitable for expansion and carbonization. Although it is likely that such indigenous materials exist or that exotic species of plants could be introduced and cultivated specifically for the purpose, there has been little reason to initiate such studies to date.

To develop roofing will require investigating suitable cements and binding agents for the carbonized particles. Some work has been done, again at Toronto, in binding the particles with low-penetration asphalt to produce a roofing board; asphalt, however, is a problem material in the tropics. Portland cement is an obvious alternative, which could produce lightweight insulating concrete for roof decks or precast roof slabs. But portland cement must sometimes be imported and, in such cases, raises the construction costs. Synthetic-resin binders may be viable in some areas, but might require pretreatment of the carbon particles.

The many variables and unknowns at this point of development suggest that the best approach is a comprehensive study in one or more tropical developing countries of the availability of suitable plant materials and an investigation of compatible binding agents to be developed specifically for use with those carbonized products that appear to hold the most potential for roofing in tropical environments.

The use of insulating building materials derived from plant products is an important concept for developing countries. They could be produced locally without draining foreign exchange reserve and could reduce the energy requirements for heating and cooling the buildings produced.

Appendix E. Hydraulic-Setting Cement Binders

This discussion deals with hydraulic-setting materials other than portland cement, which is well documented especially by the Portland Cement Association in the United States and similar organizations in other countries. The purpose here is to describe some other materials with hydraulic-setting properties that may be used as binders for roofing materials or, in some cases, as partial substitutes for portland cement.

Most materials described below offer binding properties deficient in some respects to those of portland cement. Accordingly, their usefulness as binders for roofing materials needs to be researched in terms of particular materials, applications, and locations.

It is hoped that some of these materials will offer a choice for developing a hydraulic-setting binder in areas where portland cement is available in limited quantities or not at all.

BACKGROUND AND POTENTIAL

The following six materials are starting sources for developing hydraulic-setting properties: (a) blast furnace slag, (b) fly ash, (c) limestone, (d) bauxite, (e) pozzolans, and (f) magnesia.[1]

Contributed by C. E. Bushnell, Manager, Building Products Research Unit, Armstrong Cork Company, Research and Development Center, Lancaster, Pennsylvania.

BLAST-FURNACE SLAG

Blast-furnace slag is formed in the process of iron manufacture from a combination of residues from the ore after separation of the iron, and from the limestone and ash from the coke used in the furnace. The slag rises to the surface and is removed from time to time. For use as a hydraulic-setting material, the slag is reduced in size by various means.

Finely ground blast-furnace slag alone does not produce a hydraulic set with water. Various materials must be added to "activate" the hydraulic-setting characteristic. Materials such as lime, portland cement, sodium and potassium hydroxides, and mixtures of salts giving high pH in solution are used.

Slag-based hydraulic-setting binders will probably offer lower strength than straight portland cement but otherwise should provide reasonable performance.

FLY ASH

Fly ash is a by-product of coal-burning power-generating plants. Created in abundance where such facilities operate, it is probably in oversupply since no single major use has been found for it. Probably not useful by itself as a hydraulic-setting binder material, fly ash does exhibit pozzolanic activity and is a practical extender for portland cement.

Certain fly-ash-containing concretes have demonstrated improved strength properties.

LIMESTONE

The greatest use of limestone is for portland cement manufacture; it is blended with other materials to provide hydraulic-setting properties. However, some impure limestone, usually argillaceous, possesses hydraulic-setting properties because its chemical composition is similar to that of portland cement. Lime calcined from limestone has been known to have binding properties for centuries. Hydraulic lime prepared by calcining impure carbonate materials, again argillaceous, also offers potential. Used for centuries in various regions, including South America and Asia, it has been replaced recently by portland cement and other newer materials.

With the exception of portland cement, materials derived from limestone would have less strength as binders and be somewhat water sensitive.

BAUXITE

Bauxite offers a starting point for developing aluminous cements, but it generally needs a source of limestone as well. To make hydraulic-setting materials, bauxite and limestone are fused at high temperatures and then the size of the resulting clinker is reduced. Various combinations of bauxite and calcium-producing materials can be used, and several heating methods are possible.

Aluminous cements are characteristically slow setting but are generally considered to provide high-strength material.

POZZOLANS

Pozzolans do not necessarily hydraulic set themselves, but they provide hydraulic-setting properties when combined with lime or portland cement. Natural pozzolans include certain volcanic glasses, pumices, tuffs, and high-silica-content materials such as diatomite. Some manufactured products, such as fly ash, are also considered pozzolans.

These materials may be used as extenders or with other hydraulic-setting materials. Lime alone has been used for centuries with various naturally occurring pozzolans. Properties developed will depend on the combination and amounts of pozzolans and lime or portland cement used.

MAGNESIA

Magnesia forms the basis for the so-called Sorel cements formed from a combination of magnesium oxide and a solution of magnesium sulfate. These materials, mixed together to form a binder slurry, react through a crystallization process. Magnesia can be replaced to some extent by calcined dolomite to provide wide latitude in raw material source.

These cements offer suitable strength as binders for roofing materials; magnesium oxychloride, particularly, is used to bind wood fiber into a board. However, the water sensitivity of these cements must be considered in any roofing application.

RECOMMENDATIONS FOR USE

Hydraulic-setting binders combined with various fibers and fillers should find application in preparing various types of roofing material—planks, boards, blocks, shingles, etc. Because of the nature of the setting mechanisms, hydration and crystallization, hydraulic-setting binders must form a substantial portion of the composition. In addition, the density of the composition is usually high, otherwise strength will suffer.

Hydraulic-setting binders, except in the very densest uses or where slopes are such that drainage is rapid, do not waterproof, and some may deteriorate, usually by losing strength, when wet. Thus, this class of binder generally must be used with additional waterproofing, made extremely dense, or installed on slopes steep enough to allow quick drainage.

Hydraulic-setting binders are slurried with water and mixed with fiber, filler, etc., and the resulting mix is formed in a mold or press. Just enough water to slurry and mix should be used, since excess water adversely affects strength. The formed roofing material must be cured, for several days or weeks, to develop optimum strength. Either damp curing at ambient temperatures or various elevated-temperature processes may be used to speed the cure. After cure, the finished product is dried.

APPENDIX E REFERENCES

For more detail, see

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Appendix F. Asphalt Binders

ASPHALT

Asphalts and asphaltic substances have been used by man since the dawn of recorded history. They offer excellent binding qualities along with good weathering and waterproofing properties. Asphalt is derived from many sources including the distillation of petroleum, naturally occurring deposits (e.g., Trinidad Lake), and deposits of harder materials such as gilsonite found in seams and mined out of the ground. Asphalt is available with a wide range of properties from soft and sticky to hard and brittle and is made workable by heat, solution, or emulsification. Useful binders for roofing materials can be made by all three methods.

Asphalt or asphaltic substances can be mixed with a wide variety of materials to provide waterproofing coatings or mastics, or to function as binders for fibrous sheets or boards.

TARS AND PITCHES

Tars are the volatile oily decomposition products from heat processing of bituminous and other organic substances. Pitches are the residues resulting

Contributed by C. E. Bushnell, Manager, Building Products Research Unit, Armstrong Cork Company, Research and Development Center, Lancaster, Pennsylvania.

from the distillation of tars. Some materials useful as binders for roofing materials are tars and pitches from petroleum, coal, wood, rosin, peat and lignite, shale, fatty acids, bone, and other similar materials.

All these materials have characteristic properties and will vary in such things as waterproofness and weatherproofness, softness, brittleness, etc. Most are thermoplastic, but some have thermosetting or drying qualities that further enhance their usefulness. However, none would be considered highly developed in these respects. Any source of tar or pitch could usefully be explored as a basis for a roofing-material binder.

Appendix G. Agricultural and Wood Wastes

Solutions to the roofing problem in the developing world are needed urgently. Therefore a logical start for R&D is in areas that maximize the use of materials that are already available (and cheap) in developing countries, such as agricultural and wood wastes.

