Available technologies for local building materials

INTERNATIONAL CENTRE
FOR SCIENCE AND HIGH TECHNOLOGY

Cover page insets include pictures of (from left to right):
Photo 1. Traditional house constructed of mud-walls, made with crude compressed soil and roofed with grass
Photo 2. Dinder Tourist Village
Photo 3. Raw building material

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FOREWORD

A. Sustainable building materials - technology transfer to less developed countries

The UNIDO-ICS role in South-to-South cooperation

UNIDO has been involved in a ten year partnership with developing countries in the low cost building materials and other initiatives, through its International Centre for Science and High Technology, ICS-UNIDO, Trieste, Italy, and the International Centre for Advancement of Manufacturing Technology, ICAMPT, Bangalore, India, in partnership with India's Building Materials and Technology Promotion Council, BMTPC.

Countries high on the 'needs list' for low cost building projects include Tanzania, Kenya, Malawi, Mozambique, Sudan, Uganda and Zambia. ICS is involved in initiatives for the development of low-cost-housing technologies in Mozambique and Tanzania.[1]

Some sustainable technologies, which are also low cost, can take a number of forms. Some use very traditional materials (e.g. soil) utilised in a more efficient manner. Some use innovative composite materials based on local forestry resources, such as natural fibres and plant materials, and other resources such as agricultural and industrial wastes available within small geographical regions.

Bamboo is widely grown in developing countries; new technologies have been developed to overcome problems when using bamboo caused by moisture and insects. Other technologies have enabled the production of stabilised soil building blocks, blended with cement or other binders, such as ashes and slag from furnaces and power plants.

Mineral fibre-based artificial materials, such as fibreglass, basalt fibres, fibres of blended mineral composition, etc. are significantly superior (in terms of strength, thermo-physical characteristics, durability, purity of environment, availability and cost) to plastics, wood and aluminium.

The availability of, and ability to use primary raw materials, such as quartz sand, basic rocks, carbon, etc., will diminish dependence on conventional materials and products in the construction sector.

The development of low cost environmentally friendly building materials is not just an issue for developing countries. Industrialised countries are developing strategies and setting up national policy and institutional infrastructures to support increased utilisation of secondary and locally available resources for the manufacture of construction materials. However, experience has shown that the technologies developed in the industrialised countries are too costly and sophisticated to be absorbed by the developing countries, particularly the least developed countries (LDC), and those countries in post crisis situations, where new technologies are most needed.

A number of efforts have been made in the past to strengthen institutional and individual capacities and know-how in the area of materials for the construction industry. UNIDO-ICS programmes aimed at strengthening technology diffusion, transfer and adoption, and at linking investment to national policy mechanisms, require long-term commitment and a mission-mode project approach.

To draw upon the experience and expertise in the area of building materials technology, professionals, public sector construction agencies, corporate sectors, research and development (R&D) and standardisation organisations are being associated with UNIDO programmes.

A.1 Justification of the ICS New Materials initiatives

Within the above framework, as a follow-up to the initiatives undertaken by ICS-UNIDO in 1998, 2000-2 and 2005-6, ICS-New Materials addresses problems mainly related to building materials, through three different, but linked initiatives: meetings held in Mozambique (Maputo), India (Bangalore) and Tanzania (Dar-es-Salaam).

Many countries around the world are facing major problems related to extended urbanisation, which is very often accompanied by depletion of natural resources and the environment. This growth will create unprecedented demands for additional housing and infrastructure that will require more land and increased production of building materials. Raw materials and other natural resources are limited, thus, it is imperative that innovative

[1] http://www.ics.trieste.it/new materials

technologies are designed and implemented to introduce new, sustainable production of building materials and semi-finished products to make low-cost housing accessible and to help eradicate poverty.

Based on the fact that many developing countries are facing an ever-growing problem of providing affordable basic housing, in both rural and urban areas, the aim of the conferences was to present the state of the art in advancements in building materials technologies and to disseminate up-to-date information, knowledge and experience on the potentials of composite materials based on local renewable resources, incorporating by-products of forestry, agricultural and industrial activities.

The initiatives are intended to be an opportunity for the promotion of a networking and cooperation scheme between countries in the region, for the adoption of appropriate and affordable technologies for low-cost housing, encouraged and supported by ICS-UNIDO.

In India, and in many other developing countries, it is important that professionals and entrepreneurs working in various technical areas of the construction industry become participants in promoting sustainable development. An international conference provides the opportunity for the different stakeholders to meet, discuss the realities and develop strategies.

Technical panels feature case studies, analyses, strategies and showcase technologies appropriate also for small local communities. The conference provides inputs for the design and production of semi-finished products for construction and home-interiors based on the utilisation of natural fibres and resins.

The intent is to produce not only realistic solutions to the critical problems faced by local communities in the less-developed countries, but also to move towards implementation on a large scale, thereby ensuring a life quality improvement.

B. Sustainable building materials and technology

Sustainable Building Basics applies to any engineering level, from the very simple, which can be found in the urban areas of less developed countries, to the very sophisticated urban planning projects of the western world. Buildings account for one-sixth of the world's fresh water withdrawals, one-quarter of its wood harvest, and two-fifths of its material and energy flows.[2] Building in a 'sustainable' way is an opportunity to use our resources efficiently while creating buildings that improve human health and well-being and preserving a better environment, keeping economic costs affordable.

B.1. What makes a building sustainable?

A sustainable building is a structure that is designed, built, renovated, operated or reused in a resource-efficient manner. Sustainable buildings are designed to meet certain objectives such as protecting occupants' health and well-being; improving employee productivity; using energy, water, and other resources more efficiently; reducing impacts on the environment.

B.2. What are the economic benefits of sustainable building?

A sustainable building may cost a lot to build, but over the long term there are savings related to lower operating costs. The sustainable building concept implies a Life Cycle Analysis (LCA) approach to determine appropriate choices and costs. This analytical method calculates costs over the useful life of the asset.

Cost-savings can only be fully realised if the sustainable approach is incorporated in the conceptual design phase, by an integrated team of professionals. The integrated systems approach ensures that the building is designed as a unified-system, rather than a collection of separate systems.

Some benefits, such as improving occupants' health, comfort and productivity, and reducing pollution and landfill waste, are not easily quantified and often not given adequate consideration in cost analyses. Consideration should be given to reserving a proportion of the building budget to cover the differential costs associated with these less tangible building benefits and to cover the cost of researching and analysing building options.

Even within a tight budget, many sustainable building measures can be incorporated that could produce enormous savings during the life time of the built structure, with minimal increase in up-front costs.[3]

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[2] D.M Roodman and N. Lenssen, *A Building Revolution: How Ecology and Health Concerns are Transforming Construction*, Worldwatch Paper 124, Washington, DC, March 1995, p. 5.
[3] Environmental Building News, *Building Green on a Budget*, Vol 8, No. 5, May 1999, www.ebuild.com/Archives/Features/Low_Cost/Low_Cost.html#General

C. What are the elements of sustainable buildings?

Below we describe some green building practices.

C.1. Site

The site should take advantage of the transport system. Existing landscaping and natural features should be retained. Planting should include varieties with low water and pesticide needs and which generate minimum plant trimmings. Compost and mulches will help to save on water. Recycled materials and furnishings will help in terms of cost and waste.

C.2. Energy efficiency

Most buildings could reach energy efficiency levels far beyond national standard requirements. An objective of 40% less energy usage than Title 24 standards would be realistic. The following strategies will contribute to achievement of this goal.

Passive design strategies can dramatically affect building energy performance. These include shape and orientation of building, passive solar design (i.e. use of the sun's energy for heating and cooling), and use of natural lighting. Studies have shown that natural lighting has a positive impact on productivity and well being.

Installation of high-efficiency lighting systems with advanced lighting controls include motion sensors connected to dimmable lighting controls. Task lighting reduces general overhead light levels.

There should be properly sized and energy-efficient heating/cooling systems in conjunction with a thermally efficient building shell. Light colours for roofing and wall finishing materials should be maximised; high R-value wall and ceiling insulations should be used; minimal glass on east and west exposures. Electric loads from lighting, equipment and appliances should be minimised.

Alternative energy sources such as photovoltaic (PV) and fuel cells currently available in new products and applications should be considered. Renewable energy sources (RES) are the technologies of the future.

Computer modelling helps to produce the optimum design for electrical and mechanical systems and the building shell.

C.3. Materials efficiency

Sustainable construction materials and products should be used based on evaluating characteristics such as reused and recycled-content; zero or low off-gassing of harmful air emissions; zero or low toxicity; sustainable harvested highly recyclable materials; durability; longevity; and local production. These products promote resource conservation and use efficiency. Using recycled-content products will develop the market for recycled materials being diverted from local landfills, as mandated by environmental city or state regulations.

Dimensional planning and other material efficiency strategies should be adopted. These strategies reduce the amount of building materials needed and cut construction costs, e.g. rooms should be designed on the basis of multiple units conforming to standard dimension wallboard and plywood sheets.

Reused and recycled construction and demolition materials, e.g. inert demolition materials as the hard core for parking lots, which reduces landfill waste and is cheaper.

Plans for managing materials through deconstruction, demolition, and construction.

Designs should have adequate space to facilitate recycling collection and to incorporate a solid waste management programme to reduce the accumulation of waste.

C.4. Water efficiency

Design for dual plumbing to use recycled water for toilet flushing or a grey water system that recovers rainwater or other non-potable water for site irrigation.

Minimise wastewater by using ultra low-flush toilets, low-flow shower heads, and other water conserving fixtures.

Use recirculation systems for centralised hot water distribution.

Install point-of-use hot water heating systems for more distant locations.

Use a water budget approach that schedules irrigation for garden maintenance and landscaping. Use state-of-the-art irrigation controllers and self-closing nozzles for hoses.

C.5. Occupant health and safety

Recent studies reveal that buildings with good overall environmental quality can reduce the rate of respiratory diseases, allergies, asthma and sick building syndrome, and enhance workers' performance. The potential financial benefits of improving indoor environments exceed the costs by a factor of 8.[4]

To improve indoor air quality use construction materials and interior finish products with zero or low emissions. Many building materials and cleaning/maintenance products emit toxic gases, such as volatile organic compounds (VOC) and formaldehyde which can be detrimental to health and productivity.

Provide adequate ventilation and a high-efficiency, in-duct filtration systems. Heating and cooling systems that ensure adequate ventilation and proper filtration can have a dramatic and positive impact on indoor air quality.

Prevent indoor microbial contamination through selection of materials resistant to microbial growth, provide effective drainage from the roof and surrounding landscape, install adequate ventilation in bathrooms, allow proper drainage of air-conditioning coils, and design other building systems to control humidity.

C.6. Building operation and maintenance

All systems must work well to be effective. Building commissioning includes testing and adjusting the mechanical, electrical and plumbing systems to ensure that all equipment meets design criteria, and instructing staff on the operation and maintenance of equipment.

Over time, building performance can be maintained through measurement, adjustment and upgrading. Proper maintenance will ensure that buildings continue to perform as designed and commissioned.

D. Steps to ensure successful sustainability

- Establish a vision that embraces sustainable principles and an integrated design approach.
- Develop a clear statement of the project's vision, goals, design criteria and priorities.
- Develop a project budget that allows for sustainable building measures. Allocate contingencies for additional research and analysis of specific options. Seek sponsorship or grant opportunities.
- Seek advice of a design professional with sustainable building experience.
- Select a design and construction team that is committed to the project vision. Modify the selection process to ensure the contractors have appropriate qualifications to identify, select, and implement an integrated system of green building measures.
- Develop a project schedule that allows for systems testing and commissioning.
- Develop contract plans and specifications to ensure that the building design is suitable.

[4] William Fisk and Arthur Rosenfeld, *Potential Nationwide Improvements in Productivity and Health from Better Indoor Environments*, Lawrence Berkeley National Laboratory, May 2000.. Environmental Energy Technologies Division: Berkeley

CHAPTER 1

Building materials technologies based on local resources

Introduction

This chapter discusses building materials technologies as growth factors for developing country economies. It is important to establish and diffuse the concept of affordable housing, as housing is a basic need worldwide. This chapter discusses improvements to traditional building practices from the scientific and technological points of view.

The materials we examine are categorised as *green materials* based on the contribution they make to environmental protection. This is based on renewable natural resources and recovery and recycling of materials. In both cases, savings are made on valuable raw materials and energy, and emissions of carbon dioxide and other hazardous materials into the environment are reduced.

The main focus is on:
1. Natural local raw materials as part of a sustainable option.
2. Recovered and recycled demolition materials.
3. Composite materials made from renewable forestry resources.
4. Life Cycle Analysis (LCA) and related issues to support sustainability.

1. Using soil to manufacture blocks

A LOCAL BUILDING MATERIAL EXPLOITED WORLDWIDE

As the world's population grows, so does the demand for housing. Soil has been used as a building material for thousands of years, but unprotected structures cannot withstand heavy rainfall over long periods of time. Relatively new materials, such as cement, have meant that blocks can be manufactured that last for decades; however, they are too expensive for large portions of the populations of developing countries. A solution to the problem of cost is to manufacture blocks from soil that are stabilised to add strength and durability, even in wet climates.

Appendix 1 provides some basic definitions of soil and related terms.

Figure 1. Traditional house constructed of mud-walls, made with crude compressed soil and roofed with grass.

Buildings constructed of earth/soil are the most common cheap accommodation since earth or soil is readily available almost anywhere on the planet. Some 30% of the world's population, or nearly 1,500,000,000 people, live in dwellings constructed from unbaked earth. Roughly 50% of the populations of developing countries, the majority of rural populations, and at least 20% of urban and suburban populations live in such dwellings.

1.1 What is stabilised soil?

Soil stabilisation techniques fall into three categories,

a) Mechanical
b) Physical
c) Chemical.

Mechanical stabilisation refers to compaction of the soil which changes its density, mechanical strength, compressibility, permeability and porosity. Physical stabilisation is where the texture of the soil is changed through control of the grain fraction mix, heat treatment, drying, freezing or electrical treatment. Chemical stabilisation changes the properties of the soil through the addition of chemicals. This happens via a physical-chemical reaction between the grains of soil and the materials added, or through the addition of a matrix that binds or coats the grains.

Stabilisation fulfils a number of objectives that are necessary to achieve a lasting structure from locally available soil, including better mechanical characteristics (leading to better wet and dry compressive strength); better cohesion between particles (reducing porosity which reduces changes in volume due to moisture fluctuations); and improved resistance to wind and rain erosion. Use of one or more of the stabilisation techniques listed above will achieve these objectives. Optimum methods depend on the type of soil; therefore, careful soil analysis is needed to identify the most effective method of stabilisation.

Figure 2 (a) – Production of stabilised soil bricks
Strengths of natural soil bricks – Paper presented at the – Low cost building materials – Workshop, J.K. Makunza, 2006

Figure 2 (b) – Production of stabilised soil bricks. (Makunza, 2006)

Generally, mechanical stabilisation in conjunction with a chemical stabiliser, such as cement is preferred. The quantity of chemical stabiliser required will be reduced by thorough mixing of the stabiliser and soil and use of soil with a clay fraction. The increased density increases the effectiveness of the cement matrix when the cement is left to dry in a moist environment (the hydration period required to let the cement cure) for at least 7-14 days.

Figure 2 (C) - Stabilised-soil compacted block

Fig. 3 - A house built of stabilised-soil block and an old style straw-roofed shelter.

In developing countries, houses are constructed from locally available and technologically appropriate building materials, making the houses as durable as possible, while keeping building and renovation costs low.

Figure 4 - The finished house and the proud home-owner.
Photo courtesy of the Habitat for Humanity Programme in Malawi (HFHMalawi@malawi.net)

1.2 Current trends in stabilised block production

There has been much research on use of stabilised soil-cement building blocks in many parts of the less developed world. Some of this research takes an overview of the process of soil stabilisation and examines the roles of soil structure and curing in the process. This includes methods of testing soils and adapting testing procedures and plans for their implementation.

There has also been research into the conventional quasi-static block compaction process (slowly applied pressure). Compaction efficiency and higher block density can be achieved by altering the moulding configuration, mould-wall roughness, mould-wall taper, number of applied pressure cycles and double sided pressure application. The amount of cement needed can be traded against compaction pressure for a given cured strength, although it has been shown that savings in the cost of cement associated with high-pressure compaction are outweighed by the additional cost of the compaction machinery. A high-density moulding machine, in the range $US3,000-4,500 would be needed for these benefits to become cost competitive.

Analysis of an alternative dynamic compaction process (impact blow pressure) shows that optimised dynamic compaction may produce strength equivalent to quasi-static high-density moulding with only 25-50% of the energy requirements of the latter.

1.3 Dynamic soil compaction techniques

Investigation of dynamic compaction of small soil-cement samples suggests that substantial improvements in the production of low cost housing could be achieved through the use of this technique. The use of these methods to produce full-size building blocks would have a considerable impact in areas of the third world where adequate housing is scarce and existing techniques provide only short term solutions. Various projects have aimed at designing and producing a test rig to enable research into the production of dynamic compaction building blocks.

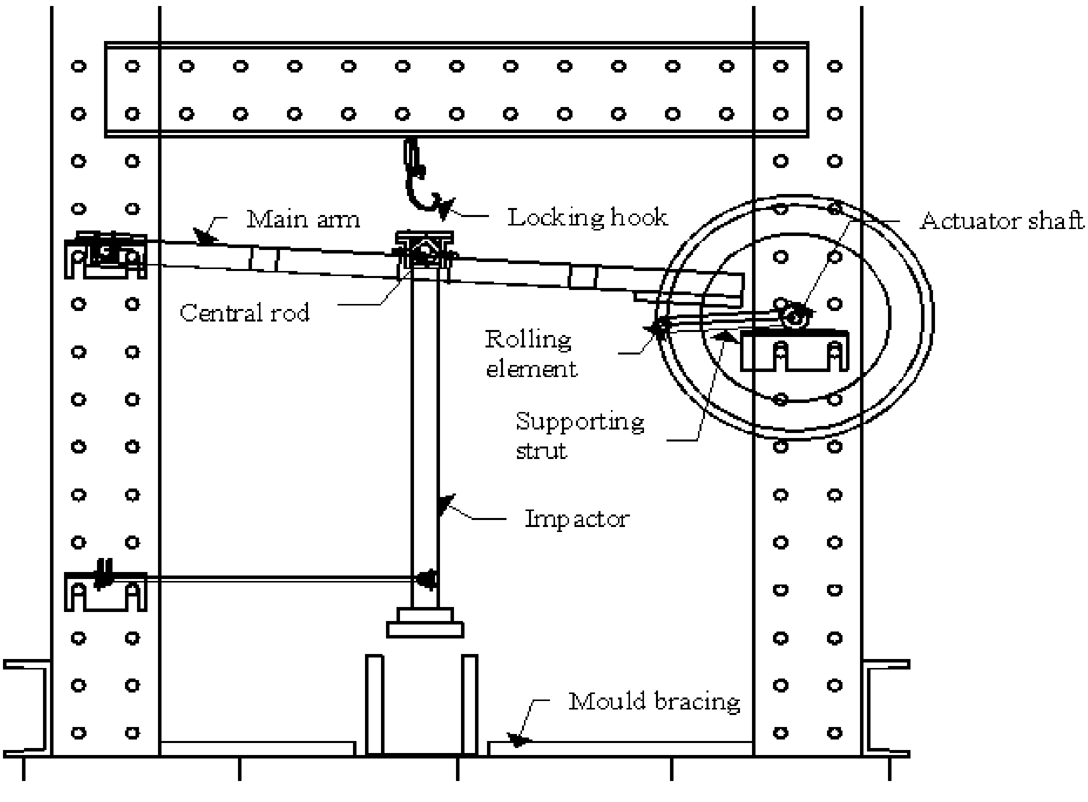

Figure 5. Schematic presentation of the dynamic compaction machine, D.E. Montgomery – University of Warwick

The objective was to show that characteristics related to small samples would occur if the technique were extrapolated to larger blocks. The test rig was designed to serve as an early machine design prototype and has produced a number of full size building blocks.

Figure 6 –Guards' house, made of stabilised earth blocks

1.4 Building blocks from processed stabilised soil

A block in a typical building structure has two main functions: to support its own weight and the weight of the block or other structure, such as a roof, that is above it. This is called the compressive strength of the block. Once the blocks become part of a structure they must, as a collection, be able to withstand attack from the elements - rain, frost and wind - for a reasonable period of time.

Even unstabilised mud-brick walls are able to withstand the compressive forces necessary for single storey structures. Use of stabilised soil blocks produces blocks of sufficient strength to support structures several storeys high. Further research in this area would be interesting in terms of improved performance of new dynamic compaction techniques, but its cost would be difficult to justify as the area has been heavily researched in the past.

The second function is linked to the first, but is more important in terms of the longevity of the structure in adverse weather conditions. It determines how long the structure will survive before it is no longer able to withstand the compressive forces. For example, in a simple mud-brick hut, once the blocks have dried they can easily support their own weight and the weight of the roof. If heavy rains come and the structure becomes saturated with water, it loses its structural strength and may collapse. If the structure could be kept dry or the mud-bricks were made impermeable to moisture then the structure would survive for a much longer period.

1.5 Dynamic compaction of stabilised soils

Dynamic compaction provides a significant energy saving (about 30%) in the production of homogeneous building blocks of a specified density (1,950-2,050Kg/m^3). As the density increases, block permeability decreases and the effects of water penetration are reduced. Thus, a denser block provides greater compressive strength and better resistance to the elements.

Greater block density also improves the efficiency of any stabiliser added to the soil mixture. A relatively small percentage of cement (between 4-6%) is sufficient to produce a block that is structurally unaffected by moisture attack at the block density described above, assuming uniform distribution of the stabiliser throughout the block.

Rendering or painting the external surfaces of a structure can protect the blocks from the elements, but such processes are expensive and usually involve imported materials. Cement is also unlikely to be locally available, but if used selectively the amounts required can be reduced. Further investigation into this area would be worthwhile.

Annex 1 - Annotated references: www.eng.warwick.ac.uk

1) Materials for low-cost building in North-East Nigeria
W. Lawson (1991)

This survey present practices, availability, cost, advantages and disadvantages of various building materials in North Eastern Nigeria, incorporating visits to a variety of educational and government institutions and building material manufacturers in Northern Nigeria and visits to the North East Arid Zone and several villages and other sites to assess present building practices. Samples were taken of some typical masonry building materials and their compressive strengths were evaluated and showed considerable variation in quality. The reasons for this are discussed and recommendations made.

2) Soil testing for soil-cement block preparation
D. Gooding (1993)

This working paper describes how to test soils to determine their suitability for use in soil-cement building blocks. Several reports covering this topic have been published since the mid 1980s by a variety of organisations. This paper provides a brief description of the effects of different soil combinations on the properties of blocks during moulding and the performance of the blocks after curing. It provides a practical critique of the published tests for selecting soil, and for determining how much cement should be added to them, identifying a number of ambiguities, difficulties in performance and actual errors. It concludes with recommended testing plans and three appendices. Appendix A describes selected procedures for field-testing soils to be used for block making, Appendix B describes laboratory test procedures: in these appendices shortcomings identified earlier have been corrected. Appendix C is a bibliography.

3) Quasi-static compression forming of stabilised soil-cement building blocks
D. Gooding (1993)

This paper examines the quasi-static compression (slowly applied pressure) method of compacting stabilised soil-cement building blocks. It describes a self-contained piece of research which was conducted to enable the comparison of quasi-static compression with the alternative dynamic methods of soil compaction. It gives an initial overview of the process of soil stabilisation and outlines the roles of soil structure and block curing in stabilisation. Alternative methods of block compaction are briefly described, followed by a discussion of the material factors that affect the compaction of stabilised soil. A number of simple theoretical models to describe the internal compaction mechanisms of quasi-static compaction are provided.

The results of an experimental investigation to asses the effect of double-sided compaction, mould wall roughness, mould wall taper and pressure cycling relative to the datum process of single-sided, single-cycle compaction are discussed. This is followed by an experimental investigation to determine the relation between compaction pressure, cement content and seven-day wet compressive strength. A formula relating cement content and compaction pressure to wet compressive strength is proposed as the best fit for the experimental data gathered. This formula is used as the basis for a simple economic analysis of high and low pressure compaction machines.

4) The potential of cement-stabilised building blocks as an urban building material in developing countries
D.E. Gooding & THT (1995)

This paper examines the level of technical achievement in production, and the level of social acceptance of cement-stabilised building blocks (alias soil-cement) currently demonstrated in nine developing countries surveyed in early 1995. The survey established that these blocks are currently in common use and are likely to be more widely used in the future. Several technical problems or deficiencies were identified in the areas visited, as were new developments pertinent to the advancement of this building technology. These deficiencies and developments are analysed and used to define the research, design and training needed to significantly improve the effectiveness of cement-stabilised blocks as a low-cost walling material in urban areas of developing countries.

5) Destructive effects of moisture on the long term durability of stabilised soil blocks
A.G. Kerali, (2000)

This working paper describes the experimental work done so far to explain the processes of moisture-linked deterioration of stabilised earth blocks. It describes the main mechanisms responsible and proposes remedial measures for their improvement.

6) Dynamic compaction of soil for low-cost building blocks
D.E. Montgomery, (2000)

This paper reports the results of experiments carried out on the process of dynamic compaction of stabilised soil. The interest in this area was fuelled by previous research that shows that the dynamic technique of compaction offers significant advantages over quasi-static compaction of stabilised soil blocks. The impulsive blow to compact a soil sample does not exert massive forces for sustained periods of time during the compaction process. Subsequently dynamic compaction has shown to be possible with thin mould walls and using low-tech mechanisms achieves similar levels of density (and subsequent strength) to hydraulically-assisted high-pressure quasi-static compression.

7) Stabilised soils for building: block types and advantages
A.G. Kerali, (1998)

This work examines the types and properties of blocks still in use. The research attempts to classify stabilised blocks being manufactured, and analyses in detail the merits of stabilised blocks. The research also compares the performance of blocks in relation to other comparable building materials such as burnt clay bricks, light concrete blocks, etc. The information provided could be of value to potential producers, researchers, designers and funding agencies. Although there is yet no internationally agreed standard system for the classification of blocks, the units produced can be conveniently differentiated according to variety, quality and type. The classification by type can be seen as the most widely used. Blocks are categorised as solid, hollow perforated and interlocking. The main characteristics of blocks which make them compete with other building materials include dimensional stability, improved performance, good appearance and flexibility of use. Improved performance, such as higher wet compressive strength, reduced reversible moisture movement, higher density, and improvement in durability, are investigated. The merits and advantages of blocks range from technical, financial, environmental, cultural and social, and flexibility of use.

8) How does cement stabilisation work?
D.E. Montgomery, (1998)

After a brief study of some relevant texts documenting the production, characteristics and use of Portland cement a description of the qualities of cement is provided. The bonding of cement is caused by the hydration of the cement particles which grow into crystals that can interlock with one another giving high compressive strength.

In order to achieve a successful bond the cement particles need to coat most of the material particles so that upon hydration a crystalline structure is created throughout the mixture of particles. Particle intimacy is important to ensure a good number of cement bonds between adjoining particles and this can be helped by mixing the cement into a mixture of particles of good size distribution. The water in the mixture needs to be monitored to guarantee sufficient hydration of the cement and ensure adequate workability of the mix. Too much water will leave voids in the mixture after the water has evaporated off and will reduce the final set strength of the material.

The limitations to cement besides the careful control of materials and moisture are that cement requires time to fully cure and that it is susceptible to chemical attack. Nevertheless, it is a highly suitable method of stabilisation and can easily be applied to a variety of different soils for use in making building materials.

9) Physical characteristics of soils that encourage SSB breakdown during moisture attack
D.E. Montgomery, (1998)

Soil is the major component of stabilised soil blocks and consequently its properties are of great interest to manufacturers of stabilised soil block manufacturers. Some soils are considered to be unsuitable for manufacturing stabilised soil blocks, some are suitable with modification; acceptable soils have certain physical characteristics. The soil properties that have been found to be suitable for stabilised soil block manufacture represent a small selection from the wide range of different soil characteristics. The properties of the soil used will determine in part how the block performs under moisture attack. Other factors, such as the forming technique and any stabilisation process applied, will also affect the performance of the block against moisture.

The general characteristics of soil are listed in this report, and those less able to withstand moisture are highlighted. If the detrimental characteristics of the soil can be isolated and rectified by some means, then the result will be a higher quality product. Those that cause expansion on wetting are the most negative characteristics. They are categorised as the presence of a clay fraction, porosity and moisture movement. If all three parts are present expansion will occur; their removal or minimisation will improve the quality of the final block. Research in this area is for future study.

10) Ideas for reducing cost in stabilised soil block construction
D.E. Montgomery, (1999)

Most manufacturers want to maximise output and quality whilst keeping costs to a minimum. This can often be achieved by modifying the production process to make the best use of the resources available and to identify the most cost effective materials, labour and processes. These same principles apply to the manufacture of soil blocks.

This report examines the entire production process of soil block manufacture, breaking it down into clear stages. Each stage is described and possible cost saving ideas suggested. Following that is a more in depth study of certain stages that could yield significant savings.

It seems that if a specific area of the production cycle is modified, then a small change in cost can be realised. But, there are real advantages if the overall process is designed so that each stage overlaps the next, minimising waste in materials, labour and handling. This requires careful study of the available resources and a production plan suited to those resources.

11) Durability of compressed stabilised soil building blocks
A.G. Kerali, (1998)

This study looks at the important question of the long term durability of stabilised soil blocks. The feasibility of producing satisfactory building materials from indigenous natural resources and the durability of such materials in adverse environments are investigated. Novel materials, although with the potential of becoming substitutes for existing conventional materials, may not be sufficiently durable under tropical conditions despite having adequate strength and other desirable performance characteristics. The study of durability is based on the introduction of stabilised blocks. The durability of blocks is influenced by bulk and surface factors. Bulk factors include the effects of the environment and physical and chemical actions. Surface factors include absorption, volume changes, permeability, etc. A deliberate attempt is made to test and validate critical factors with a view to developing a long term durability model and determining the most critical deterioration mechanisms. At the time of this research there were no international standard or unified norms for the use of stabilised blocks.

12) Critique of existing papers on dynamic compaction of stabilised soil samples
D.E. Montgomery, (1999)

Previous researchers have expressed their dismay at the lack of information in the field of dynamic compaction of soil blocks. The information that is available on dynamic compaction mainly comes from the civil engineering industry based on ground compaction methods. Whilst these provide a basic understanding of soil compaction, they are not entirely applicable to the compaction of blocks confined within a mould. Modelling of the compaction process has been attempted within this field and the mathematics is included in this report.

Dynamic compaction of soil blocks without the use of cement has been investigated to establish optimum compaction efficiencies when the energy transfer is kept constant. This has shown that between 8-32 blows gives the greatest compaction for the same total energy transfer. The research does not investigate the effect of adding cement to the compaction process. Research by the civil engineering industry briefly investigated the effect of moisture on compaction as well as the efficiency of different methods of energy transfer. These results are significant but cannot easily be applied to the research on block compaction.

Several major gaps in the understanding of soil compaction exist, and need to be tackled. It is of fundamental importance that thorough testing of dynamically compacted cement stabilised blocks be carried out in the near future. Optimisation of energy transfer can yield small increases in density, which results in comparatively greater gains in strength. More time spent researching the optimum method of energy transfer would be a valuable exercise especially with the addition of cement, which has an effect on the compaction process

13) Testing of blocks and structures
A.G. Kerali, (1999)

This work examines the testing of blocks from production to their testing in use. A wide variety of problems associated with building materials may be better understood and resolved through the combination of theoretical knowledge, study of precedents, knowledge of the property of materials and their most important features. These features include those that affect strength, dimensional stability and durability. The interest in testing blocks is likely to increase due to the large number of block structures in service which have shown faster deterioration than comparable materials. Particular emphasis is being placed on the development of testing methods related to block and wall quality, strength, integrity and performance, and durability and weather-proofing. The scope of the research is limited to producing blocks. New techniques and areas that show some potential for further development and use are suggested. These cover on-site testing, laboratory testing, acceptance testing, exposure site testing and in service testing. The need for test planning to achieve a coherent strategy is analysed closely.

14) Strength of cementitious mortars: a literature review with special reference to weak mortars in tension
G.T. Still, (2004)

Cementitious materials are commonly used for the construction of low-cost water storage tanks in developing countries. For this purpose, an understanding of their properties and particularly tensile strength, is important. The paper provides a literature review, starting with factors determining mortar strength. Optimum water content varies according to the sand:cement ratio, which will depend on the compaction method being used.

The review is followed by some analytical work based on available data, suggesting that sand:cement ratios of around 6:1 are optimal with respect to materials cost, provided that certain strength relationships suggested by the existing data hold.

