LOW COST ROAD SURFACING (LCS) PROJECT

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BAMBOO REINFORCED CONCRETE PAVEMENT ROAD CONSTRUCTION IN CAMBODIA

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FOREWORD

This document is the result of cooperation between the ILO Upstream Project Cambodia and the Low Cost Road Surfacing Initiative: "Low-cost, Labour-based Roads for Poor Communities".

This report describes the first of two alternative surfacing initiatives in the area of Puok Market, Siem Reap Province of Cambodia. Further road surfacing trials have been carried out and are described in other Low Cost Road Surfacing documents.

ILO UPSTREAM PROJECT IN CAMBODIA

In Cambodia, since 1992, the ILO has promoted labour-based appropriate technologies (LBAT) to generate employment through the improvement and maintenance of essential rural infrastructure. These technologies are "pro-poor" and effective weapons to combat poverty. The Royal Government of Cambodia (RGC) has endorsed LBAT as the technology of choice for the rural infrastructure programme. In support of this important decision, the project "ILO Technical Assistance to the Labour-Based Rural Infrastructure Works Programme, CMB/97/M02/SID", known as the "Upstream Project", was formulated. This project is primarily funded by Sweden with additional financial and technical support from the Netherlands, Ireland and Australia. This four-year project became operational on 1st July 1998. The Ministry of Rural Development (MRD), Cambodia is the main RGC counterpart to the project. The project has five capacity building targets:

1. To increase the capacity of the private sector by training ***small-scale contractors*** (SSC) to carry out the rural infrastructure works using LBAT. The RGC intends to maximize the role of the private sector. The project has been involved with the training of 22 SSC. Follow up studies indicate that the SSC are thriving.
2. To assist the Institute of Technology of Cambodia (ITC), in developing, instructing and institutionalising four engineering courses that include LBAT approaches. The project is also sponsoring ITC students to undertake their co-operative work term with the project.
3. To demonstrate best LBAT practices by implementing ***construction and maintenance works*** in Siem Reap province. These works have generated an employment effect of 575,000 workdays for rural people.
4. To improve the Institutional Capacity in the ***MRD*** so that infrastructure investments maximize the pro-poor impact. Together the MRD and the project are:
   - Formulating ***Policies and Strategies*** for the rural transport infrastructure programme,
   - ***Training*** the technical staff of the Department of Rural Roads in labour -based methods,
   - Applying ***Integrated Rural Accessibility Planning*** (IRAP) for rural infrastructure investments,
   - Undertaking ***Socio-Economic*** studies that will provide useful information for programme design, monitoring and impact assessment,
   - Convening the Cambodian ***Forum for Rural Transport and Development,***
   - Investigating ***road-surfacing*** options. MRD and the project are currently collaborating with a DFID funded project entitled "Low-cost, Labour-based Roads for Poor Communities",
   - Translating and adapting essential relevant ***training materials*** and ***technical literature***.
5. To promote partnerships and programme development: The project is collaborating with the World Bank and the Asian Development Bank to formulate and implement projects that feature LBAT and IRAP. The project is collaborating with the Engineering Institution of Cambodia to further mainstream these technological approaches.

THE LOW COST ROAD SURFACING INITIATIVE

The Low Cost Road Surfacing (LCS) initiative (Low-cost, Labour-based Roads for Poor Communities) aims to provide documentation and international guidelines on the provision and maintenance of low cost road surfaces and basic access for rural communities in economically emerging and developing countries (EDCs). It is based on a research project funded principally by the British Department For International Development (DFID) under its Knowledge and Research (KaR) programme. The initiative is led by UK-based specialist consultants Intech Associates. Collaboration is being established with a number of organisations with interests or experience in the sector, including CSIR, TRL Ltd, ILO/ASIST Africa and Asia-Pacific, the ILO-SIDA funded Upstream Project and Ministry of Rural Development Cambodia, WSP International, Ministry of Transport Vietnam, Greater Mekong Sub-region Academic Research Network, The Institute of Technology of Cambodia, Chieng Mai University Thailand, the Committee C20 (Appropriate Development) of PIARC (World Road Association) and the International Focus Group. The LCS programme is being implemented over a 4 year period from 2001 to 2004.

The LCS programme is concerned with supporting sustainable improvements in low cost, road surfacing and basic access to support poverty reduction initiatives in rural communities. This implies the effective use of local resources, particularly human resources, locally available and alternative materials, and readily available and low cost intermediate equipment wherever possible. In the situation of scarce financial resources, it also requires the application of affordable and appropriate standards and adoption of techniques suitable for use by the indigenous private sector (particularly small domestic construction enterprises) and local communities. The application of good management practices coupled with adequate technical inputs are also encouraged.

It is intended that dissemination of the guidelines will be through electronic media as well as more traditional publication routes.

INTERNATIONAL FOCUS GROUP

TRL is currently carrying out a number of research projects on low volume sealed and unsealed roads for DFID and a number of other agencies. Intech Associates is carrying out research on low cost surfacing with a number of partners. As part of these projects, an International Focus Group (IFG) has been established. The main function of the IFG is to thoroughly examine technical, economic and social issues arising from the project work. The group will also provide a focus to improve opportunities for dissemination of project results. The IFG being developed will comprise technical experts and engineers from a number of African, Asian and other countries as well as other international experts. Participation in the IFG will provide opportunities to:

- *build regional and international partnerships*
- *exchange ideas, experiences, information and data*
- *strengthen local knowledge with new information*
- *build on existing local research*
- *promote wider acceptance of the projects themselves*

Four projects listed below, are of particular interest to the IFG. Projects 1, 2 and 4 are part of the DFID's Knowledge and Research programme, whilst Project 3, is a collaborative research project involving a number of different donors:-

Project 1: Reducing Whole Life Costs: Environmentally Optimised Design
Project 2: Minimising the Cost of Sustainable Basic Rural Road Access
Project 3: Engineering Standards for Labour-based Roads
Project 4: Low Cost Road Surfacing

The document is intended to inform and provoke discussion, contributions and dissemination regarding surfacing aspects or rural roads. The LCS Project welcomes dialogue with engineers, managers, organizations, communities and individuals active or interested in the rural transport sector with the objective of the promotion of a sustainable rural access approach for EDCs.

This document is an output from a project funded by the UK Department for International Development (DFID) for the benefit of developing countries. The views expressed are not necessarily those of the DFID.

BAMBOO REINFORCED CONCRETE PAVEMENT, ROAD CONSTRUCTION IN CAMBODIA

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<u>Abbreviations</u>

ASEAN	Association of South East Asian Nations
CAFEO	Conference of the ASEAN Federation of Engineering Organisations
CSIR	Council for Scientific & Industrial Research
DFID	Department For International Development
EDC	economically Emerging and Developing Country
GMSARN	Greater Mekong Sub-region Academic and Research Network
IFG	International Focus Group
IFRTD	International Forum for Rural Transport and Development
ILO/ASIST	International Labour Office/Advisory Support Information Services & Training programme
IMT	Intermediate Means of Transport
IRAP	Integrated Rural Accessibility Planning
ITC	Institute of Technology of Cambodia
ILO	International Labour Organisation
LBAT	Labour Based Appropriate Technology
LCS	Low Cost (Road) Surfacing
MRD	Ministry of Rural Development
RGC	Royal Government of Cambodia
SSC	Small Scale Contractors
TRL	Transport Research Laboratory
VPD	Vehicles Per Day

International Labour Organisation
Technical Assistance to the Labour-Based Rural Infrastructure Works Programme
CMB/97/M02/SID

In cooperation with Intech Associates (DFID - UK funded) Knowledge and Research investigations for R7782 'Low Cost, Labour Based Paved Roads for Poor Communities'

Bamboo Reinforced Concrete Pavement Road Construction in Cambodia

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Executive Summary

Cambodia's need for durable, alternative road surfaces is growing. This led the International Labour Organisation (ILO) Upstream Project to initiate a study to investigate different surfacing options. These studies examined the potential technical benefits, employment generation, utilisation of local resources, costs, environmental effects and benefits to the local community. As part of these investigations a 2km Bamboo Reinforced Concrete Pavement (BRCP) trial was designed and implemented in collaboration with the Ministry for Rural Development (MRD). Construction took place in the year 2000.

Laterite (a naturally occurring gravel material) is often used to surface rural roads. Although initial construction costs can be lower than other surface types, in the Cambodian conditions the laterite surface wears quickly (and needs to be regularly replaced), is costly to maintain and causes dust problems. Furthermore, the finances, resources and management for proper maintenance of laterite are often not available from within the government or local community.

The study found the following advantages of BRCP compared to gravel/laterite in many situations:-

- expected long life span,
- high residual value,
- minimal maintenance,
- minimal equipment requirements (and requires only simple equipment),
- labour intensive construction and maintenance,
- suitable for both male and female employment,
- good use of local resources (especially labour and materials),
- dust-free, easy-to-clean surface, and
- tolerance to flooding.

The disadvantages of BRCP compared to unpaved surfaces are:-

- slower speed of construction, and
- higher initial investment costs.

BRCP roads may be more economically feasible than laterite roads for high laterite haul distances (beyond about 10 km) in asset whole-life-cost terms for the circumstances prevailing in Cambodia.

It is recommended that BRCP should be one of the options to consider (in technical, whole life cost and management terms) for low volume road surfacing when:-

- laterite haul distances are long,
- laterite quality is poor,
- road surface/subgrade is liable to flooding,
- local communities live very close to the road (dust nuisance), or
- there are severe doubts about future maintenance funding or capacity.

Accordingly, it should be incorporated in the Cambodian National Standards as a surface option for rural roads, and training programmes should incorporate these techniques.

It is recommended that the performance and maintenance requirements of the Puok BRCP trials should be monitored to enable the whole-life-cost estimates to be validated.

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1. INTRODUCTION

1.1 The Need

Previously the access roads to, and roads around, Puok Market itself had been surfaced using the naturally occurring gravel or laterite. This type of material has been applied to many tertiary and sub-tertiary roads in the catchment's area of Puok Market and in Cambodia a whole. The need for a more durable wearing surface was recognised by the burden of continuous maintenance of laterite surfaces and the associated strain on resources. This became more apparent following excessive flood damage during the exceptionally high intensity rainfalls of the 2000 rainy season.

Images 1 & 2: Roads damaged by flood

The higher traffic volume in the area of the market further compounded the need. The suitability of laterite as a wearing course may be said to decrease with increase in traffic volume due to the nature of the material. Laterite is lost due the effects of moisture (wet season) and through dust (dry season) and these effects have been found to increase almost proportionately with increase in traffic volume. Furthermore the economic viability of laterite as a wearing course becomes increasingly dubious with the increase in haulage distance.

A further consideration is the dust problem associated with laterite, especially in an area of high population density such as Puok, there is a need to reduce the amount of dust because of health problems, which may result in the local community. In an area such as Puok market where there are many food vendors and restaurants; large volumes of dust represent a serious hygiene problem with foodstuffs being contaminated daily. Furthermore, dust is a safety hazard for drivers since it impairs visibility. This is particularly unacceptable in an area of high population density.

Although laterite has a relatively low initial cost, ongoing periodic maintenance requirements (re-gravelling) are considerable, even more so when the traffic volume exceeds 50 four-wheeled vehicles per day as is the case for Puok. As such the appropriateness of laterite as a wearing course in such an area becomes exceedingly doubtful when life cycle costs are considered.

Furthermore, laterite is a finite non-renewable resource and as such should only be applied in cases where its use is the most appropriate option in light of economic, social and environmental considerations.

Over the last three decades, investigations of LBAT in road construction has focussed mainly on the use of gravel/laterite as a surfacing. Very little international experience has been built up in the use of alternative surface options. It is believed that a range of alternative surface options can be constructed by labour methods on a large scale, bringing employment and social benefits to the urban and rural communities that the roads serve. Successful application of LBAT in constructing and maintaining these alternative surfaces would extend the potential use of these techniques from tertiary roads to heavy duty pavements and main roads. It is important to demonstrate these techniques and provide opportunities for training and gaining experience in them.

Such were the economic, social and environmental issues, which led to alternative surface options being considered for the rehabilitation of the roads around Puok Market.