For example, locally available wood-wastes and agricultural wastes could be used to manufacture particle-board type roofing panels.[1] Research to develop roofing materials for low-cost dwellings might very well concentrate on one or more of the chemicals, present in wood and agricultural wastes, that could serve as binders.

Prime candidates are lignin and furfural. Lignin is a major ingredient in higher plants, where it binds together cellulose fibers to form the rigid woody structure. The lignin content of some plant materials that are widely available in most countries is shown in Table G-1. Furfural, too, is widely available from most agricultural wastes, which are used even in industrialized countries for the production of commercial furfural. Table G-2 shows the furfural content of some representative vegetable materials.

Considerable data are available on the use of lignin as a binder in plastics and laminated boards,[2] as well as for its use with phenolic resins, a combination which is claimed to be suitable as a wood particle-board binder. (See references at end of appendix.) Furfural also is used as an ingredient in in-

Contributed by W. Ludwig Ingram, Jr., Head, Industrial Services Division, Central American Research Institute for Industry (ICAITI), Guatemala City, Guatemala.

TABLE G-1. Lignin Content of Some Plant Materials

Plant Material	% Lignin Content
Wood	24 to 28
Bamboo	29 to 35
Rice hulls	40.0
Peanut shells	28.0
Bagasse	20.3
Coconut shells	31.9
Corncobs	30.4

Source: Based on data from *Encyclopedia of Chemical Technology*, 2nd ed. Vol. 12. 1967. Raymond E. Kirk and D. F. Othmer, eds. New York: John Wiley and Sons.

dustrial resin, especially the phenol-aldehyde type. Furthermore, it itself reacts readily with lignin, and, in the USSR, a lignin-furfural resin has been developed and used as a binder for molded wood products with encouraging results.[3]

Research aimed at developing cheap roofing suitable for developing countries might take advantage of the lignin binders already present in agricultural wastes. Research to explore using lignins alone or combined with furfural as binding agents in a particle-board type of roofing panel could be productive at this time. Of course, the furfural could also be obtained from agricultural wastes; thus, both binders could be produced from inexpensive waste materials already available locally in developing countries.

Building panels have been manufactured from agricultural and wood wastes for a number of years, and the following three general types are commercially available: hardboard, insulation board, and particle board (chipboard).

Hardboard panels, such as Masonite, have excellent physical properties and

TABLE G-2. Furfural Content of Miscellaneous Agricultural Wastes

Waste Material	% Furfural Content
Corncobs	22.0
Cottonseed hull brand	20.0
Cornstalks	16.5
Bagasse	17.0
Rice hulls	12.0
Peanut hulls	12.0

Source: Based on data from *Encyclopedia of Chemical Technology*. Ibid. Vol. 10. 1966.

have been used in some instances for the exteriors of housing in developed countries. Their ingredients can be cheaper than those of particle board, since a synthetic resin binder is not required. Hardboard, however, is usually pressed from wood fibers prepared by either the Masonite or Asplund processes, both of which require wood chipping, softening, defibrillating, and wet-sheet forming operations prior to panel pressing. Together these make a complex and costly process requiring, for developing countries, a high investment in equipment and plants. As a result, hardboard is not now manufactured in most developing countries and is an imported item even though suitable ingredients may be available locally. If lower cost processing can be achieved this might be changed.

The other two products, insulation boards and particle boards, have good physical characteristics and, with chemical additives, can be made resistant to fungus and insects. Particle boards have been made successfully from a variety of agricultural wastes as well as, more conventionally, from wood chips. The process is relatively simple, and particle board is now manufactured in some developing areas (e.g., Central America). The cost of these locally produced panels, however, is too high for it to be an ideal construction material for low-cost housing in developing areas. A major contributor to this cost is the synthetic-resin binder of petrochemical origin, which in many areas must be imported or produced locally from imported raw materials and which is required by current processing techniques.

Data published by the Food and Agriculture Organization (FAO) in 1957[4] on the production costs of three types of European-manufactured particle board indicate that raw material costs (wood scraps and resin) represent from 52 to 63 percent of the total manufacturing cost of the product. In Central America a particle-board panel made from wood chips and measuring 4 ft wide by 8 ft long and 1½ in. thick sells for $0.35 per square foot, and it is estimated that the resin binder represents over 50 percent of the total material cost in the manufacture of the particle board.

These costs suggest strongly that a low-cost building panel suitable for developing countries could be developed if processing costs could be reduced. This could be accomplished if the need for an imported synthetic resin binder could be eliminated from the particle-board manufacturing process.

Ideally presses of the type already developed for particle-board manufacture could be used. Because of the special requirements of most tropical countries, additives to enhance the insect and fungus resistance of, and to waterproof, the finished product will be necessary, but conventional chemical products currently used for these purposes may prove adequate. This approach is versatile and, in concept, could produce panels for roofing and for the exterior and interior walls of low-cost housing in both rural and urban areas. For the different uses, however, different densities may be required. For example, for roofing a low-density panel might be needed so that it could be saturated with a waterproofer such as asphalt.

Research directed toward this end might investigate new cheap, mechanical and chemical, methods for releasing lignin from woody materials. Lignin alone or in combination with furfural would have to be submitted to the usual tests of production pressure, temperature, and time and their relation to product quality.

Most developing countries lack research facilities and experienced personnel, especially in the specific case of lignin research. Although lignin has been extensively studied in industrialized countries, research for low-cost roofing materials might best be conducted in the more developed countries. However, the raw materials and the demographic, climatic, and other conditions are different in developing countries. It seems more reasonable to conduct new process development work in developing-country facilities and to appoint a principal investigator who has previously worked with lignin and is familiar with the manufacturing process of hardboard and particle board. Developing-country investigators could participate and not only learn and develop processes but also contribute significantly by supplying local statistics and such information as the availability and accessibility of suitable raw materials. In addition to laboratory equipment, a pilot-plant installation for particle-board manufacture would be desirable.

APPENDIX G REFERENCES

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4. FAO. 1959. *Tableros de Fibra y Tableros de Fibra Aglomerada.* Ch. V. p. 87.

Appendix H. Ferrocement

Ferrocement was not discussed by the committee because BOSTID had under way an in-depth review of ferrocement's potential for developing countries, which included its use for roofing. Since the committee's meeting, the ferrocement panel has published a report. Their evaluation of ferrocement is quoted here.

Ferrocement is a highly versatile form of reinforced concrete made of wire mesh, sand, water, and cement, which possesses unique qualities of strength and serviceability. It can be constructed with a minimum of skilled labor and utilizes readily available materials. Proven suitable for boatbuilding, it has many other tested or potential applications in agriculture, industry, and housing.

Ferrocement is particularly suited to developing countries for the following reasons:

- Its basic raw materials are available in most countries.
- It can be fabricated into almost any shape to meet the needs of the user; traditional designs can be reproduced and often improved. Properly fabricated, it is more durable than most woods and much cheaper than imported steel, and it can be used as a substitute for these materials in many applications.
- The skills for ferrocement construction are quickly acquired, and include many skills traditional in developing countries. Ferrocement construction does not need heavy plant or machinery; it is labor-intensive. Except for sophisticated and highly stressed designs, as those for deep-water vessels, a trained supervisor can achieve the requisite amount of quality control using fairly unskilled labor for the fabrication.[1]

The panel believes that ferrocement may prove a suitable material for low-cost roofing in developing countries. Applied-science laboratories in developing countries and technical assistance agencies should seriously consider this area for field trials and techno-economic studies. . . .

Ferrocement represents a potential solution to roofing problems because of its relatively low cost, durability, weather-resistance, and particularly its versatility. Unlike most conventional materials, ferrocement can be easily shaped into domes, vaults, extruded type shapes, flat surfaces, or free-form areas. Because ferrocement is easily fabricated, even in rural areas, by supervised local labor using mainly indigenous materials, it seems an excellent medium for on-the-site manufacture of small or large tiles (shingles) or other roofing elements. Where wooden timbers are very expensive, ferrocement beams might be made on site to replace wooden structures used to support indigenous roof coverings. Its most economical use, however, appears to be for fairly large-span roofs.