15) Minimising the cement requirements for stabilised soil block walling
D.E. Montgomery, (2001)

The monetary cost of low-cost walling in developing countries is greatly dependent on the expensive additives that are used to manufacture the building units and the cost of transportation of raw materials or finished products to the construction site. Energy is an additional cost and also provides an approximate measure of environmental impact. Within this paper several different types of existing walling materials are investigated for their overall cement and energy consumption. The purpose is to see how favourably they compare with high-density compressed and stabilised soil blocks using comparative measures. Assessment of the suitability of local and on-site production is indicated for each of the materials in this study.

16) Durability of compressed and cement-stabilised building blocks
A.G. Kerali (2001)

This work examines the interplay between three factors: constituent materials (cement, soil, water); quality of block processing methods; and the effects of exposure to natural conditions (physical, chemical, biological). It concludes that it is possible to significantly increase the strength and improve the dimensional stability and wear resistance of cement stabilised blocks to the extent that they can be safely used in unrendered walls in the humid tropics. This improvement is achieved via better inter-granular bonding, reduction in voids and lower absorption. Using the slake durability test, it is now tenable to freely discriminate, classify, and compare not only blocks but other like materials of any category and storage history. New quantitative durability gradings are recommended for future incorporation into standards for cement stabilised blocks.

17) Dynamically-compacted cement stabilised soil blocks for low-cost walling
D.E. Montgomery (2002)

This document contains the detailed results and conclusions of work carried out during PhD fieldwork to investigate the process, production and performance of dynamically compact cement-stabilised soil blocks suitable for sustainable low-cost building. The dynamic compaction mechanism was analysed to determine the forces delivered during the impact blow. These were found to be a fraction (30kN) of the forced delivered by an equivalent hydraulic press (400kN). This results in less complex and less expensive machine manufacture that is amenable to local manufacture and maintenance. Furthermore, dynamic compaction presents an economically viable and sustainable alternative to other methods of block manufacture.

18) Design of rainwater storage tanks for use in developing countries
S.J. Turner (2000)

This project investigates the problems associated with ferro-cement water storage tanks in developing countries, with the aim of providing practical hints for engineers to help with tank construction in the field. Based on the findings from the project a series of construction rules is proposed.

19) Cracking in waterproof mortars
T. Constantine (2001)

This is an investigation into cracking in cementitous renders used to waterproof cheap hand-built water tanks in the developing world. A study of the theory behind cracking in mortar is followed by a review of readily available admixtures that affect the properties of mortar. Extensive experimentation was conducted on the different mixes of mortar, with the result that the investigation suggests the use of a super plasticiser would reduce cracking and hence leakage in a mortar rendered tank. A further recommendation is to add silica fume to the mortar to increase its strength and help reduce cracking. Further investigation into the subject is recommended.

20) The effect of fines in sand for the fabrication and application of concrete in developing countries
V. Fernandes (2002)

Good quality sand is available but in short supply and expensive in developing countries due to high transportation costs. Poor quality sand, which consists of a significant proportion of clays and silts and is poorly graded, is readily available but needs to be improved for use as building material. When seven day dry compressive strength tests of comparable concretes with identical water-cement ratios were measured, the strength of the concrete was found to increase with the fraction of fines in it. It was found that despite the suitable dry compressive strength of material with a large proportion of fines, use of this material was hindered by its large cyclic movements and shrinkage on drying.

21) Countering shrinkage cracking in renders
S. Moeed (2002)

An investigation is performed into ways of reducing shrinkage cracking in cementitious renders used to line rainwater harvesting tanks. Crack reduction was measured via both leakage rates through the renders and direct measurement of the cracks propagated. Emphasis was on crack distribution and how this affected leakage rates. Methods of reinforcing mortar were analysed, the most successful being wire mesh reinforcement which reduced leakage rates by a factor of ten. Mesh reinforcement was also the most successful in reducing shrinkage. Other renders tested included fibre reinforcement and an expansive additive to compensate for shrinkage. This investigation was a refinement of work carried out by Tom Constantine in 2001 but included investigation of different methods of waterproofing renders.

Annex 2 – What is Soil?

1. Definition

Soil is the building block of civilisation and, along with water, is one of the two basic ingredients for human survival. Mankind will continue to exist only as long as the soil persists. At present there is about one fertile acre per person, but the amount of fertile land is decreasing and population is increasing. Land not suitable for agricultural exploitation can be looked at as a natural source of building materials.

Soil is the mixture of mineral matter (detritus) and organic matter (humus) that lies between the earth's surface and unweathered bedrock. It is usually vertically layered in zones or soil horizons. The vertical section through the soil-subsoil-bedrock sequence is called the soil profile.

Figure 7 is a schematic presentation of a section containing the various horizons that describe the layer sequence from surface to unweathered bedrock.

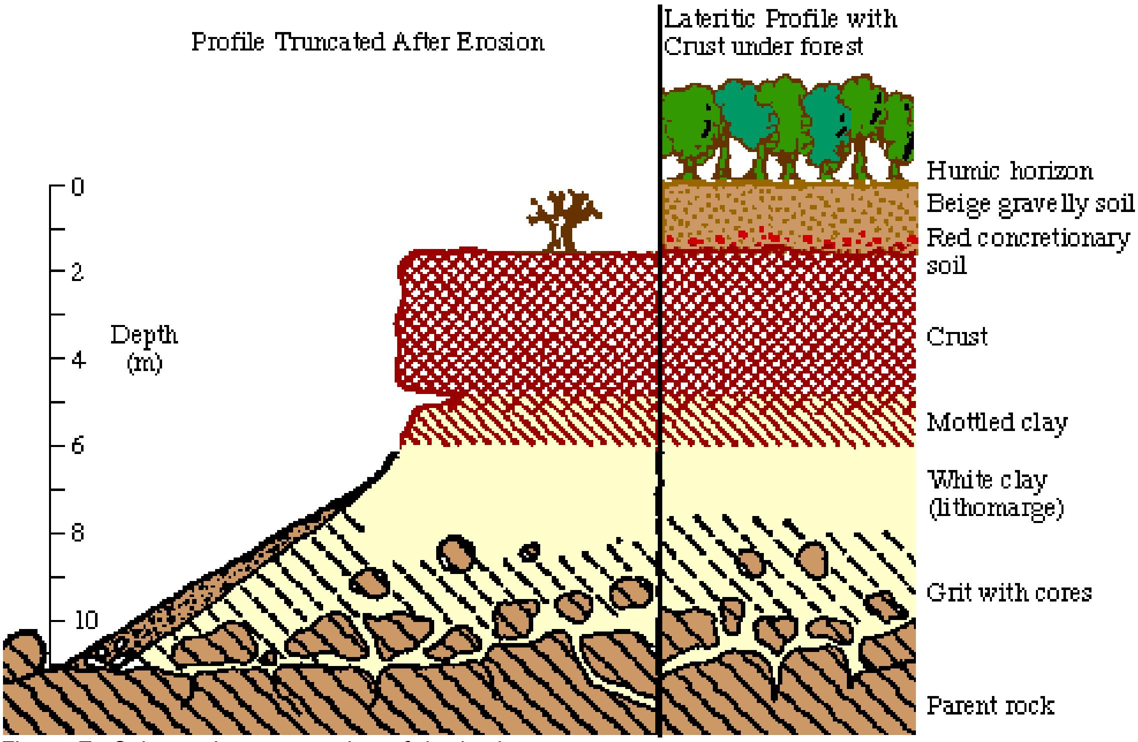

Figure 7 - Schematic presentation of the horizon sequence.

For building uses, soil can be integrated with its section below 'humus' with prevailing 'detritus' components in direct contact with 'crust'.
- Horizon (A) is where humus is abundant and chemical weathering is active. This may occur at the surface, or may underlie a horizon composed of accumulated organic matter (O).
- Horizon (B) is a zone of deposition, where clay particles are trapped and solutes are absorbed. It is thus rich in clay and/or iron and aluminium hydroxides.
- Horizon (D) is the sub-soil and consists of weathered bedrock grading into the lower unweathered bedrock; it is useful only for construction purposes.
- Horizon (E) is the original bedrock of the region or area and is the source of building stones.

The nature of the soil is dependent on its parent material, the topography, the climate, the local plant life and time.

2. Rates of soil formation

Depending on various factors governing the formation of soil, new soil can take from just a few to over 1,000 years to develop. Ash from the eruption of Krakatoa in 1883 developed a soil profile 35cm deep in only 45 years, but the climate of Indonesia is warm and ash does not require weathering to break it down. Hawaiian basalt flows evolve into soils suitable for cattle ranching in about 1,000 years. Again, this is relatively easily weathered rock and is in a warm temperate environment. The bare rock that was exposed after the ice retreated in northern Canada 10,000 years ago frequently shows no soil development. A range of 1,000 to 10,000 years seems to be realistic for the development of new, fertile soil from hard rock. This makes it essentially a non-renewable resource.

3. Physical properties of soil

Soil is a material that is capable of sustaining plant growth. The physical properties of a soil dictate its use. They determine the availability of oxygen and water and the ease of root penetration. The relative proportions of sand, silt and clay particles in a soil determine the *soil texture*. The texture affects the permeability and porosity of the soil. Textural classification is based on the relative percentages of sand, silt and clay, with loam being a mixture. A classification scheme is shown in Figure 8.

There are many variations in the texture of the soil, but they are only slight differences in relative percentages. Note that this classification does not include the organic fraction, and gravel sized particles are also excluded.

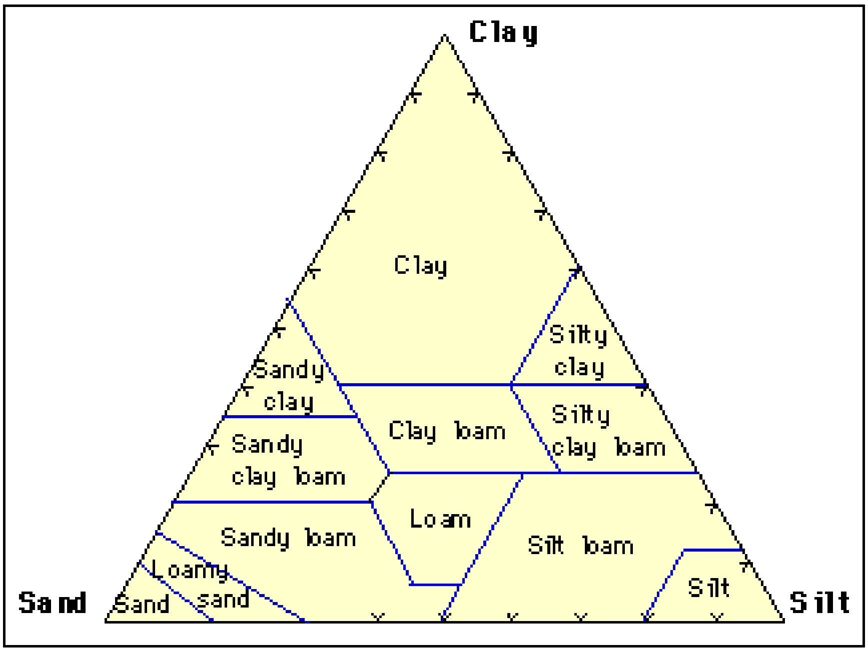

Figure 8 - Ternary diagram of soils: mixtures of sand, silt and clay

Gravel sized particles are included as a category of the soil if they comprise more than 15% by volume. Thus, loamy sand with 20% cobbles would be a 'cobbly loamy sand'. If there is more than 35% gravel, the word 'very' precedes the description. With more than 60% gravel, the word 'extremely' is used to describe the soil.

4. Soil structure

Structure refers to the arrangement of soil particles into aggregates held together by organic substances, iron oxides, carbonates, clays and/or silica. Natural aggregates are called *peds* whereas masses of soil broken into masses by artificial means, such as tillage, are called *clods*. The degradation in soil structure leads to compaction and reduction in the continuity, distribution and size of the soil pores.

This results in:
- reduced porosity (decreases infiltration, increases runoff and erosion)
- surface crusts (impedes crop emergence and reduces permeability)
- poor aeration (reduces emergence and growth and increases susceptibility to root disease)
- increased soil strength
- reduced root growth
- less easily worked, requiring bigger tractors, which produces further soil compaction, etc.

An increase in soluble and exchangeable sodium ions (Na^{+}), speeds structure degradation. Sodium ions do not effectively neutralise the surface negative charge, so adjacent soil particles repel each other because of their similar charges, leading to the destruction of solid by dispersion. The dispersed clays and small organic colloids move with water, lodging in soil pores and sealing the soil. Soil with too much sodium becomes almost impermeable to water and dries to hard crusts.

5. Soil density

There are two measures of density in soils: particle density, which is the density of the soil particles only and does not include water or pore space, and bulk density, which is the density of a dry soil as it naturally exists. Bulk density changes can be used to gauge soil structure degradation over time and to determine if soils are too compacted to allow root penetration or provide adequate aeration.

6. Soil porosity and permeability

Porosity refers to the total connected pore spaces and, therefore, how much water can be held by the soil. Permeability refers to the ease with which water can pass through the soil.

Sands have large and continuous pore spaces, whereas clays have greater porosity but much lower permeability. The best balance between water retention (small pores) and adequate water and air movement (large pores) is medium textured soils such as loams. Hardened soils formed from the precipitation of soluble carbonates, silicates and iron can create impermeable layers.

7. Soil strength

Soil strength is the degree of resistance of a soil to crushing or breaking when force is applied. It is measured either dry or wet with techniques ranging from squeezing between thumb and forefinger to dropping a 1.36kg G-pick on the sample from a height of 0.22m. Descriptive terms include loose, friable, firm, hard and cemented, with modifiers such as slightly, very and extremely.

8. Soil colour

The soil colour reflects the soil's parent material or its development. Within geographic regions, darker soils indicate higher organic content, but this cannot be correlated over diverse regions, as some partially decomposed material is darker in some environments than in others, and darker colours may also simply reflect different parent material. White colours are common when salts or carbonates are present.

9. Soil water flow

Most rapid movement of water through soil is caused by gravity. Saturated flow begins with infiltration. The movement of water through the wetted soil is termed percolation. It is percolation that leaches nutrients and soluble ions from the soil. Percolation is common in the more humid regions. Excess water moves through the soil profile, dissolving soluble ions and carrying them into groundwater. The water also moves small soil particles (clays and organic colloids) downward until they lodge in pores or are adsorbed onto ped surfaces. The leached soil layers lose most of their soluble salts and much of their adsorbed Ca, K, Mg and Na (calcium, potassium, magnesium and sodium). Acidic (hydrogen) ions from carbonic acid and other soil acids replace these, producing acidic soils in humid regions.

Gravitational water partly drains from large pores, leaving large air pockets that greatly reduce water flow rates. Water does not move appreciably from small water-filled pores into large air-filled pores

10. Tropical soils

High rainfall and warm temperatures combine in tropical regions to create conditions of very high chemical weathering. The relative mobilities of the major elements released during weathering depend on the prevailing environmental conditions, but although the precise order may vary with the weathering regime, the generally agreed sequence of mobility is

$$Ca^{2+} > Mg^{2+} > Na^{+} > K^{+} > Fe^{2+} > Si^{4+} > Fe^{3+} > Al^{3+}$$

That is, insoluble elements such as aluminium and iron are left as residual deposits after the more mobile elements are leached through the soil horizon. This selective removal of the more soluble elements may result in the formation of a hard, generally impermeable crust on the surface or in the upper horizons of soils, known as a duricrust. Of the insoluble minerals listed above, haematite, gibbsite and quartz form duricrusts.

11. Terminology

Iron-rich and aluminium-rich deep weathering profiles are generally termed laterites. The hard duricrust surfaces of these deposits are referred to as ferricrete and aluminocrete (or alcrete) respectively. Deposits that contain economically extractable aluminium deposits are called bauxite.

12. Iron laterites

Under warm, wet conditions, Fe and Al become concentrated as other minerals are slowly leached out of the soil. Goethite (FeO.OH) is one of the least soluble minerals formed during chemical weathering and forms an iron-rich crust, or ferricrete, at the surface. The lower horizons are rich in kaolinite. Between the red, iron-rich zone at the surface and the pale, clay-rich zone is a mottled zone where leaching has been concentrated in certain places. The sequence of ferricrete-mottled zone-pallid zone is called a laterite.

Ferruginous laterite is widespread and recognisable by its distinctive red colour. The term laterite is often used to indicate ferruginous laterite. The essential characteristic is the enrichment of iron. A well developed iron laterite contains over 50% ferric oxide and hydroxide. The thickness of some laterites poses a problem of where the iron came from. As granites contain only in the region of 2% iron, and basaltic rocks up to 11%, a laterite deposit will require the alteration of many times its own thickness of original rock to supply the necessary iron. For granite, about 20 times the thickness is required, so for a 9m thick laterite, some 180m of in situ alteration would need to be weathered. In some cases, if there were no iron enrichment from outside sources, it would imply a loss of 90% of silica and 81% of alumina from the parental granite. These figures are too high to be explained by weathering alone and iron enrichment is necessary. Laterites can also develop in other climates than wet tropical climates, provided that there has been a stable surface where weathering and leaching have been prolonged in well-drained sites. Wet tropical climates favour the development of laterites.

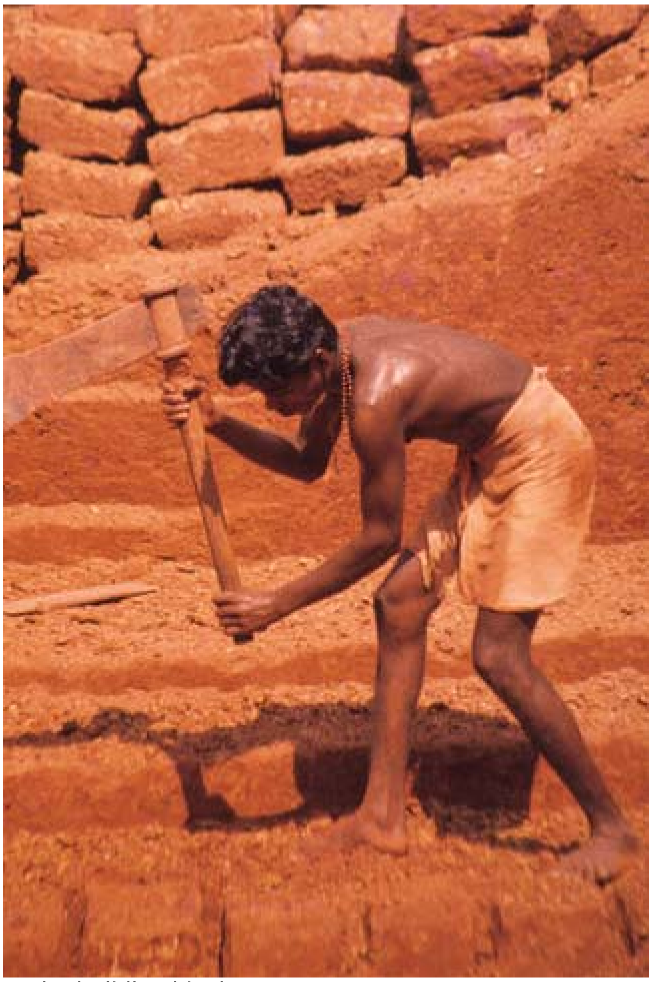

Figure 9 – Quarrying crude laterite building blocks.

Bauxites

Although iron-rich varieties of laterite are the most common, aluminous laterites, called bauxites, are the most important economically. Weathering of kaolinite produces gibbsite, $Al(OH)_3$. The silica is leached from the surface leaving an aluminous laterite. Gibbsitic bauxite deposits are the source of most of the world's aluminium. Aluminous laterite forms best in humid tropical to subtropical regions where annual rainfall is 1,200-1,500mm. Continuous rainfall favours the production of bauxite deposits, as the monosilicic acid produced during laterite formation needs to be continuously diluted and leached out so that the silica in solution is not sufficient to convert aluminium hydroxide ($Al(OH)_3$ = gibbsite) back to kaolinite.

Monosilicic acid released during laterite formation may be concentrated by evaporation transpiration following lateral movement in groundwater to more arid climatic zones, producing a siliceous surface crust called silcrete. Concentration of silica in solution may also cause resilification of gibbsite to kaolinite; so, whereas aluminocrete and ferricrete are residual soils, silcrete is essentially a secondary siliceous deposit.

Given the high quartz content of most rocks, and the near-absence of quartz in lateritic soils, developing laterites are a good source of dissolved silica. The existence of tertiary silcretes associated with laterite formations of the same age is in agreement with this suggestion of the mobilisation of silica from the laterites and redeposition in silcrete.

Silcretes are associated with semi-arid environments, where annual precipitation drops to below 250mm; in Australia, silcretes are generally found to the arid side of laterite formations. Silica precipitation is also favoured by high acidity (pH). Up to a pH of about 9, silica solubility is virtually constant, but increases markedly above this point. In alkaline environments, such as those found around ephemeral lake beds in semi-arid and arid regions, pH values may vary from 8 to 10 for short distances. Silica in solution moving from a locality above pH 9 to one below pH 9 will therefore be precipitated.

Annex 3

A short description of soil-earth building material

1. Qualified soils

Soils that qualify for both compressed earth block and rammed earth are common in most areas of the world. For example, most of the continents' rocks are granites and decomposed granite is almost perfect as a building material having ratios of feldspars to quartz that are appropriate for compaction. Basaltic soils are a little more difficult and often require additional clay. The basic formula is 30% clay with the balance loam and small aggregate. Caliche which is incorrectly used to refer to decomposed limestone in the southern part of North America and most of the Caribbean, is the name for the coral reefs that lie beneath the Dominican Republic and is compactable depending on the area. The use of decomposed limestone can be problematic unless modified with the addition of clay, Portland cement or lime.

2. Non-qualified soils

Soils that contain a large fraction of clays (bentonites) are highly expansive and normally unsuitable for earth construction without modification. The shrink and swell capacity of these soils, which is related to their clay content, can cause blocks made from them to be very susceptible to moisture, and even high humidity. However, tests shows how clays actually perform under compaction and even poor performance can be offset by stabilisation. Soil cracking after rainfall may indicate expansive soil. Soil must be tested to determine its suitability. The ideal is a block or wall that is attractive and has a lot of strength, but even ugly blocks and marginal soils can be used to build structures that will last for centuries.

- Desirable qualities for soil construction materials include:
- Strength
- Low Moisture Absorption
- Limited Shrink/Swell Reaction
- High Resistance to Erosion and Chemical Attack
- Availability

3. Soil testing

Soil testing techniques vary, and include laboratory and field testing. Testing is done in three phases: laboratory testing, construction mix testing, and quality control testing. Laboratory testing should always be done early in the design process, using representative samples of the soils to be used. Engineering properties for which soils are tested include permeability, stability, plasticity and cohesion, compactability, durability and abrasiveness. Shrinkage, swelling and compressive strength are important aspects of soil suitability.

It is possible to alter soils to make them suitable for construction by stabilising them. Stabilising soil helps to inhibit the shrink and swell potential, and helps to bind the soil components. Soil can be stabilised through chemical or mechanical means, or both. For information on mechanical methods, see Section 5.0 on rammed earth.

4. Soil stabilisation and strength

Lime, Portland cement and pozzolan (high silica volcanic ash) can be used as chemical additives. Lime is most effective on clay soils, and can be used in combination with Portland cement and pozzolan. Hydrated lime rather than quick lime, should be used. Lime is inexpensive, but care must be taken to protect workers from inhaling lime dust. Cement is relatively inexpensive, but requires large energy inputs for production. However, cement produces the strongest block and will substitute for clay-poor soils where lime will not, and the normal usage of 5-10% minimises the embodied energy, especially when compared to concrete and lumber products.

Where pozzolan is plentiful it is the preferred stabiliser. Where it is not available, commercial forms of fly ash can be used if readily available. Any building material laboratory will be able to experiment with the use of pozzolan and fly-ash as additives and provide hints for appropriate utilisation. Unfired compressed earth blocks with the addition of 5-10% cement should pass most of the requirements of national building codes. Rammed earth walls have been tested with compressive strength of 30-90psi immediately after forming. Ultimate compressive strength should reach 450-800psi.

5. Labour requirements in producing building blocks

The use of earth as a building material is inexpensive in terms of materials, but requires high levels of labour in construction. The appropriate equipment and coordinated labour are important in the soil material construction process. Even a small structure may require some 15 tons of earth, which will need to be moved and handled at least twice. A front end loader, skid steer or tractor equipped with a shovel or back hoe will be necessary for on-site extraction of soil materials, and processing the soil and loading the machinery. A large flat area with good drainage is necessary for handling and processing the materials and making the blocks. The building site needs to be accessible by truck for rammed earth constructions.

A backhoe and/or a front end loader will be needed to dig the soil on-site or handle imported soils. Soils obtained from the site may need to be dried and screened prior to mixing. Soils should be tested to prove their compactability and to determine any additions such as sand or clay.

Hydrating and mixing have traditionally been the largest labour and time consumer, whether done by hand or using a front end loader. The use of concrete and stucco mixers have proven ineffectual for large projects such as houses; however, there is earth mixing or blending machinery available that is especially cost effective for adding Portland cement or lime, and for adding water in dry areas.

Compressed earth or soil blocks can be manufactured on site using a variety of block-making machines, including hydraulic presses or mechanical presses, or various combinations. Some mechanical presses are small enough to be operated by hand.

The use of soil as the basic block material is also possible, but will have slightly different stabilisation demands. Sub soils are the basics of earth block construction. With a clay content of plus or minus 30% and a water content of 6% it becomes suitable for compression.

6. Soil block construction

With a mobile industrial block machine powered by a diesel engine, up to 800 blocks per hour is possible. Compressed soil blocks can be used immediately. They continue to cure and gain strength after they are installed. When green (before they are cured), they can be readily shaped or nailed into, using hand tools. Compressed earth blocks come in two basic types, vertical press, which produces blocks of 25 x 21cm (although there are variations) with a fixed height of 8cm depending on the soil. These blocks are treated like adobe in that they need to be mortared and cut to fit. Horizontal press blocks have the following measurements - 10 x 21 cm with some variations, with a block length of 5 to 18cm depending on the machine. These blocks do not require mortar and can be dry stacked by workers with basic skills. Blocks can be custom sized to minimise cutting for electrical, plumbing and wall changes.

7. Soil blocks wall finishing

Mortar for blocks must be applied to the entire surface of the block, as opposed to ribbon mortar beds often used with conventional bricks. Full surface mortaring allows for maximum compressive strength. The same soil used in block making, mixed with water to form slurry, is usually used as a mortar for binding blocks for floors and walls. Cement can be added to the mortar mix, but this increases the cost. The main advantage of cement mortar is stabilisation.

Block size can be varied to accommodate a variety of designs. Walls can be sculptured, rounded, or formed into keystone arches to create custom effects. Relatively unskilled labour can be utilised for constructions using compressed earth blocks.

Design of structural walls using any soil material block must take account of wall height and thickness, size of block, mass value and desired style and finish. Wall height-to-thickness ratio must be adequate for stability.

Earth block structures need not be 'pueblo' style if this is not desired. A gable or hip roof may offer better protection and will provide protection from the sun on western aspects. A bond or collar beam is necessary if the roof is supported by the walls. This will serve to spread the load over the entire wall, and stabilise the tops of the walls against horizontal movement.

Soil blocks are typically treated with stucco or plastered to waterproof them; however, any veneer or siding can be used on pressed earth blocks as they can hold a nail or staple. Interior finishes are normally plaster or earth plasters.

8. Rammed earth walling

Rammed earth, an ancient building technique, may originally have been developed in climates where humidity and rainfall did not permit the production of soil block. For soil blocks to cure uncovered, there must be at least 10 rain-free days. Soil mixtures for rammed earth are similar to those for soil block. Soils with high clay content may be more suitable for ramming, as blocks tend to crack while curing. Rammed earth soil mixes must be carefully prepared by screening, pulverising and mixing. Pulverising is important to ensure a uniform mix and to break up any clumps.

Transporting the soil mix to the forms is demanding. Large quantities of soil must be moved and transported vertically for placement in the forms. This process is different from pouring concrete as the mix is not fluid.

Rammed earth moulds must be stable and well-built in order to resist the pressure and vibration during ramming. Small, simply designed forms are the most effective. Ease of assembly and dismantling should be considered when designing forms. Forms can be made of wood, aluminium, steel or fibreglass.

Systems for keeping form work in position vary. Small clamps adapted from concrete form work techniques, work well, although small holes are left when the clamps are removed. Other methods include locking hydraulic jacks, or form work built on posts.

Once a soil 'lift' of 15-20cm in thickness is in place, the soil is rammed. Ramming can be done manually or mechanically. Manual ramming is an ancient technique using a large, specially shaped rammer with a long handle. Rammers weigh around 10Kg, and the heads are made of wood or metal. Different form shapes, especially corners, require differently shaped rammer heads.

Mechanical impact ramming uses pneumatic ramming machines. Only rammers specifically designed for soil, which are neither too powerful nor too heavy, are effective. This type of equipment is expensive, but impact ramming is highly effective, and if the soil mixture is good, creates high quality rammed earth blocks. Rammed earth begins to cure immediately; the process can take several months to several years, depending on weather and humidity conditions.

Rammed earth walls have low tensile strength, and need to be reinforced through provision of a bond or collar beam. Beams may be of concrete, wood or steel. Vertical reinforcement is also possible, and may be required by the designer.

9. Wall openings, windows and doors

All openings in rammed earth walls, such as windows and doors, need lintels to span the opening width. Water flow and moisture control is critical to protect structural walls. Special detailing to accommodate manufactured windows may be necessary in terms of wall thicknesses. All openings for doors and windows will require a frame. Wood rather than metal is recommended to avoid the corrosive action of moisture from the soil blocks. Lintels may be made of concrete, stone or wood. Careful attention to roofs, windows and doorways is necessary to protect the structure from water damage.

10. Foundations and floors

Foundations required by most codes are steel reinforced concrete. Soil block material may be used as filler between piers of a reinforced concrete in a pier and beam foundation. Historically, many earth built structures have either no foundations or only sand and gravel foundations. These latter are excavated trenches filled with two parts sand to three parts gravel. Trench bottoms are graded to encourage drainage. Soil material blocks should not be used in below grade walls unless they are supported on both sides. Natural moisture from the ground may infiltrate the block, resulting in reduced compressive strength.

Earth floors are most often used in outbuildings and sheds, but if properly installed, can also be used in interior spaces. For interiors, earth floors must be properly insulated and moisture sealed. Earth floors should be protected from capillary water action by sealing with a water tight membrane underlay.

Construction preparation includes removal of any vegetation under the floor area followed by ramming of the area. The ground must be dry before installation of the floor. After the surface has been moisture-proofed, a foundation of 20-25cm depth of stone, gravel or sand is installed. Then, an insulating layer, such as a straw clay mixture, is applied.

An appropriate soil stabilised mixture for the load-bearing layer of the floor is then installed. The load bearing layer should be 4cm thick. The floor can be finished with a thin layer of cement grout mixed with sand. Sawdust can be added to the concrete mix of rammed earth - in the proportion of one part sawdust, one part sand and one part cement.

Other construction options include monolithic earth floors which are poured in layers within guide forms. Each layer must have curing cracks filled, be treated with a mixture of linseed oil and turpentine, and allowed to dry for a week before the next layer is applied. The final floor surface can be waxed and polished.

Soil material flooring can also be installed using stabilised bricks or tiles. Such materials should be 6-9cm thick, and can be set on a 2cm layer of mortar. Concrete or masonry are other flooring options. Tiled and wooden floors are also possible.

11. Durability issues

Soil materials used for construction are often believed to be vulnerable to weather. This is true only of the outer or finished surfaces. If roof and structural design are appropriate, rainfall and severe weather will not affect the structural properties of exterior or interior walls, but only the cosmetic appearance. Normally, the clay content of the material resists extensive wetting. Structures constructed of soil materials are durable, and can last for more than 50 years. The US government has documented over 350,000 currently existing houses and commercial structures of earth construction in the US. Many of these have been in existence with minimal maintenance for the past 100 years. Some were built as long ago as the 1600s.

12. Finishing and plastering external walls

Mud plaster for exterior and interior surfaces is usually applied in two coats. The addition of straw to the mud plaster mix is recommended. This helps to reinforce the plaster, allowing for thicker coats and surface levelling. In addition, it decreases the tendency for the plaster to crack as it dries. High clay content soils in mud plaster may tend to result in a poor bond of the plaster to the wall. The finished coat is made of screened, fine materials. This layer is applied as thinly as possible while achieving full coverage. Plaster can be trawled or floated to achieve a variety of textures, and reapplied as many times as necessary to achieve the desired affect or to make repairs. When dry, the mud plaster surface will make a hard, firm set similar in hardness and texture.

Traditional cement stucco may be used on walls for a low-maintenance finish although it has some disadvantages in that it has a different expansion coefficient to the wall material. This can lead to separation from the wall; also stucco may conceal structural erosion problems which may result from leaking pipes or roofs. Stucco netting is recommended to accommodate any settling and cracking of the stucco.