1.2 Investigation

In February 2000, the ILO Upstream Project conducted a traffic characteristics survey around the market. Some of the findings of this study included; approximately 63% of the vehicles arriving at Puok Market transported produce of some sort, 35% carried passengers and only 2% were empty. Puok Market was found to be visited by an average of 13,000 vehicles per day. Approximately 556,000 Kg of produce was found to be delivered to the market daily, at the time of study.

The market area and roads were in a bad condition during the investigation. The traffic was facing difficulties in reaching the market and the transport of goods was difficult task especially during the rainy season.

Images 3 & 4: Puok Market roads condition before construction

It became apparent that a concrete wearing course would be most satisfactory after careful consideration of site-specific conditions. The factors that influenced this decision were:

- The high traffic volume of the area
- The need for the pavement to support large loads over long periods, as heavy vehicles would often be parked at the site due to its close proximity to National Road No. 6
- The susceptibility of the area to flooding
- The unacceptability of dust in the area due to the high population density.

However it was apparent that a standard reinforced concrete pavement would not comply with the desire to use a maximum amount of indigenous materials. In order to maximise the amount of local resources used, experience from the sector in Thailand was drawn upon in the application of Bamboo Reinforced Concrete Pavement (BRCP). This type of pavement utilises bamboo mesh as reinforcement rather than standard steel mesh. At present there is no steel being produced within Cambodia and the use of standard mesh would have represented a large loss in foreign currency to the local economy. Whereas the use of bamboo as reinforcement meant that a maximum amount of the projects funds would stay within the immediate community, thus maximising the benefits of the project to the local community.

Research carried out at Chang Mei University, Thailand for the Public Works Department of the Royal Government of Thailand was drawn upon in order to design and construct the pavement. Bamboo-reinforced concrete pavement was used extensively in a large-scale labour-based road improvement project initiated by the Royal Government of Thailand from 1986 to 1988. BRCP was applied in all villages, in recognition of the problems associated with dust from gravel roads.

Bamboo is available in abundance in the vicinity of Puok Market. Indeed it may be observed on the route from Siem Reap to Puok. However the local resources identified in initial investigations extend beyond just the occurrence of bamboo alone. The abundance of bamboo is accompanied by a deep understanding of the material, from harvesting to storage to working the material, amongst the local community. Examples of their skill may be found in the bamboo and rattan wares for sale at Puok market itself. The value of this indigenous knowledge and skill was considered in choosing the road surface to be used. It may be said that the closer the resources utilised are to the project area the more socially beneficial the project will be. This is particularly true when areas are prioritised for infrastructure improvement through accessibility action plans, produced with the aid of the Integrated Rural Accessibility Planning (IRAP) tool, which is based on the philosophy of sustainable accessibility and basic minimum needs and poverty reduction.

2. BACKGROUND

2.1 A Brief History

Use of bamboo as continuous reinforcement in concrete structures has a longer history than is commonly known. An early recorded instance of such an application of bamboo in construction dates back to 1919 when it was used in China for piles for the Hankow Railways. It was also used in that country as reinforcement in a hospital and in road pavements. The first recorded research carried out on the use of bamboo as reinforcement dates back to 1914. Interest in bamboo as an alternative reinforcing material for concrete structural members was renewed in South and South-East Asia during and following the Second World War, due to constraints on materials availability. However it wasn't until research was carried out at Clemson Agricultural College, USA, in 1950 that serious advances in the use of bamboo as reinforcement were made.

A study of the feasibility as reinforcing material in pre-cast concrete elements was conducted at the U.S. Army Engineer Waterways Experiment Station in 1964. In recent times there has been renewed interest in applications for bamboo in construction including reinforced concrete construction. The interest in bamboo as reinforcement has arisen primarily because most developing countries in need of alternative reinforcing materials due to their shortage of steel manufacturing capacity lie in tropical and sub-tropical belts where bamboo grows in abundance.

Extensive research has been carried out at various educational institutions throughout the world, in recent times, into the use of bamboo as reinforcement for pavement slabs on grade as well as for other structural members and much of this work continues. As much as possible, state of the art knowledge was drawn upon in the design and construction of the bamboo reinforced concrete pavement at Puok Market and in the compilation of this report.

3. GENERAL DESIGN CONSIDERATIONS

3.1 Rigid Pavement

Reinforced cement concrete is a form of rigid pavement for road construction. Rigid pavements are considered to be the highest quality pavement type; they can withstand heavy traffic even under adverse sub-grade and climatic conditions. These types of pavements generally consist of a prepared roadbed underlying a layer of sub-base and a pavement slab. A rigid pavement is designed to spread the applied load due to traffic through the slab effect. The basic materials in the typical pavement slab are Portland cement concrete, reinforcing steel (although the slab may be un-reinforced in some circumstances), load transfer devices (between slabs), and joint sealing materials. Bamboo can be used to replace the steel reinforcement. The bamboo is usually split lengthwise into splints or strips. The primary design parameter for the slab is the modulus of rupture of the concrete. While consideration must be given to expected traffic load when choosing material properties and designing the structural layer, due regard must also be given to environmental factors such as drainage and temperature change in designing rigid pavements.

Here the load carrying capacity is mainly due to the rigidity and high modulus of elasticity of the slab itself i.e. slab action. In concept, the rigid pavement slab acts as a thin elastic plate resting on soil subgrade, which is considered as a dense liquid. Here

it is assumed that the upward reaction is proportional to the deflection. The modulus of subgrade reaction is proportional to the displacement.
A certain degree of resistance to slab deflection is offered by the subgrade. This is dependent upon the stiffness or pressure-deformation properties of the subgrade material. The tendency of the slab to deflect is dependent upon its properties of flexural strength.

The resultant deflection of the slab, which is also the deformation of the subgrade, is a direct measure of the magnitude of subgrade pressure. The pressure deformation characteristics of rigid pavement are thus a function of relative stiffness of slab to that of subgrade.

3.2 Critical Load Positions

Since the pavement slab has finite length and width, either the character or intensity of maximum stress induced by the application of given traffic load is dependent on the location of the load on the pavement surface.

There are three typical locations namely the interior, edge and corner where differing conditions of slab continuity exist. These are termed critical load positions.

Interior loading*:* when the load is applied in the interior of the slab surface at any place remote from all the edges.

Edge loading: when the load is applied on an edge of the slab at any place remote from all corners.

Corner loading: when the center of the load application is located on the bisector of the corner angle formed by two intersecting edges of the slab, and the loaded area is at the corner touching the two corner edges.

3.3 Concrete characteristics

There are a number of factors that affect the performance of bamboo as continuous reinforcement in concrete. Some of these may be taken into account by careful selection and use of the bamboo itself. However other adverse factors may be mitigated against through considerate proportioning of the concrete mix to be used. The concrete should have as low a water/cement ration as workability allows while having as high cement content as is economically viable. This not only addresses the issue of bond strength, bamboo-water interaction and alkaline attack to some extent, but from a practical point of view is important in preventing the bamboo “floating” when the concrete is poured over it. Furthermore, the maximum aggregate size should be chosen with due regard to the density of the bamboo mesh as well as taking account of the curved shape of the individual bamboo splints. Because mesh is used as reinforcement for pavement slabs, care should be taken to avoid fixing and laying the bamboo splints with their concave side facing downward. If a large maximum coarse aggregate size is used, there is a possibility of voids forming beneath these splints, which would have a detrimental effect on the pavement’s overall durability.

3.4 Potential of Bamboo as an Alternative Reinforcement

Bamboo has great potential as an alternative for steel reinforcement because it has good tensile strength, it is replenishable, very cost effective and very little mechanisation is needed to prepare it for use.

Bamboo is a familiar material with a long history of usefulness, and in building it has been employed in South East Asia for housing and scaffolding. Some of the advantages and disadvantages of bamboo as a construction material are as follows:

Advantages:

- As bamboo grows very rapidly, it can be cultivated for quick and continuous return on capital,
- It can be planted easily in homesteads close to worksites (minimum transport), and harvested at the time of need without any additional expenditure,
- It possesses good mechanical properties and a high strength-to-weight ratio. Its surface is clean and hard,
- It can be dried with a simple method of air-drying and may be treated with preservatives to enhance service life,
- Culms (stems) can easily be split into strips (splints) with simple tools even by workers with a low level of skill,
- Because bamboo grows rapidly, it is a replenishable natural resource, when properly managed.

Disadvantages:

- Bamboo is not regularly cylindrical throughout, but tapered,
- It is easily perishable and thus needs protection from the elements or preservative treatment to obtain a reasonable life span,
- The hollow form makes jointing of whole culms difficult,
- Because of the plethora of factors, which affect mechanical properties, such as age, moisture content, species and environmental factors, standardisation is problematic.

3.5 Factors Affecting the Strength of Bamboo

Bamboo has a number of mechanical properties, which are advantageous to use as reinforcement for concrete, not least of which being its high tensile strength and low cost when correctly selected. The tensile strength and other properties of various species will differ. The tensile strengths of a variety of bamboo species may be seen in the table of the Appendix 1. However there are many factors which affect the strength of bamboo including:

- Moisture content,
- Species,
- Time of harvest (season),
- Age of the bamboo culm,
- Dimensional variability,

- Soil (growing medium) type,
- Presence of nodes.

Moisture Content

The moisture content of the bamboo sample is dependent on the species, time of harvest, to some extent, as well as the seasoning methods and period and the soil type. Bamboo has a high moisture demand and this has been found to have specific implications for use as reinforcement in concrete. For timber it has been established that below the fibre saturation point, the strength of wood increases with decrease in moisture content. When a sample of culms was tested in Indonesia the same, for the most part, was found to be true for bamboo.

Species

The species that were tested were *Bambusa arundinicae, B. vulgaris, Dendrocalamus asper, Gigantochloa apus, G. atterand and G. verticillatu.* The bottom, middle and top portions of three culms of each species were tested, in both green and air dry condition, for moisture content, bending strength, maximum crushing strength and tensile and shear strength. Analysis of variance showed that moisture content (green or air dry) and species have a highly significant effect on the bending strength.

In general it has been found that there is an increase in the bending strength from the green to the air-dry condition. Exceptions to this were *Bambusa vulgaris* and *Gigantochloa apus.*

The maximum crushing strength, or compressive strength parallel to the grain, of bamboo was found to be highly influenced by moisture content and species. It has been found that there is an increase in compressive strength from green to air-dry condition with the exception of *B. vulgaris*. Thus the importance of using well-seasoned bamboo culms is apparent.

Tensile strength of bamboo was found to increase from an overall mean of 29,776.1 N/cm^2 when green to 31,530 N/cm^2 when air-dry. Thus moisture content and species have little effect on the tensile strength, with the exception of *B. vulgaris*. It was also found that there was significant difference among species for shear strength and the presence of nodes does not have a significant effect on shear strength. For all species except *B. vulgaris* shear strength was found to increase with decrease in moisture content.

Time of Harvest

The moisture content, and hence the mechanical properties, of bamboo has been found to be strongly influenced by the time of harvest. Moisture content is at it's lowest during dry season and reaches a maximum during the monsoon or wet season. For this reason bamboo, for use in construction, should not be harvested during the rainy season.

Age of the Bamboo Culm

An increase in strength of bamboo is reported to occur up to 3-4 years and thereafter it decreases. Thus the maturity period of bamboo may be considered as 3-4 years with respect to density and strength. Maturity of culm is a prerequisite for the optimum use of bamboo in construction and other structural uses. Green bamboo may be dried in order to increase its strength. However, green bamboo may contain 100-150% water and so takes a longer time to dry when compared with wood of the same density. Kiln drying at high temperatures causes collapse in round bamboos. Air-drying method is, however, suitable for drying round bamboos and may take 6-12 weeks depending on the initial moisture, drying season and wall thickness. Defects such as collapse because of non-uniform culm shrinkage is a major problem in some species especially in immature culms. It is thus recommended that only mature bamboos be used. Split bamboos can be dried both by air and kiln drying methods without any difficulty.