Ferrocement is not commonly used for roofing because its promise has not generally been recognized. Its use, particularly in developing countries, must be preceded by more research and experimentation in design and production techniques suited to construction by unskilled labor.[2]

Ferrocement roofing materials can be factory mass-produced in prefabricated form, a process best suited to the concentrated demand of urban areas. Though it might be more economical to mass-produce roofing in an urban factory and truck it to a rural area (should trucking be possible), ferrocement is also easily fabricated on site in rural areas, using local labor and materials.

Freer in concept and makeup than most conventional roofing, ferrocement can be shaped into domes, vaults, extruded shapes, flat surfaces, or free-form areas.

Before ferrocement can be used widely for roofing, research and experiments will be required to determine the shapes and types of roofing members to be manufactured, and to explore designs and methods for anchoring and bolting these various shapes to supporting walls.

After this research and experimentation is completed, on-the-job training centers may be required to introduce the new material and its new building techniques. Preferably, these centers should also offer programs dealing with other ferrocement applications.

Research efforts to find ferrocement modifications that prove less expensive or easier to manufacture are highly recommended. Possibly, for example, ferrocement can be sandwiched on two sides of a core of foam concrete or other lightweight material to make a less expensive and lightweight, yet still structurally strong, material.[3]

APPENDIX H REFERENCES

1. National Academy of Sciences. 1973. *Ferrocement: Applications in Developing Countries.* Washington, D.C. p. 1. (Available free to readers in developing countries or persons engaged in technical assistance programs. See BOSTID publications at end of this report.)
2. Ibid. pp. 8, 9.
3. Ibid. pp. 35, 36.

Appendix I. Low-Cost Roofing Research in India

Over the years, roofing problems have been studied in depth at the Central Building Research Institute of India (CBRI) and are briefly described in the appendix.

CLAY

Clay roofs are common in developing countries because of the availability of clay and the low construction costs. In India, these include flat mud roofs, country-tiled roofs, and Mongalore-pattern clay tile roofs.

Research and development activities at CBRI have added several new techniques: (1) precast *Guna* clay tile units, (2) corrugated-clay roofing sheets, (3) structural-clay flooring/roofing units, (4) reinforced brick, and (5) reinforced-brick concrete. The salient features of these techniques are described below.

PRE-CAST GUNA CLAY TILE UNITS

Guna tile is a hollow, conical clay tile. A unit of the roofing system is about 110 cm long, 25 cm wide, and 12 mm deep (43.31 X 9.84 X 0.47 in.) and

Contributed by Professor Dinesh Mohan, Director, Central Building Research Institute, Roorkee, Uttar Pradesh, India.

weighs nearly 41 kg (90.40 lb). Compared with a conventional 10-cm (3.94-in.) reinforced concrete (RCC) slab, the saving in use of cement is 28 percent and of steel, 55 percent.

CORRUGATED-CLAY ROOFING SHEETS

A process has been developed for producing corrugated-clay roofing sheets (105 cm X 60 cm X 10 mm or 41.34 X 23.6 X 0.39 in.) 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 labor in villages. The tensile strength of these sheets lies in the range 100–105 kg/cm^2 (1422–1493 psi), and water absorption is below 2 percent. Each sheet weighs about 15 kg (33.07 lb).

STRUCTURAL-CLAY FLOORING/ROOFING UNITS

In several developing countries, mechanized brick production is increasing. Taking advantage of this situation, CBRI has developed two types of structural flooring/roofing units. Plastic alluvial clays (kaolinite-illite mixtures) with a fairly wide range of workability are suitable for extruding these tiles. Tiles are pre-assembled on the floor: the units are placed end to end up to the required length, a 6-mm (0.24-in.) mortar joint being provided between the tiles. A triangular cage of mild steel bars is placed within the hollow space provided in the tile for the purpose, and it is then concreted. After concreting is done, two beams are placed on bearing walls at 45-cm (17.72-in.) centers and the intervening space filled up by placing ceramic blocks of the same design in an inverted position. A deck concrete is laid on to a thickness of 3 cm (1.18 in.). Compared with a conventional 10-cm (3.9-in.) RCC slab, the system is estimated to save 40 percent in cement consumption and 30 percent in steel. Deck concrete can be eliminated by slight modification of the design, thereby effecting further economy in cement consumption.

Tiles of another design have been developed for vertical construction of floor sections in the manner of a masonry wall. After the wall panels have acquired adequate strength, they are tilted to a horizontal position to form a flooring unit and placed on the bearing walls. This type of clay tile is likely to result in an economy of 60 percent in cement and 30 percent in steel, compared with a conventional RCC slab.

REINFORCED BRICK (RB)

Reinforced brick has essentially the same features as reinforced concrete, except that brickwork in cement mortar is substituted for cement-concrete.

Reinforcement is placed in the mortar joints, which are generally 2.5 to 3 cm (0.98-1.18 in.) wide. All other joints with no reinforcement are generally 1 to 1.2 cm (0.39-0.47 in.) wide. Good-quality bricks with a minimum strength of 70 kg/cm^2 (995.4 psi) should, however, be used. These bricks are of medium absorption (8-15 percent) and free from any trace of smooth glaze on the surface. The mortar used is 1:3 (cement:sand).

RB slabs may be designed for both one-way or two-way spanning. The design principles are the same as those for reinforced concrete, except that the permissible stresses and other design factors are different. For normal residential buildings, this type of slab has yielded a saving of about 10 percent compared with an RCC slab.

REINFORCED BRICK CONCRETE (RBC)

In this type, cement-concrete is used in conjunction with the bricks as a deck over the top surface of the bricks, as well as for filling the joints. The thickness of deck concrete generally varies from 4 to 6 cm (1.57-2.36 in.) and the joint thickness from 4 to 5 cm (1.57-1.97 in.). In general, the deck concrete at the top forms the compression zone, whereas the participation of brick in resisting compression is either nil or very limited. RBC slabs are also designed like RCC slabs and are used quite extensively in India as an alternative to RCC slabs for floors and roofs of residential buildings.

ORGANIC MATERIALS

Organic materials such as wood, thatch, and leaves are very commonly used for roofing purposes in developing countries. In India, thatched roofs are built of locally available grass or palm leaves. The roof is supported on wooden posts and rafters and is tied to suitably spaced bamboo battens. The incline of the roof depends on the intensity of rainfall and is usually 30-45°. This type of roofing is most popular in villages because of its cheapness and the ease and rapidity of its construction. In the tropics, however, thatch deteriorates rapidly and harbors insects. It also presents a serious fire hazard. Chemicals are available to improve the durability of thatch and render it fireproof, but they leach away during rains and need reapplication. CBRI has developed a stabilized mud plaster, which is applied on the lower surface of a thatch roof to reduce its rate of burning. The risk of fire spreading from one roof to the next is reduced by the application of a thin wash of stabilized mud on top of the roof. This mud wash, however, needs renewal after each monsoon, especially on palm-leaf roofs.

CBRI investigations have confirmed the possibilities of preparing a roofing board based on particle boards prepared from the husks of mature coconuts. A board of density (753 kg/m^3 or 47.1 lb/ft^3), prepared with 0.5 percent P.F. resin adhesive, possesses modulus of rupture, in bending, of 232 kg/cm^2 (3299 psi). These boards can be rendered waterproof with cashew-nut-shell liquid. Tests have shown that they are self-extinguishing and need no fire-retardant treatments. CBRI has also developed a chipping machine, specially adapted for chipping the husks of mature coconuts. Because of the widespread availability of coconut husks in most developing countries, it could become a profitable source of roofing material and other products.

Corrugated-asphalt roofing sheets have recently been introduced in India. They tend to delaminate at the edges, and their dark color absorbs solar radiation and renders the internal environment uncomfortable. White-washing roofs helps to reflect the solar radiation and cools the ceiling by 2 to 3 °C.

CONCRETE

In building a strong base for industrialization, several developing countries are experiencing rapid urbanization of the countryside. In such a situation, judicious use of cement and steel can help to provide economic alternatives for the conventional in situ RCC slab. If the new techniques lend themselves to simple prefabrication, they could also help in mass housing programs. In CBRI several roofing units have been developed that economize in the consumption of cement and steel and can easily be precast at a factory or at the construction site. Some of these units are described below.