Exterior stucco walls should not be painted with traditional exterior paints, which would increase moisture impermeability. A final coloured coat of stucco or texture finishes may be used decoratively. For more information on both interior and exterior cement stucco preparation and application, see the Compendium on 'Information on selected low-cost building materials', from the UN Centre for Human Settlements (Habitat).

13. Interior walls

Interior earth walls may be painted, and also may be treated with sealing compounds to reduce the tendency for dust to develop and rub off on furniture and clothing. Oil-based varnishes and resinous liquids can be diluted for such use. If paint is to be used, a sealing or sizing coat should be applied first. Whitewash can be prepared with equal parts of lime and white cement mixed with water. Natural earth pigments can be added to this. In addition to stucco or plaster, interior walls may also be treated with a variety of veneers including gypsum wall board or other interior veneers.

14. Thermal characteristics

Earth material walls are not especially good insulators. Laboratory tests give a 25cm thick adobe wall with 2cm of stucco on the exterior and 1cm of gypsum plaster on the interior, an R (thermal resistance index value) of 3.8. A 21cm wall of similar construction is given an R value of 4.9. In spite of these fairly low values in laboratory conditions, earth materials do have good thermal mass characteristics. Wall thicknesses of 15-20cm are generally considered optimum for thermal mass performance.

A double wall construction can greatly enhance the insulation value. Applied insulation can be in the form of rigid material or spray-on insulation. Spray-on insulation must be covered with stucco to protect it. Although the addition of insulation will increase construction costs, the resulting energy savings will offset these costs. The following figures, adapted from *Adobe and Rammed Earth Buildings*, reflect the embodied energy in KJ required for the production and use of various materials. Soil block has a much lower embodied energy than many traditional materials.

Portland cement 50Kg = 360KJ
Lime hydrated 50Kg = 415KJ
Common Brick 1 block = 12KJ
Concreted Block 1 block = 28KJ
Earth Adobe 1 block = 2KJ

Annex 4

Case Study - Buildings and Building Materials Development and Use in Sudan
Courtesy of Dr. E.A. Adam

Abstract

This paper looks at the Sudanese experience and attempts to provide access to improved low cost homes. This experience is based on solid research work undertaken by the national research institutions in the country since 2000 aimed at improving local building materials and construction techniques that render durable building materials. The main research achievements include rammed earth walling, stabilised soil building blocks production and use, low cost foundations, low cost roofs, surface finishes, floors, stabilisers for block production, and block making machines. Efforts were extended to transfer these technologies and apply them on a wider scale throughout the country and to draft standards and codes of practices for these technologies prior to full-scale application. The study concludes that the local experience in R&D enables access to low cost and healthy homes

1. Introduction

In the Sudan, most buildings are constructed of local building materials using traditional skills. The basic construction materials are earth, wood, thatch and straw. Buildings made of earth provide homes for more than 80% of the urban population and over 90% of the rural population. Building with earth has many advantages such as ease of construction, availability of the materials (soil), low cost, desirable thermal properties, and the fact that using earth as a construction material saves the environment (woodless construction). On the other hand, earth buildings have many limitations, e.g., lack of durability in areas with high to medium rainfall and wind laden-sand. Due to these shortcomings, and the pressing need for home building, research was oriented towards the development of local building materials and construction techniques. The development included stabilisers, stabilisation process, equipment, building and roofing elements. These experiences were applied widely throughout the country resulting in improved environmentally friendly buildings. The following sections provide some examples.

2. Previous experience

The Carlstein block making machine was first introduced to Sudan (1954) to produce soil cement stabilised interlocking, self-aligning hollow blocks which can be laid without mortar between the courses. Using these blocks, a housing scheme of 250 houses was erected at New Deims; the buildings are in a good shape after more than 50 years.

In 1963/64, new construction techniques were introduced to AL Huda village at the Managil Extension of the Gezira Scheme. These techniques were introduced to the area by UNESCO, WHO and University of Khartoum, to include improved foundations in expansive soils, gishra walling, and cob walling plastered with cow dung (Zibala).

In 1966-1982, Prof. Agib introduced and experimented with rammed earth walls at the Building and Road Research Institute (BRRI) and the National Research Centre (NCR). Many prototypes were built of rammed earth walls, for office buildings, student's hostels for Omdurman Islamic University, and houses for the Sudanese State Bank. Housing projects were also tried out at Wadi Saidna and Kenana. Also, many private houses were built using this technique. The disadvantages of it are related to ramming in hot weather, quality control and surface finishing.

Figure 10. Rammed earth wall construction

In 1978-1983 with the help of UNIDO, an industrial unit of asphalt stabilised soil bricks (asphadobe) was introduced to Sudan and located in El Hag Yousuf to build 200 houses; for a variety of financial and technical reasons, only 16 houses were actually built.

1979-1982, a comprehensive research programme was launched at the National Council for Research (NCR), in collaboration with the Building Research Establishment (BRE), UK. Basic Sudanese soil types were identified, classified, and graded for soil stabilisation using lime, cement and gypsum. Stabilised soil building blocks were then produced using two block making machines; the Cinva Ram (2MN/m^2 and the Brepak (10MN/m^2). High quality building blocks were produced that met standard requirements.

Figure 11. Stabilised soil blocks production

Further studies were made to assess and establish the thermo-physical properties of stabilised soil building blocks. Based on the results a computer thermal model (HTB2) was constructed to assess the thermal behaviour of buildings made of stabilised soil building blocks in hot dry climates in order to optimise the use of these blocks. The results of this project were widely transferred to various parts of the country with successful results. Block making machines were successfully modified and manufactured locally in the Sudan.

3. Practical Applications

3.1. Stabilised blocks and ferro-cement roofing

The results of the research work in the field of soil stabilisation have been widely used to construct homes at acceptable cost. Various public and private buildings have been constructed using soil stabilisation technology and ferrocement roofing. The following sections describe some successful projects.

3.1.1. El Haj Yousuf Model School

The first wide-scale application of the production and use of stabilised soil building blocks technology was in the construction of El Haj Yousuf model school which was funded by UNESCO.

Figure 12. Haj Yousuf Model School

This project incorporated many research findings in the field of low cost buildings; such as foundations of expansive clays, use of special stabilised soil tiles for floors, stabilised soil building blocks for wall construction, corrugated kenaf fibre reinforced sheets for roofing, and vaulted ferro-cement roofing.

3.1.2. Reconstruction of Dongola

After the 1998 floods which destroyed most of Dongola town, stabilised soil building blocks and ferro-cement roofing were introduced to the area as an alternative low cost housing technology. More than 30 block-making machines were employed in the construction of more than 20km length of walling and 10 houses. More than 300 builders and stabilised block producers were trained and employed in other construction projects using the same technology.

Figure 13. Dongola reconstruction

3.1.3. University of Dongola staff housing

The reconstruction project at Dongola attracted the attention of the management of Dongola University which decided to use soil stabilisation technology and ferro-cement roofing to build eight senior staff houses. The local soil together with a mixture of fine mud stone and some addition of cement was used to produce stabilised soil building blocks resulting in substantial cost reductions.

Figure 14. Dongola reconstruction

3.1.4. Bejrawia tourist village

A tourist compound was constructed of high quality stabilised soil building blocks and ferrocement roofing. A first class finish was used with timber doors and windows and air conditioned rooms. Externally the walls were left fair-faced and the roof was finished in a lime-sand-cement screed for waterproofing and heat insulation.

3.1.5. Dinder National Park tourist village

A tourist village was designed and executed at Dinder National Park using stabilised soil building blocks and ferro-cement roof both vaulted and conical. The black cotton soil was treated for the production of stabilised soil building blocks. Special consideration was given to the construction of foundations as the soil in the area is expansive.

Figure 15. Dinder Tourist Village

3.1.6. Police Staff Housing-Abu Seed, Omdurman

Twelve houses forming one building block were constructed using stabilised soil building blocks and ferro-cement roofing. Each house has two bedrooms, a verandah, kitchen, toilet and bathroom in an enclosed area of 15m by 15m (225m^2 total plot area). Good quality blocks were produced using ground mud stone mixed with sand, cement and water. The total cost of the project came in at less that 50% of a similar project built in fired clay bricks, mud mortar and Libyan type roofs.

Figure 16. Police Housing - Omdurman

3.1.7. Holm English School

A private school for boys and girls, designed and constructed in stabilised soil building blocks and roofed with reinforced concrete for the ground floor, and vaulted ferro-cement roofing for the first floor. An assembly hall spanning 10m by 20m was roofed in vaulted ferro-cement at the first floor. This project is one of the biggest projects executed using this technology and consisted of about 40 classrooms, offices, a library, staff housing and related facilities.

Figure 17. Holm English School

3.1.8. Private homes

Many private homes (more than ten houses) were constructed in Khartoum State using stabilised soil building blocks and vaulted ferro-cement roofing. Good quality homes were produced at a reasonable cost. This technology is widely accepted by the public.

4. Discussion

The following aspects outline some basic parameters for accessing improved construction materials and technologies:

- Economical value in terms of materials, labour, equipment and maintenance.
- Engineering evaluation.
- Structural properties
- Environmental evaluation
- Thermo-physical properties
- Aesthetical value
- Sound insulation
- Weathering

5. Achieving low cost buildings

To realise and maintain adequate access to low cost buildings, we need to consider the following basic requirements:

1. Planning and needs assessment
2. Use of local building materials
3. Building research
4. Capacity building
5. Standards and specifications.

6. Summary and conclusions

The paper concludes that substantial efforts have been made towards improvement and promotion of local building materials since 50 years ago by the national research institutions. Search programme included areas of building materials, techniques, building design, and planning layout of dwellings. These efforts were part of the project Shelter and Habitat in the Sudan, which covers all aspects of low cost buildings.

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CHAPTER 2

2.1 Recovering and recycling materials from demolition debris

Recycled aggregate (RA) is hard inert material mostly construction and demolition waste (C&D), C&D waste can be broken concrete and bricks, excavated materials from foundation works, or broken-up road surfaces arising from road maintenance works. It should be regarded as an important resource in terms of energy savings and environmental conservation. In the western world, around two thirds of C&D is recycled, mainly as road base and backfill.

In recent years, to better sustain the environment protection, different ways to manage C&D waste have been investigated. In doing so, apart from road embankments another use has been proposed for the recovery, processing and sorting of the demolished concrete. In practice, it can be demonstrated that it is possible to produce and certify recycled aggregates, suitable for use as concrete (RAC).

Figure 18. Typical plant for recovery and rehabilitation of C&D waste
Source: Pescale Co. Italy – ROSE platform plant

Objectives

For six years, ICS has been promoting a positive attitude to the correct use of RA and RAC, through the organisation of workshops, training courses and expert group meetings, with the aim of producing low cost housing from affordable building materials. Based on this experience an extended-term programme is being established to:

a) expose young engineers and technicians to basic and advanced workshops and training courses, dealing with recycled aggregate and concrete issues, organised at ICS premises and other international institutions;
b) encourage the development of bilateral and multilateral projects, aiming at the certified production of RA and RAC, by the adoption of the appropriate recovery, rehabilitation and recycling technologies and manufacturing plants;
c) support, by direct and indirect funding, projects that may provide data for long term performance of RA and RAC.

Figure 19. Stockpiling of crushed C&D debris before being sieved by size
(Source: Pescale Co., ROSE platform plant)

Public perception

RA are considered as being derived from waste - C&D waste of inferior quality. The public is reluctant to accept use of RAC for private buildings and public institutions must promote its use in order to demonstrate the long term reliability of RAC and it full equivalence with Normal Aggregate Concrete (NAC).

From the government's perspective, the cost of setting-up and operating facilities to produce RA, as a means to reduce the land-fill disposal of C&D waste, compares favourably with the cost of providing the traditional land-fill facilities. Furthermore, both the land-filling capacity of a territory and the excavation of natural aggregates will be exhausted in the future, which should encourage the production and use of high quality RAC. These problems will be solved by the certified production and commercialisation of RA and RAC.

This will only be achieved through the development of appropriate technologies based on large R&D programmes, regardless of where in the world this development takes place. It is obvious that R&D processes will not move at the same pace in developing, as in developed countries, but it is in the former that environmental and housing needs will be more crucial.

Performance record

Reclaimed concrete material (RCM) can be used as coarse and fine aggregate in Portland cement concrete (PCC). However, concrete incorporating more than about 10-20% of fine RCM aggregates can suffer from reduction in quality because of the large amount of water required to maintain adequate workability of the concrete mix.

RCM has been accepted by many jurisdictions and is covered by conventional aggregate specifications and by several highway agency specifications,[5] including those in the USA.[6] For large projects and/or projects where suitable quality aggregate is not readily available, site-processed RCM can be significantly cheaper than new aggregate hauled to the site.

2.2 Material processing requirements

[5] G.U. Italia – Norme Tecniche per le Costruzioni – Cap- 11
[6] Collins, R. J. and S. K. Ciesielski. *Recycling and Use of Waste Materials and By-Products in Highway Construction,* National Cooperative Highway Research Program Synthesis of Highway Practice 199, Transportation Research Board, Washington, 1994.

2.2.1 *Material handling*

When RCM is collected from different sources or types of concrete, it should be blended with other aggregates or separately processed and placed in separate stockpiles to ensure uniformity of RCM aggregate properties. Crushing and screening is required to produce aggregate within the limits for concrete mix gradation.

The following lists the EU norms for aggregates.

EN 12620	Aggregates for concrete
EN 13043	Aggregates for bituminous mixtures and surface treatment for roads, airfields and other trafficked areas
EN 13242	Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction
EN 13450	Aggregates for railway ballast
EN 13055	Lightweight aggregates
EN 13139	Aggregates for mortars
EN 13383	Armourstone

2.2.2 *Quality control*

Levels of impurities, such as sulphate and chloride ions, alkali-reactive aggregate and freeze-thaw expansion of large aggregate that can result in a breakdown of the concrete causing D-cracking in concrete pavements, must be controlled to ensure that the finished concrete has consistent strength and durability.[2,3] D-cracks are closely spaced cracks parallel to transverse and longitudinal joints that multiply outward to the centre of the pavement panel. These cracks typically start in the saturated aggregate at the base of the pavement and progress upward. It has been recommended that the degree of contamination and potential reactivity of RCM aggregates should not exceed the limits permitted for virgin aggregates. [4]

2.3 Engineering properties

Some of the engineering properties that are of particular interest when RCM is used in PCC applications include gradation, particle shape, specific gravity, absorption, moisture content, durability and permeability.

Figure 20. Raw material

Samples of demolition debris, rich in brick and tile fragments, are not very suitable for new concrete production, but can be used for road construction. This kind of material should be tested for the following properties (Eng. Bressi – ANPAR, Italy)

a) *Gradation:* recycled concrete material should be crushed and screened to produce aggregate that satisfies the AASHTO M6[5] and M80 [6] gradation requirements for PCC. With appropriate adjustments, a plant can produce any desired gradation. Crushed fine aggregates (minus 4.75 mm (No.4 sieve)) are generally not used or are blended with natural sand.

b) *Shape*: Processed RCM, being 100% crushed material, is highly angular in shape. While this shape assists in increasing the strength of the mix, it can reduce its workability.
c) *Specific Gravity*: The specific gravity of processed coarse RCM aggregate ranges from 2.0 to 2.5, which is slightly lower than that for virgin aggregates. This is primarily due to the adhesion of mortar to virgin aggregate particles. The differences become more pronounced with decreasing particle size. The specific gravity of processed RCM fines is in the range of 2.0 to 2.3 [7].
d) *Absorption*: RCM aggregates can be expected to have higher absorption values than virgin aggregates. High absorption is particularly noticeable in crushed fine material (minus 4.75 mm (No.4) sieve) from air-entrained concrete. Absorption values for fine-grained RCM generally range from 4-8% (compared with 2% or less for fine virgin concrete aggregates). [7] If not accounted for in mix design, higher absorption values could adversely impact concrete workability.
e) *Moisture Content*: the in-situ stockpile moisture content for processed RCM is typically the same as that for conventional granular material.

Engineering properties of aggregates recovered from C&D waste for concrete applications are controlled with the same conventional procedures applied to natural aggregates. (Eng. Baratono – Italian Ministry of Infrastructures)

f) *Durability*: coarse-grained RCM typically exhibits good soundness characteristics and abrasion resistance. Durability and soundness properties of processed RCM are similar to those of the virgin aggregates incorporated in the concrete and generally satisfy specification requirements for concrete aggregates. [2]
g) *Permeability*: coarse-grained RCM is free draining (more permeable than conventional granular material due to lower fines content).

Some of the properties of concrete mixes containing RCM that are of interest include strength characteristics, workability, resistance to freeze-thaw, deleterious substances, alkali-aggregate reactivity, and corrosivity.

Figure 21. Materials' Properties

h) *Strength Characteristics*: in RCM mixes, compressive strength can be reduced up to 25% compared to mixes with conventional aggregates, with up to 30% improvement in the damping capacity, and higher amounts of drying shrinkage and creep. [8] For a given compressive strength (at 28 days), both the static and dynamic moduli of elasticity for recycled-aggregate concrete are significantly lower (up to 40 percent) than those for concrete containing virgin aggregate. [9,10] Concrete mixes incorporating coarse RCM aggregates generally can be expected to develop about 10% lower flexural strength at equal water/cement ratio and slump than conventional aggregates.

i) *Workability*: if fine RCM aggregates are used, concrete workability decreases (due to the high absorption and angularity of crushed RCM fines) and concrete flexural strength is reduced by 10-20%. [11]
j) *Resistance to Freeze-Thaw*: concrete incorporating RCM aggregates has good resistance to freeze-thaw exposure provided a suitable air void system is present in the mortar phase of the concrete containing RCM aggregate.
k) *Deleterious Substances*: chlorides may be present in RCM as a result of many years of de-icing salt application on old pavement. High levels of chloride in the recycled aggregate can induce corrosion of reinforcing steel embedded in a new concrete. However, the quantity of chloride typically found in old concrete pavement is below critical threshold values.[12] A threshold value of 2.4 kg/m^3 (4lbs/yd^3) is recommended by the American Concrete Pavement Association as a threshold to trigger the removal and replacement of concrete bridge decks due to corrosion potential. [7,13] Recycled concrete material may also contain coarse and/or fine aggregates that are susceptible to alkali-silica reaction. [9,13]

Figure 22. Tests on materials –About 30 tests are applied to qualify the aggregates obtained by crushing-sieving-sorting C&D waste. (Eng. Baratono – Italian Ministry of Infrastructures).

2.4 Design considerations

2.4.1 Mix Design

Crushed RCM is classified as a conventional coarse aggregate for PCC mixtures by AASHTO M80. Coarse aggregates should conform to the grading requirements outlined in AASHTO M43 [14] for the grading specified. AASHTO M6 provides the physical properties and grading requirements for concrete fine aggregate. [15] Prior to use, trial batches should be prepared according to ACI 211 procedures [16] and necessary mix adjustments made to ensure that the specified requirements are attained.

Special care is required when incorporating RCM fines to avoid dramatic reductions in concrete workability, strength and finish. Blending RCM fines with natural sand at substitution rates of 10-20% has resulted in satisfactory performance. Often, several trial mixes are required to generate sufficient data to identify the optimum substitution rate.

Due to their high absorption, pre-wetting of RCM aggregates is important. Aggregates that are not saturated will absorb water from the concrete mix.

In addition to satisfying the requirements of AASHTO M43 and M6, consideration must be given to sulphate and chloride contamination of RCM aggregates. Chloride contamination is often due to the application of de-icing salts (on pavements and sidewalks). High concentrations of chloride ions can result in corrosion of reinforcing steel. ACI 201.2R, 'Guide to Durable Concrete,' [17] provides guidance on the limits of such contaminants for various service conditions.

Where sulphate attack is of concern, the potential for deterioration should be evaluated by the ASTM C452 sulphate expansion test. [18] Sulphate-resistant cement such as Type II or V can be used, if necessary. Where alkali-silica reactivity is of concern, the potential for deterioration should be evaluated by the ASTM C289 test. [19] Low-alkali Type II cement can be used if necessary.

For reinforced concrete pavement construction or plain jointed pavements without load transfer dowels, it is important to ensure that the top size coarse aggregate is sufficiently large (typically 40mm) to provide adequate interlock across joints and cracks.

2.5 Construction procedures

The same equipment and procedures used for concrete containing conventional aggregate may be used to batch, mix, transport, place and finish concrete containing processed RCM aggregates. However, additional care and some minor changes are necessary to avoid potential problems.

2.5.1 Material handling and storage

The same methods and equipment used to store or stockpile conventional aggregates are applicable to RCM.

It is important to monitor the moisture content of RCM aggregates in stockpiles to permit determinations of the mix water requirements. Sprinkling stockpiles to keep RCM aggregates saturated is an effective method of minimising their potential to absorb moisture from the concrete mix.

2.5.2 Mixing, placing, compacting and quality control

The same methods and equipment can be used to mix, place and compact RCM concrete mixes and conventional concrete. Slip forming and finishing concrete made with RCM aggregates is improved by reducing or eliminating the RCM fines content in favour of natural sand. The same quality-control procedures for conventional Portland cement concrete pavement are required for Portland cement concrete incorporating RCM aggregates.

The slump, air content and temperature of the plastic concrete should be monitored at the time of placement, and compressive strength cylinders cast for compressive strength determinations in accordance with the ASTM C39 [20] procedure. Flexural strength can be determined using flexural strength prisms (ASTM C78) [21] or by splitting tensile tests (ASTM C496) [22] on cylinders. Due to the sensitivity of concrete pavement performance and durability to water-cement ratio, and the potential variability in RCM gradation, specific gravity and absorption, particular attention should be given to these aggregate properties when using RCM in concrete pavement mixtures, and appropriate adjustments to the quantity of mixing water completed during concrete production.

2.6 Unresolved issues

There is a need to obtain long-term performance and life-cycle cost data for concrete made with processed RCM aggregates to assess its durability, performance and expected service life.

Limits on chloride and sulphate contents of concrete materials are well established. However, further investigation is needed concerning the effect of other impurities that RCM may contain (other than chloride and sulphate) such as wood, asphalt, and earth on concrete performance. Also, there is a need for guidance regarding the monitoring and restriction of impurities in RCM.

Further, there is a need to determine whether alkali-silica reactive or D-cracked concrete can be recycled as aggregate and to develop appropriate specifications for the use of such materials.

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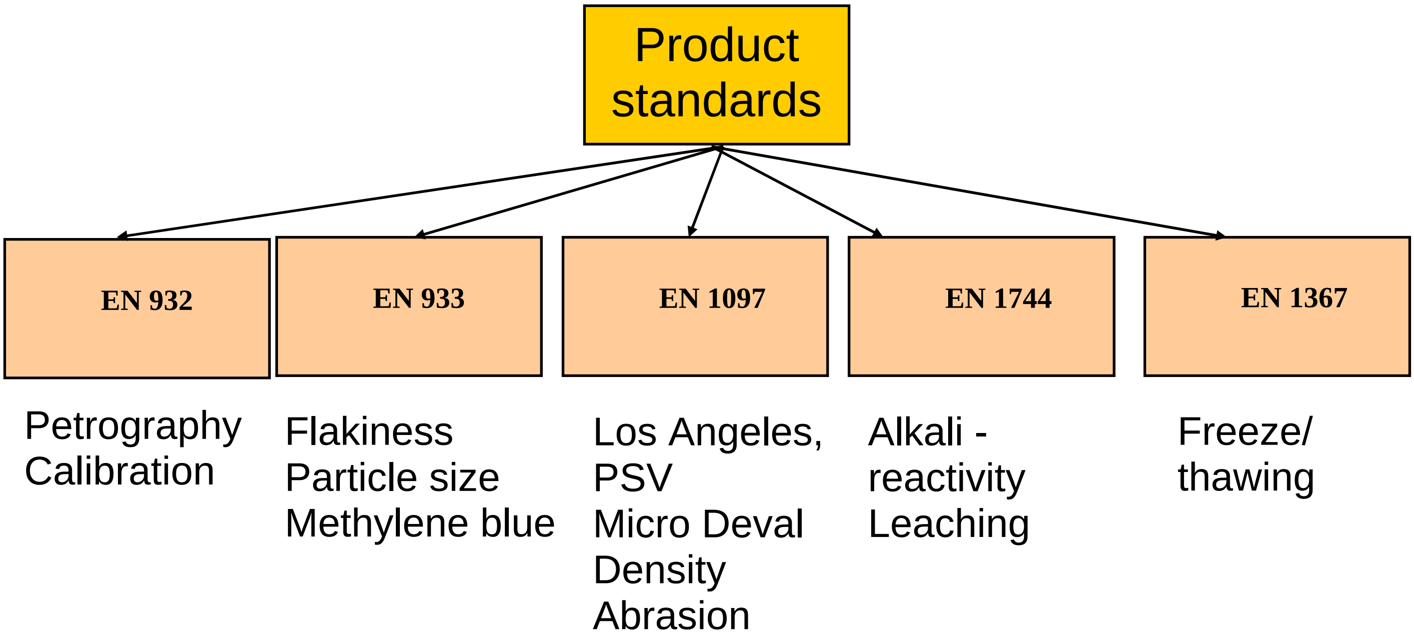

Figure 23. Different product's standards

Figure 24. Minimum rest frequencies for general properties

Property		Clause	Notes/ references	Test method	Minimum test frequency
1	Grading	4.3.1 4.3.6		EN 933-1 EN 933-10	1 per week
2	Shape of coarse aggregate	4.4	Test frequency applies to crushed aggregates. Test frequency for uncrushed gravel depends on the source and may be reduced	EN 933-3 EN 933-4	1 per month
3	Fines content	4.6		EN 933-1	1 per week
4	Fines quality	4.6	Only when required in accordance with the conditions specified in annex D.	EN 933-8 EN 933-9	1 per week
5	Particle density and water absorption	5.5		EN 1097-6	1 per year
6	Alkali-silica reactivity	5.7.3		[a]	When required and in case of doubt
7	Petrographic description	8.1		EN 932-3	1 per 3 years
8	Dangerous substances [b] In particular: Emission of radioactivity Release of heavy metals Release of polyaromatic carbons	H.3.3 H.4	[b]	[b]	When required and in case of doubt

[a] In accordance with the provisions valid in the place of use.
[b] Unless otherwise specified, only when necessary for CE marking purposes (see annex ZA).

Figure 25. Minimum test frequencies for properties specific to end use

Minimum test frequencies for properties specific to end use

Property		Clause	Notes/ references	Test method	Minimum test frequency
1	Resistance to fragmentation	5.2	For high strength concrete	EN 1097-2	2 per year
2	Resistance to wear	5.3	Aggregates for surface courses only	EN 1097-1	1 per 2 years
3	Polishing resistance	5.4	Aggregates for surface courses only	EN 1097-8	1 per 2 years
4	Resistance to surface abrasion	5.4.2	Aggregates for surface courses only	EN 1097-8:1999, annex A	1 per 2 years
5	Resistance to abrasion from studded tyres	5.4.3	Only in regions were studded tyres are used.	EN 1097-9	1 per 2 years
6	Freezing and thawing	5.7.1		EN 1367-1 or EN 1367-2	1 per 2 years
7	Chloride content	6.2	For marine aggregates see Table H.3	EN 1744-1:1998, clause 7	1 per 2 years
8	Calcium carbonate content	6.5	Fine aggregate for concrete surface courses	EN 1744-1:1998, 12.3 EN 196-21:1989. clause 5	1 per 2 years

Figure 26. Minimum test frequencies for properties appropriate to aggregates from particular sources

Property		Clause	Notes/ references	Test method	Minimum test frequency
1	Shell content	4.5	Coarse aggregates of marine origin	EN 933-7	1 per year
2	Volume stability - Drying shrinkage	5.7.2		EN 1367-4	1 per 5 years
3	Chloride content	6.2	Aggregates of marine origin	EN 1744-1:1998, Clause 7	1 per week
4	Sulfur containing compounds	6.3	Blastfurnace slag only Aggregates other than air-cooled blastfurnace slag	EN 1744-1:1998, Clause 12 EN 1744-1:1998, Clause 12	2 per year 1 per year
5	Organic substances: - humus content - fulvo acid (when indicated humus content is high) - comparative strength test - stiffening time - lightweight organic contaminators	6.4.1		 EN 1744-1:1998, 15.1 EN 1744-1:1998, 15.2 EN 1744-1:1998, 15.3 EN 1744-1:1998, 14.2	 1 per year 1 per year 1 per year 2 per year
6	Dicalcium silicate disintegration	6.4.2.1	Blastfurnace slag only	EN 1744-1:1998, 19.1	2 per year
7	Iron disintegration	6.4.2.2	Blastfurnace slag only	EN 1744-1:1998, 19.2	2 per year

CHAPTER 3

A CRITICAL OVERVIEW OF CONCRETE DEMOLITION AND RECOVERY

Abstract

Demolition, processing and recycling of the materials are often analysed separately and not considered as a chain-process. 'High quality' recycled material does not always correspond to a product with the highest value, but rather the most feasible product in a specific project or region. It is by analysing the whole disposal and supply-chain, including the substituted material, that the best effects of recycling can be achieved. Demolition is most often the first, and not the last phase of a building's life. There is almost always an existing building where a new one is to be built and some materials transfer should be considered.

It is well known that environmental issues are a growing concern in the world. There are a number of ways to include environmental issues when planning demolition and recycling activities. The market for recycled materials as integrated demolition and waste management is outlined in this chapter. Analyses of what happened in Kosovo and of the potential market for demolition materials in Hong Kong are presented as case studies.

3.1 Introduction

Since Agenda 21, the Rio Declaration on the Environment and Development, was launched in 1992 sustainable development has been a key issue for modern society. The recycling of Construction and Demolition (C&D) waste has emerged as a socioeconomic priority within the European Union and a considerable amount of research and development (R&D) has taken place within the frame of RILEM (the international union of testing and research laboratories for materials and structures).

In 1981 European and Japanese members of RILEM took the initiative to complete the first RILEM technical committee on the demolition and recycling of concrete, including several material research projects in this field. The research of the RILEM technical committees on recycling was published in proceedings from three international symposia held by RILEM in Antwerp, Belgium 1985 [1], in Tokyo, Japan, 1988 [2] and in Odensee, Denmark, 1993 [3].

In 2000 a report of RILEM Technical Committee 165-SRM on the state-of-the-art in Sustainable Raw Materials edited by C.F. Hendriks and H.S. Pietersen, was published [4].

In parallel with the work of RILEM, recycling of concrete has emerged in the USA. For example, the Federal Highway Association has implemented recycling of concrete pavements in the reconstruction of highways. The American Concrete Institute (ACI) has also done work on the recycling of concrete. Some years ago, ACI realised that although concrete is an environmentally friendly material, Portland cement is the critical component of modern-day concrete. To address this issue and the relationship between sustainable development and concrete technology, the ACI Board of Direction, in 2000, formed a Task Group on sustainable development and concrete technology. Its mission was to encourage the development and application of environmentally friendly, sustainable concrete materials, design and construction. One of the most important issues related to sustainability was the use of recycled aggregate [5].

Fortunately, some ACI members were sufficiently far-sighted in 1985 to organise Committee 555 – Concrete with Recycled Materials. In 2001 the committee submitted a report 'Removal and Reuse of Hardened Concrete' [6], which became the basis for future work by ACI on the sustainability and recycling of concrete. At the ACI Spring Conference 2003 the ACI Committee 555 arranged a seminar on recycling of building materials. The papers were published in a special ACI publication *Recycling Concrete and Other Materials for Sustainable development, ACI Committee 555* [7].

3.2 The need to minimise waste

In all communities it has been common practice to retrieve valuable materials from waste, e.g. metals and building materials. After some decades in the last century of an increasing 'use-and-throw-away' philosophy it was recognised that we cannot continue this uninhibited use of natural resources and pollution of the world with waste. It is necessary for habits to change and former practices common within the building and construction industry, as well as in other industries, households, etc. to be revised.

In many countries, industrial and other C&D waste is considered harmless, inert waste, which does not give rise to problems. However, C&D waste consists of huge amounts of materials that can cause problems and encourage the illegal dumping of other kinds of waste. Whether C&D waste originates from clearing up operations after natural disasters or from human-controlled activities, the utilisation of such waste by recycling can provide opportunities for saving energy, time, resources and money [8, 9, 10]. Furthermore, recycling and controlled management of C&D waste results in lower land usage and more efficient ways of handling other kinds of waste.

3.3 C&D waste streams in the EU and USA

A large proportion of C&D waste derives from demolition, rehabilitation and new construction following normal development, as well as from natural and technological disasters. For example, the production of building materials and goods involves surplus ready-mixed concrete, concrete elements, articles made of wood, etc., which can be classified as industrial waste.