Dimensional Variability

Bamboo is not straight and the dimensional variance along the length of a sample of bamboo strongly influences its mechanical properties, samples closer to the base being stronger than the top because of the tapered shape of bamboo. Thus strength varies along the culm height. Furthermore the mechanical properties of bamboo vary with distance from the outer surface. The outer part of the culm has been shown by some researchers to be almost three times stronger in tension than the inner portion. The inner, softer part of the bamboo accounts for 70% of the culm wall. This zone is the part of the bamboo with the greatest moisture absorption capacity. The outer part of the culm wall is denser, stronger and absorbs only a minimum amount of water.

Soil (Growing Medium) Type

It has been reported that the quality and mechanical properties of bamboo are influenced by environmental factors, especially the soil condition. It has been found by previous research work that the moisture content of bamboo grown in humid soils is higher than that of bamboo grown in dry soils. In a study of the species *Dendrocalamus asper* as concrete reinforcement it was found that the moisture content of *D. asper* grown in humid soil was higher than that from dry soil. Bamboo from the dry soil had better dimensional stability because the shrinkage percentage from green to air-dried was lower than that of the bamboo from humid soil. The density of dry soil bamboo was also found to be higher than the one from humid soil. The mechanical properties; modulus of rupture (MOR), modulus of elasticity (MOE), compression, tension and shear, varied significantly between the bamboo from each soil type. Values of mechanical properties were higher for *D. asper* from dry soil.

Presence of Nodes

While the prominence of nodes may improve bond characteristics of bamboo used as continuous reinforcement in concrete, the nodes are disadvantageous for use as reinforcement in terms of strength. In a study of the physical properties of the node and internode of culm and branch of *Dendrocalamus hamiltonii* the internode of the culm was found to have higher moisture content and volumetric shrinkage with lower specific gravity. The opposite is true for branches of bamboo. Although the node has higher specific gravity, the presence of the node has been found to reduce strength of the bamboo culm. The reduction of strength by the node is due to the shorter, thicker and forked fibres and the randomly orientated vascular bundles in the nodal part.

3.6 Special Considerations when Using Bamboo as Reinforcement

Bamboo-Water Interaction

Bamboo consists of two distinguished layers of fibres, the outer layer, which contains

40–70% fibres, and the inner layer, which contains 15–30% fibre. The yellow coloured outer fibre has a high silica content and is hence stronger and stiffer. Older bamboo and the lower portion of the bamboo culm have been shown to contain more fibre. When bamboo is used as continuous reinforcement in concrete the bamboo can absorb the moisture from the fresh concrete causing swelling. During the curing phase of the concrete, the water absorbed by the bamboo is used for hydration of the cement particles and so is drawn back out of the bamboo through a change in energy potential. When this occurs the bamboo can shrink leaving a void between the bamboo and the concrete.

The magnitude and rate of volume absorption of water of the bamboo is dependent on the bamboo properties, the physio-chemical properties of the water, types of cement and aggregates and the water/cement ratio. The most important factors are the fibre characteristics, especially the inner portion, and the water/cement ratio.

To minimize the effect of bamboo-water interaction on the bond between the bamboo and the concrete, mature and seasoned bamboo only should be used, low water-cement ratio should be used (no more than sufficient to ensure workability), culms should be split to improve bond.

Bond Strength

The bond between the concrete and the bamboo is another important consideration. Bamboo has poor bond strength because of its smoothness as well as its swelling-shrinking characteristics. The following observations have been made based on previous studies.

- Seasoned bamboos possess greater bond strength compared with unseasoned (green) bamboo
- Bamboo nodes when present improve bond characteristics
- Increased cement content and/or decreased water/cement ratio improves bond
- Bond properties may be improved by moisture-proofing the bamboo
- Mechanical means such as the use of nails or spikes, winding the bamboo in coir or metal wire and the use of shear connectors may be used to improve bond

Both bond strength and the bamboo-water interaction are related to the moisture content of the bamboo. The moisture content of a bamboo sample is dependent on a number of variables as previously discussed. The most influential of these is the fibre content, with bamboo near the base and split into splints having a minimum amount of high moisture demand fibres. Hence it is recommended that splints be used for reinforcement of concrete.

For the most part bamboo-reinforced concrete has employed splint reinforcement to date and any design methods and methods of improving bond are based on the use of splints for reinforcement. Many methods of improving the bond characteristics of bamboo splints have been proposed in the past. The most practical of these include simple yet effective roughening of the outer smooth edge, use of locally available latex where possible and applying a coat of bitumen and sand. Many methods which have been proposed are so expensive as to render their use impractical for low cost roads, such as the suggestion of Pama et al. (1976) to immerse the bamboo material in 2% zinc chloride, or in a Neoprene adhesive mixed with sand. Kowalski (1974) recommended the use of polyester resins or epoxy adhesive, both of which are very expensive, and silica powder as part of the treatment. Fang et al. (1976) recommended that first a sand blasting treatment be applied followed by sulphur and sand treatment.

Many researchers have found that an improvement in the bond strength may be effected by addition of a waterproofing coat. It has been noted in some work that a coat of varnish on the surface of the bamboo strips increased bonding strength and enhanced other mechanical properties as well. It has also been observed that the maximum strength of the bamboo can be reached by increasing the width of the rectangular profile by 30% at the nodes. The mechanical properties of various methods of bond improvement may be seen in Appendix 1.

Natural Durability

Since bamboo is an organic material it is susceptible to attack by fungus and insects. This is of little consequence when used as continuous reinforcement encased in concrete, however alkali attack of the bamboo may occur over time. Alkali attack occurs when the calcium hydroxide component of the hydrated cement is leached from the concrete and breaks down the cellulose structure of the bamboo fibres. There is little data available on this phenomenon and also in relation to the long-term durability of bamboo as reinforcement in concrete. Addition of a pozzolan may alleviate this to some extent or use of a lower water/cement ratio in conjunction with superplasticiser and good compaction to produce a denser concrete may have a positive effect but there has been little research carried out to confirm this. It is generally recommended that splints be used and treated with a waterproofing treatment in order to subdue alkali attack of the bamboo when used as concrete reinforcement.

The lifetime of bamboo in contact with atmosphere and soil is 1-3 years, 4-6 years under cover and 10-15 years under cover in a not very humid climate (i.e. when used for rafters of a house). Attack from fungus, termites and powder post beetles is a problem before the bamboo is utilised however. Hence precautions should be taken against this when harvesting, seasoning and storing the bamboo culms.

Because of the fore-mentioned factors, bamboo is most effective as continuous reinforcement in concrete structural members which are not subjected to excessively large live loads during the structures service life and for slabs on grade such as pavement slabs.

Harvesting Method for Bamboo

Because the method of harvesting affects the mechanical properties of bamboo, a brief description of proper harvesting method is described hereafter.

Only adult culms should be cut. Young culms should be left in their place, not only to mature, but mainly to provide food for the plant. Care should be taken not to remove too many culms or the plant may die. The age of the culm may be estimated by the colour but this is somewhat uncertain. The most positive method to determine the age of the culm is to put a mark on all culms each year at the same place. If in a certain situation culms are ripe after four years then all culms with four marks can be cut.

Harvesting should be done in the dry season, because then the bamboo culms have lower moisture content. During the rainy season no felling should occur.

Usually bamboo culms are cut with a sharp machete, but for heavier culms a pruning saw or an axe can be used. Bamboo can be divided into two types: the clump type and the running type. In the clump type bamboo grows in clumps of 50 or 100 culms and in the running type the culms are evenly distributed over the area.

In the clump type the old mature culms will be found in the centre with the young ones at the circumference. An entrance to the centre has to be made which results in a horseshoe pattern. Culms should be cut 20 – 30 cm above ground level in order not to damage the roots and just above a node in order to avoid water collection with subsequent rot.

In the running type, bamboo culms can be cut at ground level, because the roots remain protected in the ground.

Splints (i.e. split culms) are generally more desirable than whole culms for the reinforcement of concrete. Larger culms should be split into splints approximately 20 - 25mm wide.

Splitting the bamboo can be achieved by separating the base with a sharp knife or saw, then a dulled blade should be used to split the culm lengthwise. The technique will force the stem to split open and retain the continuity of the fibres.

Transport of Bamboo

Transport of bamboo can be difficult for the following reasons:

- Small quantities to be collected from a large area
- Access is sometimes difficult
- Low stacked weight per volume

Therefore, when possible, bamboo should be used locally to where it is grown. This will minimize transport costs and potential for damage to the bamboo.

Storage & Treatment of Bamboo

The storage of bamboo requires special care. The ground must be clean, free of refuse of all kind and free of termites. Bamboo should be stored under cover to protect it from rain and clear of the ground (20 or 30cm). Good ventilation and frequent inspection are necessary. Fresh bamboo, standing vertically will dry in at least four weeks; a horizontal position doubles this time. Bamboo should be well supported when it is stored in order to prevent excessive warping of the culms.

Serviceability Risks

The assessment of risks is an important consideration when reviewing surfacing options for rural roads. In the situation of provision of basic access roads, quality assurance (QA) arrangements can sometimes be deficient. In this respect BRCP is considered to be reasonably tolerant of QA arrangements. Poor workmanship on the concrete surface is generally immediately apparent on the finished product. Simple (and low cost) inspection procedures can ensure adequate preparation, materials quality, placing and curing of BRCP without complicated testing requirements.

Most deficiencies in construction can be rectified with simple labour, tools and materials. For Basic access roads it is unlikely that poor BRCP workmanship would lead to route impassability, however safety and vehicle operating costs could be compromised by poor design or workmanship.

4. PAVEMENT DESIGN

This section of the document sets out the specific considerations for the Puok Market BRCP design.

4.1 Design of Bamboo Reinforced Concrete Pavement

Policy Design Requirements

- All-weather road
- Maximum use of local resources
- Labour-based construction methods
- Long life span, easily maintained by labour-based methods
- Resistance to effects of flooding/high intensity rainfall
- Elimination of dust

General Design Requirements

The design standards used for the Puok Market bamboo reinforced concrete pavement are:

Road category:	Tertiary
Carriageway width (single lane):	4m
Shoulders (on both sides):	500mm
Carriageway crossfall:	2%
Shoulders crossfall:	4%
Embankment slope (if any):	1:3 (Vertical: Horizontal)
Design speed:	40 Km/hr
Maximum super elevation:	5%
Longitudinal elevation:	1% - flat terrain
Average Daily Traffic (ADT):	500
Design Wheel Load(DWL):	10 tonne
Design Axle Load (DAL):	20 tonne
Design life span:	40 years

Detailed designs are given in Appendix 4.

The bamboo reinforced concrete pavement was designed on the basis of research carried out at Chang Mei University, Thailand but with due regard to current practice in design of Portland cement concrete rigid pavements. Load tests using a ten-wheeled truck were carried out on pavements of varying thickness with varying bamboo mesh positions within the depth of the pavement slabs. The overall findings of the fore mentioned research are:

For a relatively rigid existing soil the position of the bamboo mesh within the depth of the pavement had little significance with regard to resistance provided against the imposed load of the ten-wheel truck used for the tests.

The non-reinforced test sections showed a significant increase in deflections during the test when compared to sections reinforced with bamboo mesh.

The suitable thickness for BRCP in view of the limited tests carried out indicate no significant difference. Hence the present practice of specifying a slab thickness of 15cm may be reduced to 12.5cm or even 10cm provided proper care is taken in preparing a good supporting subsoil (recommended C.B.R. > 25)

The C.B.R. values recorded for the Puok trial area indicated the subsoil to be typically weak, sandy soil found in Cambodia, with in situ soil CBR values of about 7. Thus a pavement thickness of 150mm was selected.

A 50mm well-graded sand subbase compacted to not less than 98% standard Proctor density was provided to ensure good load transfer and distribution to the supporting subsoil.

The bamboo mesh was placed in the top third of the concrete slab, 50mm from the pavement surface, with the intention of the bamboo being utilised to control cracking due to shrinkage during initial setting and curing and to aid in the control of cracking due to temperature variations. The bamboo mesh had grid dimensions of 200mm × 200mm. Splints measured 25mm in width on average. Basal and distal ends were varied in order to obtain a uniform reinforcement area. This configuration has been found to perform satisfactorily in Thailand. Recommendations, presented at the end of this report, were rigorously followed in the selection, preparation and utilisation of the bamboo for reinforcement.