PRECAST DOUBLY CURVED TILE UNITS

The concrete tile unit is square–68.6 cm × 68.6 cm × 19 mm (2.25 ft × 2.25 ft × 0.75 in.). Its surface is curved in both directions, which enhances its resistance to both sustained and impact loads. It weighs only 27.2 kg (59.98 lb), and no reinforcement is needed in the edge beams. The casting process is very simple: To construct the roof, precast RCC beams are laid at 76.2-cm (30-in.) centers and provided with two temporary wooden props at middle-third points along the length. The tiles are laid on a bed of mortar put on the beam edges and carefully positioned. The haunches are next filled up with the cement concrete, leaving only a small ridge uncovered. The waterproofing-cum-insulating treatment is then provided over the roof in the conventional manner. The roof is suitable for single-story schools, offices, and residential buildings where it is not likely to be subjected to a concentrated or heavy load and the spans do not exceed 4.25 m (13.94 ft). It results in substantial savings in cost, as well as in the consumption of cement and steel. For example, at a site in Delhi, the saving in the consumption of cement was 25 percent and of steel, 25 percent, compared with the conventional RCC slab.

PRECAST CELLULAR UNITS

These rectangular, concrete units could be used for roofs and floors. The unit size is 1 m X 0.5 m X 100 mm (3.28 X 1.64 X 0.33 ft), and it weighs nearly 55 kg (121 lb). It is provided with three to four hollow, hexagonal cells, running through its entire length. The unit is cast with the help of single timber formwork and provided with hexagonal slots at the two ends through which timber forms for creating the hollow cells are inserted.

For casting the roof, the units are placed on either rectangular beams or composite T-beams. Most beams are precast T-beams; temporary propping is needed. With rectangular beams, however, construction is relatively simple, and no supports are necessary during the construction, nor is reinforcement needed in the top concrete. With either type of beam, it is necessary to lay a minimum of 35 mm of lean concrete on top of the units to enhance their resistance to impact loading. The complete roof assembly has been tested and found suitable for a load of 0.19 kg/cm^2 (400 lb/ft^2). Compared with conventional RCC slabs, the percentage savings in the consumption of cement are about 30 percent and of steel, 70 percent, when rectangular beams are used to support the units. With T-beams, the corresponding savings are 20 and 50 percent.

CORED UNITS FOR ROOFING

CBRI has also developed prefabricated-concrete, doubled-cored units that provide a flush ceiling. They need no temporary propping. The units weigh about 136 kg (299.88 lb), and their dimensions are 30 cm X 12.7 cm X 3.7 mm (11.81 X 4.99 X 0.15 in.). Recently, a prototype of a machine using a pressure-cum-vibration technique has been developed at CBRI for casting concrete-cored units up to 61 cm (2.5 ft) in width and of various shapes and sizes.

The use of these units could effect savings of 15 percent in cement and 10 percent in steel, compared with the conventional 10-cm (3.94-in.) RCC slab (3.7-m or 12.14-ft span).

PRECAST-CHANNEL UNIT FLOORING/ROOFING SYSTEM

A precast RCC element, trough-shaped in section, the unit is structurally complete in itself and does not need propping during construction. It is generally 300 mm (11.91 in.) wide, 125 mm (4.92 in.) deep (the depth may vary depending upon the span and loading), and is 2.4 to 4.2 m (7.87-13.78 ft) long. The length can also be adjusted to suit the span. The shape of the unit allows for space between adjacent units for negative reinforcement over supports and laying of concrete in situ, which develops a monolithic structure and permits flexibility in designing the floor/roof as a continuous one-way slab. The wooden molds for the units are made of an outer rectangular frame and a trough-shaped inner frame. The units are precast with the flange on the underside and the ribs on the upperside and in the usual manner of casting concrete members. A unit 300 mm X 125 mm and 3.6 m long (11.81 X 4.92 X 141.73 in.) weighs about 122 kg (268.91 lb). A comparative-cost study of a continuous (3 bays of 3.5 m, or 11.48 ft, each) conventional RCC roof slab and a channel-unit roof of the same dimensions revealed almost no saving in steel, but saving in cement is about 40 percent.

PRECAST-CONCRETE WAFFLE UNITS

Recently, a scheme for precast-concrete grid floors and roofs for longer spans was developed at CBRI. It consists of waffle units 0.6 m^2 (6.46 ft^2) laid in a grid pattern. The reinforcements are laid in the gaps between the units, and concrete is placed to act as grid beams in two mutually perpendicular directions. The shape of the units was worked out to ensure load transfer from one unit to the adjacent one through the in situ concrete between them. Elimination of in situ deck concrete above the units is a distinct feature of the system. This system results in a saving of about 8 percent in steel and 30 percent in concrete, compared with the conventional 10-cm (3.94-in.) RCC slab of equal span.

MISCELLANEOUS MATERIALS

Metals, such as galvanized iron and aluminum, and minerals, such as natural stone, asbestos, etc., are also used for roofing in the developing countries. The use of corrugated aluminum sheets is gaining ground in Africa, the southeast Asian region, and Argentina. They improve physical comfort to some extent because of their high heat-reflecting factor in the initial stages. Roof framing is of the rafter and purlin type.

Slate roofs are generally adopted in hilly areas of India. They are laid over wooden trusses and purlins. The slates are normally 61 cm X 91.4 cm X 215 cm (2 ft X 3 ft X 1 in.) in size. Asbestos-cement corrugated sheets are also very commonly used for roofing in India. For this purpose, the chrysotile variety of asbestos is imported each year at a cost of Rs. 100 millions (U.S. $14 million). To conserve foreign exchange, the CBRI has developed a process for full or partial replacement of imported chrysotile with indigenous amphibole asbestos.

Appendix J. Potential Roofing Materials and Composites

During the committee's deliberations many materials were identified that might be considered when planning a research program to solve developing country roofing problems. The following list was developed by the panel early in their meeting. Because of time limitations no consideration was taken of the practicality of any of the materials (e.g., durability, pest resistance, strength). This list is included here only to convey a sense of the range of materials locally available in the developing world whose properties may make them worth considering for use in low-cost roofing research projects. For completeness, some materials already in standard use are included.

The list is divided into the following categories.

1. General roofing materials
2. Potential components of composite roofing materials
   binders
   reinforcement
   fillers/aggregates
   coatings

1 GENERAL MATERIALS THAT MIGHT BE USED FOR LOW-COST ROOFING IN DEVELOPING COUNTRIES

Plastic (as sheet, perhaps as a fiber in an "artificial thatch," or foamed or formed)

Bituminous products (either formed, built-up or as shingles)

Concrete (e.g., reinforced, ferrocement, foamed concrete, lightweight aggregate concrete)

Minerals (e.g., slate, stone, gypsum)

Formed clay products (e.g., as tiles or sheets)

Other materials from soil (perhaps stabilized or foamed)

Wood products [e.g., shingles/tiles, plywood, particle board, wood wool (wood fibers in concrete) or formed paper]

Vegetable products (as thatch or woven mats, e.g., grass and reeds, canes, bamboo)

Fabrics (e.g., canvas)

Animal products (e.g., leather, hides)

2 POTENTIAL COMPONENTS OF COMPOSITE MATERIALS

BINDERS

Portland cement

Other hydraulic-setting cements (e.g., products from blast furnace slag, fly ash)

Clay, calcinated clay, earth, etc.