In the European Union, whose population in 2000 was approximately 370 million, it is estimated that the annual generation of C&D waste is 200-300 million tons equivalent to some 0.5-1 ton per capita per year [8, 11]. Precise figures on recycling do not exist in every EU member country. An EU study calculated that an average of 28% of all C&D waste was recycled in the late 1990s [12]. In the Netherlands 95% of all C&D waste is recycled and in Denmark 90% is recycled.

Most EU member countries have established goals for recycling that range from 50% to 90% of their C&D waste production, in order to substitute for natural resources such as timber and quarried material and steel. Recycled materials are generally less expensive than natural materials, and in Germany, Holland and Denmark recycling is less costly than disposal [8, 11, 12].

The C&D waste streams in the USA were assessed by Robert H. Brickner in 2002 [13]. It is estimated that the amount of C&D waste in 2002 was 250–300 million tons per year and that 20–30% is recovered for recycling (1996 figures).

According to Metha [14] the global concrete industry uses approximately 10 billion tonnes of sand and rock each year and more than 1 billion tonnes of C&D waste is generated each year.

3.4 Challenges of recycling

According to the EU Waste Directive on Prevention and Reduction of Waste the key issues are:
-Recycling, Reuse and Recovery (the 3Rs) of waste
-Management and planning of C&D waste handling
-'Polluter-pays' principle.

This section focuses on C&D waste which has a high recycling potential because the majority of it consists of masonry, concrete and steel. In Europe up to around 90% of C&D waste consists of concrete and masonry. Buildings erected before the middle of the last century were mainly constructed of masonry, and buildings in the second half of the 1900s were mainly constructed of concrete. The situation in the USA is probably the same, at least for the major infrastructures and public buildings.

Based on a global overview [14] it is estimated that the potential for recycling is approximately 50%, which is equal to approximately 500 million tons, which is equal to 5% of the global consumption of sand and rock.

At present, only very limited amounts of C&D waste are recycled as high-value materials, such as recycled aggregates in new concrete. The majority of such waste is disposed of or used as fill. Since the amounts of C&D waste are constantly increasing, there are many reasons for focusing on methods that promote an increase in the recycling of C&D waste (dumping fees in Europe and the USA are constantly increasing). Present results in Europe show very favourable recycling possibilities in this field.

From a purely economic point of view the recycling of building waste is only attractive when the recycled product is competitive with natural resources in terms of cost and quality. Recycled materials will normally be competitive where there is a shortage of both raw materials and suitable deposit sites.

With the use of recycled materials, economic savings in the transportation of building waste and raw materials can be achieved. In larger recycling projects, such as urban development, renovation of motorways, or clearing of war-disaster-related damage, total project costs will be dominated by transportation costs. These transportation costs involve the removal of demolition products and the supply of new building materials. In these cases the use of recycled materials is very attractive.

The prospects for systematic recycling of C&D rubble in various parts of the world have been analysed [8, 15]. In order of importance, the three main factors affecting recycling of C&D waste are:
-population size and density,

-occurrence of and access to natural raw materials, and
-level of industrialisation.

3.5 Opportunities for recycling

In order to meet the challenges of recycling, it is necessary that all opportunities, barriers and obstacles are identified and considered. The opportunities must be exploited, can include recycling of concrete and masonry into aggregate, substituting natural materials:
- aggregate bound in concrete
- unbound sub-base and base materials.

The opportunities for the production of concrete from recycled concrete are generally described in the ACI 555 report [6]. The recycling of concrete waste in a global perspective is described by Torben C. Hansen and Erik K. Lauritzen [8], Mats Torring [16] and Mats Torring and Erik K. Lauritzen [17].

The overcoming of these barriers and obstacles must be planned and carried out through a long-term action plan combined with adequate R&D. Implementation of the necessary legal, economic and technical instruments requires that initiatives involving legislation and regulations be undertaken.

3.5.1 Economy

The choice of recycled or natural materials depends on price and quality. The quality of concrete made using recycled aggregates can be the same as that of concrete made with natural aggregates, but recycled concrete aggregates are regarded with suspicion. Hence, recycled concrete materials will only be preferred where their price is considerably lower than that for natural materials, even when the recycled aggregates meet all the required specifications.

Introducing economic instruments that encourage recycling and the use of recycled materials can help to overcome the economic barriers. For example, several countries have introduced special taxes and fees favouring recycling. In 1986 the Danish government introduced a tax on waste that is not recycled but disposed of at landfill sites. This tax is currently around €50/ton of waste disposed of in landfill.

The major issues related to the cost-benefit for society are:
- -willingness to pay for the impact on the environment
- -willingness to accept the impact on the environment.

3.5.2 Policies and strategies

C&D waste must be regarded as a specific individual type of waste associated with the building and construction industry. It is important that the management and handling of waste is carried out by the industry itself. The building and construction industry is generally relatively conservative, and changes in normal procedures often take time and need long-term policies and strategies.

One of the most important barriers is the different interest in building waste. Usually it is the environment politicians, departments and public offices that prepare the policies and issues concerning waste recycling and reduction, while the building and construction industry is controlled by laws, departments and offices concerned with housing, construction and public works. To co-ordinate the interests of all parties, particularly with respect to the implementation of cleaner technologies in industry, it is necessary that long-term policies and strategies should be prepared, implemented and followed up by adequate legislation and regulation at all levels - national, regional and local.

3.5.3 Certification of recycled materials

Demolition and crushing techniques for the production of recycled materials are well established and based on existing technologies. However, some changes to the demolition process, compared with traditional demolition, are required as described below. Even when recycled materials fulfil current standards for natural materials, and even when their price is competitive with the price of natural materials, certain barriers still exist.

Owing to tradition and psychological barriers the general attitude towards recycling in the building and construction industry is largely against the utilisation of recycled materials. Therefore, it is of great importance that recycled materials are officially certified and accepted by all parties in the building and construction industry. In June 1994 RILEM published recommendations for concrete made from recycled aggregate [18]. A review of international classification and certification of use of recycled C&D waste is presented by Henrichsen [11].

It is recommended that considerable emphasis be placed on specifying the areas of utilisation and quality standards for recycled materials. These must be in accordance with local demand in order to improve confidence in recycled materials and solve any problems in terms of responsibility for using such materials.

3.5.4 Planning demolition projects

A necessary condition for the recycling of building waste is careful sorting of the waste. Waste from new constructions and rehabilitation is sorted either at the production site or at a special treatment site. This separation into materials categories is fairly simple.

The sorting of waste from demolition, however, is a more complicated process. Demolition until recently has been regarded a low technology process. Rapid demolition and disposal of structures were the main aims of contractors. Special measures to separate the different types of materials were not possible, owing to the time factor, and also were not desirable.

Optimal handling and recycling of C&D waste depends on the materials being sorted in situ and in co-ordination with the demolition process, using demolition technologies and methods as described in the ACI 555 report [6]. This requires alteration to the traditional methods of demolition and introduction of selective demolition. It also requires that before and during the demolition process an effective sorting of the different materials categories is carried out, thereby preventing any mix of materials leading to pollution, for instance, of recyclable concrete/masonry rubble by wood, paper, cardboard, plastics, etc. Since selective demolition takes more time than traditional demolition, detailed planning is considered mandatory.

It is recommended that demolition projects should be planned and controlled in detail, in the same way as all other building and construction projects, to ensure selective demolition and correct handling of the demolition waste.

3.5.5 Education and information

The most important means to identify and exploit the opportunities and overcome barriers and obstacles is education and information. It is necessary that the message about and understanding of recycling should be discussed at technical universities, and by private enterprise and public servants.

3.6 Integrated resource management

In order to achieve the maximum benefit from recycling a management system must be established on a project basis in relation to a specific construction project, e.g. an urban development master plan, or on a permanent basis in relation to a long-term municipal and C&D waste management system.

An integrated resource management system comprises environmentally and economically balanced management of the following elements:
-demolition (selective demolition)
-recycling, reuse recovery
-handling of hazardous C&D waste materials and non-recyclable materials
-transportation
-substituting (saving) natural resources.

An assumption in the success of an integrated resource management system is that effective co-operation between all stakeholders/decision makers has been established in order to avoid conflicts of interest. Conflicts between recycling companies and raw materials companies, for example, could prevent initiatives aimed at recycling.

Integrated resource management can be implemented according to the normal routines of project management in the construction industry, e.g.:
-Final Report that is a descriptive document on the development and findings of the specific work packages and the project in general.
-National policies (legal and fiscal instruments)
-Regional strategies (control of C&D streams, stationary or mobile recycling plants)
-Concepts (high versus low value recycling)
-Feasibility studies (specific proposals for recycling)
-Computer optimisation (waste-resource streams and economic models)
-Master planning
-Design
-Supervision
-Quality and environmental management.

The opportunities for recycling and integrated resource management depend on the size and the time frame of the project.

In bigger projects, such as

- development of old industry sites, hospitals, airports, etc.
- reconstruction after disasters and wars
- urban renewal and development of cities,

where the recycling of concrete and other building materials must be considered carefully.

3.7 Global visions

The construction industry must aim at durability and sustainability as described by Metha [14]. A holistic life cycle based approach is recommended in order to reduce the environmental impact. Further, the resource efficiency of the concrete industry would increase by a factor of 5 if the service life of most structures built today were 250 years instead of the conventional 50.

Looking at recycling, it is estimated - based on a global C&D waste production of 1 billion tons per year - that potentially 50% should be recycled and could substitute approximately 5% of the global consumption of sand and rocks.

However, there is a long way to go before this level of recycling can be attained in developing countries, where many other environmental problems must be set as priorities. But there is no reason why the industrialised nations cannot begin implementation of integrated resource management systems, aiming of 90% recycling and maximum substitution of natural resources. There is no doubt that results and experience from European R&D can be transferred to other parts of the world and enable natural (primary) raw materials to be replaced by recycled materials, especially in urban renewal and rehabilitation projects.

3.8 Conclusion

The development of technologies for the recycling of concrete and the market for various types of recycled concrete materials has proved the viability and sustainability of recycling concrete. The challenges of recycling are dominated by a very high potential of concrete waste all over the world and a demand for recycled materials in order to substitute natural resources. The opportunities for recycling are based on economics, policies and strategies, certification of recycled materials, planning of demolition projects, and education and information.

The current success of recycling concrete in some European countries is based on integrated resource management. The success of recycling is based on global visions for the implementation of recycling concrete world-wide in order to save environment an natural resources.

3.9 Examples and case histories

3.9.1 The Kosovo project

In June 1999, the hostilities in Kosovo officially ceased and the huge task of reconstructing the province commenced. One of the major challenges was clearing the urban and rural areas of damaged buildings and rubble. It was initially estimated that nearly 10 million tons of demolition waste would be collected and handled.

Based on previous experiences with the recycling of rubble from the demolition of damaged buildings on the former confrontation line in Mostar (Bosnia & Herzegovina from 1995 to 1997), the Danish Ministry of Foreign Affairs (DANIDA) decided to establish a Building waste Management System, comprising demolition of damaged buildings and recycling of building waste materials in Kosovo. A robust mobile crusher and a screening unit that could travel with the demolition teams and process the rubble at recycling depots were needed for this purpose.

During the project in Kosovo, all of the recycled materials produced were sold to both public and private clients. This 100% sales level has only been possible through extensive workshops and seminars demonstrating the use of the recycled gravel for road construction and as engineering fill. The main customers included NATO's forces in Kosovo, which required significant quantities of gravel for their army bases. Also local contractors bought the recycled material for construction of roads.

Testing the recycled material was not possible in Kosovo since its laboratories had been damaged in the hostilities. So the Waste Demolition and Recycling (WDR) organisation managed by DEMEX in Kosovo had to 'export' the gravel for materials testing in neighbouring Macedonia and then translate the results into Albanian for local use. This cumbersome procedure proved worthwhile, as the recycled materials complied with all the

Yugoslav materials specifications for road construction.

Also ownership of the rubble had to be discussed. When it was recognised that WDR was able to turn the rubble into a valuable product, some of the building owners were concerned about 'giving' their rubble away and on numerous occasions WDR had to barter with village leaders.

This project added to the evidence that the recycling of the demolition waste generated from reconstruction activities after disasters and wars is a sustainable solution and an important contribution to waste management during this often difficult and chaotic phase.

3.9.2 The Kai Tak recycling facility in Hong Kong

In 2001 DEMEX designed a recycling facility to be installed at the abandoned Kai Tak airport in Hong Kong until the land was ready for development. The total generation of C&D waste materials forecast for the whole Hong Kong region for the year 2002 was approximately 13.7 million tons. This represented a daily generation rate of approximately 14,000 tons. It was estimated that 30% of the total C&D could be delivered to the recycling plant. The average total of 4,200 tons/day was used for the preliminary detailed design of the Kai Tak recycling facility.

A pilot C&D recycling facility comprised two crushers and two screening units set up in a single process line. Further expansion of the plant capacity would be required to go beyond 3,500 tons/day.

The results of the feasibility study indicated a profitable business opportunity for recycling C&D materials in Hong Kong, with the condition that the land rent was set a zero. Entering the construction aggregates market at 80% of virgin materials prices, it was expected that the Kai Tak C&D facility would turn a healthy profit.

However, the problem was that the political situation in Hong Kong in 2001 was not sufficiently mature for the implementation of a C&D recycling project. In Europe, inhabitants are used to paying for waste collection and treatment of waste. It is evident that the driving forces of recycling are linked to economic instruments, in which waste fees and transportation costs are the most important.

In Hong Kong there has been a tradition of free waste collection for citizens. Therefore, there were no incentives for the construction sector to deliver its waste to the recycling plant, and the overall economy of recycling would not be satisfactory.

This example shows that even though the need for recycling is clearly demonstrated, the political decision and the implementation of the *polluter pays principle* is a fundamental condition for recycling.

3.9.3 European integrated resource management

In August 2003 a major European project on integrated resource management was launched with the objective of developing and demonstrating models and management tools for the rehabilitation of buildings and recycling of building waste materials in urban renewal. The project is being undertaken by 17 participants from 8 EU countries with support from the European Commission. The project was presented by García [19].

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CHAPTER 4

National CASE STUDIES

4.1 Recycling of Demolition Material

Introduction

The company ORMAN for which I worked, is one of the leading companies in Bosnia & Herzegovina and is specialised in demolition works. This case study is based on one of our recent and most important projects – demolition of Sarajka mall/shopping centre. The data in this case study were obtained from our project documentation, plus my own research and estimates.

Project background

Figure 27. Sarajka mall before demolition

Sarajka mall was located in the very centre of Sarajevo, the capital of Bosnia & Herzegovina. It was built during the socialist regime. This regime, as many people from Eastern European countries know well, was famous for its huge concrete box-shaped buildings for housing large numbers of people. Sarajka mall was in the same style. It was mainly constructed of concrete rebar beams, walls, floors and ceilings, stairs, etc. with metal frames and glass windows forming the facade. It was located in a square in the pedestrian area of Sarajevo with many buildings around it, which made it impossible to demolish it using explosives since damage to the neighbouring buildings could be significant. Thus, the investors in the new project decided to demolish it mechanically. The new project design was for a modern business centre.

Demolition process, materials and recycling

During the demolition process two types of materials where recycled – concrete and steel rebars. The total amount of demolition material was 17,035.38 m^3 or 38.443,80 tons.

93% of the structure, i.e. 12,609.09m^3 or 30,261 tons was concrete rebar, which was traditional in buildings in Bosnia from that period. Of that, grained pure concrete without rebar comprised 81% of the total amount of the structure. All of the concrete was thickly rebarred and therefore the amount of extracted steel during demolition was significant – ca 1,513 tons of steel. For the destruction of all construction elements we used heavy equipment, such as pneumatic pulverisers, which grind concrete and cut steel into small pieces, hydraulic hammers, and manual cutters.

Figure 28. Demolition process

At the same time our company was involved in another project to build roads around Sarajevo. The concrete from the mall was ground up and loaded on to trucks that transferred it to the road construction sites. More than 50% of demolition concrete was used for the base course of these roads. The total amount of demolition concrete was 28,730 tons. The company saved significant amounts of money on purchase of material for the base course. Significant amounts of concrete were also used for ground substitution in the field on which it was planned to build a timber factory. The remaining grained concrete was sold off for the construction of access roads to people's houses. We managed to reuse 95% of the demolition concrete, and the remaining 5% went to local landfill.

Another important aspect is that Bosnia & Herzegovina have no proper land fills for the disposal of construction materials; thus if this concrete had not been recycled and reused it would have had to have been disposed of in city dumps.

Figure 29. Demolition process

Another material that was reused and recycled was steel rebar from the concrete construction. The amount of steel (rebar) in the structure was around 12% or 1,513 tons out of the total amount of rebar concrete. All the steel was cut into pieces by pulverisers and loaded on to trucks with magnetic greifers and then transported to a local company, SMB, which trades in steel. SMB had a contract with Mittal Steel, which melts down old steel and creates new material. 98% of extracted steel was recycled, which yielded significant income for my company. There was also a large amount of copper that was reused. The structure contained about 1% of copper in the electrical installations. The wires were manually cut, stripped of their protective rubber and transported to SMB.

The other material in the structure was tin sandwich panels which were on the facade of building. Some panels were used to build containers for storage of tools and to make a roof construction for covering bags of cement and various materials on our sites, but most of these panels could not be reused and had to go to local landfill.
We also recycled some old steel tables, shelves, some elevator equipment and pipes from the heating system.

Conclusion

The recovery index for demolition material was estimated at 90%. These results are good economically and cost effective. We reduced environmental impacts by reducing the amount of space used in existing landfills.

Demolition cost:	116,394.26 €
Landfill cost:	19,714.77 €
Total cost:	**126,109.03 €**
Steel sold:	279,307.69 €
Concrete reused and sold:	49,111.11 €
Copper and other materials sold:	19,692.30 €
TOTAL (earned by recycling):	**212,002.07 €**

Table 1. Demolition costs

4.2 Reuse of demolition bituminous layers of road pavement to construct a new base asphalt pavement

Abstract

Road construction is a field of civil engineering that, more than any other, offers potential for reducing environmental impact and providing significant technical-economic benefits. In terms of just the huge quantities of materials employed in embankment and pavement constructions, there is good opportunity to recycle waste products from industrial processes or demolition of civil buildings.

For many years, in-place and in-plant recycling of road pavement material has been operating. It is an example of cheap regeneration of a structure, that carries no transport or disposal of milled material charges. The demolition material from bituminous layers of aged road pavements in the form of milled particles, usually called RAP (Reclaimed Asphalt Pavement), is used to construct the new base or binder courses for asphalt pavements using a cold stabilisation process, involving cement or bituminous emulsion.

The practice of in-place cold recycling is common in Europe, particularly in countries with good climatic conditions (i.e. Italy and Spain). The mix design, however, has not been perfected and many design aspects have yet to be defined (RAP grading curve, wetting condition, binder quantity and compactive effort), especially in bituminous emulsion stabilisation. It is urgent that there should be more R&D in this area.

What follows summarises the results of an experimental study on the performance of cold recycled asphalt mixtures with bituminous emulsion and cement, highlighting the specificity of the interaction between RAP and the binding phase.

Key words: Reclaimed asphalt pavement (RAP), cold recycling, bituminous emulsions.

Introduction

The recovery of waste material satisfies the most modern entrepreneurial approach, which recommends optimisation of resources, technological innovation and preservation of the territory. In this approach waste material becomes a valuable resource, to be reintroduced into the productive process.

The recycling of road asphalt pavements should be more properly defined ‘reuse’, because the material from the old pavement structure is not transformed, but is reutilised to generate new asphalt concrete.

Recycling removes the two problems - of disposing of the demolition material and finding new mineral aggregates for rebuilding the pavement; the recovery of asphalt concrete from old road pavements to construct the lower layers of the new one, reduces the new mineral aggregate requirement to only the wearing course.

The technique of in situ cold recycling protects the environment, the health of operators and produces actual cost savings. The cold recycling technique enables 100% of the milled material to be recovered. In situ recycling avoids transport of material, with connected benefits in terms of pollution and cost.

Cold recycling of road asphalt pavements

The material to be recycled is RAP (Reclaimed Asphalt Pavement), which consists of mineral aggregate covered with a thin film of bitumen. It is obtained from the grinding to blocks (scarification) or cold milling of the asphalt concrete layers from road pavements.

The process of cold (i.e. ambient temperature) milling, is performed by a milling drum that pulverises the old pavement by striking the course that has to be removed. This process produces varied grade distribution of the granulated material compared with the mineral aggregates in the original mixture. Cold recycling is characterised by the use of bituminous binders in liquid state at ambient temperature, which provides effective and durable binding shortly after application. Bituminous emulsions, i.e. bitumen dispersion in water with the addition of surfactants, have been improved to stabilise the cold recycled asphalt concrete.

The asphalt mix is in the form of minute spherules, ranging from 1-3 metres, in a percentage varying from 50-69% according to the type of emulsion and the required viscosity. In order to avoid the droplets of bitumen flocculating and coalescing, their surface must be covered with an emulsifier, which, by settling at the interface bitumen-water, makes the droplets electrically charged with the same sign, which forces the spread. Different emulsions can be produced through modifications of the bitumens or by adding polymers to the emulsions obtained from natural bitumens.

The properties of RAP are related to the original material. The process by which the RAP is milled, the rotation speed of the milling drum and the forward speed of the recycler influence its quality, determining the final grading distribution. In general, compared to virgin mineral aggregate, RAP has a slight lower specific gravity.

The bitumen covering the aggregates is very friable, subject to ravelling and lacks binding power due to the oxidation processes and the effect of ultraviolet rays as it aged.

Experimental study

Experimentation was carried out in the laboratory to compare the mechanical characteristics of cold-produced mixtures from both recycled and virgin mineral aggregates and check aspects such as binders and curing time.

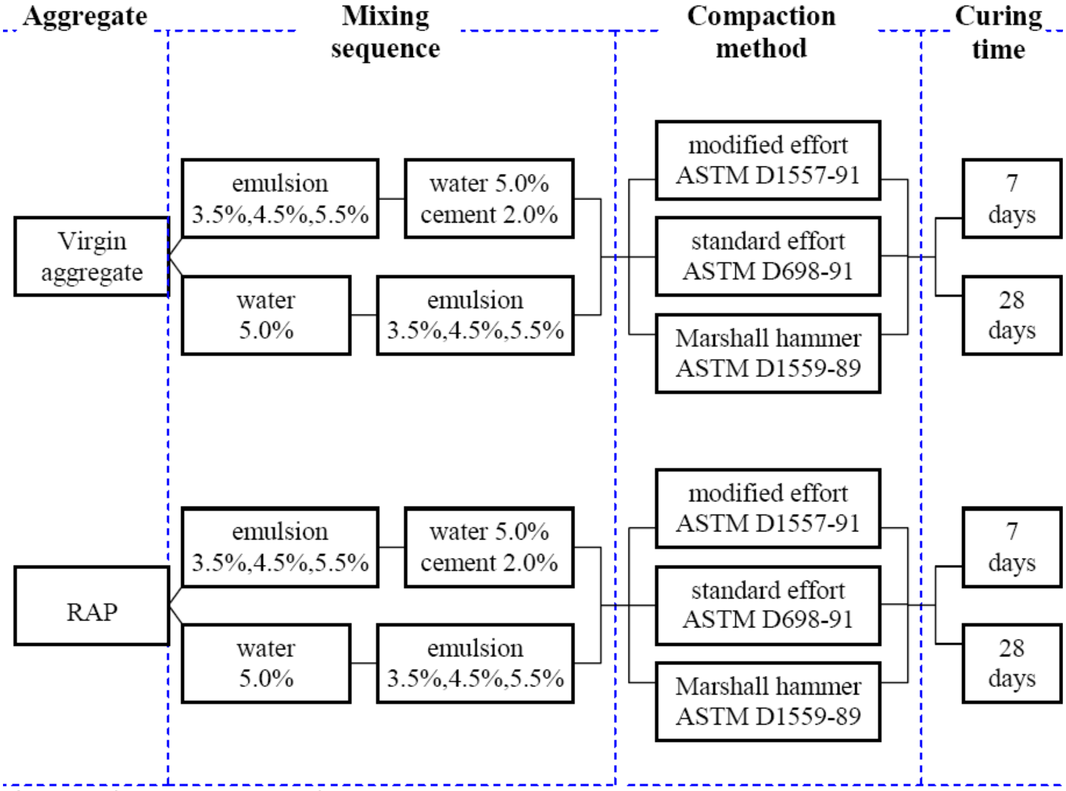


Figure 30. Scheme for samples manufacturing.

Materials

The RAP comes from the milling of wearing and binder courses originally produced from mineral aggregates of 25mm maximum nominal size. The grading distribution of RAP, as well as the distribution of virgin aggregates, is shown in Table 2. It refers to the grading curve for binder courses of cold-recycled asphalt concrete fixed by the recent specification for road works of the Italian Ministry of Public Works [1].

Sieve (UNI)	% Passing
25	100
15	95
10	70
5	53
2	44
0.4	24
0.18	15
0.075	8

Table 2. Aggregate grading curve

The bituminous emulsion used to stabilise the concrete is type CS60B: it is cationic, produced from modified bitumen specifically for cold-recycled asphalt concrete with cement addition. Three different percentages of bituminous emulsion (3.5%; 4.5%; 5.5%) are used either as unique binders or with cement addition, in six different combinations (Figure 29).

The cement percentage was fixed at 2.0% of the RAP dry mass. This percentage is based on previous experience [2,3,4], which point to its technical and economical value. The cement used is pozzolanic, type 32.5.

The water content as an output of the storage-phase and the milling procedure (cooling water for the milling machine) was set at up to 5%, including the moisture content of the material. Water is added to the aggregates either before the emulsion or together with the cement (disguised as slurry).

Mixture manufacture and compacting

The mixing of the components was according to the sequence aggregate-emulsion cement, and compaction occurred within 15 minutes of mixing.

The samples were compacted with different energy, following both the Proctor standard method (ASTM D 698-91) and the Proctor modified method (ASTM D 1557-91). Cylindrical samples of 110.6mm by 116.6mm height were obtained and were cured for 7 and 28 days in the laboratory. These samples were then subjected to a dynamic modulus test (ASTM D 3497-79) and to an unconfined compressive strength test.

Finally, indirect tensile strength tests were carried out on samples produced using the Marshall procedure (ASTM D 1559-89) with the same binding combinations and grading selection, to produce 101.6mm diameter by 63.5±3.2mm height cylinders. Two samples were prepared for each combination of aggregates, binders, compaction energy and curing times; a total of 120 samples (Figure 30). The tests results were taken as the average value of two independent experiments.

All the tests were carried out at ambient temperature (20°C).

Figure 31. Samples in the laboratory

Unconfined compressive strength test

Unconfined compressive strength tests were carried out by applying to the cylindrical sample a 1.0mm/min deformation rate with a 10.0mm overall lowering.

Analysis of the test results shows how the material behaves when it is bound with emulsion and cement, or only with emulsion (Figure 30). The presence of cement characterises the macroscopic differences in specimen collapse. Emulsion alone produces a more ductile behaviour, so that when the sample breaks, the process of splitting is more homogeneous. The addition of cement results in the highest compressive strength values with low emulsion contents; compaction energy end curing time are the same as in previous tests [5]. The two binders need to be distributed precisely in the mixture; during compaction an excess of fluid content (water + bitumen) does not allow optimal density to be achieved.

In case of mixtures of virgin mineral aggregates bound with cement and emulsion, and with long curing time, the influence of the compaction energy on mechanical strength does not essentially change. A shorter curing time produces a higher compaction energy and thus greater strength. The mixtures prepared with RAP and bituminous emulsions are more sensitive to compaction energy, which significantly conditions mechanical performance (Figures 32 and 33).

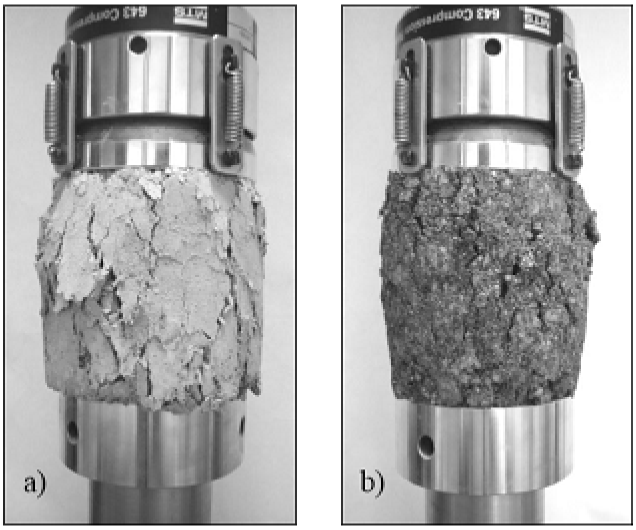
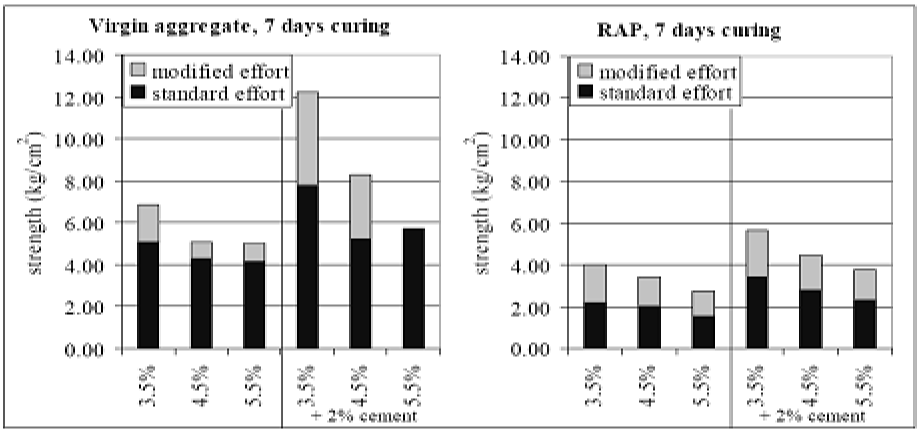


Figure 32. Cold recycled mixtures with RAP and emulsion + cement (a) and emulsion (b)



Unconfined compressive tests on 7 days cured specimens with different efforts.

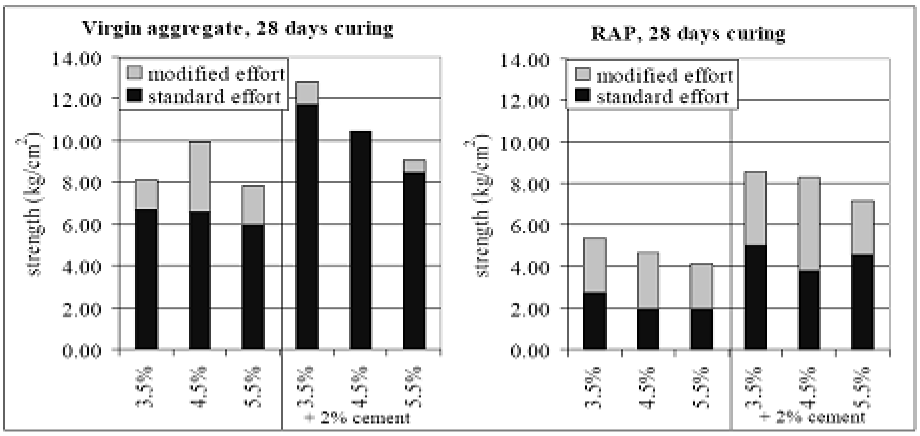


Figure 33. Unconfined compressive tests on 28 days cured specimens with different efforts

In general, compressive strength values obtained with RAP mixtures are lower, compared with similar mixtures prepared with virgin mineral aggregates. This shows that the bitumen, which covers the aggregates of the milled matter, reduces the effectiveness of the bituminous emulsion or that virgin aggregates and RAP, with the same grading distribution, require different water contents to obtain maximum density.

Analysis of the stress-strain diagrams enabled evaluation of maximum strength of the material and the deformation that specimens can tolerate before reaching maximum load. It can be seen that in case of virgin aggregates and RAP mixtures the deformation corresponding to breaking-peak is fairly uniform, about 2-3%. It varies significantly only in the case of mixtures with RAP compacted with Proctor modified effort and cured for 7 days, where the deformation reaches 4-5%.

The biggest deformations were in mixtures prepared with high percentages of bituminous emulsion (5.5%).

Indirect tensile strength test

The indirect tensile strength tests were carried out in displacement-control configuration (0.85mm/s). The results of the indirect tension tests (carried out on specimens compacted with the Marshall method) show that the mixtures prepared with virgin mineral aggregates provide a higher strength compared with those prepared with RAP (Table 3). This is probably due to the water absorption of the virgin aggregates, which reduces the quantity of liquids in the mixture and produces better compaction. The RAP, being already covered by a thin film of bitumen, does not require the quantity of water to be reduced.

A 2.0% cement addition does not increase the tensile strength of mixtures made from virgin aggregates, while in RAP-mixtures this improves mechanical characteristics (Figures 31 and 32). The increase in bituminous emulsion produces greater tensile stress strength, especially with virgin mineral aggregates (Figure 31).