The use of tied shoulders or a widened width of pavement has been proven to be beneficial to overall performance of rigid pavement. However, the traffic volume of the area was deemed insufficient to justify the added expense of such a construction in the case of Puok Market. Well-compacted laterite shoulders, 500mm in width, were constructed using the laterite of the original wearing course. The starkly contrasting shoulder colour and texture is beneficial to road safety in the area. Furthermore, the contrasting colour will minimise traffic operations on the shoulder since the concrete pavement is the preferred route. Any treatment that will minimise operations on the shoulder will benefit the performance of pavements in the travelled way and on the shoulder.

Expansion joints were provided at 250m intervals and detailed design specifications may be seen in the drawings of Appendix 4. The primary function of expansion joints is to provide space for the expansion of the pavement, thereby preventing the development of compressive stresses, which can cause the pavement to buckle.

Since the slab was considered to be un-reinforced and the bamboo was considered only to control cracking in initial stages, contraction joints were provided at 5m intervals. The positioning of contraction joints is critical for BRCP since the function of contraction joints is to relieve tensile stresses due to temperature, moisture, and friction, thereby controlling cracking. If contraction joints were not installed, random cracking would occur on the surface of the pavement. This would have serious implications for pavement durability, especially for BRCP.

Given the susceptibility of the area to flooding and the critical nature of drainage design in relation to the satisfactory performance of any pavement, special consideration was given to drainage design for the BRCP.

4.2 Drainage Design

The design philosophy applied in the design of the drainage emphasised interception and removal of surface water in a timely manner, given the relatively high traffic volumes, high population density, economic importance of the area and the desire to prevent infiltration of water into the supporting subbase and subgrade layers beneath the pavement slabs. Details of the drainage design may be seen in Appendix 5.

Varying details were specified for different areas around the market depending on the level of drainage required. Because Puok is an important market centre a high level of drainage was required around the market itself, since this has in the past been flooded. The drainage system around the market was constructed to be uncovered to allow for ease of maintenance in the future. Two basic types of drainage structure were specified in the design, an open rectangular channel drain constructed of lean concrete and plastered brickwork and a v-shaped gutter constructed of concrete. The drainage was constructed to appropriate levels such that all water would be transported away from the market to the nearby river running through the town.

Images 5 & 6: Side Drainage Arrangements

4.3 Material Requirements

Concrete:

A mix proportion of 1:2:4, cement: sand: aggregate with a water/cement ratio of 0.45 was specified for the pavement concrete works. This was found to be the minimum water/cement ratio applicable while obtaining a reasonable slump value, and hence workability, such that the concrete could be placed and compacted using labour-based methods. A minimum compressive strength of 21MPa, as determined by tests of 150mm cubes in accordance with British Standard 1881, was specified for the concrete. In addition a maximum aggregate size of 20mm was specified in order to ensure sufficient compaction would be achieved, without voids forming beneath the concave surface of the splints. For the drainage works, a mix proportion of 1:3:6, cement: sand: aggregate with a water/cement ratio of 0.45 was specified and a minimum compressive strength of 10MPa determined as the concrete mentioned above.

Bamboo:

The bamboo was selected in accordance with the criteria discussed earlier in this document, such that sufficient bond between the bamboo splints and the concrete would develop upon curing of the concrete. Thus the bamboo would effectively control crack formation during setting and curing of the concrete as well as limiting the tensile stresses in the concrete due to temperature variation. It is difficult to calculate the magnitude of the bamboo's effect in controlling cracks as well as the bamboo's contribution to the load bearing capacity of the pavement because of the inhomogeneity of the materials mechanical properties. Experience within the sector in Thailand and elsewhere has shown bamboo to be effective in such a role if sufficient steps are taken to ensure adequate bond develops.

Image 7: Bamboo mesh located 5cm below finished slab level

Load Transfer Devices:

14mm diameter mild steel reinforcement bar (of length 500mm) dowels at 250mm centre-to-centre spacing were specified as load transfer devices at all expansion and contraction joints.

Joint Sealant:

Bitumen and sand was specified for sealing all joints. A sufficient reservoir of bitumen was placed at each joint to allow for the effects of movement at the joints.

Image 8: Finished Joint

5. CONSTRUCTION

5.1 Preparatory Work

Setting Out

The extent of the embankments were marked by fixing wooden pegs along the road alignment at ten to twenty metre intervals or closer if required. The pegs were placed approximately half a metre beyond the outer edge of the embankment and painted with luminous paint. Standard surveying practice was used to obtain the grade and profile specified by the design.

Image 9: Setting out of road alignment and level

Preparation of Existing Ground as Sub-grade

As much as was practically possible, the embankment material and previous laterite wearing course was left untouched since a degree of consolidation, which would be beneficial to the new construction, was achieved through the everyday use of the road. The surface was simply shaped and levelled in accordance with the design specifications. Following this the surface was wetted using a water bowser and hand held watering cans and then compacted using a one tonne twin drum pedestrian vibrating roller. The number of passes was specified such that satisfactory compaction of any new material or remixed layers would be achieved.

5.2 Sand Sub-base

A sand sub-base was required in order to ensure good load transfer and distribution to the supporting sub-grade. A 50mm thick sand sub-base, of Fineness Modulus (F.M.) not lower than 1.80 and well compacted, was provided. The sand sub-base was compacted by a one tonne twin drum pedestrian vibrating roller to obtain compaction of not less than 95% Maximum Dry Density (M.D.D).

Image 10: Placement of Sand Sub-base
Compaction of Sub-grade and Sub-base Layers

Proper compaction of sub-grade and sub-base layers is of paramount importance with regard to the satisfactory performance of a rigid pavement. This is particularly essential in Cambodia where in-situ soils tend to be very weak, as demonstrated by the low California Bearing Ratio (CBR) values, derived from the Dynamic Cone Penetrometer (DCP) test. For this reason particular attention was given to the compaction of sub-grade and sub-base layers. All layers were placed and compacted in layers of not more than 150mm thickness. The material was laid in the dry state and wetted to as near as Optimum Moisture Content (OMC) as practically possible using a locally constructed water bowser. Efforts were made to ensure that the material was within ±5% limits of OMC. Immediately after each layer was placed, wetted, shaped and graded to the required camber, it was thoroughly compacted using a one tonne pedestrian vibrating roller. The number of passes was specified in the construction specifications and all compaction work was overseen meticulously.

Image 11: Sub-base Compaction Construction of Pavement (to be inserted)

5.3 Construction of Formwork

All forms were constructed of 30mm planks of local wood. The forms were constructed to be mortar tight and rigid enough to retain the specified shape and position during placing and compaction of the concrete. This was achieved through the use of bracing, metal ties and anchors.

5.4 Bamboo Reinforcement

Care was taken to vary the basal and distal ends of the bamboo splints when fabricating the bamboo mesh. This would ensure that a uniform area of reinforcement would be obtained throughout the area of the pavement. The bamboo was placed 50mm from the top of the pavement such that it would serve to control cracking during initial setting and also assist in the control of cracking that could occur due to temperature variations. The bamboo mesh of 250 × 250mm was placed on 100mm wooden spacers, which ensured the desired 50mm cover to the reinforcement would be maintained. The wooden blocks were removed as pouring of concrete progressed. The construction configuration and methodology utilised was similar to those found to produce satisfactory results in larger projects in Thailand.

Image 12: Placement of Bamboo Mesh, wooden spacers to be inserted under mesh

5.5 Mixing of Concrete

All concrete was mixed on site in small capacity batch mixers. Mixers with a capacity less than one bag of cement were not used and no mixer was charged in excess of its' rated capacity. The first batch of materials placed in each mixer contained a sufficient excess of cement, sand and water such that the interior of the drum as coated in order to prevent loss of mortar to the mix. After any considerable pause in mixing the mixers were washed out thoroughly before use again. Containers for measuring aggregates, water and cement were manufactured locally. The coarse aggregate and cement were placed in the mixer first and mixed together for a number of minutes in order to ensure the coarse aggregate particles would be thoroughly coated in cement. Following this the sand was added and mixed in the dry state for some minutes.

Image 13: Mixing of Concrete

This was carried out in an attempt to obtain as homogenous a mix as possible and thus achieve the best results from the materials available locally. Finally water was added in two doses and mixed for not less than two minutes. Every batch was mixed until a concrete of uniform consistency was obtained. The mixing of each batch was observed and the volume of each constituent used in each batch was recorded.

5.6 Placement of Concrete

Prior to placing the concrete, all formwork and reinforcement was thoroughly inspected by the engineer. All wood chips, dust, sand, construction debris and any other deleterious material was removed from the formwork and reinforcement prior to placing the concrete. All formwork was wetted to ensure it was damp when the concrete was poured. This operation was carried out to prevent water being absorbed by the wood and hence prevent altering the specified concrete water/cement ratio, which would modify the characteristics of the fresh concrete. Care was taken during this operation such that pools of excess water did not form in the base of the formwork and also that the bamboo mesh was not wetted. Workers were organised such that one team mixed a continuous supply of fresh concrete, while another brought the concrete to the point of placement and yet another team spread and compacted the concrete.

A sun shelter was fabricated to protect the placement workers and fresh concrete.

Images 14 & 15: Placement of Concrete and Sun Shelter

Efficient organisation of labour ensured no construction joints in a slab were necessary, which would have weakened the pavement structure. Wheelbarrows and specially constructed stretchers were used to transport the fresh concrete. The position of the bamboo mesh within the depth of the pavement was modified as the pouring progressed to ensure than the desired position 50mm below the pavement surface was maintained. Any bracing or dowels used within the formwork were removed as pouring progressed.

5.7 Compaction of Fresh Concrete

Once the concrete had been placed uniformly within the forms, compaction was carried out using a mechanical poker vibrator of 25mm diameter, powered by a small portable generator. Care was taken to ensure a good bond between layers of fresh concrete placed separately by vibrating the two layers together until a satisfactorily homogenous cross section was obtained.

No concrete was compacted after initial setting had proceeded. Initial setting was recognised by a loss of flowability of the concrete. All concrete was compacted until no air bubbles appeared on the surface of the fresh concrete. Concrete was not compacted beyond this point, to prevent segregation within the mix. Care was also taken not to touch the formwork or embedded reinforcement with the vibrator since this would result in concrete having begun initial setting being exposed to re-vibration. It could also have a detrimental effect on the bond between the concrete matrix and the bamboo reinforcement.

5.8 Surface Finishing

A two per cent camber was ensured along the length of the pavement through the use of a straight edge screed plank. Details of this operation are shown in images 18 and 19. After placement and compaction of the fresh concrete the camber was shaped in the fresh concrete to lines and levels set out using the simple locally constructed hand tool. In order to improve the skid-resistance of the surface and to shorten the vehicles' breaking distance, grooves were etched in the fresh concrete surface. A special rake consisting of a steel wire teeth attached to a wooden head and handle was manufactured locally for this purpose.

Image 16: Grooving Rake

Images 17 & 18: Surface Finishing

5.9 Contraction Joints and Expansion Joints

Contraction joints, 10mm in width, were provided every 5m to relieve tensile stresses. Experience has shown that in most climates, joints are required at 5m intervals in order to inhibit early formation of cracks, to relieve temperature stresses, and to accommodate initial volume changes that take place in concrete as it hardens. With concrete roads constructed in hot weather, contraction of the concrete predominates as the weather becomes cooler. In any subsequent expansion it is unlikely that all joints will be able to close to their original dimensions. For this reason expansion joints were provided at 250m intervals. This configuration has been found to perform satisfactorily in similar pavements in Thailand. All joints were sealed using a mixture of bitumen and sand and a reservoir of bitumen was provided at the top of the joint. All joints were provided with load transfer devices to limit the vertical movement between slabs as vehicles pass over.

In the Puok market area where overloading of vehicles is common, the provision of load transfer devices between slabs was especially important. 14mm round steel dowels, 500mm in length, at 250mm centre – to – centre were provided at all joints. Where the joint was an expansion joint, the dowel bar was anchored into the concrete at one end and the other end was coated with bitumen and the fitted into a PVC sleeve in order to ensure free movement in the longitudinal direction. Where the joint was a contraction joint, the PVC sleeve was omitted.