Limestone, lime or gypsum

Magnesium oxychloride sulfate

Glass

Sulfur

Asphalt, coal tar derivatives, and petroleum derivatives

Pitches, rosins and gums (e.g., tall oil pitch, cottonseed pitch, soya bean oil residue)

Lignins, furfural

Starches (e.g., from grains or root crops)

Oils (e.g., drying oils such as linseed or cashew-nut-shell liquid, with or without catalyst)

Rubber and natural latex

Adhesive proteins [e.g., casein, animal and fish blood, legume protein, bone/hoof glue (animal glue and tannery waste)]

Animal grease

Silicates [e.g., sodium silicate (water glass)]

Plastic resins

- Unsaturated polyesters, polyolefins, etc.
- Urethanes
- Urea-formaldehyde

Other thermoplastics
Shellac

REINFORCEMENT

Metal (rod, fiber, wire mesh, "expanded" metal)

Mineral fibers (asbestos; wallostonite; amphibole; long fiber chrysotile; rock wool from blast furnace slag; glass fibers)

Vegetable waste (e.g., rice hulls; bagasse; cottonseed; peanut hulls and other seed hulls; cotton, jute, sisal and other textile-fiber wastes; coconut husks; straw)

COATINGS

Sulfur
Polymers/paints
Metal coatings (e.g., galvanized or metal foil)
Silicones
Cashew-nut-shell liquid
Bituminous products
Mineral particulates
Whitewash
Sand

FILLERS/AGGREGATES

Sand, soil, rock and clay

Expanded (bloated) clays, expanded shale, expanded perlite, expanded slag and glass

Sintered fly ash

Shells

Pozzolans

Diatomaceous earth

Waste glass

Air (as in foams)

Organic materials [e.g., bark; wood (sawdust, chips); cork and pitch, paper, coconut shell]

Carbonized plant products (charcoal expanded husks, cereal grains, seed hulls, etc.)

ESPAÑOL

Recomendaciones

El propósito de este informe es identificar una amplia variedad de materiales que los investigadores científicos pueden considerar en su selección para un nuevo sistema de techos en los países en desarrollo. Como las particularidades, necesidades, clima y disponibilidad de materiales y recursos de los países en desarrollo difieren extensamente, cada uno de ellos debe determinar independientemente cuáles de los cursos de investigación son los más promisores. Sin embargo, el comité cree que un plan organizado y sistemático en el establecimiento y finalidades de los programas de investigación e implementación dentro de los países en desarrollo puede conducir a prontos resultados para su utilización inmediata, en todos los países o al menos en la mayoría.*

1. COMITÉ ASESOR INTERNACIONAL

Debería establecerse un comité asesor permanente bajo el auspicio internacional apropiado. Sus esfuerzos deberían encauzarse específicamente a acelerar, expandir y consolidar los bien dispersos programas existentes de

*Este informe fue terminado antes del reciente aumento en los precios del petróleo crudo. Substancialmente el aumento de costos de los derivados del petróleo les afectará adversamente su posición competitiva con los adhesivos poliméricos y plásticos porosos (recomendaciones 2 y 3) aumentando la preferencia por las tecnologías que no hacen uso de subproductos del petróleo, discutidas en las recomendaciones 4 y 10.

investigación para techos de bajo costo en los países en desarrollo. El comité debería concentrarse en enfocar el problema desde el punto de vista global y no simplemente regional.

Típicamente el comité debería encausar la necesidad de efectuar un inventario de los materiales para techo y de las prácticas de diseño y construcción actualmente utilizados en los países en desarrollo, como también de los problemas que en la actualidad están siendo estudiados por esos países y otras organizaciones investigativas. Este inventario deberá facilitar la identificación de áreas aun no cubiertas en la investigación y de aquellas que requieren mayor atención.

La mayoría de los miembros del comité deberían ser expertos en vivienda para las regiones en desarrollo y otros deberían proceder de las más apropiadas organizaciones mundiales académicas e investigativas y de organizaciones de ayuda técnica que tengan un interés substancial y recursos considerables dedicados al aspecto de la vivienda en los países en desarrollo (tales como AID, Banco Mundial, Programa de Desarrollo de las Naciones Unidas, Centro de Planificación, Construcción y Vivienda de las Naciones Unidas, Banco Interamericano de Desarrollo, Organización de Estados Americanos y CARE.

2. CONGLOMERANTES POLIMÉRICOS

Los programas de investigación, demostración y desarrollo para cubierta de techos deberán encauzarse al uso de poliésteres no saturados y polímeros apropiados, existentes comercialmente, para producir combinaciones aglutinantes con materias primas (v.g. fibras vegetales, entelados y tierras) de los países en desarrollo seleccionados.

Estos esfuerzos pueden ser productivos porque actualmente la tecnología para productos empleados en la fabricación de edificios, usando fraguación térmica (v.g. poliésteres no saturados), resinas termoplásticas y polímeros correspondientes en combinación con otros materiales, está altamente desarrollada y bien documentada (véase apéndice A). Si estos productos son compatibles y pueden mezclarse con las materias primas disponibles localmente, será posible fabricar piezas de formas y dimensiones ilimitadas para satisfacer los diseños requeridos por las diferentes tradiciones y costumbres. El comité piensa que mediante un programa concertado de desarrollo y prueba, a nivel piloto se podrían producir materiales compuestos apropiados para sistemas de techo a bajo costo en la mayoría de los países en desarrollo.

La tarea mayor en desarrollar compuestos de bajo costo que puedan resistir elementos destructivos tales como humedad, rayos ultravioleta, fungus e insectos. Deberá darse especial énfasis a la identificación de los peligros potenciales asociados con el uso de productos de materiales plásticos. Por ejemplo, si se cocina con llama abierta en el interior de la vivienda, ciertos elementos plásticos del techo pueden inflamarse y producir humos dañinos o gases tóxicos. Los polímeros pueden ser tratados mediante técnicas relativamente simples para soportar la exposición directa al fuego, pero hasta ahora la aplicación de estos polímeros tratados ha sido relativamente costosa.

Si se pueden elaborar materiales a un costo razonable y de alta confiabilidad, la tecnología de su fabricación probablemente podría ser transferida con poca dificultad a los países en desarrollo; la simplicidad en producir materiales de resina sintética para techos permitiría una fácil difusión de la tecnología y su pronta comercialización por empresas pequeñas. Los productos para terminación de edificios prometen competir económicamente con el hierro corrugado, inclusive ofrecen un precio más conveniente.

Los costos de fabricación de los compuestos para techos pueden ser muy bajos. El sistema sería versátil y se prestaría a una intensiva producción manual.

En su estado crudo, las resinas y polímeros básicos son estables pudiendo ser almacenados por cierto tiempo, pero para mantener sus características específicas deben mantenerse en un sitio frío y a la sombra. Como estos están concentrados, sólo requieren un espacio limitado para su transporte y almacenamiento y su valor intrínseco es muy pequeño hasta ser convertido en material de construcción. Si dentro de los países en desarrollo no se dispone de polímeros y resinas básicas, estos tendrían que ser importados pero probablemente sólo representarían una porción inferior a la del costo del techo terminado. No existen problemas de logística de importancia en la importación de resinas y polímeros a granel—existen numerosos fabricantes y abundante aprovisionamiento—ni tampoco es dificultuoso manejarlo, almacenarlo o transportarlo a su sitio de uso final.

Los estudios investigativos concernientes a este tipo de aplicación deberán incluir un análisis de costos-beneficios entre las resinas importadas y las alternativas opuestas, tales como el hierro corrugado importado.

3. PROCESAMIENTO DE PLÁSTICOS POROSOS

Deberá iniciarse un proyecto piloto para el procesamiento de materiales a base de plástico poroso apropiado para cubrir techos y para la fabricación de un equipo móvil a pequeña escala y cuya producción pueda resultar económico en los países en desarrollo.

Los plásticos porosos de baja densidad son substancias celulares producidas por la inyección de burbujas de gas durante la fabricación de compuestos plásticos—que representan un significativo potencial como material versátil, de peso liviano y alto aislamiento para techos y que puede ser producido en el sitio de la obra en una variedad de formas y dimensiones (véase apéndice B). Hasta la fecha el uso de plástico poroso ha sido limitado severamente por falta de un equipo mezclador sencillo, confiable y de bajo costo, capaz de elaborar un producto uniforme de alta calidad.