		Virgin aggregates		RAP	
emulsion (%)	cement (%)	7 days (kg/cm^2)	28 days (kg/cm^2)	7 days (kg/cm^2)	28 days (kg/cm^2)
3.5	0	2.60	3.01	2.54	2.81
4.5	0	2.90	3.97	2.52	3.16
5.5	0	1.61	4.30	2.49	2.79
3.5	2	2.03	3.49	3.08	3.65
4.5	2	1.81	3.24	2.96	3.26
5.5	2	1.78	3.90	2.77	3.37

Table 3. Values of indirect tension strength

Dynamic modulus test

The data from the dynamic modulus tests confirm the high viscosity of mixtures stabilised only with bituminous emulsion. This viscosity is shown by a greater phase angle. Compaction does not fundamentally influence phase angle values (Table 4).

With different curing times, the phase angle of mixtures made from RAP decrease from 7 to 28 days (the material becomes more elastic), while the elasticities of mixtures made from virgin aggregates remains almost unchanged.

Dynamic modulus is not influenced by compaction effort for either virgin aggregate or RAP, but it is significantly characterised by the cement content.

			Virgin aggregates 28 days		RAP 28 days		Virgin aggregates 7 days		RAP 7 days	
emulsion (%)	cement (%)	compaction effort	Dynamic modulus E (Pa)	Φ (°)	Dynamic modulus E (Pa)	Φ (°)	Dynamic modulus E (Pa)	Φ (°)	E E (Pa)	Φ (°)
3.5	0	modified	1.71E+09	16.60	1.85E+09	16.17	2.61E+09	16.44	1.15E+09	21.03
3.5	0	standard	1.84E+09	19.36	1.09E+09	17.80	1.65E+09	16.30	1.27E+09	18.58
4.5	0	modified	1.36E+09	21.38	1.08E+09	21.09	1.22E+09	17.68	1.15E+09	22.28
4.5	0	standard	1.94E+09	20.47	9.25E+08	21.67	2.01E+09	14.39	7.94E+08	23.73
5.5	0	modified	1.89E+09	22.68	1.21E+09	20.49	1.47E+09	19.64	7.50E+08	25.89
5.5	0	standard	1.30E+09	21.41	9.43E+08	21.94	1.66E+09	16.25	1.07E+09	21.37
3.5	2	modified	3.66E+09	9.91	1.92E+09	12.31	4.43E+09	6.60	2.06E+09	15.44
3.5	2	standard	2.22E+09	11.39	1.42E+09	13.22	2.49E+09	10.77	1.84E+09	15.81
4.5	2	modified	2.43E+09	11.35	2.35E+09	13.90	1.78E+09	12.05	1.44E+09	17.77
4.5	2	standard	4.04E+09	9.87	2.09E+09	15.79	1.21E+09	12.23	1.50E+09	16.86
5.5	2	modified	1.21E+09	13.96	1.87E+09	17.17	3.35E+09	9.97	1.27E+09	18.43
5.5	2	standard	2.07E+09	13.22	1.70E+09	13.54	1.65E+09	12.91	-	-

Table 4. Dynamic modulus and phase angle at 4Hz frequency

Conclusions

This experimental investigation allowed comparison of asphalt concrete and RAP cold-stabilised with bituminous emulsion and cement, and asphalt concrete prepared with the same binders and by the same technique, but using virgin mineral aggregates. We evaluated the influence of several variables on the mixtures produced by virgin mineral aggregate and those containing RAP.

Table 5 shows the influence of single project parameters on the final mechanical performances of asphalt concrete.

	Mixtures with virgin aggregates				Mixtures with RAP			
	compressive strength 7 days	compressive strength 28 days	indirect tensile strength	dynamic modulus	compressive strength 7 days	compressive strength 28 days	indirect tensile strength	dynamic modulus
% emulsion	–	–	+	+	–	–	=	+
% cement	+	++	=	++	+	++	+	++
compaction	=	=	/	=	+	++	/	=
curing time	+	+	++	=	+	+	+	+

Table 5. Influence of the different variables in the experimental study

This Table 5 provides an easily understandable qualitative evaluation, but does not allow full understanding of all the factors that might affect the cold recycling process. In this process cement plays an important role, since it significantly increases mechanical strength, and is also an effective regulator of breaking of the bituminous emulsion.

4.3 Guidelines for the Reconstruction Organised Solving Enterprise (ROSE)

Figure 34. R.O.S.E. Project

Introduction

On the basis of previous experience, it can be confirmed that losses in terms of finance can be huge in construction and urbanisation projects, in areas where the industrial sector is insufficiently developed and there are inadequate transport infrastructures. In the case of 'disaster areas' experience shows that the provision of basic shelters is the first priority followed by living quarters, and public facilities such as schools and hospitals, in addition to essential local infrastructures.

The financial help offered by the international community is usually limited and in many cases not enough to cover needs. Therefore, it is crucial to utilise locally available resources. Often following a disaster there are many buildings and infrastructures that are damaged and the large amounts of debris represent a barrier to traffic of people and vehicles. To clear, recover, recycle and use this debris is a fundamental objective, from both an economic and an environmental point of view.

The list below reports the essential and complementary components necessary to build a single storey dwelling, for private or public use.

1. Foundations:
   - concrete (sand + gravel + cement + water)
   - clay bricks and concrete blocks
   - iron poles for reinforced concrete;
2. Coverings:
   - beams of wood or cement
   - roof tiles and concrete slabs
   - other materials available in the area (composite bamboo slabs);
3. Doors and windows;
4. Plumbing:
   - piping for water and drainage
   - taps
   - sanitary fittings;
5. Electric and telephone systems:
   - wiring
   - lighting components;
6. Flooring:

- wooden boards
- concrete supports
- ceramic tiles (not essential);

7. Water supply and drainage of wastewaters.

In disaster areas and their surrounding areas there are often no production structures able to fully or even partly provide for these needs. Therefore, a precise analysis is necessary to evaluate the costs of construction materials and semi-finished components, and labour costs, in order to make best use of the available financial resources. The large quantities of inert materials necessary for roads construction and repair must not be underestimated.

For example, consider the weight of a house to be equal to 100; more than 80% consists of sand, gravel and cement, with the possibility of a reduction of 10% in relation to the eventual presence of clay products. More in-depth analysis shows that the quantity of cement does not exceed 10% of the inert materials component. It is evident that most of the building is made of inert stony material.

These stony inert materials can be of two types: primary raw materials extracted from natural pits or secondary raw materials recovered from demolition or destruction. In both cases crushing, selection and classification are necessary. In areas where large amounts of these types of material are available, as in many disaster areas, the construction on site of a plant for the production, selection and storage of inert materials is relatively advantageous. Such a plant can be rapidly planned and built based on needs, which makes management less expensive and allows economy scale-up due to:

- elimination of mining costs due to use of demolition waste,
- reduced clearance costs, due to the possibility to deliver demolition debris to a plant located nearby, and lower impact on the environment
- substantial reduction in transport costs, because the plants are close to the area under reconstruction,
- reduction in the costs of building materials and products.

Cement, bitumen and steel are essential components of the construction process; it may be cheaper to import these supplies and to deliver them directly to the reconstruction site.

As outlined above, the approach to any reconstruction project should be the planning of a complex enterprise, such as the ROSE Platform, to produce large quantities of aggregate for roads, foundations and masonry work and semi-finished building products; any remaining financial aid should be reserved for purchase of cement, bitumen and steel.

Aim of the ROSE project
The aim of a reconstruction project is the realisation of ready-to-use materials, and semi worked products to be prepared and worked within the framework of an integrated platform project, such as ROSE, located near the inhabited centre and the infrastructures.

The platform should be in a location that allows easy transportation of waste materials in a fenced off area. It will require an area of some 100,000m^2, divided into three or four connected sub-units for the production of:

1. primary and secondary raw materials, derived from demolition debris and mining products;
2. ready-mix concrete, prepared on site;
3. bituminous conglomerates for road surfaces;
4. concrete blocks, slabs and beams;
5. reinforced-concrete floors;
6. stabilised earth bricks.

The central management of the system should allow for and encourage ‘just-in-time’ production, i.e. supply of components at the time and place that they are required. The technology included in this proposal can also be used to process natural stony material, which means that the platform can remain in use after the emergency period.

The production units have been devised and planned specifically to produce the components listed above. They consist of machinery and special equipment designed to be compatible with primary materials and products. It will be managed in an orderly way, according to the sustainability that characterises the entire platform.

Particular attention should be paid to ‘stabilised earth-bricks’, a type of building material that responds to the needs of local architectural traditions. Their production will make use of a mix of recycled and primary natural materials that will be compacted with bonding additives, reminiscent of how ‘mud and earth’ houses are made.

ROSE Platform Realisation

To establish this integrated production unit, it will be necessary to have sufficient fenced off land, served with an access road, water piping and a reservoir. In the case of a limited external supply of electricity, it can be produced by diesel motor driven generators. Following this preliminary set up, the building-up of the production units should take another 6-9 months.

Figure 35. Building site

The core unit of the platform where recovered demolition materials are crushed, sieved and sorted to produce recycled aggregates.

Once an area has been fenced off, it should be assigned for the storage of debris materials allowing space for an access road and vehicular traffic. These waste materials will represent the primary source for the subsequent continuous production.

Follow-up opportunities

The realisation of a system such as that proposed in this project will provide not only the production of basic building materials, to cover the immediate needs of the reconstruction emergency, but will act as a building technologies reference-point for effective and economic establishment of a future building materials industry in the area.

Production process

The input materials for the platform will be carefully checked at the weighing station, and stored in three piles: heterogeneous rubble, concrete and natural materials. Checking will involve the use of viewing devices that can verify the nature of the materials. Once the materials are off loaded the plant can be fed using a four-wheeled loader. The feeding chute allows the transfer of materials to the plant. Any materials not suitable for treatment are identified and removed.

The next phase involves out-sifting to exclude the fine fractions (with a 0-30mm separation range) that would cause unnecessary wear of the crusher and wasted energy. This sifting also allows the separate production of sands and natural earths. These fine fractions are diverted and stored or reinserted into the treatment cycle after the crushing phase.

The material suitable for treatment is put into the crusher, which, in addition to reducing particle-size, allows separation from the metal bars of the reinforced concrete blocks. The crushed materials are conveyed on a primary transportation belt to the primary de-ironing conveyor belt. The metal is stored in a collection bin and can be sold.

When the de-ironing phase is complete, the material proceeds to the first vibrating sieve. In this phase the first separation of the largest light fractions (paper, plastic, wood, etc.) is achieved and the resulting waste material stored in a container and disposed of. A second separation eliminates the light fractions before recycling to the primary feeding chute.

All the process phases are protected by special water- and fire-proof cloth coverings, in addition to other devices to dampen down the dust.

Principal phases

The process involves the following operations.

Checking (visual):
This is a very important phase that may minimise problems in the subsequent steps and help to obtain the best results in terms of quality and economics of the final product,

Storage (on the ground in piles with a fork lift):
The separating into piles according to characteristics allows the manager to design the mix of the final product. This involves the feeding of the plant with known percentages of different types of available inert natural waste that produce a mix (recycled/natural) with constant characteristics.
Crushing (hopper, crusher):
This is carried out in a crusher that can be regulated in terms of distance and velocity of the jaws, so as to guarantee output of the size. The input material for the crusher comes either from storage or the recycling belt, thus increasing the yield of the finer fractions.

Selection (de-ironing, dust reduction, ventilation, vibrating sieves):
The quality of the final product is essentially characterised by the mixing of particle sizes and the removal of undesirable materials (essentially biodegradable materials). The selection station is the most important part of the plant for guaranteeing the quality of the product.

Homogenisation (transport belts):
An appropriate mix and homogenisation of the worked material is achieved by the transportation belts, and especially the recycling and the swivelling belts. The latter are also capable of automatically distributing the material uniformly through the heap for a better particle size mix.
Plant for ready-mix concrete

The size and economics of the production process requires a dedicated plant. The feeding of the respective silos is done with a four-wheeled loader from the aggregates (natural and recycled) storage area. Special weighing equipment determines the particle size mix, which is introduced - using the first transport belt - to the concrete mixer in the loading phase.

Additives (accelerants and recasting agents) can be introduced into the concrete mixer in liquid form, with the water. Using the same weighing and dispensing equipment, a second feeding line with a special mixer to obtain a higher level of performance for the concrete, carries the product to the vibrating moulds. The concrete mixes for the internal production of floors are fed from this second line.

The ready-mix concrete production plant with aggregate pile-ups produced with the help of the central core unit of recovered materials, i.e. crushing, sieving and sorting.

Plant for the production of asphalts

One of the objectives of a reconstruction unit is to build various infrastructures, which requires two different technologies and plant engineering techniques: the classic (production of bituminous conglomerates with a specific plant) and the basic (consisting of a surface treatment that allows, without specific dedicated investments, a first and satisfactory level of road surfacing).

In areas without any organised infrastructures, the most suitable method is the cold production of bituminous emulsions for surface treatments. If the context of the reconstruction allows, it might be possible to add another plant for hot production of conglomerates.

The bituminous asphalt mixtures production 'aisle' to get both hot and cold products for roads pavements.

Plant for the production of concrete blocks

In the poly-functional plant there will be an area for prefabrication of components for the construction of single storey houses. Prefabricated concrete blocks will be necessary for the construction of the supporting walls and partitions in these houses. Concrete for casting could be supplied by concrete mixers directly from the plant on the poly-functional platform. The vibrating mould is a machine for making concrete components. Completely automatic and on wheels it can work directly either on the track or on the bench.

Unit of production of the prefabricated components

Horizontal structural components for use in the construction of floor panels will be needed for the construction of houses. For each type of building the designer will have to draw up construction details, including reinforced string-courses for the walls and the fitting of floors.

Floor panels production 'aisle' of pre-fabricated elements

An area for the construction of floor panels is planned within the poly-functional platform. It should be laid with moulding frames in metalwork, 4mx1.2m in size. Reinforcement will be positioned within them and in some cases pre-stressing technology will be implemented.

Next to this area will be the iron processing zone for floor panel reinforcing and general metalworking. Concrete prepared in the plant and mixed in a pump concrete mixer will be poured into the moulding frames.

Storing the panels is possible only when the concrete is resistant to cracking or other deformation on moving.

Plant for the production of stabilised earth bricks

Use of earth, with aggregates of various components such as gravel, sand, slit and clays, as construction material is ancient practice. Compacted earth bricks have much lower energy costs than terracotta bricks. Earth blocks are much more sustainable since the introduction of cold stabilisation which substitutes traditional cooking with the use of natural presses and binders and/or chemicals, thereby reducing pollution.

The production process for bricks in stabilised earth is very simple and involves the accumulation of materials from pits and/or production waste, pulverisation in crushers, sieving, transport on the dispenser feeders, transport in mixers, addition of water and binders, mixing, pressing and moulding, stacking and transport to storage, storing of bricks for maturation.

Description of the functional service units

At the entrance to the area, on the right, next to the weighing platform, is the first support building which houses:

- the administration offices (entrance/exit of all goods and accounting)
- the management offices
- the technical laboratories for the various materials and for the checking of the individual production processes
    - classrooms for technical and professional training
    - sick bay;

A second building which houses:

- meeting rooms
- canteen
- guest house;

A third building for lodgings;
Lastly, a fenced off building with:

- workshop
- warehouse
- vehicle shelter.

On the left of the entrance there is the security post where daily entrances and deliveries are checked and where the 24-hour security guard service operates from.

Material testing laboratory

Within the poly-functional platform will be a materials testing laboratory which will be appropriately equipped according to the regulations of the country.

The testing lab will be divided into sectors.

Sector 1): **materials to be used in a loose state** for the construction of the parts of the road body. This sector will host the equipment for testing, both in the lab and on site, typically road geo-techniques and stone aggregates for concrete;

Sector 2): **materials to be used after 'improvement' or 'stabilisation'**, with the addition of relevant binders. In this sector the equipment should be set up for carrying out tests for classification of the materials, carrying capacity, sensitivity to water, resistance to freezing, etc.;

Sector 3): **materials for the formation of cement conglomerates**, destined for structural building parts and for the internal production of the platform. In this sector the equipment should be set up to identify the suitability of the aggregates, the particle-size curves, the consistency of the fresh conglomerate, the class of resistance of the hardened cement conglomerate;

Sector 4): **materials for the prefabrication of concrete blocks**, for the construction of walls or for prefabrication of other simple components in concrete. This section could be the reference point for training in the Vocational School;

Sector 5): **bituminous emulsions and bitumen liquids**, for the production of surface treatments for paving of roads or for earth stabilisation, in order to increase resistance of foundation layers. In this sector equipment for bituminous emulsions should be housed, to check homogeneity, sedimentation trends and stability over time;

Sector 6): **hydraulic binders** are used to examine specific characteristics of cement, for use with cement conglomerates or for the stabilisation of earth for the foundation layers of the road. This sector should be equipped to carry out the testing required for cement analysis;

Sector 7): **a plant for the production of bituminous_conglomerates**, in countries where techniques of construction and maintenance are developed.

Vocational school

Within the platform, closely connected to the materials testing laboratory, it is proposed that a Vocational Training School should be established.

Reuse compartment

The objective of the ROSE platform is to turn out large quantities of the materials required to rebuild an area in a country in crisis. It should also enable a small market area that can be used for the handling, storage and exchange of small quantities of new and used materials.

This would be a covered market area, of light construction, with direct access from the outside . It should have a section for the exchange of all types of (non-food) goods and an area for specific components recovered from buildings. Over time, it is possible that the materials going to this exchange market may have to be regulated, but in the initial period this space should be accessible to everyone as an incentive to use the materials available. Initially, it will deal only with building materials. Later, it should be possible to make available part of this dedicated area for a more specific reuse of pieces that can be sold, perhaps with added value in terms of adjustments/repairs, e.g. locks, tiles, roof tiles, channel irons, ceramics, tubes, beams, etc.

Final remarks

It is important to underline that the aim of ROSE platforms is to improve the quality of the construction industry and professions. During the platform's operational life, workers on the platform will interact with other workers through the exchange market enabling exchange of experience and knowledge that will promote personal skills and increase competences, thus contributing to the improvement of the local working class.

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CHAPTER 5

Composite materials – Will they become 'buildings'?

Before trying to answer this question, we need to define the 'composite' concept especially in terms of objects related to the building industry. It is clear that composites may range from millimetre size components, as in the case of advanced electro-ceramic materials, to large items such as vehicle and boat bodies. A composite material is made of at least two components, namely a matrix with an embedded dispersed material, either as fibres or particles. The properties of the composite can be designed by an appropriate combination of the matrix/dispersed material ratio and the geometry of the body itself. Strong elastic fibres may make a weak plastic polymeric matrix that behaves like a relatively rigid and strong body. Similarly, hard particles may increase the matrix hardness value through appropriate particle size distribution and volume dispersion.

5.1 Composite materials

Composites are one of the major developments in materials engineering, they refer to a structure made from more than one material - Fibre Reinforced Plastic (FRP) and Glass Reinforced Plastic (GRP). GRP plastic body matrices are reinforced with fine glass fibres and were originally developed in the early 1940s as a replacement for plywood for military aircraft constructions. The first main civilian application was for boat building, where it gained acceptance in the 1950s and now plays a dominant role.

FRP materials have the advantages of being light and easily mouldable to intricate designs. Unlike conventional materials, it is necessary with composites to determine the amount of fibre and resin for a given thickness and a large research effort has been made on fatigue of fibre reinforced composite materials. The most pressing need in composite materials research is the establishment of a body of reliable information on materials properties and behaviour on which the design engineer can rely. The FRP industry is experiencing significant growth as more products are being constructed from reinforced plastics for greater durability and strength.

5.2 Natural fibres

There is much research interest in using natural fibres to replace glass in fibre reinforced composites. Natural fibres derived from renewable resources are generally available at a much lower cost, they have lower embodied energy contents and they can be disposed of at the end of the product life cycle by composting or incineration. A major issue with plant fibres is whether they have the necessary mechanical performance to replace glass fibres. Composites are being used for the manufacture of prefabricated portable and modular buildings as well as for exterior cladding panels that simulate masonry or stone. In interior applications, composites are used for the manufacture of shower enclosures and trays, baths, sinks, troughs and spas. Cast composite products are widely used for the production of vanity units, bench tops and basins. Natural Fibres Composites (NFC) are playing an increasing role as an alternative to wood in buildings. Their benefits have proven attractive in many low stress applications. The use of high performance NFC in higher strength structural applications, however, has been slower to gain acceptance although there is much development activity.

5.3 NFC in the Indian scenario

Natural fibres, as a substitute for glass fibres in composite components are becoming more popular, especially for household items and automobile interiors. Fibres such as jute, sisal, coconut fibre (coir), ramie, banana, flax, hemp, etc. are cheap, have better stiffness per unit weight and a lower impact on the environment. Structural applications are rare since existing production techniques are not applicable for producing semi-finished materials of adequate quality. The moderate mechanical properties of natural fibres prevent them from being used in high-performance applications, but for many reasons they can compete with glass fibres. Lower specific weight of NFCs results in higher specific strength and stiffness compared to glass fibre and is a benefit especially in parts designed for bending stiffness.

The advances and progress that have been made in India in the exploitation and use of natural fibre in composites was reviewed by Soumitra et al. in an article titled 'Development of Natural Fibre Composites in India'[7]. The abstract is quoted below:

> *India, endowed with an abundant availability of natural fibres such as jute, coir, sisal, pineapple, ramie, bamboo, banana etc., has focused on the development of natural fibre composites primarily to explore value-added application avenues. Such natural fibre composites are well suited as wood substitutes in*

[7] Soumitra Biswas et al., Development of natural Fiber Composites in India, www.tifac.org.in/news/cfa.htm

the housing & construction sector. The development of natural fibre composites in India is based on a two-pronged strategy of preventing depletion of forest resources as well as ensuring good economic returns for the cultivation of natural fibres.

Jute & coir based composites have been developed as substitutes for plywood & medium density fibre boards. Panel & flush doors have also been developed out of these composite boards especially for low-cost housing needs. Other product development activities include usage of sisal fibre based composites as panel & roofing sheets. Incorporation of glass with jute brings about large increases in mechanical properties of composites. The natural fibre composites can be very cost-effective material especially for building & construction industry (panels, false ceilings, partition boards etc.), packaging, automobile & railway coach interiors and storage devices. Due to an occurrence of a wide variety of natural fibres in the country, Indian researchers have directed efforts for quite some time in developing innovative natural fibre composites for various applications. While the national research agencies in India have excellent scientific achievements to their credit for development of natural fibre composites, efforts on their commercialization have been limited so far. In order to improve upon the laboratory-industry linkages towards application development & commercialization including the natural fibre composites, the Advanced Composites Mission programme was launched by the Department of Science & Technology (DST), Government of India. The Mission mode activities are being implemented by Technology Information Forecasting and Assessment Council (TIFAC), an autonomous organization under DST.'

Virtually all the natural raw materials that exist in India also exist in all African countries. Researchers in various universities and research institutes have been working on available natural resources to produce composites. Data have been accumulated and are being accumulated. It is time to start to think about the production or manufacturing from available resources.

The production of natural fibre reinforced composites or simply bio-composites from identified raw materials is looked at using the modern design and manufacturing principles as embodied in CAD/CAE/CAM (Computer aided- design, engineering and manufacture).

5.4 Agricultural bio-mass and waste

Agricultural wastes are the waste from harvesting or processing of a crop. To date the main uses for agricultural wastes are as biomass and manure. Most of this waste is burnt causing environmental pollution. On average over, 14,770,000 tonnes of agricultural wastes are generated annually in Kenya (Onchieku and Githiomi, 2000). The following is a short, not exhaustive list of fibres that might be used in production of composites and that have received attention from African and Indian researchers.

Sisal fibre tow and flume, which are the waste from the decorticating process, have been used to produce woven materials, and laminated to produce composite panels useful in the building industry and with sound mechanical and physical properties (Bisanda, 1988).

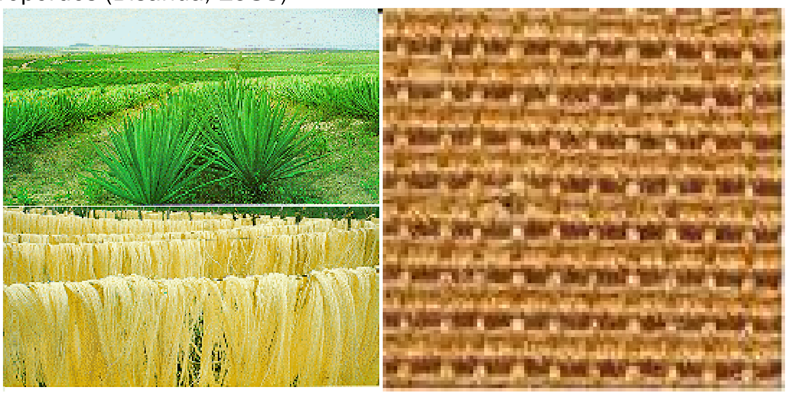

Figure 36. Sisal plantation with nearby drying fibres and sisal carpet.

Coir and coconut fibres

The fibrous material surrounding the nut of the coconut fruit is a useful reinforcement for certain ceramics and polymers (Owalabi et al., 1983). Coconut pith and coir waste have been utilised as a filler in natural rubber products such as rubber cork, teamat, cellular sheet, partition board, packaging materials, etc.(Chandaran et al., 1995). Coconut leaves blended with cashew nut shell liquid (CNSL) have been successfully used for roof thatching.

Figure 37. Coir fibres and coir mat.

Coconut fibres (retted or un-retted) with CNSL or cement have been produced for roofing (Rai, 1997). Coconut pith with cement or bitumen have been used as insulation boards and expansion joint filler. Coconut chips with Phenol Formaldehyde (PF) have been used as particle boards (Rai 1997). Coir fibre with fly ash as lime or cement as the binder has been used as bricks and blocks for walling. Coir fibre cement bonded panels in densities of 1,300-1,400 kg/m^3 have been used as panels in door shutters, windows and several other engineering applications.

Kapok fibre, a cellulose plant fibre sometimes referred to as ‘silk cotton’ can be processed to produce hybrid textile material by blending it with cotton or to produce reinforcement material for composites in polymeric matrices for building industry (Mwaikambo and Bisanda, 1997).

Papyrus fibres have been processed to provide reinforcement for polymeric matrices giving lightweight composites for general purpose building applications (Bisanda, 1997). Bamboo has been used in grid shells for the construction industry (Vasavada, 1986), as a reinforcement material for rainwater cisterns (Robles-Austrialo, 1991) and in the production of paper and fibreboards. Bamboo (spilt) and pulp with mud and cement have been used as panels for walls and concrete for posts, roofs, rafters. electric poles etc. Bamboo has also been successfully used as an electric conduit (Bisanda, 2000).

Bagasse, the fibrous residue of sugar cane has been processed to produce fibre and particleboards (Hesch, 1993, Ayensu, 1996). These can be pressed into panels and blocks using Urea/Phenol Formaldehyde (UF) resins.

Figure 38. Sugar-cane is the raw ma

Rice straw and husks, the residue obtained from paddy grain processing have been successfully used to produce particleboards using synthetic resins (Shukla et al., 1985). Its pozzolanic properties have enabled production of Portland cement or hydrated lime (de Gutierrez, 1994; Okpala et al., 1993). Coffee husks, a by-product of coffee processing, have been successfully used to produce particleboards using both synthetic and natural resins (Ogola, 2000). The nano-sized silica particles in the rice-husk are used as a raw material for synthesis of high-tech ceramic materials.

Figure 39. Rice straw can be used in the production of panels

Maize wastes in form of maize cobs and husks have been successfully used with synthetic resins to produce particleboards for the building industry.

Other useful wastes under research include groundnut shells, pineapples, beans, sunflower, wheat straw and hyacinth.

5.5 Indian scenario

Production activities have been undertaken to develop cost effective building materials for urban and rural areas. In this context, certain developments concerning glass fibre reinforced polymer composites, natural fibre composites and industrial waste based composites have assumed importance. The key restricting factors in the application of composites are the initial costs of raw materials and inefficient conventional moulding processes. Industry and design experts consider that the adoption of advanced technologies and some standardisation would resolve these problems. Various products are being developed in the building and construction industry, such as prefabricated, portable and modular buildings, exterior cladding panels, interior decorations, furniture, bridges and architectural mouldings.

The following describes development activities in various academic institutions and R&D laboratories in India in partnership with industry.

5.5.1 Fibre Reinforced Plastics (FRP)

The scarcity of wood for building products is encouraging the manufacture of low cost FRP building materials to meet housing and building sector demands. Sandwich composite construction is popular in door fabrication and provides critical advantages such as high specific strength and stiffness, low weight, impact resistance and uniform smooth surfaces. FRP doors and doorframes have been designed and developed using this technology at the RV-TIFAC Composite Design Centre (CDC) in Bangalore within a project launched by the Advanced Composites Mission of the Technology Information, Forecasting and Assessment Council (TIFAC) under the Department of Science and Technology (Govt. of India).

Many components are now produced in natural composites, mainly based on polyester or polypropylene and fibres such as flax, jute, sisal, banana or ramie. Their introduction in this industry was motivated by price and marketing (processing renewable resources) rather than technical demands. They can be used as substitutes for wood or masonry for partitions, false ceilings, facades, fences, flooring, roofing, wall tiles, etc.

The wide usage of ligno-cellulosic fibres as reinforcement in thermoplastic, such as polyethylene and polypropylene, is based on their low cost, low density, high specific strength, flexibility and reduced wear of processing machinery. To improve the impact strength of composites, it has been found that olefinic based impact modifier (containing carboxylic functions) results in higher mechanical, flexural and impact strengths than the elastomer based modifier. This is due to presence of the carboxylic functional group which provides better bonding with jute fibre and homogeneity with the polypropylene matrix.

5.5.2 Coir reinforced plastics

The regional research laboratory, Thiruvananthapuram, carried out detailed analysis of the effect of fibre length and fibre content on the tensile properties of coir fibre reinforced polyethylene composites. The strength modulus and failure strain of the composites increased with length up to maximum fibre length of 20mm and fibre volume fraction of 0.26. Further increase in fibre length resulted in decreased fibre-fibre interaction and poor compaction of fibre in the matrix. Although coir fibre processes 60-70% lower tensile strength than sisal and pineapple fibres, coir-polyethylene composites have comparable tensile strength and higher failure strain than sisal and pineapple fibre based composites. This is due to the presence of a natural waxy layer on the fibre resulting in better interfacial bonding between coir and polyethylene.

Because of their inherent advantages, these composites have been developed by the Central Building Research Institute (CBRI), Roorkee.

5.5.3 Sisal and jute composites

CBRI has carried out development efforts using sisal fibre and wollastonite as synergistic reinforcement alternatives to glass fibres in moulding compounds to widen their usage in the housing sector. Sisal based moulding compounds can be used for developing building materials such as checker floor plates and roof tiles.

CBRI has also attempted to fabricate jute poltruded doorframes using woven jute cloth and phenolic resin. Phenolic resins are often used for the fabrication of jute-composite products mainly because of their high heat resistance, low smoke emissions, excellent fire resistant properties and compatibility with jute fibres. CBRI has developed a technology for production of coir-cement roofing sheets of 6-8mm thickness. The manufacturing process involves soaking coir fibre in mineralised water and then mixing it with dry cement in the ratio 1:5 by weight. A sheet is made with this wet mix of cement coated fibres and is held under pressure for 4-8 hours. Long-term performance under actual conditions has been ascertained.

CBRI has developed medium density composite doors containing coir fibre, CNSL as natural resin and para-formaldehyde as the major constituents. Coir fibre contributes mechanical strength to the composite while the CNSL with para-formaldehyde acts as a binder. Coir is impregnated with CNSL and is compression moulded under high temperature. The pressure required during casting of the board/sheet depends upon the required density of the final product. These boards can be used as wood substitutes for panelling, cladding, surfacing and partitioning and other interior applications. The boards 0.5-0.9gms/cm^3 density, and can be cut, sawed, nailed and screwed. The boards have very low water absorption and negligible swelling.

5.5.4 Indian capabilities

India has excellent knowledge in various resins, catalysts and curing systems coupled with an adequate availability of various raw materials and could carve out a niche in the emerging technology of composite fabrication. The Advanced Composites Mission programme for composite technology development and commercialisation was launched by the Department of Science and Technology (DST), of the Government of India. Mission-mode activities are being implemented by the Technology Information, Forecasting & Assessment Council (TIFAC) and an autonomous organisation under DST.

A systematic study was carried out at CBRI on sisal and jute fibre composites for application in the construction sector and has established process know-how for fabricating these natural fibre composites. The sandwich composite panels are lightweight and have excellent bending stiffness as well as good thermal and sound insulation. For semi-structural applications hybrid composites with glass fibre, sisal fibre and polyester resin have been developed.