5.10 Curing of Concrete and Special Measures

High temperatures increase the rate at which concrete hydrates. Typically this results in two difficulties related to pouring concrete in hot climates. The concrete sets more rapidly, losing its workability resulting in difficulty in achieving thorough compaction. On site the workability was rigorously checked using concrete slump as an indicator. A slump test was carried out for each batch of concrete mixed, a slump of not less than 100mm being required. Rapid early gain in strength of concrete experienced in hot climates can be accompanied by shrinkage and cracking of concrete with the result that the subsequent gain in strength is much less than with concretes cured at lower temperatures. Specific measures were taken to combat the effects of high temperature and direct sunlight. All aggregates were stored under cover before use. Mixing water was kept in a shaded area of the site. As the concrete was being placed and compacted the surface was protected from direct sunlight and drying wind by a specially constructed tent structure, which was moved from bay to bay as pouring proceeded, plastic sheeting being used to replace the tent.

Image 19: Curing and Protection of Concrete

The concrete was cured by spreading sand over the surface of the pavement and repeatedly wetting the sand for a period of 28 days. A 14-day curing time, and even a 7-day period, may suffice depending upon the mix design and local circumstances. No traffic was allowed on the pavement until a period of 28 days had elapsed. Suitable temporary diversions were made for continued flow of normal traffic. Such measures were necessary due to the uncertainty in relation to loading and overloading of trucks delivering goods to the market or hauling road-building materials in the area. Simple bamboo barricades were constructed of bamboo failing to meet the criteria for use as reinforcement. These served to prevent pavement use until the 28-day curing period had elapsed.

5.11 Construction of Drainage

Particular attention was devoted to the design of drainage, given the importance of effective drainage on the overall satisfactory performance of the road structure. Drainage design resulted in a two per cent camber for removal of water from the pavement surface. In the urban section of the road, further provision was made to transport runoff to nearby drainage systems through a network of open box gutters and v-shaped gutters at the side of the road. The design philosophy was towards interception of all surface water as quickly as possible rather than allow for infiltration into sub-base and sub-grade layers.

In the non-urban sections of road the carriageway was situated on an embankment; the laterite shoulders were shaped to fall away from the road surface at 4% and shed the rainwater evenly to the side of the embankment without causing erosion.

Excavation and Preparation of Channel Bed

All drains and gutters were set out by the site engineer prior to excavation. The drains, box or v-shaped as specified by the design specifications, were first excavated to the desired shape and depth. Next the required longitudinal gradient was provided. The beds of the channels were then lined with 50mm of sand, which was wetted and compacted using vibratory plate compactor or a hand rammer where necessary. Appropriate hand tools, shoulder baskets, stretchers and wheelbarrows were used in the excavation of the drains.

Images 20 - 23: Drainage Works

Lean Concrete Bed Lining

A 100mm thick layer of lean concrete was placed in the bed of each drainage channel and compacted using a mechanical poker vibrator. The concrete had proportions of 1:3:6, cement: sand: aggregate. The concrete was mixed by hand on plastic sheeting next to the area of use. Batches were small enough to ensure no concrete was wasted due to onset of initial setting before placement.

Brickwork

Bricks are manufactured in the proximity of the market and so brickwork was chosen for the structural form of the drainage channel walls. The bricks were cleaned before use and mortar joints of not more than 8mm were used. All walls were constructed to the engineers' lines and levels. Once the brickwork had been completed care was taken by the bricklayers to make sure the drainage channels had been cleaned of any debris or mortar that may have been left.

Plastering

One day after construction of the brickwork, plastering of the brickwork began. A standard mortar mix was used. The brickwork was wetted prior to application of the mortar coat. Experience has shown that where measures are not taken to mitigate against the effects of high velocity flows, pitting and other erosion effects rapidly appear on the surface of newly constructed concrete structures. Concern over the large volumes water, which the drainage system would have to transport lead to the decision to add a further layer of cement paste over the mortar in order to obtain a smooth finish.

5.12 Construction of Shoulders

As much as was possible, laterite from the original wearing coarse was used in the construction of the shoulders. Any imported material had to meet the specified standards following laboratory sieve analysis and testing. The laterite was placed in layers of not more than 150mm, wetted to OMC and then compacted using a one tonne twin drum pedestrian vibratory roller. The second layer of laterite was then placed in order to raise the thickness of the shoulders to 200mm after compaction and compacted in the same way.

5.13 Quality Control Measures on Site

Various quality control measures, many of which have already been briefly mentioned, were implemented on site. These may be broadly divided into to categories:

- Control of materials
- Control of works

Control of Materials

Material properties were specified in the design specifications such as; Fineness Modulus of sand, maximum coarse aggregate size, reinforcement dimensions, sealant type and quality etc. were all specified within the specifications of the contract documents. It was important to ensure such specifications were followed in obtaining all materials used. Relevant documentation was obtained, including suppliers' certificates and results of various material tests carried out at the Ministry of Public Works and Transport laboratory in Phnom Penh. Sand and coarse aggregate were screened on site to ensure a maximum particle size as specified. Coarse aggregate was washed prior to use. All aggregates and cement was stored in a shaded, clean and dry location on site. All cement was checked for lumps and dampness before use. Water for concrete mixing was obtained locally and stored in barrels in a shaded place on site. The water barrels were filled every night in order to ensure water of a minimum specified turbidity was obtained.

Control of Works

Various tests were carried out during the course of the works. Slump was measured for each batch of concrete prior to its' placement. All constituents of each concrete mix were measured in containers manufactured locally specifically or the purpose. All placement and compaction of concrete was carefully followed and registered. Formwork and reinforcement details were inspected before placement of concrete commenced. Where new aggregate was delivered to site and were judged by the engineer to be of too high a temperature, water was spread over the aggregate and the amount of water in the mix reduced accordingly.

Image 24: Slump Test

6. COST ANALYSIS

Road construction costs can be divided into two categories; direct costs and indirect costs. The direct costs involve all items that are directly incurred by, or related to, a specific construction activity carried out at site. These include material, labour, equipment hire, site camp and transportation etc.. Indirect costs are the costs that are not directly linked to the project activities at site. Indirect costs include such items as preliminaries, risks and company costs. Further discussion of costs can be found in Reference 21. It can be expected that costs would vary considerably in other regions and local costs should be verified for any cost comparison between techniques, particularly for materials haulage.

6.1 Direct cost of BRCP

Material cost

There is a large variance in cost of materials from province to province within Cambodia. The variation in material cost is mainly caused by the condition of primary road networks and material transportation costs. Costs can also vary by season, reflecting the road conditions. Table 1 below shows the typical material cost depending on haulage distance. It should be noted that the haulage distance affects mainly the natural gravel and the aggregate costs. Cost of cover sand usually does not vary much due to the availability of the material with short haulage distances in most areas of the country. It should be noted that ten per cent was added to the bamboo volume as waste.

Item	Unit	Quantity	Unit rate US$			Cost per Km for haul		
			10 Km	50 Km	100 Km	10 Km	50 Km	100 Km
Sand	m^3	270.0	5.0	6.0	7.0	**1,350.0**	**1,620.0**	**1,890.0**
Aggregate	m^3	540.0	9.0	14.0	24.0	**4,860.0**	**7,560.0**	**12,960.0**
Cement	Ton	180.0	65.0	68.0	70.0	**11,700.0**	**12,240.0**	**12,600.0**
Form work	m^3	0.7	50.0	50.0	50.0	**35.0**	**35.0**	**35.0**
Sand (cover)	m^3	10.0	3.0	3.0	3.0	**30.0**	**30.0**	**30.0**
Bamboo	Bundle	138.0	1.5	1.5	1.5	**207.0**	**207.0**	**207.0**
Steel 14 mm dia	Ton	0.97	345.0	345.0	345.0	**334.7**	**334.7**	**334.7**
Binding wire	Kg	100.0	0.68	0.68	0.68	**68.0**	**68.0**	**68.0**
Bitumen	Kg	50.0	2.0	2.0	2.0	**100.0**	**100.0**	**100.0**
					Total Cost in US$ Per Km	**18,685**	**22,195**	**28,225**

Table 1: Cost of Materials for 1km of BRCP based on haulage distance[1]

Labour Cost

The labour may be divided into two categories: skilled and unskilled. Skilled labour refers to those tasks, which require some knowledge and previous experience such as operating equipment like concrete mixers, plate compactors, rollers, or acting as a gang leader. Unskilled labour refers to those tasks that do not require previous experience or knowledge such as loading, unloading, spreading, etc. The cost of an

1 Based on 4 metre wide pavement, mid-2000 prices.

unskilled labourer was 4000 Riel *(US$1.05 equivalent)*[2] and 6000 Riel *(US$1.55 equivalent)* for an skilled labourer per day. It was also estimated that each twenty five workers will form a gang led by a skilled labourer called gang leader. Table 2 below shows labour costs for construction of one kilometre of BRCP based on the Puok Market trials field experiences.

No.	Activity	Unit	Quantity	Work Norm Unit/worker -day (Wd)	Worker-days	Wd Cost USD	Total Cost USD
1	**Survey & set out**	m	10,000	50	200	1.05	**210**
2	**Clearing**	m^2	7,000	70	100	1.05	**105**
3	**Sand spreading**	m	1,000	20	50	1.05	**52.5**
4	**Binding Bamboo**	m^2	4,000	20	200	1.05	**210**
5	**Form work**	m	1,000	20	50	1.05	**52.5**
6	**Concreting (mixing, loading, etc.)**	m^3	600	0.22	2,728	1.05	**2,865**
7	**Earth work at side slope**	m^3	2,090	2	1,045	1.05	**1,098**
8	**Gravel spreading at shoulders**	m^3	252	5	51	1.05	**54**
9	**Compaction**	m	5,000	50	100	1.05	**105**
10	**Curing of concrete**	m	1,000	50	20	1.05	**21**
11	**Side slope**	m^2	6,000	20	300	1.05	**315**
12	**Turfing**	m^2	6,000	30	200	1.05	**210**
13	**Gang leader and skilled workers**				200	1.55	**310**
						Total Cost in US$ per Km	***5,608***

Table 2: Labour Cost for Bamboo Reinforced Concrete Pavement

Equipment Cost

The equipment used for the construction works consisted of mainly hand tools and simple small plant to complement the labour where necessary. All equipment was of the type already in use by small-scale contractors within the sector. Equipment costs were based on daily rental fees from the market. Table 3 below shows the cost of equipment used for the bamboo reinforced concrete pavement construction.

No.	Activity	Equipment	Unit	Quantity	Unit cost USD	Total Cost USD
1	**Transport**	Etan (light truck)	Day	33	20.0	**660**
2	**Water transport**	Etan bowser	Day	33	20.0	**660**
3	**Concrete mixing**	Concrete mixer 0.2 m3	Day	33	15.0	**495**
4	**Concrete compaction**	Concrete Vibrator	Day	33	2.0	**66**
5	**Electrification for equip.**	Generator	Day	33	5.0	**165**
6	**Compaction**	Plate Compactor	Day	66	5.0	**330**
7	**Operation cost**			33	10.0	**330**
					Total Cost in US$ per Km	***2,706***

Table 3: Equipment Costs

2 US$1 = Riel 3,900 mid 2000.

Tools

Simple hand tools can be used for the pavement construction. Table 4 below shows a list of tools that are required for 1 Km of BRCP road construction.