El equipo usual para procesar plástico poroso genera químicamente la espuma y luego distribuye, por pulverización, la masa congelante de finas burbujas en la posición deseada. En el pasado el equipo de procesamiento usado para este tipo de demostraciones en los países en desarrollo, era bastante complicado y sensitivo, y requería un mantenimiento costoso. Sin embargo, los últimos adelantos en el diseño de equipos ha eliminado muchos de los problemas experimentados anteriormente. En consecuencia parece ser que esta es la oportunidad más apropiada para incorporar tales avances en el desarrollo de un sistema mezclador móvil y de pequeña escala que pueda ser producido en masa por los países en desarrollo. Este sistema en combinación con una demostración que pruebe que los plásticos porosos pueden ser utilizados para agregar rellenos y capas de refuerzos como material para capas inferiores y de cubierta para techos, puede dar lugar a la formación de empresas lucrativas locales que podrían producir el equipo y diversos productos de plástico poroso.

El proyecto piloto recomendado deberá ser organizado claramente como un experimento para evaluar y documentar el rendimiento del equipo, así como su economía, aceptación por el consumidor, uso, longevidad y durabilidad de los techos prototipos producidos. El proyecto puede ser perfectamente conducido como un esfuerzo cooperativo entre empresas de los EE.UU. y de los países en desarrollo, con participación de instituciones académicas, organizaciones comerciales y profesionales de la industria constructura, más la asistencia técnica de organismos especializados en vivienda.

Debe hacerse notar que recientemente "the U.S. Federal Trade Commission" estableció que ciertos productos plásticos de poliuretano y poliestereno usados en construcción de viviendas pueden ser peligrosos para la salud y la vida cuando se exponen al fuego. Este hecho es bien conocido por los técnicos en vivienda. Sin embargo ahora existen ciertos plásticos con baja producción de humo y propagación de llama, y se esperan mayores progresos en el futuro. A pesar de ello, los investigadores dedicados al desarrollo de materiales plásticos para techos en los países en desarrollo deberán estar advertidos de los peligros potenciales relacionados con el fuego y deberán mantenerse informados de los adelantos técnicos en esta materia.

4. AZUFRE

Debe prestarse seria consideración al empleo del azufre como material aglutinante para otros materiales nativos, como capa de revestimiento, como material para relleno de junturas y para la fabricación de productos pequeños para techos, por ejemplo, tejas.

A pesar que el azufre no ha sido usado extensivamente como material para construcciones, su empleo tiene muchas aplicaciones para techos a bajo costo en los países en desarrollo, que deben ser exploradas (véase apéndice C). El uso de este material para fines de construcción en los países en desarrollo ha estado sujeto a una comprensiva investigación científica, en la última década. Su uso en tales países es particularmente digno de consideración en vista de la abundante existencia de azufre debido a las actividades volcánicas y a ser un subproducto del petróleo. El azufre puede constituir un artículo de importación a bajo costo para aquellos países que carecen de azufre en estado natural.

Las pruebas e investigaciones previas han sido dirigidas principalmente a su empleo como agente adhesivo de superficie en el concreto sulfurado. El azufre elemental es un agente aglutinante con propiedades únicas: Su punto de fusión es 240°F, ligeramente superior al del agua; es insoluble en agua, teniendo propiedades de impermeabilización; es inodoro; no produce efectos tóxicos en su uso normal; es un mal deficiente conductor del calor; su vida de almacenamiento es ilimitada y puede ser procesada nuevamente. Todas estas características indican un excelente potencial para su uso como material para techos en los países en desarrollo.

El azufre elemental es particularmente apropiado para métodos de construcción de trabajo pesado teniendo ciertas limitaciones: es altamente inflamable y debe ser convertido a estado líquido antes de añadir agregados o rellenadores. Los fabricantes y aquellos que lo usan deben estar prevenidos del posible desprendimiento de ácido sulfúrico en presencia de las humedad, así como de sus efectos perniciosos si llega a ser ingerido. Sin embargo, sus ventajas sobrepasan las desventajas, justificando todo esfuerzo de desarrollo e investigación en la actualidad.

5. MATERIALES DE PLANTAS CARBONIZADAS

Se deberán efectuar estudios investigativos de laboratorio y demostraciones concernientes a la transformación de resinas poliésteres no saturadas y polímeros relativos combinados con productos de plantas ricas en almidón, no comestibles carbonizadas y expandidas (véase el apéndice G) en planchas para techos de peso liviano y de bajo costo. La investigación deberá incluir la identificación de tipos y cantidades de los productos de plantas apropiadas para este propósito, así como su disponibilidad en los países en desarrollo.

6. RESIDUOS AGRÍCOLAS Y DE MADERA

Se deberá iniciar un programa extenso tendiente a desarrollar procesos económicos para la fabricación de resinas provenientes de productos agrícolas nativos (v.g. vegetación natural, residuos de caña) para ser utilizados principalmente como aglutinantes o adhesivos.

Como puede notarse en el apéndice G (Ref. 1) la lignina y furfural en vegetación pueden ser usados como adhesivos *in situ* si se les aplica presión y calor. Esta tecnología es bien conocida en los países industrializados y es probable que métodos de procesamiento simplificados puedan permitir a los países en desarrollo, producir una abundante cantidad de paneles apropiados para construcciones.

7. RESIDUOS DE INDUSTRIAS PRIMARIAS

Las cenizas y escoria del coque de los altos hornos empleados en la industria del acero tienen características que las hacen apropiadas para ser usadas como cementadores aglutinantes y deberán ser investigadas (véase el apéndice E). Estos residuos pueden ser de particular valor en aquellos países que carecen de piedras calizas y de recursos de cemento portland.

El "barro rojizo" que es un copioso subproducto de la refinación de la bauxita, abundante en muchos países en desarrollo, también merece seria consideración así como los residuos metálicos de la producción de hierro y acero. La eliminación de estos residuos y de otros productos similares constituye una carga constante para la industria pesada en todo el mundo; su conversión a productos útiles serviría un propósito doble. Las investigaciones para tales alternativas pueden atraer a las industrias afectadas hasta el punto de inducirlas a contribuir con fondos o materiales.

8. CONCRETO

Deberá efectuarse un programa analítico y de pruebas de laboratorio encaminado a desarrollar productos de concreto reforzado más económicos y apropiados (véase el apéndice H, hierro-cemento). Las investigaciones deberán concentrarse en el uso de materiales para refuerzos tales como malla de alambre, fibras de vidrio y lana pétrea disponibles localmente así como diferentes productos vegetales tales como bambú (Ref. 2), cortezas y fibras de madera (las fibras de madera se conocen en ciertas partes del mundo como "lana de madera" o "virutas de madera" (Ref. 3). También deberá prestarse consideración a los substitutos para cemento portland, algunos de los cuales se sugieren en el apéndice E.

9. MATERIALES A BASE DE ARCILLA

Se deberá conducir un programa de investigación para desarrollar métodos tendientes a mejorar el desempeño general y la amplitud de aplicaciones de los materiales a base de arcilla, greda o barro para techos (véase el apéndice I).

10. PRODUCTOS DE FIBRA

Deberá explorarse la conveniencia y efectividad del uso de residuos de las materias primas empleadas en la industria textil y otras industrias de fibras [basadas en fibras de yute, henequen (sisal), cáñamo, kenaf y algodón] que son comunes en los países en desarrollo, para aprovecharlos como mezcladores en un material compuesto para piezas de techos.

En resumen, existen numerosos medios promisorios de exploración y el comité asesor opina que es el momento de aprovechar al máximo estas ventajas.

CAPÍTULO III–REFERENCIAS

1. Véase también *Producción de paneles utilizando residuos agrícolas,* diciembre 1970. Informe No. 1D/79 (WG 83/15/Rev. 1) Ginebra: Organización de Desarrollo Industrial de las Naciones Unidas.
2. Par informaciones, véase *Refuerzo expedito para concreto usado en Asia Sud Oriental.* por F.B. Cox y H.G. Geymayer, Informe técnico C-69-3, Vicksburg, Mississippi: U.S. Corps of Engineers.
3. Para mayores informes, comuníquese con el Dr. J.W.S. De Graft-Johnson, Director, "Building and Road Research Institute," CSIR, Kumasi, Ghana.