The Advanced Composites Mission aims to improve upon the laboratory-industry linkages for application development and commercialisation. The Mission has successfully launched 22 projects across the country in active collaboration with industry and some national laboratories. Some of the important projects launched by the Mission in the building and construction sector include FRP poltruded profiles, FRP doors and doorframes, jute-coir composite boards, etc.

Such an objective oriented and time bound programme on composite technology with the involvement of stake holders will go a long way towards developing innovative composite applications, meeting international quality and achieving wider acceptance by users, thus contributing to the growth of knowledge-based business in India.

5.6 Bamboo as a building material

Bamboo is a woody perennial evergreen plant of the fastest renewable kind, with a maturity cycle of 3-4 years, thus making it a highly attractive natural resource compared to forest hardwoods. It can grow even in cold mountainous regions, but thrives in hot tropical regions, from East and South Asia down to northern Australia. Bamboo also occurs in sub-Saharan Africa and in the Americas from the southeast USA to Chile, reaching the furthest south at 47°S latitude. Major areas with no native bamboos include Europe, North Africa, western Asia, northern America and most of Australia.

Figure 40. Long stem bamboo that may be developed into building poles.

Some of its members have large potential as timber substitute and, when treated, bamboo forms a very hard-wood which is both light and exceptionally tough because of its fibrous structure. In tropical climates it is used in elements of house construction, as well as for fences, bridges, construction scaffolding and in some cases as a substitute for steel reinforcing rods in concrete construction. When bamboo is harvested for construction purposes, care is needed to select mature stems that are several years old, as first-year stems, although full size, are not fully woody and are not strong. It should be remembered that bamboo wood is easily infested by insects unless treated with preservatives and kept fairly dry.

Bamboo offers good potential for being processed into composites to replace plywood laminate products in many applications such as furniture, doors and windows and their frames, partitions, wardrobes, cabinets, flooring, etc.. Modern companies are introducing bamboo flooring made of steamed bamboo pieces, flattened, glued together and cut as tiles.

Bamboo is an important resource in the socio-economic and cultural-ecological contexts with more than 1,500 uses. It is a fast growing, wide spread, versatile, low-cost renewable and environment-enhancing resource with potential to improve livelihood security in the years to come, in both rural and urban areas. Apart from traditional uses bamboo has various new applications as an alternative to more expensive construction and interior building materials.

There is a need to modernise the bamboo-based industry sector by introducing better technologies, processing and manufacturing supports, as well as improved managerial practices. The scope of the institutions that deal with building materials and technologies should be widened to include greater awareness about the importance of bamboo in economic development, and training of human resources in the processing of bamboo for engineering purposes.

5.6.1 Green buildings and related technologies

We could define as 'green' any building that is designed, sited, constructed, operated and maintained for the health and well being of the occupants, and to minimise the negative impact on the environment.

The same approach can be taken to the selection of related technologies. There are different products made from environmentally friendly materials that can be defined as 'green' during construction, renovation and demolition. Bamboo ranks highest as it can qualify as 'green' in many stages of the building's life.

Bamboo is currently being looked at as an alternative low-cost material for the enormous housing problems faced by many developing countries. It exhibits high specific tensile strength compared to mild steel, and high strength to weight ratio and high specific load bearing capacity. Bamboo requires less energy for production and its service life can be enhanced by suitable preservative treatment. As it is a fast growing species it is very efficient at sequestering carbon dioxide from the atmosphere thus contributing to reducing the greenhouse effect.

For construction purposes it can be converted into panels and composite materials with enhanced strength and toughness properties suitable for structural applications. Bamboos possess high residual strength, even after initial breakage, to absorb shocks and impacts (toughness) required for construction of houses that need to resist seismic and high wind forces.

Bamboo laminates are made from slivers milled from the bamboo culm. After primary processing comprising cross cutting, splitting and two-side planing, the slivers are treated to remove the starch and prevent termite and boring insect attack. The slivers are subjected to hot air drying followed by four-side planing to achieve uniform thickness. The slivers are coated with glue and arranged systematically. They are the cured in a hot steam press at about 70°C at pressures of about $17 Kg/cm^2$. The pressed laminate (panels or tiles) is put through trimming, sanding and grooving machines to give a pre-finished shape.

5.6.2 Benefits

Bamboo flooring tiles, partitions, racks, door and window panels introduced into the market will reduce use of hard wood. Promotion of bamboo for housing and infrastructures will require more planting and cultivation of bamboo, which will benefit the agro-forest industry and the eco-system. More extensive cultivation of bamboo will generate employment opportunities and boost income for rural communities.

An example of the work that has been done in India is the project on the development of bamboo laminates that was launched by the Advanced Composites Programme of TIFAC with technology support from the Department of Polymer Science and Technology, University of Calcutta. The project aims at developing value-added products from bamboo using an innovative resin system that reduces the energy required for processing.

To reduce formaldehyde emissions in compliance with international norms, a low-temperature curing water based resin system (melamine fortified urea formaldehyde) has been developed within the project. A water based acrylic pre-coat has been developed that prevents bamboo composites from deteriorating due to moisture absorption and gives a long storage life. This pre-coat protects against fungal attack during transit in reconstituted wood sections in furniture. A UV cured melamine acrylate system as a finishing coat has been developed for bamboo floor tiles.

Various stages of bamboo processing from cross-cutting, parallel splitting, knot removal, two-side planning, anti-fungal treatment, drying, four-side planing, glue application and hot pressing have been developed and become operational.

Figure 41. Natural fibres and bamboo in building modules designed and produced at the Composite Technology Park located, Kengeri Satellite Township, Bangalore.
Courtesy of Dr. Gopalan, Director. drgopal@bir.vsnl.net.in

Products such as floor tiles, furniture sections, reconstituted wood, air locked sections, mat boards, etc. have been developed within the project. The finished products such as flush doors fabricated with bamboo veneer boards and an inner honeycomb core, made of waste bamboo rings are forecast to become popular in the market.

Planning and investment requirements for the Indian market are available from the Technology Information, Forecasting and Assessment Council, advcomp@tifac.org.in

5.6.3 Answer about the feasibility of 'composite materials' in the building industry

The situation in India provides an answer to our original question about the feasibility of composite materials in low-cost, lightweight building materials. R&D institutions have produced a large number of prototypes of both building components and whole-building units that are one-step before final industrialisation.

CHAPTER 6

Selected Papers from the workshop ‘Low cost building materials’, Dar-es-Salaam, Tanzania – December 2006

6.1 Coal cinder as building material

By: Bollen Kilimba and Alex Sosthenes
Kiwira Coal & Power Co. Ltd.

Introduction

There are 7,200 tonnes of coal cinder generated by the coal fired power station at Kiwira Coal and Power Co. Ltd (KCP) annually. The waste dispersal dump is located at the mine close to the village. It poses a threat in terms of pollution, to those people living near this waste dump. In the rainy season, water can percolate through the dump and get into the streams of water used by the villagers for domestic purposes.

Recent research done by a team of Engineers and Technicians from the building and civil section working with KCP, has found that cinder ashes can be formed into stable building cinder blocks if they are mixed with small amounts of cement. Currently, cinder ashes from the power plant are used to make cinder blocks to fabricate low cost buildings and to minimise environmental contamination.

Nature of cinder ashes

When cinder ashes have been piled up for a long time they form very strong solid stone, manifesting some of the characteristics of cement. Experience has shown that it this waste is difficult to deal with if piled up for too long.

Research work

The self cementing action of cinder ash attracted the attention of engineers and technicians working in KCP to pursue research on it. The first trials were related to road repairs around the KCP owned township. The cinder ash was spread on the road formation level and compacted at optimum moisture content. The cinder ash reacted with the sub base, the base and the uppermost layers. Road surfaces proved durable in all weathers.

The second research was on cement cinder block fabrication. Different mix ratios were cured for different times - 3, 7, 14 and 28 days - compressed in a machine and their performance compared to fired bricks and cement sand blocks. The cinder block behaved as well as cement sand blocks of weak mix.

However, cinder blocks vary significantly in terms of compressive strength depending on the ash content of the coal used in the boiler of the power generating plant.

Fabrication of cinder blocks has enabled the construction of housing at the KCP site and the surrounding villages, at low cost.

Figure 42. Building constructed from cinder blocks

Figure 43. Buildings being completed for a settlement

Figure 44. Buildings being completed for a settlement

Figure 45. Buildings being completed for a settlement

Conclusion

The most economic ratio for block fabrication is one bag of cement (50kg) to 400kg of cinder ash, which produces 50 blocks. Further research will be conducted involving the use of Ciava-Ram devices for block production.

6.2 Design and manufacture of natural fibre reinforced composites for low cost building materials

BY: DR. G.O. OLUWADARE, DEPT. OF MECHANICAL ENGINEERING, COVENANT UNIVERSITY, OTA, NIGERIA

Abstract

There is a great deal of R&D on the design and production of natural fibre reinforced composites in Africa, specifically to increase the availability of affordable building materials. Action plans have been formulated and recommendations made on the use natural fibres for the production of low cost building materials.

Introduction

Cost can only be kept low if most or all the raw materials required can be sourced locally. In order to produce high quality building materials, measures must be taken to improve the properties of these raw materials. One way of doing this is to use composite materials in which one material forms the matrix and another provides the reinforcement, e.g. by use of a fibre, which is added to achieve properties superior to those in either of the materials on its own.

In Nigeria's rural areas, houses have been constructed from cheap materials that are easily available. The most popular material is mud, [1] formed into bricks, and galvanised iron sheets for roofing. In urban areas there are variants of these mud bricks used for building (cement stabilised earth bricks, burnt bricks, etc.), all of which reduces the costs of erecting a building. The main focus in Nigeria is on keeping the amount of cement to the absolute minimum since cement is expensive and the establishment of more cement plants has not worked to reduce prices. [2,3]

The advances that have been made in India in the exploitation of natural fibre in composites was reviewed by Soumitra et al. [4] in an article entitled 'Development of Natural Fibre Composites in India'. The abstract of this paper is reproduced below:

> *India, endowed with an abundant availability of natural fibres such as jute, coir, sisal, pineapple, ramie, bamboo, banana etc., has focussed on the development of natural fibre composites primarily to explore value-added application avenues. Such natural fibre composites are well suited as wood substitutes in the housing & construction sector. The development of natural fibre composites in India is based on a two-pronged strategy of preventing depletion of forest resources as well as ensuring good economic returns for the cultivation of natural fibres.*
>
> *Jute & coir based composites have been developed as substitutes for plywood & medium density fibre boards. Panel & flush doors have also been developed out of these composite boards especially for low-cost housing needs. Other product development activities include usage of sisal fibre based composites as panel & roofing sheets. Incorporation of glass with jute brings about large increases in mechanical properties of composites.*
>
> *The natural fibre composites can be very cost-effective material especially for building & construction industry (panels, false ceilings, partition boards etc.), packaging, automobile & railway coach interiors and storage devices.*
>
> *Due to an occurrence of a wide variety of natural fibres in the country, Indian researchers have directed efforts for quite some time in developing innovative natural fibre composites for various applications. While the national research agencies in India have excellent scientific achievements to their credit for development of natural fibre composites, efforts on their commercialisation have been limited so far. In order to improve upon the laboratory-industry linkages towards application development & commercialisation including the natural fibre composites, the Advanced Composites Mission programme was launched by the Department of Science & Technology, Government of India. The Mission mode activities are being implemented by Technology Information, Forecasting and Assessment Council (TIFAC), an autonomous organization under DST.*

Virtually all the natural raw materials that exist in India are also available in all the African countries. Researchers in various universities and research institutes have been working on available natural resources to produce composites. Data are being accumulated and production and manufacture using available resources is becoming urgent.

This paper examines the production of natural fibre reinforced composites or simply bio-composites from identified raw materials, using modern design and manufacturing principles as embodied in CAD/CAE/CAM (computer aided-design, engineering and manufacture).

Design and manufacturing

What do we want to design and manufacture? We want to produce composites from naturally occurring and readily available raw materials: (i) cement based composites and (ii) polymer (naturally occurring) based composites. These could be used for roofing sheets, ceiling material, flooring material, door panels, wall panels and partitioning for prefabricated houses, and furniture.

Manufacturing is transformation of materials and information into goods to satisfy human needs. Low cost building materials must be manufactured by the most economical methods in order to minimise costs. There is an interaction between design and manufacturing as illustrated below in Figure 46.

Figure 45. Interaction between design and manufacturing

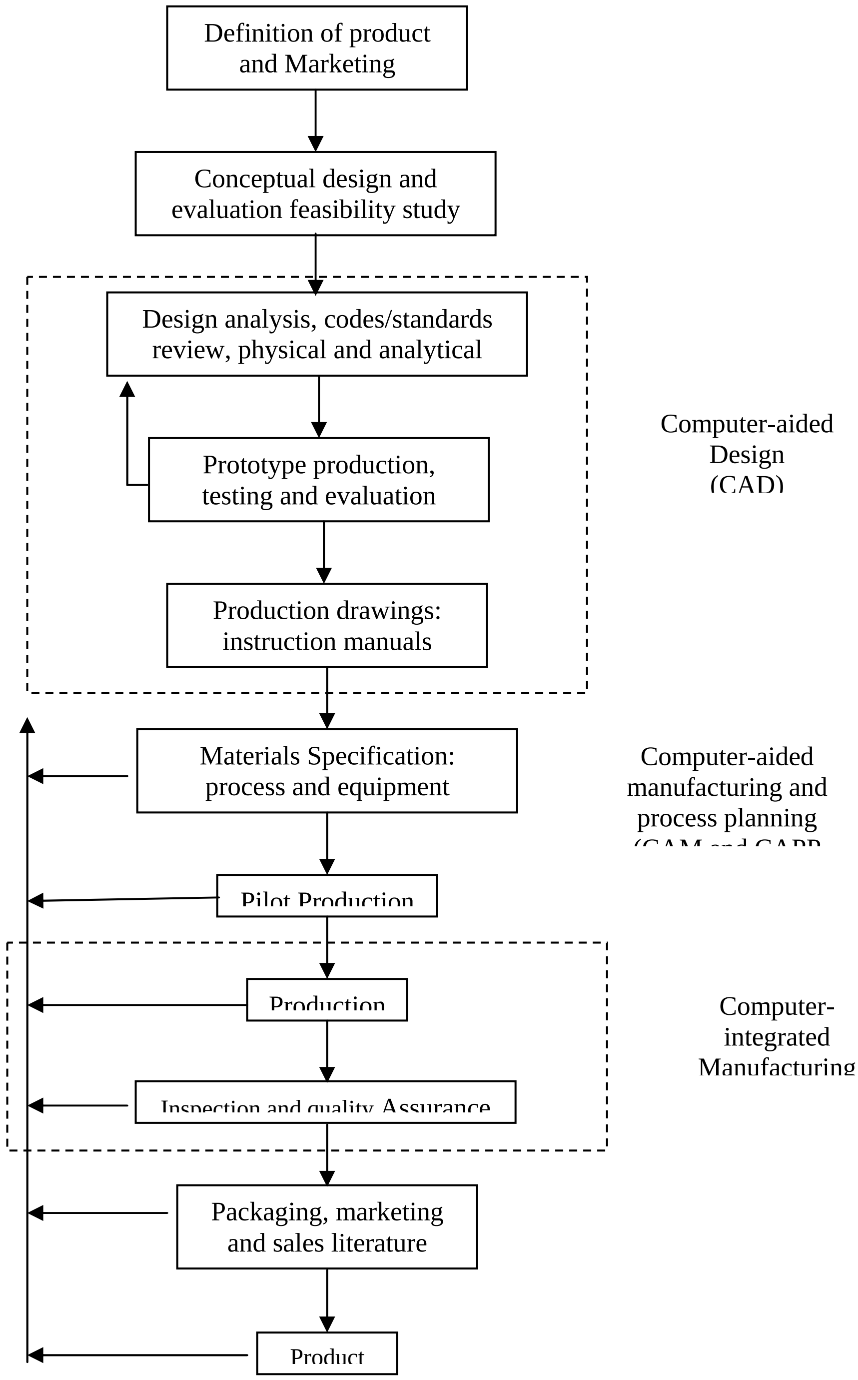

Figure 46 shows that:

- The design process for a product requires a clear understanding of the functions and the performance of that product.
- The design and manufacturing activities are no longer sequential but take place simultaneously or concurrently and involve concurrent engineering.[8]
- CAD, CAE and CAM techniques allow digital simulations and prototypes can be produced and tested using rapid prototyping methods and techniques.

Action plan for production of low cost building materials

To carry out the design and manufacture of natural fibre reinforced composites, various multidisciplinary data are required. All relevant data should be gathered and collated for most effective use.

1. The existing data provide ideas and suggest possibilities about how composites can be used, based on the raw materials available. Needs for various environments must be identified and activities oriented to meeting these needs.
2. Efforts must be made to generate more data that are transparent and accurate. There are still many materials that have not been investigated. Interaction with colleagues in all areas of science and technology will support this effort.
3. Research leaders and/or supervisors of masters and PhD students should use the ideas and data generated to formulate research topics for junior colleagues and students

Recommendations

1. Proper funding of research activities is crucial for success.
2. Research students' work in higher institutions should be properly focused and funded.
3. Research networks need to be created. Equipment must be available. A data bank must be created showing what equipment is available and where.
4. Regular meetings and workshops should be held to review progress, compare notes and share data.
5. In addition to low cost building materials we must devise low cost (affordable) manufacturing equipment that local entrepreneurs can acquire to manufacture these new products. Mechanical engineers should investigate equipment design for low cost building materials.
6. Training workshops should be provided on the proper characterisation of composite materials using modern analytical tools in order to generate more and accurate data.

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[8] Concurrent engineering is a systematic approach integrating the design and manufacture of products with the view to optimising all elements in the life cycle of the product. The life cycle approach means that all aspects of a product, such as design, development, production, distribution, use, and ultimate disposal and recycling are considered simultaneously.

6.3 Influence of laminate thickness and fibre type on bending strength of fibre reinforced plastic

By Mutai Alice Jepkorir

Abstract

This research aims at accurately determining the strength characteristics of polyester resin composites containing two types of reinforcing materials: glass and sisal fibres.

It is hypothesised that the concentration and type of reinforcing materials used in the composites will have varying effects on the strength of the different laminates. A universal testing machine available at Kenya Bureau of Standards (KEBS) is used to measure the laminate deflection with increasing loads. Laminates moulded from resin containing glass strand mats and sisal fibre reinforcing materials will be cured and tested. Test data will be entered into an Excel spreadsheet to calculate the force on each laminate, its deflection, stiffness and maximum stress at failure.

The results are expected to show that the two fibre types have significant difference in terms of laminate stiffness and strength therefore their industrial applications will be different.

General introduction

Among the major developments in materials in recent years is the production of composites, which have become one of the most important classes of engineering materials. A 'composite', is defined as a structure made from more than one material. A tree is a natural composite consisting of wood held together by sap. Concrete is also a composite (http://www.dreamscopes.com.pages.glossary.htm).

Glass Reinforced Plastic (GRP) is a composite material containing fine glass fibres, and fibre-reinforced plastic (FRP) is a composite made of plastic reinforced by fine fibres. GRP was originally developed in the United Kingdom during the Second World War as a replacement for the moulded plywood used in aircraft bodies. The first main civilian application was for boatbuilding where it gained acceptance in the 1950s and now plays a dominant role (http://www.bluebird-electric.net/composites/glass fibre reinforced plastic.htm).

There has been a rapid growth in the use of fibre reinforced materials in engineering applications and there is every indication that this will continue. Fibre-reinforced composites have the advantage of being light and easily mouldable to intricate designs. Light vehicles are more fuel and energy efficient.

Driven by the need to revitalise an aging infrastructure using innovative materials and structural systems that will be longer lasting and require fewer maintenance costs (Bakis et al., 2002) research has focused on the use of FRP. High quality FRP materials are available in shapes and forms more attractive to civil engineers. The challenge is to make them more cost effective for large civil engineering structures (Mirmiran et al., 2003).

Unlike conventional materials, it is necessary with composites to determine the amount of fibre and resin for a given thickness and a large research effort is being devoted to fatigue in fibre reinforced composite materials. Fatigue experiments in tension and compression are indispensable for accurately modelling the fatigue behaviour of composites. Bending fatigue experiments also yield a lot of useful information (Ferry et al. (1997), Herrington and Doucet (1993). The most urgent need in composite material research is the establishment of a body of reliable information on material properties and behaviour that design engineers can trust.

There is much research interest in using natural fibres to replace glass in fibre resource reinforced composites. Natural fibres derived from renewable resources are generally available at a much lower cost, as much as 20% less per tonne, have lower embodied energy content and can be disposed of by composting or incineration. A major issue with plant fibres is whether they have the necessary mechanical performance to replace glass http://www.bc.bangor.ac.uk.suscomp.index.htm

Objectives of the study

The overall objective of this study is to analyse the influence of laminate thickness and fibre type on the bending strength of glass and sisal fibre reinforced plastics.

The specific objectives of this research are to:

- Determine the physical and mechanical properties of glass fibres currently used by Sai-Raj Company.
- Compare the physical and mechanical properties of Sai-Raj fibreglass laminates with the recommended standards issued by Kenya Bureau of Standards (KEBS).
- Develop fibreglass and sisal fibre laminates that meet KEBS standards.

Hypotheses

(i) The physical and mechanical properties of fibreglass currently used in Sai-Raj do not exceed the standards recommended by KEBS.
(ii) The physical and mechanical properties of Sai-Raj laminates do not vary greatly from the KEBS recommended standards.
(iii) Developing fibreglass and sisal fibre laminates will not improve the physical and mechanical properties of composites.

Justification

Fibre-reinforced composite materials are finding increasing application in the aerospace and naval industries and in high-technology designs, due to their high specific stiffness and strength (Paepegen and Degrick, 2001). The fatigue properties of polymer matrix composites are of paramount importance in many potential applications where components are subjected to load, which may vary over time (Pegorelti and Ricco, 1999). Research developments initiated by the Department of Industrial and Energy Engineering, Faculty of Engineering and Technology, Egerton University (Njoro, Kenya) indicate that Sai Raj construct and use glass-reinforced laminates as vehicle body panels, but their physical and mechanical properties are not known.

The goal of this research project is to help laminate designers to determine the amount of fibre and resin for a given laminate thickness based on the fact that:

- there is increasing application of fibre reinforced composites
- there is a need to reduce weight and cost of automotive body parts
- light vehicles are more fuel and energy efficient.

Literature review on Reinforcing materials

The FRP industry is experiencing significant growth as more products are being made from reinforced plastics for greater durability and strength. These include building materials, sporting equipment, automotive/aircraft parts, boat/canoe hulls and bodies for recreational vehicles (http://www.p2pays.org/ref/32/31016.htm).

Fibres

Fibres are fine hair-like structures of animal, vegetable, mineral or synthetic origin. Commercially available fibres come in diameters ranging between 0.004mm-0.2mm and they come in several forms: short fibres (chopped), continuous single fibres, untwisted bundles of continuous filaments (yarns). Fibres are classified according to origin, chemical structure, or both. They can be braided into ropes and cordage and made into fells (non-woven or knitted into textile fabrics or in the case of high-strength fibres used as reinforcements for composites (Encarta Encyclopaedia).

Fibres are very strong and rigid because the molecules in the fibres are all arranged longitudinally, and their cross-sections are so small that there is little likelihood of any defects in the fibres. Glass fibres can have tensile strengths up to 4,600 MPa (650Psi) whereas the strength of glass in bulk form is much lower. Glass fibres are stronger than steel. Short fibres generally have an aspect ratio (length to diameter ratio) between 20 and 60, and long fibres between 200 and 500 (Kalpakjian, 1995).

Glass fibres

Glass fibres were invented in the 1930s and were used in numerous low cost applications. They are the most commonly used and least expensive of all reinforcing fibres (http://www.compositesontour,2006/2007). The composite material is called glass-fibre reinforced plastics (GFRP) and may contain 30-60% glass fibre per volume. Glass fibres are made by drawing molten glass through small openings in a platinum die. The most generally used glass fibre composition is E-glass or 'electrical type' glass. Its popularity among structural composites is related to the chemical durability of the borosilicate composition (Shakelfield, 1988).

By impregnating glass fibres with resins, a composite fibreglass is formed that combines the strength of the inertness of glass with the impact resistance of the plastics (Encarta Encyclopaedia, 2004). The strength and stiffness of fibre glass/plastic composite are provided by the glass fibres, which are extremely strong; their elasticity can be 50 times greater than that of the plastic (http://ojs.ucok.edu.98.T98.ORLOSK.HTM).

The strength of small diameter glass fibres is combined with the ductility of the polymeric matrix. The combination of these components provides products that are superior to either component on its own (Shakelfield, 1988). Chevrolet corvette bodies are made from composites using unsaturated polyester matrices and glass fibres (http://www.coe.montana.edu/mie/).

The non-renewable energy requirement for the production of fibreglass is 54.7Mj/kg. Incineration of glass fibres requires energy of about 1.7Mj/kg, thereby increasing the total net energy requirement (www.msstate.edu). To date the effects on human health and wear of machinery of substituting glass fibres with natural fibres have not been analysed.

Sisal fibres

There is much research interest in using natural fibres to replace glass in fibre-reinforced composites to reduce over-reliance on non-sustainable resources. Natural fibres have a number of advantages over glass:

- generally available at a much lower cost;
- lower embodied energy content;.
- derived from a renewable resource;
- can be disposed of by composting or incineration.

Sisal is a short-lived xerophytic perennial. The stem is commonly referred to as the bole and can reach heights of 1.2m at maturity. The leaves are borne on the boles and can reach lengths of 2m. A massive peduncle arises from the centre of the plant and is referred to as the pole. The crop is grown mainly for its leaves from which the fibres are extracted.

Production of sisal does not require excessive amounts of agrochemicals. Sisal fibre yield per hectare ranges from 0.6-1.2 tonnes. The sisal fibre is only 3-4% of the total weight of the leaf (www.msstate.edu/) the remainder of the leaf consists of cuticle vascular tissues and fleshy mesophyl and is commonly referred to as sisal waste. Sisal fibres are used for the manufacture of ropes, marine binder cordage twines, sacks, carpets and mats. However, the use of long vegetable fibres may provide other benefits. For example, it has been reported that replacement of wood fibre by flax/sisal in the interior door panels of Mercedes-Benz E-class cars resulted in a weight reduction of 20% and increased strength in those components (http://www.bc.bangor.ac.uk/suscomp/index.htm).

Plastic resins

Plastics are organic high polymers that are formed in a plastic state either during or after their transition from a small-molecule chemical to a solid material. Resin is any of a large class of synthetic products usually of high molecular weight having some physical properties of natural resins while being very different chemically. The two basic groups of plastic materials are thermosets and thermoplastics.

Thermosets

Thermoset plastics react during processing to form cross-linked structures that cannot be re-melted and reprocessed. They may be supplied in liquid form or as a partially polymerised solid moulding powder in their uncured condition. They can be formed to the finished product shape with or without pressure and polymerised by using chemicals or heat. (http://www.suscomp.net/)

Epoxy resins

Epoxies are used by the plastics industry in many ways, one of which is combination with glass fibre. They are thermosetting resins in which the uncured epoxy is reacted with a curing agent or hardener. Fibres are impregnated with liquid epoxy resins to produce high-strength composites providing electrical and chemical properties and heat resistance. Typical uses of epoxy-glass reinforced plastics are in aircraft components, pipes, tanks, tooling jigs and fixtures. Major outlets for epoxies include adhesives, protective coatings and industrial equipment (http://www.bc.bangor.ac.uk/suscomp/index.htm).

Phenolic resins

Phenolic resins, first commercially available in 1910, were some of the first polymers. Today phenolics are some of the most widely produced thermosetting plastics (Encarta Encyclopaedia, 2004).

As moulding powders these resins can be found in electrical uses, as automotive distributor caps, fuse blocks and connectors and appliance handles/knobs and bases. Phenolic is the most popular binder for holding the plies in plywood together (http://.www.suscomp.net/).

Polyester resin

Polyester resin is a thermosetting resin made from an unsaturated polyester (UP) such as is formed from glycol and malic acid or fumaric acid. The reinforced resin is used chiefly in laminates and in making casts and moulded products (http://ojas. ucok.edu/98/T98/ORLOSK.HTM).

Thermoplastics

Thermoplastic resins consist of long molecules each of which may have side chains or groups that are not attached to other molecules. They can be repeatedly melted and solidified by heating and cooling so that any scrap generated in processing can be reused (http://www.bc.bangor.ac.uk/suscomp/index.htm).

Figure 47. Stress/strain curves for fibrous reinforcement and matrix

Figure 46 shows the essential differences in the stress/strain properties of the two phases. The fibre should be stiff and strong. The matrix is less stiff, has a larger extension at break so that the fibre reaches its full extension and achieves full strength before the matrix fails The energy stored at failure (area under stain/stress curve) is large which indicates a tough composite. During the fabrication processes, it is the matrix that must soften and flow before it hardens.

Fillers

In order to impart certain specific properties, polymers are usually compounded with additives, which modify and improve certain characteristics of the polymers, such as stiffness, strength, colour, flammability and resistance, for electrical applications and ease of subsequent processing.

Because of their low cost, fillers are important in reducing the overall cost of polymers. Fillers are also known to improve strength, hardness, toughness and stiffness of plastics. In reinforced plastics, the effectiveness of the filler depends on the nature of the bond between the filler material and the polymer chains (Kalpakjian, 1995).

Catalysts

A catalyst is a substance that accelerates the rate of a chemical reaction at steady temperature, without itself being transformed or consumed by the reaction. A catalyst participates in the reaction, but is neither a chemical reactant nor a chemical product. Catalysts enable reactions to occur much faster or at lower temperatures because of the changes that they induce in the reactants.

Fabrication techniques

These include compression moulding, vacuum-bag moulding, contact moulding filament and winding and pultrusion.

Contact moulding

Contact moulding is used to make products with high surface area to thickness ratio, such as swimming pools, boat tubs, shower units, and housing. This is a 'wet' method in which the reinforcement is impregnated with resin at time of moulding. The simplest method is the hand lay-up where the materials are placed and formed in the mould by hand, and squeezing action expels any trapped air and compacts the part. The strength of any part resides in the fibres not in the resin.

Moulding may also be done by spraying (spray-up). Although spraying can be automated, these processes are relatively slow and labour costs are high. However, they are simple and the tooling is inexpensive. Only the mould-side surface of the part is smooth and the choice of materials is limited. This process is used to make many types of boats.

Pultrusion

The pultrusion process makes long shapes with various constant profiles such as rods, profiles or tubing. In this process, the continuous reinforcement is pulled through a thermosetting polymer bath and then through a long heated steel die. The product is curved during its travel through the die and cut into the desired lengths. The most common material used in pultrusion is polyester with glass reinforcement (Depro et al.,2002).

Filament winding

This is a technique that is most easily described as loom combined with a CNC machine. Single or multiple tows (yarns) are wound around a mandrel. This type of manufacturing is expensive, but yields a product that can be engineered and therefore is stronger than typical fabrication techniques using prepregs or wet lay up with vacuum bagging (Depro et al., 2002).

Previous studies

Several studies have been done in the field of fibre-reinforced composites, across the world, to establish the reinforcement effects of composite materials. Three studies that are relevant to the present study are: Inside II: Measuring Reinforcement effects in Composite Materials in Bartlesville, Oklahoma - USA conducted by Stephanie L. Orlosili (http://gas.co.uk/edu/98/T98/ORLOSK.HTM); Compatabilisation of natural fibres for use in polypropylene matrix in Wales, Bangor, UK, conducted by Spear, M. J. (2002) and Fatigue damage mechanism and failure prevention in fibreglass reinforced plastic – Sao Carlos (2005).

Bartlesville study

This study sought to determine the strength characteristics of polyester resin composites containing two types and five configurations of reinforcing materials. It hypothesised that the composition and concentration of reinforcing materials used in the composites would have varying effects on the strength of the different test coupons. A standard test was used to measure coupon deflection with increasing load. Coupons moulded from resin containing carbon fibre and glass strand reinforcing materials were cured and tested. Test data were entered into a computer spreadsheet to calculate the force on each coupon, its deflection, stiffness and maximum stress at failure.

The results showed that glass strands as reinforcement significantly increased coupon stiffness and strength compared to resin alone. Carbon fibres in equivalent volumes increased this even more. Figures 47 and 48 show the average stiffness values for the different coupons tested.

The results show that both reinforcing materials increased coupon strength to various degrees depending on their percent of fills. The charts of stiffness and strength showed that doubling the reinforcement volume fill does not double the strength of the coupon.