No.	Activity	Tools	Unit	Quantity	Unit cost USD	Total Cost USD
1	**Setting up alignment**	Ranging Rod Profile board	No.	10	6	**60**
2	**Carriage**	Wheel barrow	No.	5	25	**125**
3	**Spreading, loading**	Hoes	No.	10	3	**30**
4	**Spreading, loading**	Shovel	No.	10	5	**50**
5	**Checking alignment**	Steel template	No.	1	30	**30**
6	**Finishing**	Traveller, Finisher	LS			**50**
7	**Loading**	Basket	No.	10	0.25	**2.5**
8	**Water**	Bucket	No.	20	1	**20**
9	**Setting up**	String line	Kg	5	1.2	**6**
10	**Measurement**	Measuring tape (5m)	No.	2	2.5	**5**
11	**Measurement**	Measuring tape (5m)	No.	1	7	**7**
12	**Form work**	Hammer (2Kg)	No.	5	2	**10**
13	**Form work, corrections**	Chisel	No.	5	1	**5**
14	**Safety**	Safety requirements	LS.			**30**
					Total Cost in US$ per Km	***431***

Table 4: Hand tools cost

Total Direct Cost

The total direct cost of the Bamboo Reinforced Concrete Pavement (BRCP) will depend primarily on the haulage distance as shown in Table 5. Note that these figures are specific for the circumstances of the Puok Market trials area.

No.	Item	Cost US$ per Km for principal materials haul distance of		
		10 Km	**50 Km**	**100 Km**
1	**Material**	18,685	22,195	28,225
2	**Labour**	5,608	5,608	5,608
3	**Equipment**	2,706	2,706	2,706
4	**Tools**	431	431	431
Total Cost US$ per Kilometre		***27,430***	***30,940***	***36.970***
Total Cost US$ per square metre		***6.86***	***7.74***	***9.25***

Table 5: Total Direct Costs for BRCP per Kilometre and per Square Metre

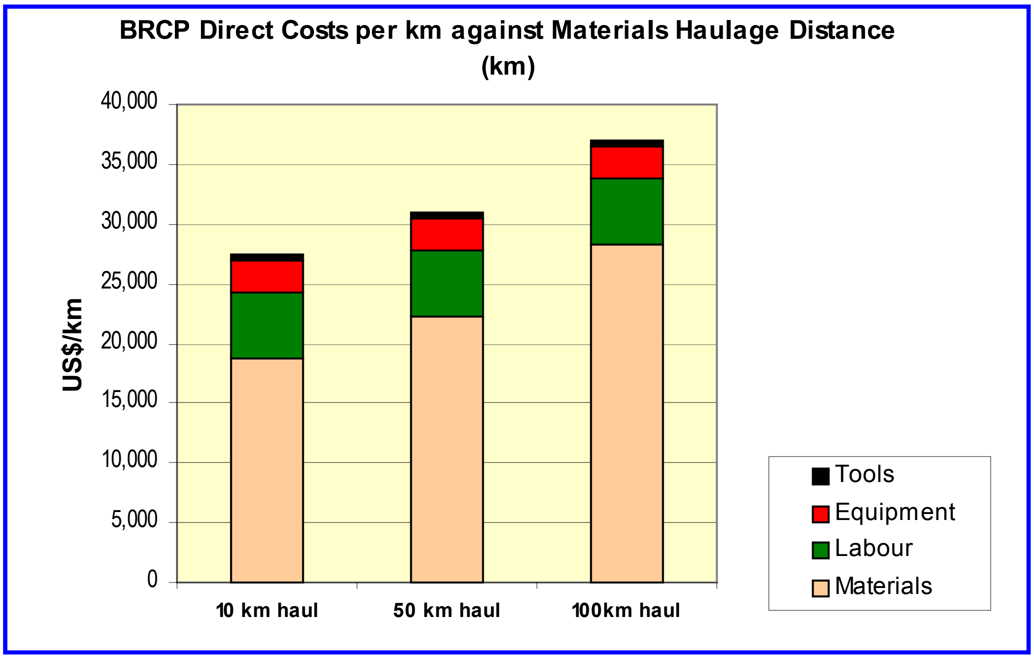

Chart 1: BRCP Direct Costs per km against Materials Haulage Distance

6.2 Indirect Costs of BRCP

As mentioned earlier in the document, indirect costs may be divided under the following sub-headings:

Preliminaries: additional costs directly related to the work such as mobilization, setting up site base, supervision, supervisors transport, quality control arrangements, health and safety insurance for workers and equipment, security and other similar costs.

Risk allowance: this factor includes risks related to construction projects such as bad weather, re-work, clients' financial security and other similar costs.

Company costs: these costs involve the cost of the company such as bidding and marketing costs, office rental, administration staff, interest on bank loans and other. This cost can be distributed on different projects carried out by the contractor at the same time.

In addition after covering all costs the contractor will expect to make a profit for his efforts and deployment of resources.

From the experiences of the project the indirect cost can be assessed as a percentage of the direct cost. Four per cent of the direct cost was added for preliminaries and risks. Ten percent was added for overheads and profit, based on the 10km haul of principal materials. The trials were held under a closely supervised environment with training and mentoring provided for the contractor, and prompt payments of all due amounts. It would be expected that preliminaries, risk, overhead and profit elements could vary somewhat for other contractual circumstances.

No.	Item	Cost US$ per Km for principal materials haul distance of		
		10 Km	50 Km	100 Km
1	Material	18,685	22,195	28,225
2	Labour	5,608	5,608	5,608
3	Equipment	2,706	2,706	2,706
4	Tools	431	431	431
5	Overheads+Profit	3,840	3,840	3,840
Total Cost US$ per Kilometre		***31,270***	***34,780***	***40,810***
Total Cost US$ per square metre		***7.82***	***8.70***	***10.20***

Table 6: Overall Construction Costs of BRCP

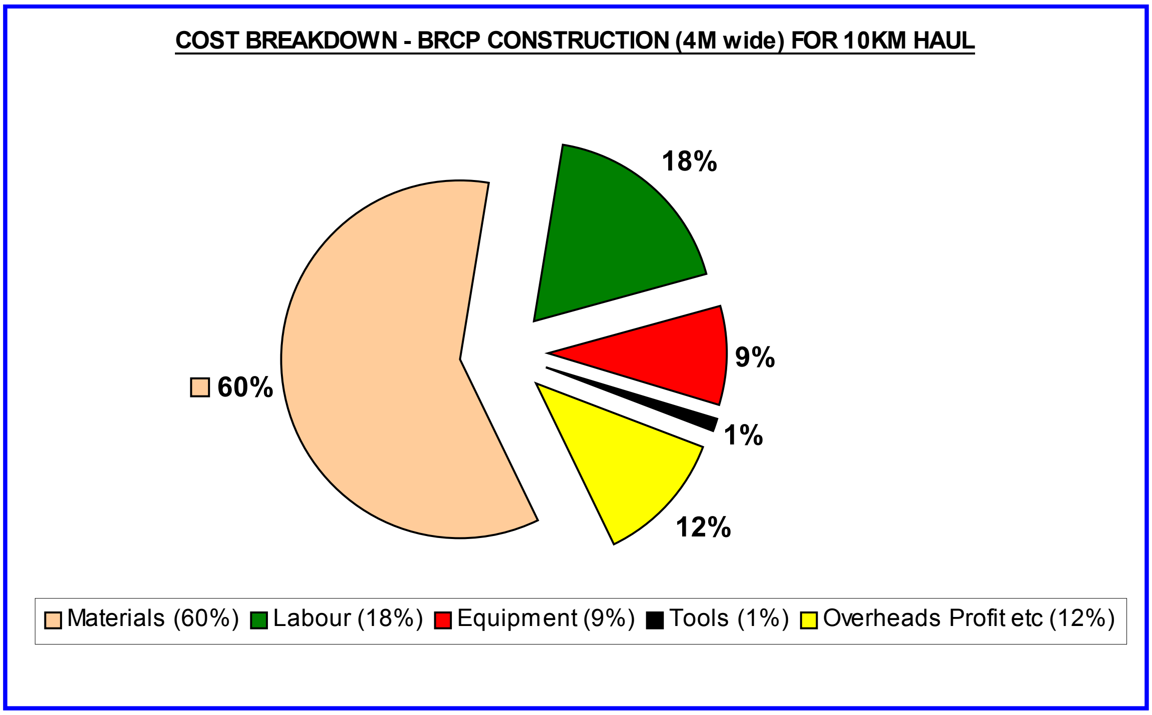

Chart 2: Cost Breakdown - BRCP Construction (4m wide) for 10km haul

6.3 Other Related costs

Side drains

Side drains were constructed around the market only. The costs of the side drains are separated in this report to show a more detailed analysis. Separation of the cost of drainage structures allows a direct comparison of pavement costs only. This is necessary to correlate the expenses rather than the analysis resulting in a comparison of costs between individual projects as a whole, which could be misleading.

The costs of labour and material for the two types of drainage structure applied at Puok Market are presented in the following tables.

No.	Item	Unit	Quantity	Unit rate US$			Cost US$ per m for haul		
				10 Km	50 Km	100 Km	10 Km	50 Km	100 Km
1	Sand	m^3	0.0225	5.00	6.00	7.00	0.1125	0.135	0.1575
2	Aggregate	m^3	0.045	9.00	14.00	24.00	0.405	0.63	1.08
3	Cement	kg	11	0.07	0.07	0.07	0.77	0.77	0.77
4	Sand bedding	m^3	0.03	5.00	6.00	7.00	0.15	0.18	0.21
5	Cement (mortar)	kg	7.35	0.07	0.07	0.07	0.5145	0.5145	0.5145
6	Sand (mortar)	m^3	0.012	5.00	6.00	7.00	0.06	0.072	0.084
7	Bricks	Pcs	75	0.03	0.03	0.03	2.25	2.25	2.25
8	Cement (plastering)	kg	2.73	0.07	68.00	70.00	0.1911	0.1911	0.1911
9	Sand (Plastering)	m^3	0.06	5.00	6.00	7.00	0.3	0.36	0.42
	Cement (Net Finishing)	kg	2.27	0.07	0.07	0.07	0.1589	0.1589	0.1589
						Total Cost in US$ per metre run	***4.91***	***5.26***	***5.84***

Table 7: Side-drain Material Cost

No.	Activity	Unit	Skilled	Unskilled	Total Cost US$
1	Concrete work	%			0.47
2	Walls	Wd	0.13	0.195	0.41
3	Plastering	Wd	0.065	0.13	0.24
4	Net cement finishing	Wd	0.033	0.033	0.09
5	Curing of concrete	Wd		0.033	0.35
6	Local carriage	Lump sum			0.02
				Total labour cost in US$ per metre run	***1.58***

Table 8: Side-drain Labour cost

V-Shape Side Gutters

The calculation of the gutter costs are similar to the one for the side drain. Table 9 shows the material costs for the construction of the side gutter.

No.	Item	Unit	Quantity	Unit rate US$			Cost US$ per m for haul		
				10 Km	50 Km	100 Km	10 Km	50 Km	100 Km
1	Sand	m^3	0.0155	5.00	6.00	7.00	0.0775	0.093	0.1085
2	Aggregate	m^3	0.031	9.00	14.00	24.00	0.279	0.434	0.744
3	Cement	kg	7.59	0.07	0.07	0.07	0.5313	0.5313	0.5313
						Total Cost in US$ per metre run	***0.89***	***1.06***	***1.38***

Table 9: V-Shape Gutter Material Cost

It was observed that labour cost consists of approximately thirty five percent of the material cost i.e. about US$ 0.31 per linear metre. Hand tools costs was assumed to be 1 per cent of the material costs.

Indirect costs

Six per cent of the direct costs were added for preliminaries and risk and ten percent for contractor overheads and profit.

7. COST COMPARISON OF BRCP VS. LATERITE

An important consideration is the comparison of overall costs of Bamboo reinforced concrete compared to a laterite gravel surface. For the purposes of this report the comparison compares initial costs and expected maintenance costs during a nominal 'life' or analysis period. The cost comparison takes into account the overall costs of the surface layer only, since other costs (earthworks, structures and drainage arrangements) are the same for both paving options. Therefore items 7,11 and 12 of Table 2 have been excluded from the analysis.

There are other management, social and environmental considerations that should affect the choice of paving materials, however with the available knowledge it is not possible to include an assessment of these in this report. These factors include:-

- The risk that the routine and periodic maintenance of the laterite gravel surface will not be funded and arranged in a timely manner, and that the road will deteriorate to the state that it will require costly rehabilitation. This would have economic and social consequences for the road owner and users[3],
- The environmental, health and social costs of dust emissions from gravel roads,
- The environmental costs of periodic re-gravelling with respect to using up a finite and non-renewable resource, and damage to haul routes by (possibly overloaded) gravel haulage trucks,
- The comparative employment and skills dissemination effects of the paving options.