FRANÇAIS

Recommandations

Ce rapport énumère une grande variété de matériaux qui pourraient intéresser des chercheurs pour la mise au point de nouveaux systèmes de couverture des toits dans les pays en voie de développement. Ces derniers ont des besoins, des climats, des matériaux et des ressources si différents qu'ils doivent déterminer individuellement les domaines dans lesquels la recherche apportera les meilleurs résultats. Cependant, le comité est d'avis que l'établissement et la direction de ces programmes de recherche et de développement devraient procéder d'une démarche systématique et organisée. Les pays en voie de développement obtiendraient ainsi des résultats immédiats qui pourraient être utilisés par la plupart d'entre eux, sinon par tous. Le comité propose donc les recommandations suivantes*:

1. UN COMITÉ CONSULTATIF INTERNATIONAL

Un comité consultatif permanent devrait être créé sous les auspices d'organisations internationales compétentes. Ses efforts devraient être particulièrement dirigés vers l'accélération, l'élargissement et la consolidation de programmes dispersés de recherche sur les toitures à bon marché qui existent

*Ce rapport a été terminé avant la recente augmentation des prix du pétrole brut. L'augmentation importante des prix des dérivés du pétrole se répercutera sur la concurrence des liants polymères et des mousses plastiques (recommandations 2 et 3) et augmentera l'attrait des techniques basées sur les produits qui no sont pas tirés du pétrole. Ces techniques sont examinées dans les recommandations 4 à 10.

déjà pour les pays en voie de développement. Le comité devrait mettre l'accent sur l'aspect régional plutôt que sur l'aspect mondial.

Représentatifs des besoins qu'un tel comité pourrait aborder seraient non seulement l'inventaire des matériaux de couverture, la conception et les pratiques de construction qui sont en usage dans les pays en voie de développement, mais aussi les problèmes de couverture des toits actuellement à l'étude dans ces pays et dans d'autres organismes de recherche. Un tel inventaire permettrait d'identifier tant les lacunes qui existent dans la recherche que les domaines qui réclament plus d'attention.

Le comité devrait être composé en majorité d'experts du logement venant des régions en voie de développement. Les autres membres devraient provenir d'organismes de recherche et d'établissements universitaires du monde entier et aussi d'organismes d'assistance technique dont l'intérêt majeur et les ressources considérables sont dirigés vers le logement dans les pays en voie de développement: l'AID; la Banque mondiale; le Programme des Nations Unies pour le développement; le Centre des Nations Unies pour le logement, la construction et la planification; la Banque interaméricaine de développement; l'Organisation des États américains; CARE, etc. . .

2. LIANTS POLYMÈRES

Les programmes de recherche, de mise au point et d'essais pratiques des couvertures et toitures, devraient être axés sur l'emploi des polyesters nonsaturés et des polymères connexes existant sur le marché, comme liants dans les mélanges de matériaux produits localement, tels que les fibres végétales, des terres et des tissus en provenance de pays en voie de développement déterminés.

Un tel effort pourrait être productif actuellement puisque les techniques qui utilisent les résines thermoplastiques et thermodurcissables, les polyesters, par exemple, ainsi que les polymères connexes en combinaison avec d'autres substances pour la fabrication de matériaux de construction, sont parfaitement au point et tout à fait documentées (voir annexe A). Si de tels produits se mélangent bien avec elles, ils pourraient etre fabriqués dans une variété de formes et de tailles dont le nombre est pratiquement illimité et se plier ainsi aux différentes coutumes et traditions. Le comité est d'avis qu'un programme-pilote concerté de recherche et de développement pourrait engendrer dans la majorité des pays en voie de développement la production de matériaux mixtes convenant à des systèmes de couverture bon marché.

La plus grande difficulté à surmonter sera la mise au point de matériaux mixtes peu onéreux et qui résistent à l'action destructrice de l'humidité, des rayons ultraviolets, des insectes et des moisissures. Il faudra mettre particulièrement l'accent sur l'identification des dangers qui sont inhérents à l'emploi de produits contenant des matières plastiques. Par exemple, si la cuisine est faite sur des foyers à flamme nue, certains éléments de couverture pourraient se trouver enflammés par des étincelles et produire ainsi des fumées délétères ou des gaz toxiques. A l'aide de techniques simples on peut traiter les polymères pour qu'ils aient une bonne tenue au feu. Mais, jusqu'à présent les applications de ces polymères traités ont été plutôt onéreuses.

Si des substances d'une bonne tenue peuvent être mises au point à un prix raisonnable, on pourra probablement transmettre sans difficulté leurs procédés de fabrication et leurs applications à tous les pays en voie de développement. La simplicité de la fabrication de matériaux de couverture à base de résines synthétiques permettrait une diffusion rapide des techniques et une commercialisation facile par les petites entreprises. Les produits finis de construction pourraient faire face à la concurrence de la tôle ondulée ou être d'un prix plus avantageux. Ces matériaux pourraient etre utilisés également dans d'autres domaines que la couverture des toits.

Le prix de revient de matériaux mixtes pour toitures pourrait être très bas. Le système serait très souple et pourrait s'adapter à une production utilisant une main-d'oeuvre importante.

Les résines et les polymères sont stables à l'état brut et peuvent ainsi être stockés pendant un certain temps, mais, pour garder leurs propriétés, ils doivent etre entreposés dans un endroit frais et à l'abri de la lumière. Du fait qu'ils se présentent à l'état concentré ils sont peu encombrants pour l'expédition et l'emmagasinage. Leur valeur intrinsèque est relativement faible tant qu'ils ne sont pas transformés en matériaux de construction. Si on ne trouve pas ces résines et ces polymères dans les pays en voie de développement, ils devront être importés. Même dans ce cas ils ne représenteront qu'une faible partie du coût total de la toiture. Pour l'importation en gros de ces résines et polymères, il n'y a pas de problème particulier de distribution–les stocks sont importants et il existe un grand nombre de fabricants. La manutention, l'emmagasinage et le transport à l'arrivée ne présentent pas de difficulté.

Les efforts de recherche sur place de ce type d'application doit comprendre une analyse couts-bénéfices des résines importées par rapport à un produit de remplacement importé tel que la tôle ondulée.

3. FAÇONNAGE DES MOUSSES DE PLASTIQUE

On devrait mettre en place un projet-pilote pour le façonnage de mousses plastiques qui puissent servir de matériaux de couverture et à cet effet mettre au point des appareils mobiles relativement petits que les pays en voie de développement soient à même de produire économiquement.

Les mousses plastiques–substances cellulaires légères produites par l'introduction de bulles de gaz dans les composants plastiques au cours de la fabrication–offrent un potentiel important en tant que matériaux souples et légers de toitures, tout en possédant une haute valeur isolante. Ces matériaux peuvent être fabriqués sur place dans une grande variété de formes et de tailles (voir annexe B). A ce jour, l'emploi des mousses plastiques a été sérieusement limité parce qu'il n'existait pas d'équipement de fabrication des mousses, simple, fiable et peu onéreux, qui soit capable de donner un produit uniforme de haute qualité.

L'équipement habituel de façonnage des mousses plastiques produit la mousse chimiquement et ensuite projette la masse écumeuse de fines bulles à l'endroit voulu. Autrefois, l'équipement de démonstration qui était utilisé sur place dans les pays en voie de développement, était complexe et fragile et exigeait un coûteux entretien. Néanmoins, les progrès récents apportés à la conception de l'équipement ont permis d'éliminer la plupart des problèmes auxquels on se heurtait auparavant. Il semblerait donc que le moment est venu de mettre à profit ces améliorations pour créer de petits appareils de façonnage de la mousse qui pourraient être fabriqués en série par les pays en voie de développement. De tels appareils, associés à une démonstration prouvant que les mousses plastiques peuvent être utilisées en combinaison avec des substances de renforcement et des enduits d'origine locale comme matériaux de couverture et de support, pourraient conduire à l'établissement profitable d'entreprises locales qui fabriqueraient non seulement l'équipement mais aussi divers produits en mousse de plastique.