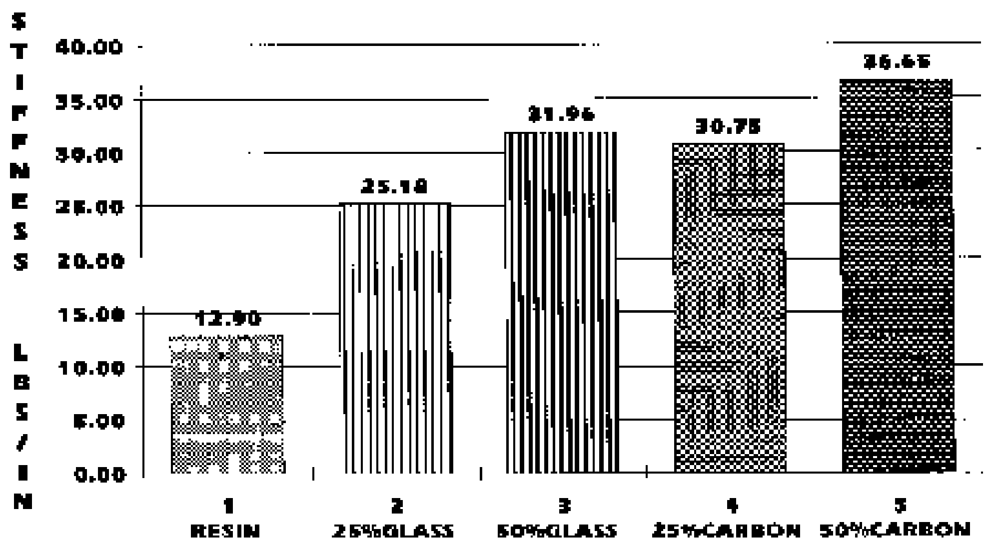

Figure 48. Average stiffness values for the different coupons tested

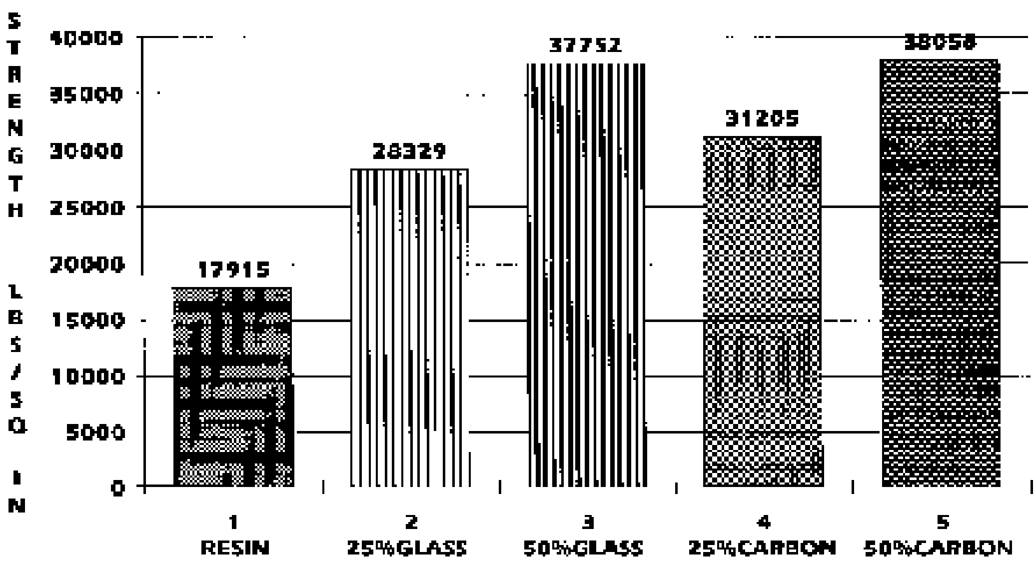

Figure 49. Average strength values for the various test coupons

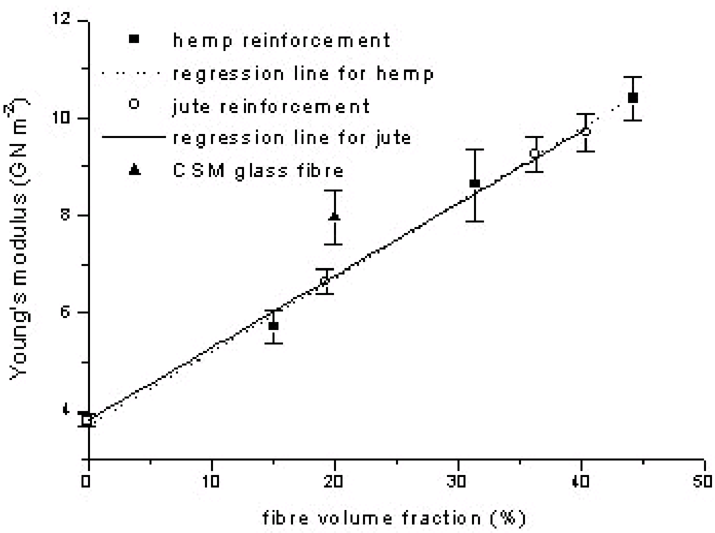

Figure 50. Fibre volume fraction

Standard deviation of measured stiffness values for all tests averaged 8%. Standard deviation of failure strengths derived from the test data averaged 17%.

The Welsh study

The aim of this research was to investigate the use of natural fibres (flax, hemp, etc.) as reinforcement in thermoset and thermoplastic matrices. It became apparent that the potential of natural fibres is far from being realised. It was observed that whilst the stiffness and to a lesser extent the strength (on a volume by volume basis) of hemp reinforced polyester is on a par with that of glass fibre reinforced material; toughness is substantially inferior. A significant contribution to the high strength to fracture exhibited by glass fibre reinforced composites is attributed to fibre pull out.

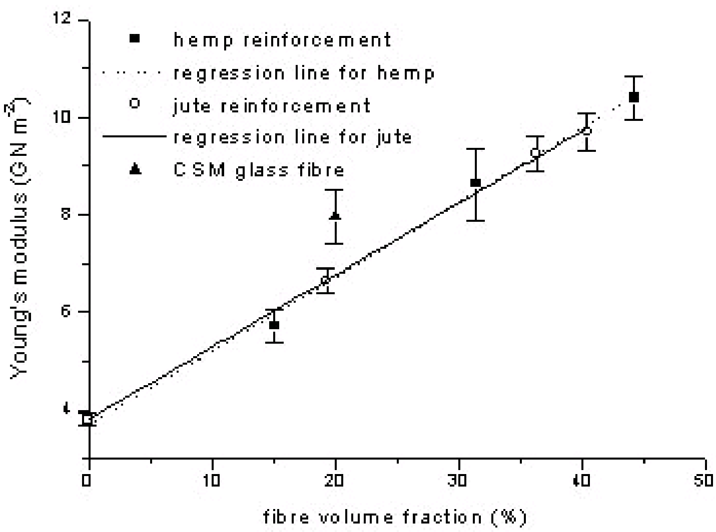

Figure 51. Variation of Young's modulus with fibre volume fraction (non-woven hemp, jute and chopped strand mat glass fibre reinforced polyester laminates)

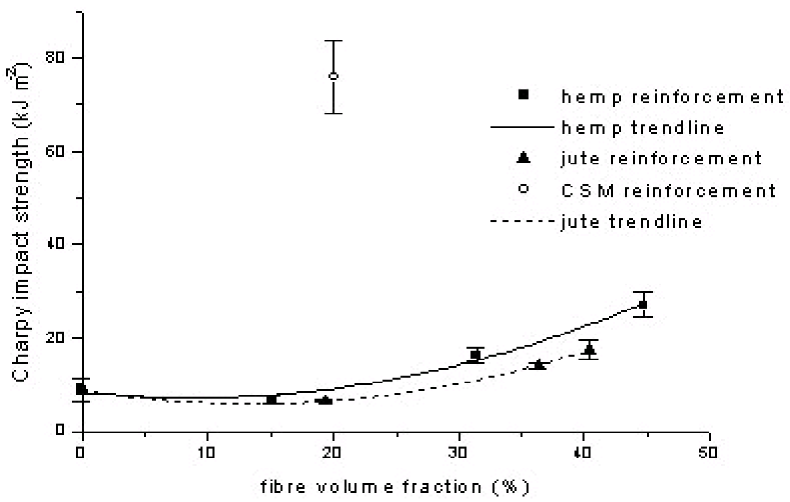

Figure 52. Variation of Charpy impact strength (unnotched) with fibre volume fraction (non-woven hemp, jute and chopped strand mat glass fibre reinforced polyester laminates).

6.4 Sao Carlos study

This study investigated the damage formation and propagation during fatigue tests of two composite laminates with symmetric and asymmetric distribution of E-glass fibre layers in an orthophtalic polyester matrix. Short fibre mats and bi-direction woven fabric textile were evaluated. Different maximum applied stresses were evaluated and uniaxial tensile and compression tests were conducted in order to determine the ultimate strengths of the laminates.

The results show that symmetric distribution of layers allows better accommodation of internal stresses reducing the number of points of stress concentration and delaying the formation of transverse cracks. The laminate with 10 layers displayed higher fatigue resistance than the laminate with 12 layers. Also virtually no signs of damage were observed in 10 layer laminates after 29% of the fatigue test whereas 12 layer laminates revealed extensive delamination after 34% of the test.

Research methodology

Study area

This research was conducted in the workshop of Sai Raj Fibreglass Company Ltd, Nairobi. The testing of the prepared laminates was conducted at Kenya Bureau of Standards (KEBS). Sai-Raj uncovered the problem being investigated. Vehicle body panels were constructed using estimated amounts of fibre and resin. The resulting materials were not tested to determine mechanical properties.

Experimental set-up

The first step in the experiment is to gather the tools and materials needed which include:

Tools

- Brushers
- Mixing cups
- Stirring sticks
- Hand rollers
- Measuring devices-steel rule, Vanier callipers
- Protective equipment
- Squeegees.

Materials

- Chopped stand fibreglass mats
- Parting agent
- Gel coat

- Hardener
- Sisal fibre
- Resin.

Experimental procedure

The first step involved preparing the mould by coating it with a parting agent to allow easy removal of the test specimens, followed by mixing the polyester resin with the hardener. The second step is to have the first layer of the reinforcement laid out and the resin worked into it then leaving it to cure at room temperature. The hand lay-up technique is used. This process involved no added heat or pressure and uses simple equipment and tooling. After curing, the thickness is measured and recorded since it is this parameter that will vary. Samples were cut to dimensions of 120mm by 30mm.

To produce laminates of differing thickness, the same procedure is followed but with the addition of second and then third layers.

The third step is the actual test procedure. The test specimens are subjected to varying loads and the deflection noted and recorded at the mechanical laboratories at KEBS. The load is increased gradually in terms of quantity until the breaking point of the specimen is reached. The deflection at specimen yield and failure is read and recorded. This procedure is repeated for each test piece.

The experiment is set up as illustrated below. The test specimens rest on supports as shown. The load W is subjected to the test pieces. The dotted lines show the test specimen on subjecting it to load W and the resultant deflection ‘y’, of radius R.

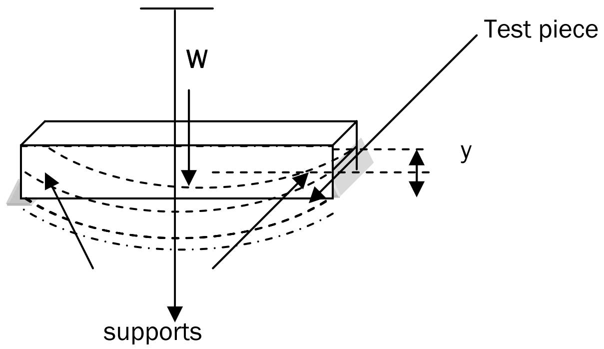

Figure 53. Three Point Bend Test set up.

The test specimens are subjected to a three-point bend test as shown above. The other tests applied are the tensile test, water absorption test and screw withdrawal test. The test results will be compared with KEBS standards and ASTM standards and will be used as the basis for selection and matching of materials to potential uses.

Data analysis

Since the hypothesis is that the type of reinforcing material and laminate thickness will have varying effects on the strength of the test specimens, the data are entered into an Excel spreadsheet to calculate for each laminate the force, deflection, stiffness and maximum stress at failure. The force at yield is divided by the specimen deflection to arrive at the stiffness value of the test piece with units of Newton/millimetre (N/mm). The results are used to construct a graph of deflection as a function of load, for analysis of the deflection effects of thickness on the strength of the various laminates. This procedure is repeated for the other reinforcing material. The equations applied in the calculations are:

$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$$

where:

W (N) _ applied force
b (mm) _ breadth
d (mm) _ width
M (Nmm) – applied bending moment
I (N/mm^4) – second moment of area about the neutral axis and

$$I = \frac{bd^3}{12}$$

σ (N/mm^2) – direct stress and $\sigma = \frac{Force}{Area}$

y (mm) – deflection i.e. distance of layer from neutral axis to outside fibre

E (N/mm^2) – elasticity of the material of the beam and $E = \frac{Stress}{Strain}$

R (mm) – Radius of curvature of the subsequent bending.
Normal stress = Force/area at contact point
= N/mm^2

3.5. Expected results

The results are expected to show the:
i) specifications in strength of the fibres
ii) optimum strength in specific quantity of fibre and resin
iii) the industrial applications for the two fibres.

The reinforcing materials exhibit differing percentages of deflection at yield and at failure.

Dissemination of results

The researcher will brief all stakeholders in the research on the developments and progress of all stages of the research via monthly and final reports and a dissemination seminar.

The stakeholders include;
(i) Sai-Raj Company Ltd., Nairobi, Kenya.
(ii) Kenya Bureau of Standards, Nairobi.
(iii) Egerton University, Njoro, Kenya.

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6.5 The potential of agricultural wastes for the building industry

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Abstract

Kenya has an agricultural based economy. The harvesting activity produces agricultural wastes that are normally burnt causing environmental pollution and global warming. Recent research developments have shown that the agricultural wastes can be used to produce useful engineering products that can be used in the building industry.

Dwindling wood resources have threatened rainfall reliability and wildlife survival as a result of deforestation caused by human activities. The use of agricultural wastes to produce useful building products will go a long way to reduce the current pressure on wood and wood based products. Synthetic resins have adverse health effects on the end users. Research developments have revealed that natural resins derived from processing natural products have less health effects and are environmentally friendly. Some have higher physical and mechanical properties than the synthetic resins.

The paper reviews the various non-wood based plant fibres that have been successfully used in the recent past. The paper indicates some of the mechanical and physical properties of the non-wood plant based building products. It compares some of the physical and mechanical properties of non-wood plant based building products made from both synthetic and natural resins, and non-wood plant based reinforcement materials from agricultural wastes. The paper concludes that it is possible to make useful building products from non-wood plant based agricultural wastes, synthetic resins and naturally occurring resins that have better physical and mechanical properties than existing wood-based products.

Introduction

When Kenya achieved independence in 1963, food, shelter and clothing were recognised as the most important basic requirements. The Kenyan government formulated policies aimed at eliminating disease, poverty and ignorance. It was not until the early 1980s that food and shelter were generally available to the majority of the Kenyan population. Kenya is a developing country and is faced with the challenge of improving the living standards of its people while preserving the environment. The population of Kenya has grown from some 9 million in 1963 to about 31 million in 1999 (Anon, 1999).

Demand for shelter has massively outweighed supply leading to ‘squatter’ communities in Kenya. The majority of the Kenyan people live in rural areas and are poor, using wild grass (thatch) or in very few cases iron sheets for roofing, mud reinforced with grass for building house walls and poles for partitioning, and pruned branches for cross linking walls. Floors are generally scraped with mud, a composite of soil and water supplied by nature. The majority of these rural Kenyans depend on agriculture as their main activity and source of income.

Housing in urban areas usually consists of roofs from corrugated iron sheets, ceramic tiles and sometimes asbestos-cement corrugated sheets. The internal constructions for ceilings and partition walls are usually fibreboard, hardboard and linings of soft and hard boards. The population increase has not been matched by an increase in housing materials availability in either rural or urban settings.

The increased demand for affordable housing materials has led to high rates of depletion of natural forests, woodlands, wild grass lands and the emergence of slums accompanied by lower levels of rainfall and increased desertification. The environment and ecosystem have been affected, and wildlife is being threatened by the population's need for shelter.

To address the twin issues of deforestation and transfer of technology, appropriate and affordable technologies are required. The development of plant fibre reinforced composites through technology transfer is a solution that is environmentally friendly and addresses the problem of dwindling wood resources. Kenya boasts abundant varieties of plant materials, such as sisal, cotton, coir, kapok, banana, pineapples, palm leaf, papyrus, bamboo, etc., whose fibres could be used to reinforce polymeric and ceramic matrices to produce useful composite materials, which would solve rural and urban housing problems. Only a few of these fibres have been exploited commercially due to lack of appropriate technology for product manufacture and initial capital for investment. Synthetic resins are generally expensive and not readily available. Their resources are also depleted. Kenya is rich in naturally occurring matrix materials available from trees, such as wattle tannin, cashew, and also from the paper industry (Ogola, 2000).

Strategies for addressing housing problems in Kenya

There was a meeting of world leaders at the special Millennium Summit of the United Nations in September 2000, to establish a series of goals for humanity in the 21st Century. This was based on key policy documents from the series of major United Nations conferences held in the 1990s, including Agenda 21 and The Habit Agenda.

The most important target in the context of this discussion is Target 11:'By 2020, to have achieved a significant improvement in the lives of at least 100 million slum dwellers, which builds upon the Cities Alliance's 'Cities Without Slums' initiative'. This contrasts with the fact that 67% of Kenyans live in the countryside.

Kenya's first attempt at a national housing policy was in Session Paper No.5 of 1966/1967. It was the result of an investigation into short and long term housing needs in Kenya, conducted by a United Nations Mission on behalf of the Government. The Mission made recommendations on the policies to be pursued within the framework of the nation's social and economic development. The main principles guiding the development and control of housing in Kenya were outlined in the Urban and Rural Housing Policy; Finance for Housing; Administrative Organization; Housing Programme; Research and Education. The Government was convinced that:

> Housing is a vital factor in the nation's economic and social development and its effects have a bearing on the morale and stability of Kenya; The productive capacity of Kenya's labour force was related to the state of its health; Decent living environments are conducive to good health.

At the time Kenya's population was well over 9 million, 8 million of whom lived in the countryside. Annual population growth was estimated at 3% for the whole country and 5-6% in urban centres.

One of the main recommendations of the UN Mission was that a National Housing Authority should be created to be the main instrument for the prosecution of Government housing policy 'the supervision of the housing programme for the country as a whole must rest with the Government through the Ministry responsible for Housing'.

If towns are not to develop into slums, and centres of ill-health and evil social conditions, low income urban housing and slum clearance must continue to form the major part of the nation's housing programme. It will be the responsibility of local authorities under their by-laws, as well as the national housing authority to ensure close supervision of such projects so that buildings are erected according to approved plans and specifications, and to avoid the creation of slums.

These noble objectives were really no more than a 'wish list'. The situation was exacerbated by a population explosion, rapid urbanisation, widespread poverty, and escalating costs of housing. Kenya's revised National Housing Policy as articulated in Session Paper No.3 of 2004 is intended to address the deteriorating housing conditions countrywide and to bridge the shortfall in housing stock arising from demand that far surpasses supply, particularly in urban areas. The shortage in housing is manifested in overcrowding, and the proliferation of slum and informal settlements especially in urban areas. In rural areas the shortage manifests itself in the poor quality of the housing fabric and lack of basic services such as clean drinking water. The policy aims at:

- enabling the poor to access housing and basic services and infrastructure;

- encouraging integrated, participatory approaches to slum upgrading, including income-generating activities that effectively combat poverty;
- promoting and funding of research on the development of low cost building material and construction techniques;
- harmonising existing laws governing; Facilitating increased investment by the formal and informal private sector, in the production of housing for low and middle-income urban dwellers;
- creating a Housing Development Fund to be financed through budgetary allocations and financial support from Development partners and other sources.

The Economic Recovery Strategy for Wealth and Employment creation launched by the Kenyan Government in June 2003 is intended to introduce a National Housing Policy that comprehensively addresses the problem of providing shelter, including informal settlements. This Session Paper comprises four elements, the policy targets, and highlights urban housing, rural housing, slum upgrading and vulnerable groups; and proposes solutions to include poverty alleviation.

Housing problems and challenges in Kenya

Investments in the housing sector since the 1966/67 Policy have been minimal and sporadic. The demand for housing still far outstrips supply. Research into low cost building materials and construction techniques has been limited and thus not helpful to the development of the sector. Stringent planning regulations and high infrastructural standards have been an impediment to the delivery of housing. The high level of poverty has rendered access to decent housing an elusive dream and the ranks of people living below the absolute poverty line are continuously growing.

The problem in urban areas is mainly one of acute shortage of habitable dwellings, inadequate infrastructure, community facilities and services, overcrowding and extensive slums and squatter settlements. The major problems in rural areas are mainly poor quality of shelter fabric and limited access to safe drinking water.

Estimated current housing needs are 150,000 units per year for urban areas and 300,000 units per year for rural areas. Current production of new housing in urban areas is only 20,000-30,000 units annually, a shortfall of over 120,000 units per annum. This has produced more squatter and informal settlements and overcrowding.

Various interventions and strategies have been devised in an attempt to alleviate this situation. The overall goal of the Housing Policy is to facilitate the provision of adequate shelter and a healthy living environment, at affordable cost, to all socio-economic groups in Kenya in order to foster sustainable human settlements. This will minimise the number of citizens living in shelters that are below habitable living conditions. It will also curtail the mushrooming of slums and informal settlements, especially in the major towns.

The poor's pragmatic approach to housing should be harnessed by community-based organisations in effective and well-defined participatory initiatives. Community involvement as a planning tool will be advocated in all housing programmes targeting the poor.

Government recognises that security of land tenure as well as availability of adequate areas of land in suitable locations at affordable prices is a central requirement for clearing the backlog of housing demand for the poor. Housing programmes for the poor will be pursued on a scale that is commensurate with need and availability of resources.

Developments in reinforcement building materials from agricultural wastes

Agricultural wastes are the residues from harvesting or processing of crops. Waste is used for biomass and sometimes as manure. The majority is burnt, increasing environmental pollution. On average over, 14,770,000 tonnes of agricultural wastes are generated annually in Kenya (Onchieku and Githiomi, 2000).

Sisal fibre tow and flume, which occurs as wastes from the decorticating process, have been used to make woven materials, and laminated to produce composite panels with sound mechanical and physical properties used in the building industry (Bisanda, 1988).

Coir, the fibrous material surrounding the nut of the coconut fruit, is a useful reinforcement for certain ceramics and polymers (Owalabi *et al,* 1983). Coconut pith and coir waste have been utilised as fillers in natural rubber products, such as rubber cork, teamat, cellular sheet, partition board, packaging materials, etc. (Chandaran et al., 1995). Coconut leaves blended with cashew nut shell liquid (CNSL) have been successfully used for thatching.

Coconut fibres (retted or unretted) mixed with CNSL or cement has been produced for roofing (Rai, 1997). Coconut pith mixed with cement or bitumen has been used as insulation boards and expansion joint filler. Coconut chips mixed with Phenol Formaldehyde (PF) have been used as particle boards (Rai 1997). Coir fibre with fly ash as lime or cement as the binder has been used for bricks and blocks for walling. Coir fibre cement bonded panels of 1300-1400 kg/m³ densities have been used as panels in door shutters, windows and several engineering applications.

Kapok fibre, a cellulose plant fibre, sometimes referred to as 'silk cotton', can be processed to produce hybrid textile material by blending it with cotton to produce textile materials or reinforcement material for composites in polymeric matrices for the building industry (Mwaikambo and Bisanda, 1997).

Papyrus fibre (*cyperaceae*) family has been processed to provide reinforcement for polymeric matrices giving light weight composites for general purpose building applications (Bisanda, 1997). Bamboo from the *bambusoidae* family has been used in grid shells for the construction industry (Vasavada, 1986), as a reinforcement material for rainwater cisterns (Robles-Austrialo, 1991) and in the production of paper and fibreboards. Bamboo (spilt) and pulped with mud and cement has been used as wall panels and as concrete for posts, roofs, rafters, electric poles etc. Bamboo has also been successfully used as an electric conduit (Bisanda, 2000).

Bagasse, the fibrous residue of sugarcane, has been processed to produce fibre and particle board (Hesch, 1993, Ayensu, 1996). These can be pressed into panels and blocks using Urea Formaldehyde and Phenol Formaldehyde resins.

Rice husks, the residue obtained from paddy grain processing have been successfully used to produce particleboard using synthetic resins (Shukla et al., 1985). Its pozzolanic properties have enabled it to used to produce Portland cement or hydrated lime (de Gutierrez, 1994; Okpala et al., 1993). Coffee husks, a by-product of coffee processing, have been successfully used to produce particleboard using both synthetic and natural resins (Ogola, 2000).

Maize waste in form of cobs and husks has been successfully combined with synthetic resins to produce particleboard for the building industry. Other useful wastes under research include groundnut shells, pineapples, beans, sunflower, wheat straw and hyacinth.

Table 6 shows some of the non-wood plant based fibres that are produced in Kenya (Onchieku and Githiomi, 2000) using the waste factors used by Bisanda (1999) to estimate annual wastage.

Table 6 - Estimates of the annual production of agricultural wastes from some crops grown in Kenya. (Onchieku & Githiomi, 2000)

Waste	Primary Product	Waste Factor	Primary Product Production ('000 tonnes)	Estimated Amount of Waste ('000 tonnes)
Coffee husks	Coffee bean	0.2	79.9	15.98
Rice husks	Paddy rice	0.325	14.0	455
Rice straw	Paddy rice	3.78	14.0	52.92
Coir	Copra	0.7	-	-
Coconut husks	Copra	2.0	-	-
Bagasse	Sugar cane	3.3	4.100	43,530
Sisal tow/flume	Sisal fibre	2.0	25.6	51.2
Corn cob	Maize	0.25	287.2	71.8
Corn straw	Maize	2.0	287.2	574.4
Groundnut shells	Groundnuts	0.6	-	-
Cashew nut shells	Cashew kernel	-	-	-
Wheat straw	Wheat	3.5	132.8	469.8

Potentially available natural resins/binders

Due to the scarcity and dwindling resources of otherwise expensive imported synthetic resins, such as urea formaldehyde, phenol formaldehyde, etc., there is a need to look for and research local readily available resins. Further, synthetic resins emit formaldehyde during their life, which, when inhaled, is hazardous. Kenya is rich in environmentally friendly resins obtainable from natural resources, as shown in Table 6.

Table 7 - The potential natural resins in Kenya

RESIN TYPE	PRIMARY SOURCE	LOCATION	QUALITY
Tannins	Wattle tree	Eldoret, Thika	Abundant
Cashew Nut Shell Liquid (CNSL)	Cashew tree	Kenyan coast	Abundant
Oleo-resin	Pinus Patula, P. Caribaea trees	Nakuru, Machakos	Abundant
Oleo-gum-resin	P. Elliottii, P. Radiata trees	Taita Taveta	Abundant
Lignin-based adhesives	Pine needles. Populus (poplar) trees, Willow (Salix) tree	Pulp and paper mills Webuye	Abundant

Some useful results from agricultural waste engineering products

Tables 8, 9 and 10 show some of the results sourced from different researchers showing the mechanical and physical properties for the various particleboards from various agricultural wastes. It can be seen that there is great potential for the use of agricultural wastes in Kenya.

Table 8. Modulus of elasticity (MOE), modulus of rupture (MOR), impact and tensile strength of the various particleboards.

Particleboard	Density (kg/m^3)	MOE (MPa)	MOR (MPa)	Impact (KJ/m^2)	Tensile strength (MPa) (||)
Coffee husks/UF	1032.9	1089	5.15	3.36	0.66
Coffee husks/Tannin	1034.8	1216	6.47	11.32	2.27
Wood Tannin	962.5	1332	12.86	-	-
Maize husks/UF	190-540	427	5.7	-	5.8
Maize cobs/UF	190-540	930	6.5	-	6.9
Rice husks/PF	1300		33.9	-	1.3
BS 5669 part 2 grade C_1		1920	13	-	-

Table 9. Water absorption properties for the various particle boards (Ogola, 2000)

	Water absorption as a %				
Particleboards	Density (Kg/m^3)	Q_{1hr}	Q_{2hrs}	Q_{24hrs}	Q'_{2hrs} (Boil test)
Coffee husks/UF	1032.9	24.29	27.86	27.86	Disintegrated
Coffee husks/tannin	1034.8	8.4	14	14	56.6
Wood /tannin	1007.9	14	23	32	106
Rice husks/ PF	1300	-	8.43	14.55	-

Table 10. Thickness swelling properties of the various particleboards. (Ogola, 2000)

	Thickness swelling as a %				
Particleboards	Density (kg/m^3)	λ_{1hr}	λ_{2hrs}	λ_{24hrs}	λ'_{2hrs}(Boil test)
Coffee husks/UF	1032.9	20.21	26.24	54.02	42.4
Coffee husks-Tannin	1034.8	6.02	7.6	15.3	-
Maize husks/UF	190-540	-	-	-	-
Maize husks cos/UF	190-540	-	-	-	-
Rice husks/PF	1300	-	3.07	11.53	-
BS 5669 part 2 grade C_1	-	-	-	-	-

Available technology systems for manufacture of composites from agricultural wastes

The selection of composite processing methods depends on the raw materials and the binder being used. The most common method is hot compression moulding when thermosetting resins are used. Agricultural wastes in the form of random materials can be used in hot compression moulding. If they are pulped, convection pulping techniques can be used to produce the desired type of pulp to produce paper and fibre boards. The binding materials required to meet the desired mechanical and physical properties and the necessary chemical modification must be taken into account.

Laminated composites can be produced using moulding techniques and techniques such as injection moulding and extension for non-continuous fibres and thermoplastic matrices. Nearly all convection techniques for composite manufacture can be employed for plant fibre reinforced composites.

Drawbacks to bio composites technology in Kenya

Although there is a lot of raw material (agricultural wastes) available in Kenya, very little R&D has been done on how to make these wastes useful because of lack of information on composite materials, lack of trained personnel, absence of a national forum and framework to provide a close link between researchers, private entrepreneurs and the end users, lack of interest from investors in new product developments, poor attitude to locally made materials, and insufficient information on potential renewable resources. There is no regional co-operation and there is a lack of co-ordination of the R&D that is being conducted. In addition, standards need to be formulated related to products based on agricultural wastes.

Solutions to R&D problems in bio-composites technology in Kenya

In order to promote bio-composites development nationally, regionally and internationally, the following measures should be adopted.

i. Provision of information on bio-composites technology development through conferences, seminars, the Internet, databases, etc. and related institutions, and through networking of researchers and entrepreneurs in the field.
ii. Sharing of limited research facilities in Kenya.
iii. Detailed inventory and characterisation of raw materials.
iv. Exchange of research scientists amongst institutions and industries in this field.
v. Dissemination of research findings and demonstrations and open days to improve user confidence in these products.
vi. Creation of an appropriate intellectual property rights regime to encourage publication of research findings and acquisition of patents.
vii. Establishment of KEBS standards to apply to the new products.
viii. Greater national, regional and international co-operation among researchers and industrialists.

Conclusion

The above shows that the potential for agricultural wastes to be used to manufacture building materials could benefit mankind and to ease the current pressure on wood, benefiting wild life and conserving rain forests.

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CHAPTER 7

7.1 The Life Cycle Assessment (LCA) method

The LCA method involves four steps:
1) Goal and Scope.
2) Life Cycle Inventory.
3) Impact Assessment.
4) Interpretation.

These steps are described in the international standards (ISO 14040, ISO 14041). The steps are iterative.

Step 1: Goal and scope

This step defines the goal and scope of a study. The execution of the LCA method will vary according to the goal of the study. There are several factors related to goals:
1) Whether the work is intended for an audience of company decisions-makers, which would mean that the study would need to be less rigorous than if it were to inform policy-makers.
2) Whether the goals are strategic or tactical. This affects the level of risk involved, and determines the level of certainty required. A tactical goal, such as deciding between two materials, involves little risk and a streamlined study would be adequate. A full study would be required when the goal of the study is to assist in making strategic decisions, which involve significant revenue or major cost implications.
3) Whether a 'critical review' will be desirable, or even necessary, which would involve an independent third-party panel of experts to review the work (ISO 14040).

The scope of a study establishes how and where the data are to be compiled, including the system boundaries and functional unit for the study.

System boundaries are defined according to the intended goal. System boundaries determine what will be included in the study and what can be left out. Central to this is the functional unit for the study — this explicitly defines the service or function provided by the system (e.g., structural integrity for 50 years, hazardous waste disposal to defined criteria).

The results of the LCA study will relate directly to the functional unit; e.g., if the functional unit is 1kg of a product, the results will include the amount of pollutants released for every kg of product that is made.

'Unit processes' are defined usually through a process flow diagram, to establish the physical sequence of mass and energy activities across the life cycle. For simple, macro-level studies there may be a few unit processes; for complex studies, particularly if primary data are to be collected, the number of unit processes may be in the hundreds.