7.1 Initial Cost of Laterite Surface

The cost of the laterite surfaced carriageway is also dependant on the laterite haulage distance. Table 10 below shows the direct cost of constructing a laterite surface, 5 metres wide. These cost have been derived from Upstream Project records and experience.

No.	Item	Cost US$ per Km for haul 10 Km	50 Km	100 Km
1	Material	2,600	8,450	16,900
2	Labour	4,037	4,037	4,037
3	Equipment	1,980	1,980	1,980
4	Tools	363	363	363
5	Overheads Profit etc.	1,437	1,437	1,437
	Total US$ per Kilometre	***10,417***	***16,267***	***24,717***
	Total US$ per Square Metre	***2.08***	***3.25***	***4.94***

Table 10: Cost analysis of Laterite Surface Construction

3 This is a very real risk in developing countries such as Cambodia.

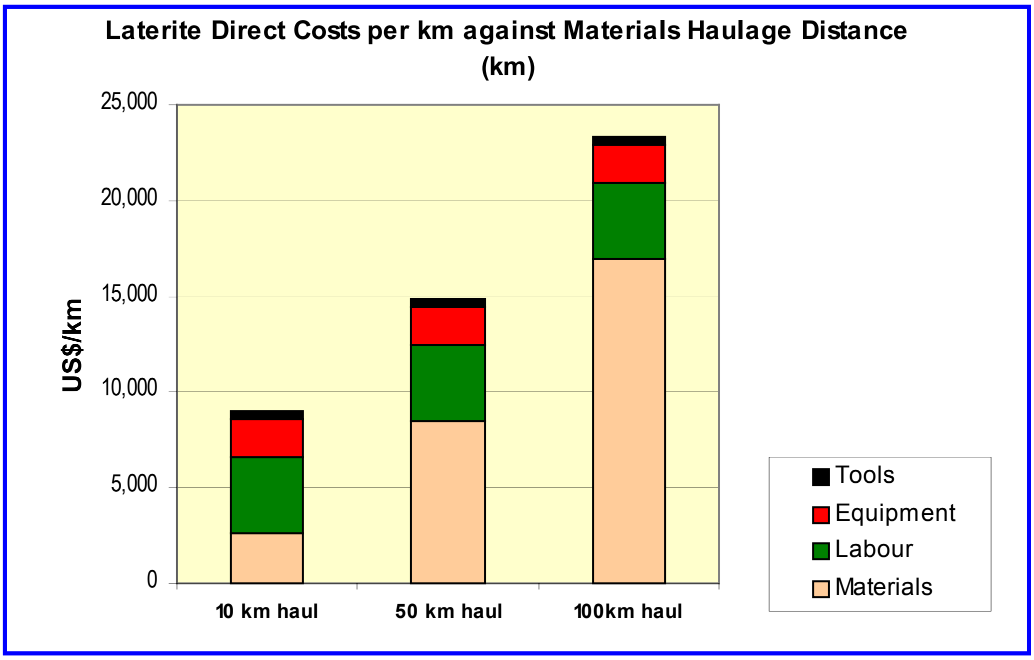

Chart 3: Laterite Direct Costs per km against Materials Haulage Distance

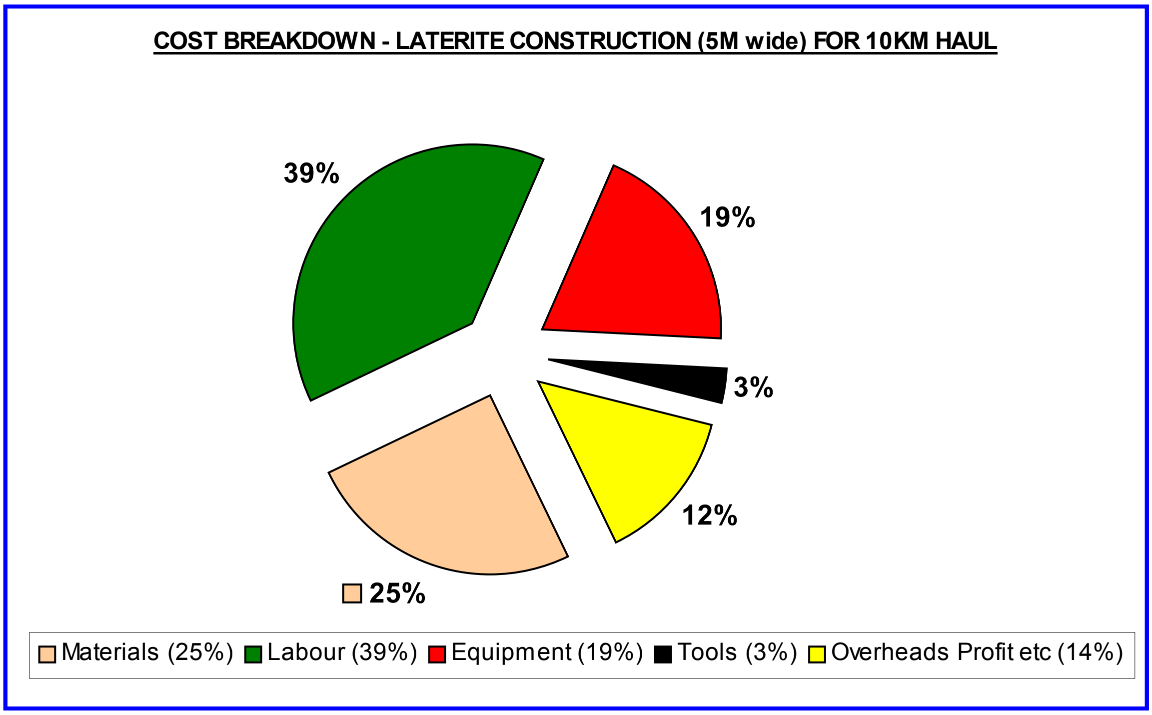

Chart 4: Cost Breakdown - Laterite

7.2 Cost of Maintenance

Routine Maintenance

The experience to date has been that there has been no need for any maintenance of the approximately 2 km of BRCP in the first two years of service. Inspections to date reveal no deterioration whatsoever of the concrete paving. The side drainage around the market requires occasional cleaning. The shoulders have not required any maintenance.

For the purposes of this analysis, it is assumed that routine maintenance for BRCP will require only some labour for sweeping the surface and minor repairs to shoulders amounting to less than a total of US$150/km/year.

Table 11 shows a summary of the estimated cost of routine maintenance for one kilometre of laterite road for one year. This is based on the experiences of the Upstream project in Siem Reap Province. A realistic organizational overhead is included which covers management by a force account organization or local contractor.

Routine Maintenance Item	Annual Cost US$/km for Material Haulage Distance		
	10 Km	50 Km	100 Km
Labour	120	120	120
Tools	40	40	40
Materials	75	244	488
Organisational overhead	150	150	150
Total	***385***	***554***	***798***

Table 11: Estimated Annual Routine Maintenance costs for laterite surfaced roads

It should be noted that no routine mechanical grading has been allowed for. Therefore the analysis would only be appropriate for low traffic of less than about 100 vpd on the laterite road. The BRCP would be able to take very much higher traffic levels with little increase in maintenance levels.

Periodic Maintenance

Very little periodic maintenance is required for bamboo reinforced concrete paved roads. It will be expected that some minor slab damage or joint re-seal work may be required, possibly every 5 years. The work could be carried out by a local building contractor. It is estimated that US$400/km every 5 years will be sufficient to meet this need.

Periodic maintenance however is essential and considerable for laterite surfaced roads due to ongoing gravel loss due to traffic and weather. With typical net gravel losses of 40mm per year experienced on low traffic roads in the Puok Market area, and an assessed minimum sub-grade cover requirement of 80mm, an initial 200mm layer of laterite will require re-gravelling every three years. Table 12 shows a cost summary for one occasion of periodic maintenance for one kilometre of laterite surfaced road. This table includes the indirect cost related to such a task such as overhead costs, company cost, profit, etc.

Periodic Maintenance Item	Re-gravelling cost US$/km for haulage distance		
	10 Km	**50 Km**	**100 Km**
Labour	150	150	150
Tools	80	80	80
Materials	3,120	4,225	8,450
Compaction	300	300	300
Transport	200	200	200
Site cost	70	70	70
Technical support	87	87	87
Technical transport	113	113	113
Miscellaneous	50	50	50
Overheads and Profit	417	417	417
Total	***4,587***	***5,692***	***9,917***

Table 12: Estimated cost of periodic maintenance for laterite surfaced roads

7.3 Life Cycle Cost Analysis

Comparison of varying surface options based on initial cost only, may result in ill-informed decisions due to lack of information in relation to maintenance cost and residual value. Life cycle cost analysis may be used to determine the total cost of a facility or structure over its' design for service life. Thus maintenance costs are taken account of. The decision maker has the advantage of choosing the most appropriate option in full consideration of future financial burden as well as initial cost. Equally important is an assessment of whether the financial and physical resources will be available, and the management capacity to organise the works effectively. As such, life cycle cost analysis may be looked upon as a powerful decision making tool.

The following analysis gives a simple comparison between laterite-surfaced roads and the BRCP. This is achieved by comparing the costs of different pavements over the lifetime of the pavement including maintenance costs.

Using a discount rate puts an opportunity cost on the capital deployed and expenditures over the life of the road. If the capital were invested elsewhere it could generate a return or profit.

It should be noted that the residual value, which is much higher for the BRCP than the laterite surface, has not been considered in the calculations. Savings in Vehicle Operating Costs (VoC) were not considered either.

The omission of residual values, VoCs, social and environmental costs assessment are expected to favour laterite in such a comparison.

Net Present Value (NPV)

The NPV is simply assessed as the difference between the discounted costs over the project analysis period.

$$NPV = \sum_{i=0}^{n-1} \left((b_i - c_i)/(1+r/100))^i\right)$$

Where:

n	is the project analysis period in years
i	is the current year, with i=0 in the base year
b_i	is the sum of all benefits in a year
c_i	is the sum of all costs in a year
r	is the planning discount rate as a percentage

Assumptions:

Interest rate:	8%, 10%, and 12%
Life span of BRCP pavement:	40 years
Frequency of laterite periodic maintenance:	3 years
Residual value of pavement:	Ignored

The following Table 13 provides the analysis results.

It is interesting to note that over the 40 year analysis period the BRCP is substantially cheaper than laterite in undiscounted whole life costs, for similar materials haul distances, even for a haul distance of only 10 km. 10 km is often taken as a 'rule of thumb' guideline for the suitability of gravel as a rural road surface (for low traffic roads).

This is an important conclusion for network management considerations. Network managers are not so concerned with discounting, as in any year an approximately regular portion of a gravel road network will need to be re-gravelled. A network manager will aim to reduce the investment and maintenance costs to a level within the budget constraints to preserve the serviceable network. Low maintenance surfaces help to achieve this.

With discounting at 8% to 12%, gravel is indicated to be the most cost-effective investment for a haul distance of 10km. This accords with the above rule of thumb.

At longer haul distances the discounted costs of BRCP become steadily more attractive.

Materials haul distance is clearly an important determinant of the most cost-effective surface option.

As is the case in most developing countries, provision for future maintenance is a particular uncertainty. In this respect the BRCP would be more tolerant of lack of maintenance. If a laterite road is not maintained in a timely manner it will rapidly become 'un-maintainable' and need to be reconstructed at great cost.