Le projet-pilote recommandé devrait être organisé seulement à titre d'expérience pour permettre d'évaluer et de documenter le rendement de l'équipement, aussi bien que l'aspect économique, l'acceptation par les consommateurs, l'emploi et la durée des toitures prototypes ainsi réalisées. Le projet pourrait bien être conduit en coopération par entreprises américaines et celles des pays en voie de développement, et aussi avec la participation de centres de recherche, d'organismes professionnels orientés vers les matériaux de construction, d'organisations commerciales et avec le concours technique d'organismes s'occupant du logement.

Il est à noter que la U.S. Federal Trade Commission á récemment mis en garde les consommateurs sur le fait que les mousses de polyuréthane et de polystyrène, quand elles sont exposées au feu, peuvent offrir des risques pour leur vie ou leur santé dans certaines de leurs applications pour le logement. Ce fait est parfaitement connu des technocrates du bâtiment. Cependant, on dispose maintenant de mousses à faible production de fumée et ne permettant pas la propagation des flammes. Il est vraisemblable que de nouveaux progrès seront encore faits dans un proche avenir. Toutefois, les chercheurs qui mettent au point des plastiques moulés pour les éléments de toiture dans les pays en voie de développement, devraient être informés des dangers possibles d'incendie et tenus au courant des progrès techniques réalisés dans ce domaine.

4. SOUFRE

On devrait porter une attention particulière aux possibilités offertes par le soufre en tant qu'élément entrant dans la composition des liants pour d'autres matériaux d'origine locale, en tant qu'enduit et substance d'injection des joints et en tant que matériau à partir duquel on peut fabriquer des éléments de toiture de petite taille : les tuiles, par exemple.

Bien qu'on n'ait pas beaucoup utilisé le soufre comme matériau de construction, on devrait étudier l'étendue de ses possibilités comme liant dans les couvertures à bon marché dans les pays en voie de développement (voir annexe C). C'est seulement au cours de la dernière décennie que l'emploi de ce matériau dans la construction a fait l'objet de recherches scientifiques approfondies. Son utilisation dans les pays en voie de développement devrait être particulièrement étudiée du fait que beaucoup de ces pays disposent de soufre en quantités importantes, soit qu'il provienne d'une activité volcanique ou du raffinage du pétrole. Le soufre peut également représenter un article d'importation peu onéreux pour les pays dont il n'est pas une ressource nationale.

Les recherches et les essais déjà faits dans ce domaine étaient principalement dirigés vers l'utilisation du soufre dans le béton–béton au soufre–et comme liant superficiel. Le soufre élément est un liant aux propriétés exceptionnelles. Il fond à 115 °C, quelques degrés à peine au dessus du point d'ébulition de l'eau. Etant insoluble à l'eau, il est ainsi imperméable à ce liquide. En emploi courant il n'a pas d'odeur et n'est pas toxique. Il est mauvais conducteur de la chaleur. Enfin, il peut être conservé indéfiniment et peut être recyclé. Toutes ces qualités en font une matière première de choix pour la couverture des toits dans les pays en voie de développement. Le soufre élément se prête particulièrement bien aux méthodes de construction utilisant une importante main-d'oeuvre. Toutefois il a certains inconvénients. Il est hautement inflammable et doit être liquéfié avant qu'on puisse y ajouter les agrégats ou la masse de remplissage. Les producteurs et les consommateurs du produit doivent être mis en garde contre les émanations possibles d'acide sulfurique en présence d'humidité et sur les conséquences dangereuses que pourait entraîner son ingestion. Les avantages semblent contrebalancer les inconvénients, cependant il est indispensable actuellement qu'un effort soit fait dans la recherche et le développement.

5. MATÉRIAUX VÉGÉTAUX CARBONISÉS

Il faudrait mettre sur pied un programme de recherche en laboratoire et d'essais pratiques sur la possibilité de transformer en plaques légères et bon marché des produits végétaux non-alimentaires et à haute teneur en amidon, carbonisés et expansés, qui ont été combinés avec des résines polyester non-saturées et les polymères connexes et qui pourraient servir pour les toitures (voir annexe G). La recherche devrait inclure des études sur place qui permettraient d'identifier le type, la quantité et l'existence dans les pays en voie de développement de produits végétaux qui pourraient servir à cet effet.

6. DÉCHETS AGRICOLES ET FORRESTIERS

On devrait établir un programme de recherche intensive sur les procédés de frabrication des résines destinées à être employées principalement comme liants à partir de produits agricoles locaux (végétaux, bagasse).

Comme on l'a noté dans l'annexe G[1], la lignine et le furfural des végétaux peuvent être utilisés sur place comme liants avec application de chaleur et en exerçant une certaine pression. Cette technique est bien connue des nations industrialisées. Il est probable que des méthodes simplifiées de fabrication permettraient aux pays en voie de développement de produire en grande quantité des panneaux de construction donnant toute satisfaction.

7. DÉCHETS DES INDUSTRIES DE BASE

Les déchets, tels que les escarbilles et le laitier de hauts-fourneaux provenant des aciéries, ont des propriétés qui leur donnent la possibilité d'être utilisés comme liants (voir annexe E). Ces déchets devraient être étudiés et ils pourraient présenter un intérêt particulier dans les pays qui ne disposent pas de ressources en calcaire et en ciment portland. Un sous-produit du raffinage de la bauxite, la boue rouge, qui est surabondante dans de nombreux pays en voie de développement, mérite également une sérieuse attention, au même titre que les déchets métalliques venant de la fabrication du fer et de l'acier. La disposition de ces déchets et d'autres résidus similaires pose un problème toujours grandissant pour l'industrie lourde du monde entier. Un double but serait atteint si on pouvait les transformer en produits utilisables. En fait, leur utilisation possible pourrait présenter un tel avantage pour les industries concernées qu'elles seraient incitées à fournir des fonds ou des matériaux pour la recherche dans ce domaine.

8. BÉTON

Un programme d'essais analytiques et en laboratoire devrait être mis sur pied pour la mise au point de produits en béton armé plus appropriés et plus économiques (voir annexe H sur le ciment armé). L'effort de recherche devrait être axé sur l'emploi de matériaux d'armature tels que le treillis métallique, la fibre de verre, la laine minérale et divers produits végétaux comme le bambou[2], l'écorce et la fibre de bois–le béton à la fibre de bois est connu sous le nom de "laine de bois" dans certaines parties du monde.[3] Une attention particulière doit aussi être apportée aux substituts du ciment portland dont certains sont énumérés à l'annexe E.

9. MATÉRIAUX À BASE D'ARGILE

On devrait établir un programme de recherche sur les méthodes destinées à améliorer le rendement et le champ d'application des matériaux pour toitures à base d'argile. (Voir annexe I.)

10. FIBRES

L'industrie textile et les autres industries apparentées utilisent des matières premières telles que le jute, le sisal, le chanvre et le coton qu'on trouve communément dans les pays en voie de développement. Il serait donc intéressant de rechercher si les déchets provenant de ces industries peuvent être utilisés en mélange dans un matériau mixte pour des éléments de toiture et quelle en serait l'efficacité.

En conclusion, le comité consultatif est d'avis qu'il existe de nombreuses voies à explorer et qu'il faudrait les mettre à profit dans les circonstances présentes.

RÉFÉRENCES DU CHAPITRE III

1. Consulter également: *Fabrication de panneaux à partir de déchets agricoles.* Décembre 1970.
   Rapport n° ID/79 (WG.83/15/Rev. 1). Genève: United Nations Industrial Development Organization.
2. Pour de plus amples renseignements, voir F.B. Cox et H.G. Geymayer. 1969. *Armature avantageuse du béton pour l'Asie du sud-est.*
   Rapport technique C-69-3. Vicksburg, Mississippi: U.S. Corps of Engineers.
3. Pour de plus amples renseignements, contacter M. J.W.S. De Graft-Johnson, Directeur de l'Institut de recherche pour le bâtiment et la construction routière, CSIR, Kumasi, Ghana.

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10. **Food Science in Developing Countries: A Selection of Unsolved Problems.** 1974. 81 p. Describes 42 unsolved technical problems with background information, possible approaches to a solution, and information sources.
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