Step 2: Life cycle inventory

The Life Cycle Inventory (LCI) analysis (ISO 14041) involves compiling an inventory of the relevant inputs and outputs of a product system, covering multiple environmental aspects. The data inventory for each unit process is defined by the system. Depending on the study and aims, first hand data may be collected through measurements and estimates of key energy and materials usage, which relate directly to process optimisation and to economic savings.

Step 3: Impact assessment

Life Cycle Impact Assessment (ISO 14042) evaluates the possible environmental impacts associated with measured environmental inputs and outputs. It is important to note that LCA is not a single-issue tool; rather, the analysis encompasses numerous environmental issues (e.g., energy, water pollution, climate change), thus allowing for broad consideration of the impacts of the system. The results of a Life Cycle Impact Assessment will be a quantitative profile of environmental parameters. Information may be examined at a disaggregated level from the inventory (e.g., carbon dioxide, nitrogen oxide) or may be grouped or aggregated according to environmental indicator categories, such as greenhouse gases or toxicity. Many studies are taken to a point where results are expressed as selected environmental indicators or scores, whether for large-scale system comparisons, technology scenarios or internal improvement assessments.

Ranking and scoring are optional elements, guided by ISO 14042. In this step, LCA can be extended beyond quantitative measurement and analysis to a point where an evaluation or judgment is made. At its simplest, this may be an assessment of what is better or what is worse; for example deciding between two production processes. The intent is to provide insights into priorities based on the data; value judgments have no scientific basis.

> LCA provides structure and direction to help decision-makers focus on key priorities for environmental sustainability. Sets of indicators have been developed, addressing commonly agreed and important environmental impact categories. Note, however, that additional environmental and other analysis will still be necessary to complete any decision.

Judgments about the relative importance of specific issues are challenging. Depending on the goals and scope of the LCA study, different indicators will exhibit different value. If the decision is narrow and local versus global and strategic, considerations related to global warming potential versus toxicity versus water use will differ.

Note: Indicator results are for illustrative purposes only, and are not intended to be representative of LCA study indicator results.

Step 4: Interpretation

Interpretation (ISO 14043) is the final phase of the LCA. The analyst looks at environmental aspects (energy use, greenhouse gas emissions, etc.), contributions to indicators or scores, and significant unit processes in the system. For example, if the results of an impact assessment indicate a particularly high value for the indicator for global warming potential, the analyst could refer back to the inventory to determine which outputs are contributing to this high value, and which unit processes those outputs come from. This can also be used as a form of quality control. It helps to provide more certain conclusions and recommendations. The procedure typically involves examination of the sensitivity of results, performance of a scenario analysis, review of data quality, and a comparison of the results with the original goals of the study.

7.2 State of practice and validity of a product approach

Applying LCA to the 'product' provides a tangible focal point for environmental consideration of processes beyond the chosen product. The product perspective provides a framework within which decisions can be made: there are markets for products; businesses make products, and consumers use products. A product-oriented approach is based on concepts that are already known in traditional product evaluations, but simultaneously is broadened to include consideration of environmental issues connected to the whole product life cycle.

End-product sectors with significant activity and application of LCA include:
- Appliances
- Automotive
- Buildings and construction
- Detergents and chemicals
- Electronics
- Food
- Military equipment
- Packaging
- Paper products
- Waste management.

In product-focused environmental management, the product represents the tangible outcome of a production system that delivers an economic value (e.g. cement for the cement industry). However, in the functional unit approach, services are analysed alongside LCA. Sectors such as waste management use the LCA tool in decision-making to understand and evaluate long-term technological options for management and policy.

When a product-orientation approach is applied, consideration of environmental issues is extended. Conventional frameworks for environmental management include the facility (e.g., permits for emissions control), the sector (e.g., industry regulations), the medium (emissions to air, water or soil), habitat and, more recently, even a single chemical substance (e.g., chlorine). Using the product as a focus for information, requires both existing and new datasets. Production, use and disposal information on a product demands extensive data sets.

Ability to see trade-offs

Single issues (such as solid waste or energy) can be seen in perspective and aligned with broader priorities (such as resource utilisation, climate change, or toxic reduction). The product life cycle (PLC) helps identify potential problem shifting, i.e. where a waste might be combusted to air, but subsequently precipitated to surface water, eliminating the waste but not the real problem. LCA provides a way to see trade-offs between issues, and across different activities. This approach provides a constructive perspective for broader and more comprehensive environmental management.

Limitations of the LCA method

Systems analysis, structured around the functional unit, tends to obscure important factors necessary to determine real environmental impacts. Both spatial and temporal specificity are usually lost during the inventory; thus the life-cycle impact assessment step can only approximate potential environmental impacts, and does not address or estimate real impacts. This challenge is an area of continuing LCA research.

In the early days of LCA the tool was seen as a panacea, a means of providing conclusive environmental evaluations of products and systems. Since the mid-1990s, particularly after the release of the first ISO standard in 1997, the tool has found a more realistic position in the environmental toolbox. Early use of LCA for comparative assertions led to guidance defined in ISO 14040 to prevent misuse of the tool. LCA should be understood as a source of information that can feed into sustainability decisions. Economic contexts, social priorities and other environmental data are also required.

One of the more challenging parts of an LCA study is the final determination of significant environmental issues. Although the method structures this step, using data and indicators, the value-choices in the judgment are ultimately provided by the sponsors or analysts of the study. This applies to tools such as cost benefit analysis or engineering design, where, if objectives are clear, the decision can be transparent and conclusive. If goals and objectives are not clear, there will be a degree of uncertainty, leading to inconclusiveness and loss of credibility

CHAPTER 8

8.1 LCA Concepts for Low-Cost Building Materials

Foreword

1. 'Sustainable development' aims at preserving the earth's natural resources in order to elevate physical, economic and social living conditions for present and future generations. The global environmental crisis cannot be ignored and the world's economic development, achievable through its industries, is crucial to its existence. Environmental management tools are needed to ensure environmental sustainability.

2. 'Building Materials for Low Cost Housing' should, as far as possible,, withstand environmental effects.

3. 'Life Cycle Analysis' is a process-oriented environmental management tool for determining the environmental impact of a product, service and process through its holistic life cycle - the production, usage and disposal stages of its lifetime. This will enable decision makers to understand the impact that a product, process or service will have on the environment. LCA helps to identify the areas in a production process that are very polluting. It is advantageous for the planning and design stages, and the final stages, i.e. disposal, of a product's life cycle.

Overall, LCA to support product development can provide innovative, economic, health and environmental benefits. In other words, it eliminates some of the risks in financing and undertaking the implementation of a project (in this case, alternative materials for low cost housing). By taking account of the industry's environmental consequences, approval, acceptance and project success can be more easily assured. LCA results will facilitate decision-making while ensuring that environmental impacts are considered. The environmental impact of a product is to a largest extent determined by the type of materials used (chemical and physical properties) and on waste management.

8.2 LCA of timber as a building material

Forestry products and hard-wood timbers in particular, have a long history as building materials - for framing, lining, cladding, flooring and roofing in domestic and industrial constructions, as well as bridges, wharves, railway sleepers, and so on. In relatively recent times, a range of materials, such as steel, aluminium, concrete, etc. have been introduced into the construction industry. New wood products, such as particle-board and glue-laminated-boards, have also been developed. As a result, there is a range of building materials available whose choice involves several factors. In the past, the factors influencing the choice of building material were predominantly related to 'suitability', 'cost', 'availability' and 'appearance'. Now, consumers are becoming more and more concerned about the impact these products may have on the environment in relation to global warming, wildlife and human health and especially in relation to the impact of the use of timber and timber products. Wherever possible, wood products are being substituted.

For comparisons to be valid, all environmental impacts during the life of all products should be accounted for. However, here we are concerned with overall net benefit. The process of evaluating the total environmental impact of products can be approached by using LCA techniques to measure the impact of a product on the environment - from raw materials extraction, through the product's life, to when it is disposed of or recycled. LCA is also described as 'cradle-to-grave' analysis, eco-balance, product life-cycle-analysis, and resource and environmental profile analysis.

LCA methods are based on traditional ways of comparing product characteristics such as the 'embodied energy' of a product - that is, the energy used to produce the materials, process them, transport them to where they are needed and construct and maintain the finished product. LCA methods extend the concept of embodied energy by including the pollution associated with obtaining, using and disposing of products, and the extent to which resources are depleted or damaged in the product's manufacture, use and disposal.

There is no single LCA methodology, although the International Organization for Standardization is coordinating the development of global guidelines for LCA methods. LCA models vary in complexity. At the simplest there are systems such as the UK 'Eco-labelling' approach - an approach similar to the 'Energy Rating' system applied in Australia. At the other end of the spectrum there is the Canadian approach which attempts to quantify and include factors, such as manufacturing effluents and water demand, in the assessment.

One LCA approach that applies to the Australian construction industry is the Building Material Ecological Sustainability Index (BES Index), which was developed at the University of New South Wales. This index enables products to be rated according to the following factors.

A) In the area of resource depletion:
1. the damage caused by the extraction of raw materials;
2. the extent of damage relative to the amount of material produced;
3. how much of the raw material exists;
4. how much of the product consists of recycled materials;
5. the environmental cost of maintaining the finished product; and
6. the extent to which the product can be recycled.

B) In the area of pollution:
1. the amounts of solid and liquid waste, greenhouse gases, toxins and particulates (dust) resulting from extraction, manufacture and production;
2. the environmental cost of fabrication and on-site waste and packaging;
3. the environmental impact during the building's life (such as that involved with heating, cooling and lighting); and
4. the environmental impact at the end of the life of the building (e.g., the cost of disposal).

C) In the area of energy use:
1. the energy required to obtain raw materials, process them and produce the building material;
2. the energy used in transporting the material (at all stages); and
3. the energy used in construction and eventual demolition.

Life cycle assessments can help designers to compare the environmental and ecological credentials of substitute products and can help manufacturers identify where improvements in extraction, processing and disposal need to be made. However, they are not perfect tools.

In using LCA methods it is important to acknowledge that results:
1) are often based on incomplete data, especially in relation to specific local or regional conditions;
2) by necessity, may involve some qualitative judgment;
3) become mostly focused on environmental factors and, sometimes, do not address relevant technical, economic or social aspects of the product or process under assessment; and
4) may depend on particular assumptions about the life of a product.

Nevertheless, LCA methods can provide valuable insights into the nature of products and materials processes.

By definition, LCA is a holistic approach. However, for ease of presentation and comprehension, the various components of LCA methods are treated separately but it must be emphasised that no one impact of a product at any stage of its life can be regarded as indicative of the product as a whole.

The greenhouse effect

The greenhouse effect, the periodic gradual warming of the earth's atmosphere, is a natural process. However, the effect is enhanced by the output of certain gases into the atmosphere, which is often the result of human activity. The most significant gas in terms of quantity is thought to be carbon dioxide.

There is an important link between trees and carbon dioxide. During their period of active growth, as part of the process of photosynthesis, trees absorb carbon dioxide from the air and 'sequester' (store or fix) it in their woody tissue - thus reducing the greenhouse effect. Mature trees have little ability to continue to sequester carbon dioxide, although carbon storage does continue in the ecosystem, e.g. in leaf litter. It is sometimes believed that, because of the relationship between trees and carbon dioxide, the harvesting of timber contributes significantly to the acceleration of the greenhouse effect. However, if at the time that trees are harvested as saw logs, their capacity to absorb carbon dioxide is lower, their ability to contribute to slowing the greenhouse effect will diminish. Also using saw logs for long-life products, such as buildings, ensures that the carbon dioxide remains 'fixed' for long periods, while continually replacing felled trees with actively growing trees ensures that the sequestration of carbon dioxide continues.

Another misconception is that, because products such as steel, aluminium and concrete do not release carbon dioxide to the atmosphere as they age, their use is more environmentally-friendly. However, this ignores their process of manufacture which releases large amounts of carbon dioxide into the atmosphere. For example:
a) steel making, which requires energy and involves the burning of non-renewable fossil fuel, liberates about 2 tons of carbon dioxide for each ton of steel produced;
b) a steel-framed house accounts for the release of 3.5 tons of carbon, but the equivalent house framed in timber can store 3.1 tons of carbon;
c) timber stores up to 15 times the amount of carbon dioxide released during its use, whereas steel and aluminium store negligible amounts.

The carbon dioxide released and stored by various building materials during their formation and use are summarised in Table 11.

Table 11: Carbon released and stored in the manufacture of building materials

Material	Carbon released (kg/t)	Carbon released (kg/m3)	Carbon stored (kg/m3)
Rough sawn timber	30	15	250
Steel	700	5320	0
Concrete	50	120	0
Aluminium	8700	22000	0

Source: Presented in Ferguson, I., La Fontaine, B., Vinden, P., Bren, L., Hateley, R. and Hermesec, B. 1996, 'Environmental Properties of Timber', Research Paper commissioned by the Forest & Wood Products Research & Development Corporation.

Thus, if trees are continually replanted and the timber is used in long-life applications (such as buildings), use of timber contributes much less to the enhanced greenhouse effect than substitutes in the construction industry. Consumers are increasingly aware of the need to conserve scarce resources and are keen to buy products and adopt practices that are energy-efficient. But efficient operation is only one aspect of a product. In any LCA study, total embodied energy must be considered.

Overall Energy Requirement

This section looks at the energy embodied in the manufacture, transport, construction and maintenance of the product. Because climate, design and location vary significantly for individual buildings, no data are presented for energy used in the operation of buildings.

Energy use in manufacture

The majority of energy consumed in association with building materials is used during the processes of manufacture. As can be seen from Table 12, the manufacture of rough sawn timber uses vastly less fossil fuel energy per unit volume than steel, concrete or aluminium.

Table 12: Fossil fuel energy used in the manufacture of building materials

Material	Fossil fuel energy (MJ/kg)	Fossil fuel energy (MJ/m3)
Rough sawn timber	1.5	750
Steel	35	266.000
Concrete	2	4.800
Aluminium	435	1.100.000

Source: Presented in Ferguson, I., La Fontaine, B., Vinden, P., Bren, L., Hateley, R. and Hermesec, B. 1996, 'Environmental Properties of Timber', Research Paper commissioned by the Forest & Wood Products Research & Development Corporation.

Energy use in transport

In some cases, the transport of raw and processed materials consumes a significant amount of energy. The exact amount depends on the weight of the material, where the materials are extracted, processed and used, and the type of transport used. Because these factors vary on a case-by-case basis no exact data can be given here.

However, when transport costs are considered in LCA, the use of domestically grown timber could be shown to be more environmentally friendly than the use of imported timber - although even this depends on the distances over which the material is transported and the type of transport used. Some general data are available, e.g. road transport can be about six times more energy-intensive than rail transport and 15 times more energy-intensive than sea transport.

Energy use in construction and maintenance

Table 13 presents data on construction and operation of houses built with different materials. It provides estimates of energy embodied in the walls of a standard sized house in terms of the initial energy required for the construction, and the total energy, allowing for maintenance over a 40 year life.

Table 13: Energy embodied in construction and maintaining buildings with different wall materials

Type of Construction	Energy per unit area of assembly (MJ/m2)	Energy used to complete construction (MJ)	Energy used in maintenance over 40 years (MJ)
Timber frame, timber clad, painted	188	31,020	24,750
Timber frame, brick veneer, unpainted	561	92,565	0
Double brick, unpainted	860	141,900	0
Autoclaved Aerated Concrete, painted	464	76,560	24,750
Steel frame, fibre cement clad, painted	460	75,900	247,50

Source: Presented in Lawson, W.R., 1996, 'Timber in Building Construction: Ecological Implications', Research Paper commissioned by the Timber Development Association (NSW) Limited.

Again, the correlation between high timber use and low embodied energy is apparent. The data in Table 13 are from a single study and therefore should be seen only as indicators.

While the amount of embodied energy in a building obviously varies with its design and location, the following examples are interesting:

- a steel beam requires more than 10 times the production energy of the equivalent timber beam;
- brick cladding for houses uses significantly more energy than wood cladding;
- aluminium window frames use over 50 times the energy of equivalent wooden frames;
- on a weight-for-weight basis, the manufacture of sawn timber involves approximately 10-30% of the energy needed to manufacture steel and less than 6% of the energy needed to manufacture aluminium;
- much of the energy used in drying kilns is waste material from the harvesting process. In comparison, most of the energy used in the extraction and processing of substitute materials is non-renewable fossil fuels.

Pollution

This section compares the by-products from the manufacture of various building products. In terms of specific gas emissions, the manufacture of timber products is associated with lower emissions of carbon dioxide, carbon monoxide, sulphur dioxide and volatile organic compounds than steel manufacture. While timber produces more weight of solid wastes, these wastes can be reused, e.g. to produce particleboard, fibre-board, mulch or fuel.

The following summarises some aspects of waste products and emissions from various building materials.

Timber and timber products

a. Forests act mainly as net sinks for sulphur dioxide and nitrogen oxides and for particulate matter. Continually replacing felled trees in plantations of actively growing trees ensures that this absorption continues.
b. Timber wastes can be (and usually are) recycled as, e.g., particleboard, fibreboard, mulch or fuel for drying kilns.
c. Current processes reduce the extent of 'bleeding' of creosote (used in preserving timber) to a minimum, and poles and piles treated with creosote are invariably used in situations in which they pose little hazard. Copper Chrome Arsenic (CCA) preservatives are used to slow the decay of timber in situations ranging from insect attack to exposure to marine conditions. States and territories have legislation limiting contaminant levels.
d. Improved light organic solvent preservative treatments will overcome excessive solvent use and 'bleeding'.

Iron and steel

a) In the manufacture of iron and steel, there are emissions to air of carbon monoxide, sulphur dioxide, and nitrogen oxides (totalling 40kg/t of steel), and to water of heavy metals and oils.
b) Large quantities of solid waste (mainly slag) are created during manufacture, in addition to smaller quantities of hazardous waste, which may require disposal to landfill.
c) About 150,000 litres of contaminated water (containing hydrocarbons and other organic compounds, sulphides, phenolics, ammonia, metals, cyanide, oil and grease) are produced for each ton of steel.

Aluminium

The most notorious by-products of aluminium production are caustic mud and red sand. Over 15 million tons (dry base) are generated each year in Australia and over 200 million tons are presently stock piled. Aluminium smelting is the source of fully fluorinated compounds (FFC) which are much more powerful greenhouse gases then carbon dioxide because of their extremely long lives. Controls over these compounds are improving.

Cement and concrete

a) The manufacture of cement can involve the emission of up to 240g of sulphur dioxide and of up to 6kg of nitrogen oxides per ton of cement.
b) Water consumption and liquid effluents are a significant aspect of concrete production and usage. Between 1,500 and 3,000 litres of alkaline effluents (pH8) may be generated by each cubic metre of concrete.

The estimated dollar value of the environmental costs incurred in the production of comparable wood and steel walls is shown in Table 14. The environmental externality cost imposed by timber is less than 30% of that imposed by steel.

Table 14: Environmental externality costs

Pollutant	Cost ($/kg)	Wood wall (4)	Steel wall (4)
Electricity		1.46	4.67
CO2	0.15	47.00	145.65
SO2	1.80	0.66	6.65
NOX	4.47	4.52	7.04
Particulates	2.62	0.49	1.55
Effluents	0.05	0.61	24.80
Total		54.74	190.57

Source: Presented in Lawson, W.R., 1996, 'Timber in Building Construction: Ecological Implications', Research Paper commissioned by the Timber Development Association (NSW) Limited and the Forest & Wood Products Research & Development Corporation.

Overall, it can be stated that, in terms of waste products and emissions, timber out-performs steel and aluminium and compares very favourably with cement and concrete.

Sustainable development

Resource depletion

Using any material decreases the available supply of that material - at least in the short term, and in some cases for ever. Trees are a renewable resource; whereas substitute-building materials are generally non-renewable. Steel is manufactured from the non-renewable resources iron ore, alloy metal ores, coal and limestone, and, although the supply of those resources at current rate of usage is guaranteed for many hundreds of years, the same may not be true for some of the minerals (chromium, nickel, cobalt, vanadium) needed to form the alloys that give steel its special properties.

Ecologically Sustainable Development (ESD)

The term ESD refers to designing development so that ecosystems (the interactions of flora, fauna, soil, water and air) can be sustained, for the benefit of current and future societies. It is in this area that timber has the potential to be more environmentally expensive than substitute building materials. However, industry codes of practice and legislation are increasingly ameliorating this impact.

Most of the mandatory requirements have been developed by state governments which have primary responsibility for the health of forests. Many national governments have been active in this field, including the creation of a national conservation reserve system. These reserves, appropriately managed, will help meet national biodiversity and endangered species targets.

Of course, alternative building materials are not 'ESD-neutral'. The extraction and pre-processing of ores disturbs wilderness, wildlife habitats and ecosystems, and involves solid and liquid waste disposal, noise and dust, subsidence, accelerated release of ground methane and site contamination due to fuel spillage.

Wildlife and biodiversity

Biodiversity - the existence of diverse ecosystems, species and genes - is important because human life depends on these resources and their interaction, for food, many medicines and industrial products and much of its cultural values. Forests are an essential component of ecosystems and their harvesting has an inevitable impact on biodiversity.

Mining operations also involve disturbance to the environment and to ecosystems. The obvious ones (such as scarred landscapes) affect smaller areas than timber harvesting, but their less visual impacts (such as impact on specific species) may be significant.

In considering the impact of timber on biodiversity, the following points should be remembered:
a) The Resource Assessment Commission found, no evidence to suggest the risks of extinction resulting from logging present an immediate threat to the ecological processes on which forest systems depend. Nevertheless, the Commission adopted precautionary approaches in framing recommendations for the protection and management of vulnerable species and ecosystems. These are now being implemented through the joint Commonwealth/State Regional Forest Agreements. Worldwide, Australia is seen to be in a leading position in relation to the protection of biodiversity.
b) The Resource Assessment Commission also stated that 'The principal threats to endangered forest and woodland species are agricultural expansion and grazing. Timber harvesting has the potential to directly affect about 5% of all endangered species and vulnerable plant species, an additional 30% of these species may be indirectly affected'.
c) Codes of Forest Practice are required steps in the Regional Forest Agreements being developed between the Commonwealth and the States.
d) Wilderness recreation is to be zoned under Regional Forest Agreements now in train, and most wilderness areas are already protected and within the prospective conservation reserve scheme.

Soil and agricultural land

Forestry operations impact on soils in a number of ways. Removal of vegetation in form tracks exposes the soil to increased erosion, and the movement of machinery may result in displacement and compaction of soil. However, the impact of forestry operations is not all negative. Two examples of positive influences are provided below.

If plantations are established on previously cleared agricultural land, the impact may be beneficial in that soil conditions can be improved through the application of fertilisers. Furthermore, aeration of soils by tree roots, and addition of organic matter by way of leaf litter, may improve the overall condition of the soil. Soil erosion can actually be reduced by tree roots and leaf litter and the sheltering effects of a plantation. Plantations have been successful in ameliorating soil salinity caused by raised water tables.

Water

The use of forests for timber production has distinct but often complex interactions with waterways. Forestry tracks can be a major source of sediment input into streams in small catchments - although good design and use of roads will minimise this effect. Fertilisers, herbicides and pesticides can leach into watercourses - but to a lesser extent than from pastures and short-life crop usage. Pesticides are only used in native forests in the establishment phases of plantations. *Permanent* removal of trees can lead to a rise in the water table - but replanting can mitigate this.

If plantations are established on previously cleared agricultural land, the impact may be beneficial in that:
a) trees can slow the rate of erosion and the movement of eroded soil into waterways;
b) deep-rooted trees (as opposed to shallow-rooted crops) can act to lower the water table;
c) trees shade aquatic ecosystems from excessive heat and light which contribute to algae blooms.

Recycling

LCA of products includes examination of the environmental impact of the product at the end of its life. How a product is recycled or disposed of is relevant, therefore, to the assessment of any product. In considering the issue of recycling, the following points should be taken into account:

a) almost all the timber waste produced at the manufacturing stage is reused as fuel for drying kilns, or to make wood products such as particleboard, fibreboard, chips or mulch;
b) research into the safe disposal of treated timber is currently underway;
c) while metals such as steel and aluminium may be recycled, the recycling processes themselves consume energy, and release carbon dioxide and wastes.

Such is the increasing demand for recycled hardwood in Australia that it is estimated that demand will outstrip supply in ten years.

Summary of comparative costs on an LCA basis

The amount of any particular material used in finished constructions varies. This may be due to the design of the finished construction or the different strength characteristics of different materials which dictate how much is used in the construction. Table 15 uses the BES Index to rate the total environmental impact of a range of common building assemblies. Timber is shown to compare favourably.

Table 15: Comparisons of some common building materials (BES Index)

Element	Resource depletion	Inherent pollution	Embodied energy*
Autoclaved Concrete block	16.8	7.8	3.5
Autoclaved Concrete panel	16.8	6.2	5.4
Cement render	19.5	9.2	2.0
Cement mortar	15.5	55.9	2.0
Clay brick	13.4	4.2	2.0
Clay tile	13.4	4.2	2.0
Concrete - in situ	15.6	6.9	2.0
Copper sheet	30.2	28.9	100.0
PVC u/g pipe	14.0	17.3	79.0
PVC floor tiles	16.0	22.1	79.0
Plasterboard	13.5	9.3	4.5
Basic Oxygen Steel, sheet	18.2	19.2	38.0
Basic Oxygen Steel, stud	18.2	19.5	38.0
Electric Arc Furnace steel rod	8.3	9.5	19.0
Timber, softwood stud	9.2	5.7	3.5
Timber soft particleboard	9.2	7.1	8.0
Timber, hardboard (hardwood)	13.3	5.4	24.0
Timber, Red Cedar frame	13.6	6.8	4.5
Timber hardwood engineered	11.2	4.1	11.0

Source: Presented in Lawson, W.R., 1996, 'Timber in Building Construction.

Table 16 - Total environmental impact of a range of common building assemblies

Table 16 uses the BES Index. Once again, timber is shown to compare favourably.

Assembly		Resource depletion	Inherent pollution	Embodied energy
Ground floors	Timber on clay brick piers	12.0	4.9	2.7
	Autoclaved Aerated Concrete panels on Autoclaved Aerated Concrete block walls and concrete footings	50.0	21.0	9.5
	Concrete raft slab	58.0	26.0	8.4
Upper floors	Timber	3.7	2.6	1.9
	150 mm Autoclaved Aerated Concrete	22.0	8.5	5.4
	150mm concrete slab	57.0	26.0	8.8
External walls	Timber frame + weatherboards, plasterboard lining	4.1	2.6	1.5
	Timber frame + brick veneer, plasterboard	34.0	12.0	5.5
	Double (cavity) brick	63.0	20.0	9.2
Internal walls	Autoclaved Aerated Concrete bock with render	16.0	6.3	4.8
	Clay brick with render	36.0	13.0	13.0
	Timber studs with plasterboard	3.6	2.4	1.3
	Steel studs with plasterboard	2.8	2.2	1.9
	Reinforced concrete, no render	37.0	17.0	5.3
Roofs	Corrugated iron on timber framing	5.2	4.0	5.0
	Clay tiles on timber framing	13.0	5.6	3.4

CHAPTER 9

9.1 LCA Investigation of Low Cost Building Materials: for the Tanzanian Environment and Economy

Dar-es-Salaam, the capital of Tanzania, is one of the fastest growing cities in sub-Saharan Africa. Throughout Tanzania low-income housing projects are in great demand predominantly due to increasing urbanisation and lack of government-sponsored projects to support the majority of the population. The increasing demand for housing is exerting pressure on the environment, raising severe challenges and producing problems that need to be overcome.

All industrial products have a life cycle; environmental impact assessment (EIA) tools enable evaluation and prediction of a product's environmental impact (EI) or environmental footprint (EF) on the earth. As environmental impacts occur throughout the product's life cycle, a systematic Life Cycle Assessment (LCA) approach accounts for these processes from raw materials or natural resources extraction through to the point of their return to the earth, i.e. their disposal.

Material life cycles involve the material's extraction, manufacture, consumption and use, recycling, and disposal, based on which, an evaluation of total resource consumption, environmental emissions (air, water and soil) is possible. The relevancy of LCA for building materials is based on the idea that projects should not be based solely on providing immediate housing solutions, but should also foster environmental conditions and awareness, economic improvements and sustainable development and improve living standards for the future.

LCA studies can promote new approaches to the management of building materials by considering energy efficiencies, environmental conservation and the adaptation of new technologies with socio-economic and environmental factors. LCA studies on energy and resource saving opportunities can reduce the short and long-term cost implications. The aim of such studies is to support engineers' and stakeholders' decision-making from an environmental sustainability perspective. Their application is most effective when they are included in the planning stages of a technically oriented project.

9.2 Environmental Issues

Global
Tanzania—*e.g. resource availability, natural resource depletion, renewable resources, number of biomes (flora and fauna) threatened by the development, environmental health*

Tanzanian Economy (focus on the building industry)

Scenario
Predicaments
Alternatives

Sustainable Development Objectives

Prevent Environmental Degradation
Achieve Energy Conservation
Maintain and Ecological Balance
Long term prosperity
Economic strength
Harmonise economic growth with environmental conservation and protection
Recycle Industrial and Agricultural Wastes[9]

Life Cycle Phases (Building Industry)

Resource extraction
Processing of Structural Materials
Construction of Residential Buildings
Building Use and Maintenance
Destruction
Disposal and/or recycling

9.3 LCA Concepts

LCA History and Background (brief)

Sustainable Development (brief)
International Initiatives & Agreements—e.g. Agenda 21' Chapter 30 – the role of business and industry through effective and clean production with life cycle analysis.

[9] To provide a resource for the materials industry

Environmental policies and regulations—e.g. Building Materials quality enhancement through LCA
Environmental Guidelines—e.g. hazardous materials and waste, land exploitation
Tanzanian Environmental Policies, Regulations and Guidelines—e.g. are there regulations regarding the environmental impact of land use and construction and are they being enforced? Are there (enforced) guidelines for environmentally acceptable (non-toxic) products or sustainable design and construction regarding energy efficiency implementation?

LCA: Introduction

Common Terminology —e.g. Life Cycle Inventory (LCI), 'Cradle to Grave', Life Cycle Impact Assessment (LCIA), and more
Common Life Cycle Assessment Indices—e.g. Embodied Energy, Global Warming Potential (CO2) (GWP), Air Emissions, Water Emissions, Solid Waste, Ozone depletion potential (ODP), Acidification, Eutrophism and Desertification

9.4 Overview of LCA Methodology

Laid down by ISO 14040 International Standards and elaborated by the Society for Environmental Toxicology and Chemistry (SETAC).

Goal and scope —ISO 14041

Goal of Study: state intended application, reason for performance of study and intended audience.
Scope of Study: Accurate description: function(s) of system to be analysed; functional unit for which data will be presented; system boundaries; allocation procedures adopted; data requirements; any assumptions made; study limitations; type and format of any study report
Inventory analysis —Data is collected and calculations carried out to quantify significant inputs and outputs of the system (accounts of raw materials, energy consumption, solid, liquid and gaseous wastes), disposal scenario
Impact assessment —ISO 14042
Assessment of environmental impact derived from the Inventory results. Simplification of results achieved by quantification in regards to environmental issues (indices). E.g. global warming potential, acidification, ozone depletion potential, etc.
Life Cycle Assessment — ISO 14043
Relation of results with initial goal definitions lay down. Revision of Scope and System boundaries. Assessment of data accuracy.

Identifying and Setting Boundaries for Life-Cycle Stages

Quality of the work depends on accurate description of system boundaries, i.e. to define where each stage of a life cycle begins and ends.

Raw Material Extraction —*materials and energy from earth, transportation of raw materials to point of raw material processing*
Materials Processing — *processing raw materials to a finished product*
Product Fabrication — *processing material for filling or packaging*
Filling/Packaging/Distribution — *manufacturing processes required to fill, package and distribute the finished product. Transportation to accomplish these wastes are also included in this stage*
Use/Reuse/Maintenance — *use and maintenance, includes environmental wastes generated at this stage.*
Recycle/Waste Management—*includes energy requirements and environmental wastes generated, waste management options such as recycling, composting, incineration*

Issues to be regarded at all Stages

Energy and Transportation
Environmental Waste Aspects
Waste Management Practices

9.5 Alternative Materials for Low Cost Housing

Description—*e.g. Material Requirements (resource abundance, quality, durability, reparability, life-time (aesthetics, economical, functionality, physical (use and maintenance), technical performance).*
Which Materials have been identified?
Identified Manufacturing and construction processes
Case Study

Comparison of Conventional with Alternative Materials for Low Cost Housing

Case study, trade-offs
Manufacturing and construction processes, cost and social issues
Environmental Impacts—*e.g. energy consumption during manufacture, renewable or non-renewable resources, wastage and pollution*

9.6 LCA Tools (Software)

To provide guidance and analysis along the steps involved with an LCA study.

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