Year	Annual Costs US$ per surface and haulage distance					
	10km		50km		100km	
	Laterite	BRCP	Laterite	BRCP	Laterite	BRCP
0	10,417	29,647	16,267	33,157	24,717	39,187
1	385	150	554	150	798	150
2	385	150	554	150	798	150
3	4,972	150	6,246	150	10,715	150
4	385	150	554	150	798	150
5	385	400	554	400	798	400
6	4,972	150	6,246	150	10,715	150
7	385	150	554	150	798	150
8	385	150	554	150	798	150
9	4,972	150	6,246	150	10,715	150
10	385	400	554	400	798	400
11	385	150	554	150	798	150
12	4,972	150	6,246	150	10,715	150
13	385	150	554	150	798	150
14	385	150	554	150	798	150
15	4,972	400	6,246	400	10,715	400
16	385	150	554	150	798	150
17	385	150	554	150	798	150
18	4,972	150	6,246	150	10,715	150
19	385	150	554	150	798	150
20	385	400	554	400	798	400
21	4,972	150	6,246	150	10,715	150
22	385	150	554	150	798	150
23	385	150	554	150	798	150
24	4,972	150	6,246	150	10,715	150
25	385	400	554	400	798	400
26	385	150	554	150	798	150
27	4,972	150	6,246	150	10,715	150
28	385	150	554	150	798	150
29	385	150	554	150	798	150
30	4,972	400	6,246	400	10,715	400
31	385	150	554	150	798	150
32	385	150	554	150	798	150
33	4,972	150	6,246	150	10,715	150
34	385	150	554	150	798	150
35	385	400	554	400	798	400
36	4,972	150	6,246	150	10,715	150
37	385	150	554	150	798	150
38	385	150	554	150	798	150
39	4,972	150	6,246	150	10,715	150
40	385	400	554	400	798	400
Total Costs (US$) undiscounted	85,448	***37,647***	112,423	***41,157***	185,558	***47,187***
NPV @ 8% p.a.	***29,437***	29,578	40,463	***32,828***	65,296	***38,411***
NPV @ 10% p.a.	***25,185***	28,649	34,966	***31,840***	56,139	***37,322***
NPV @ 12% p.a.	***22,127***	27,864	31,001	***30,998***	49,546	***36,382***

Table 13: NPV assessment of Surface and Haul distance Options

The foregoing table clearly demonstrates that if laterite haulage distances are long, and concrete aggregates are available closer, then the BRCP should become a more attractive option.

It should also be noticed that the assumed annual laterite loss rate is forty millimetres. which is specified from site experiences in Siem Reap Province, Cambodia. This assumption is modest especially in market areas where the laterite loss rate might exceed this amount since:

- Traffic volume is much higher that fifty vehicles per day,
- Heavy vehicles traffic, such as trucks, is high,
- Climate, topography and the regime of local rivers networks as well as the Tonle Sap lake, all combine to make the area prone to flooding on an annual basis,
- Local laterite is a low quality gravel when considered for road construction, especially as a wearing coarse. This can be noticed from test results and sieve analysis for laterite quarries from different parts of Cambodia. This was noticed in the same area after lack of routine maintenance for one rainy season caused severe damage to the laterite surfaced road and re-gravelling was required.

The comparison between the two surfaces should also take into account the weather condition in the area. It was clearly noticed that the BRCP has a very high resistance to severe conditions. The road was open and heavily trafficked during the excessive flooding due to the intensive rainfall in the region that Cambodia suffered for two consecutive years following construction of the trials. Follow up inspections to the pavement showed no damage to the pavement, not even hairline cracks. While major parts of the nearby laterite road network were severely damaged.

Images 25 - 28: Puok Market BRCP trial paving during flooding

8. CONCLUSIONS

Bamboo Reinforced Concrete Pavement (BRCP) is a durable strong pavement with an estimated life span of forty years. It can be constructed by small scale local contractors or communities with the minimum of equipment. The pavement requires minimal routine maintenance for the shoulders and occasional re-filling of the slab expansion joints with bitumen. This activity is important to conserve the sub-grade layer from local failure under the joints because of water ingress. Cracking on the concrete slabs may appear. This can be treated by filling the cracks with bitumen for the same reason mentioned above, since the slab material itself will not loose its strength. It should also be mentioned that this type of pavement can crack or fail if failure occurs in a large area of the sub-grade layer, since the overall strength and performance of the rigid pavement is a combination of the concrete slab strength and the sub-grade support. Rigid pavements should have well designed drainage (slight surface camber, shoulder drainage and formation drainage) to ensure a long and durable service.

Advantages of BRCP	Disadvantages of BRCP
• Strong and durable surface, i.e. long life span • Tolerance to severe weather conditions such as flooding. • Minimal maintenance required, Simple maintenance activities • Slab effect. i.e. load carrying capacity even with local failure/weakness in the sub-grade • Use of local resources • labour intensive construction and maintenance • Minimal equipment requirements • Suitable for both male and female employment • Suitable for construction by Small Scale Contractors • Suitable for heavy traffic areas • Dust-free, easy-to-clean surface • High residual value	• Higher initial investment than unpaved roads • Slower speed of construction than unpaved roads • Requires occasional bitumen filling for the maintenance of joints

Table 14: Advantages and disadvantages of BRCP

Bamboo Reinforced Concrete Pavement proved to be a suitable type of pavement for heavily trafficked areas such as district and market centres. It can also be used for road sections through villages to reduce dust hazards and maintenance requirements.

The use of bamboo fulfilled the design objective to control cracking due to shrinkage during initial setting and curing, and to aid in the control of cracking due to temperature variations.

Although the evaluation of whole life cost of the pavement did not include the savings of the vehicle operating cost, BRCP is still more economically feasible than laterite surfaced roads for higher material haul distances. This is true especially when the laterite haulage distance exceeds 50 km.

9. RECOMMENDATIONS

The following recommendations are made for future rural road surfacing work (potentially) involving Bamboo Reinforced Concrete Pavement options:-

Planning

- Whole Life Costs, Community Benefits and Environmental Implications of feasible surface options should be compared.
- Liabilities, arrangements, resourcing and funding for maintenance should be discussed with construction financers and the community for the various surfacing options.
- Surfacing and maintenance options should be part of the consideration in the Integrated Rural Accessibility Planning (IRAP) process.

Design

- Consideration should be given to the advantages, costs and risks of draining the road formation to the embankment edge or side drain on a continuous, rather than intermittent, basis. This is particularly important for moisture susceptible sub-grades.
- Road formation level should where possible be above flood level to avoid soaked sub-grade and the increased risk of pavement damage in flood conditions.

Construction

After considering the many factors, which affect the performance of bamboo as continuous reinforcement in concrete, the following recommendations may be said to represent current state of knowledge and best practice at present:

Selection & Preparation of Bamboo:

1. Bamboo to be used as reinforcement should be harvested only when it is mature so as to avoid the swelling and shrinkage, and the consequent adverse cracking and loss of bond. Also, bamboo reinforcement should be used in the split form, after proper seasoning and effective treatment to prevent decay and minimise its capacity to absorb water. Bamboo showing a pronounced brown colour will generally be of the required maturity.
2. Bamboo should be cut and allowed to dry and season for three to four weeks and up to six weeks before using. The seasoning culms must be supported at regular spacing to reduce warping.
3. Avoid the use of bamboo cut in the rain season. This bamboo will generally be weaker due to the high fibre moisture content.
4. Do not use whole culms of green, unseasoned bamboo.
5. Select the largest diameter culms available.
6. Splitting the bamboo can be done by separating the base with a sharp knife and then pulling a dulled blade through the culm. The dull blade will force the stem to split open; this is more desirable than cutting the bamboo since splitting will result in continuous fibres and a nearly straight section

7. Split bamboo should be reasonably straight, its width not exceeding 20-25mm.
8. Bamboo splints can receive a waterproofing coat to reduce swelling on contact with the wet concrete, especially if more than 4 per cent bamboo is used (Reference 13). Suggested coatings include native latex, coal tar, paint, dilute varnish, water glass (sodium silicate) or other suitable coatings. Only a thin coating should be applied because a thick coating will lubricate the surface and weaken the bond with the concrete.

Placement of Bamboo:

9. If possible split bamboo should <u>not</u> be placed with its concave side facing downwards, as this could lead to poor bond due to entrapment of air during casting.
10. While placing, the basal and distal ends of the reinforcement must be alternated so that a uniform reinforcing area is obtained along the length of the member.
11. Being light in weight bamboo reinforcement tends to float in the concrete during casting. This should be prevented by tying the reinforcement to the formwork or by employing other suitable means, and ensuring a low water cement ratio.
12. The clear spacing between bamboo reinforcements, and the clear cover, should be at least equal to the greater of the following: (a) the width of the bamboo splints +7.5mm, and (b) the maximum size of the aggregates +7.5mm.
13. Bamboo reinforcements may be spliced, either by providing an overlap of 16 times the width of the splint, or by using suitable mechanical splices. Splices should be staggered and preferably not located at sections of high stress.
14. Bamboo may be permanently bent if heat, either dry or wet, is applied while applying pressure. This procedure can be used for forming splints into C-shaped stirrups and for putting hooks on reinforcement for additional anchorage.

Concrete:

15. In order to avoid difficulties in the placement and consolidation of concrete, the maximum size of aggregate to be used should not exceed 10-12mm.
16. The use of low water/cement ratios, higher cement contents, plasticiser, and high early strength cement, is beneficial in minimising cracks where possible.
17. In order to achieve a reasonable bond, concrete with a minimum compressive strength of $20N/mm^2$ should be used.
18. Other researchers have recommended that bamboo reinforced concrete sections should be designed with a maximum permissible design moment, M_{cr}, calculated from the concrete section only. Thus for a concrete pavement, for example, the pavement would be designed as un-reinforced and the bamboo reinforcement would help to control shrinkage during initial setting which is important given the lower water/cement ratio and high cement or cementitious material content.

- Quality control arrangements should ensure particularly that specified drainage, and layer thicknesses and tolerances are achieved.

Maintenance

- Although the surface maintenance of the BRCP is minimal, arrangements should be made, particularly for filling the joints and cracks (if any) with bitumen, to keep the lower pavement and subgrade as dry as possible.
- Arrangements for off-pavement maintenance, particularly drainage, are important for the sustainability of the paving.

Socio-economic issues

Further investigations are required into the socio-economic issues related to BRCP and other surfacing options.

Potential for reduction of cement use

Investigations should be carried out to explore the possibilities of reducing the cement content (and therefore costs) by the partial substitution of pozzolans derived from rice hush ash. Rice husk is a widely available waste product in Cambodia and therefore its use could have important local resource and environmental benefits.

'Mainstreaming'

BRCP should be incorporated in the Cambodian National Standards as a surface option for rural roads, and training and educational programmes should incorporate these techniques.

It is recommended that the performance and maintenance requirements of the Puok BRCP trials should be monitored to enable the whole-life-cost estimates to be validated.

References

1. Jules J.A. Janssen, *The Importance Of Bamboo As A Building Material,* Proceedings of the Fifth International Bamboo Workshop and the Fourth International Bamboo Congress, Ubud, Bali, Indonesia, 19-22 June 1995.

2. Soenardi Prawirohatmodjo, *Comparative Strength of Green and Airdry Bamboo,* Proceedings of the International Bamboo Workshop held in Cochin, India from 14-18 November 1988.

3. Tavip Soeprayitho, Togar L. Tobing, Elizabeth A. Widjaja, *Why the Sudanese of West Java Prefer Slope Inhabiting Gigantochloa pseudoarundinacea to those Growing in the Valley*, Proceedings of the International Bamboo Workshop held in Cochin, India from 14-18 November 1988.

4. Surjono Sujokusumo, Naresworo Nugroho, *A Study on Dendrocalamus asper as Concrete Reinforcement*, Proceedings of the Fifth International Bamboo Workshop and the Fourth International Bamboo Congress, Ubud, Bali, Indonesia, 19-22 June 1995.

5. M.A. Sattar, *Traditional Bamboo Housing in Asia: Present Status and Future Prospects*, Proceedings of the Fifth International Bamboo Workshop and the Fourth International Bamboo Congress, Ubud, Bali, Indonesia, 19-22 June 1995.

6. Oscar Hidalgo, *Study of Mechanical Properties of Bamboo and its Use as Concrete Reinforcement: Problems and Solutions,* Proceedings of the Fifth International Bamboo Workshop and the Fourth International Bamboo Congress, Ubud, Bali, Indonesia, 19-22 June 1995.

7. M.F. Kabir, D.K. Bhattacharjee, M.A. Sattar, *Physical Properties of Node and Internode of Culm and Branch of Dedrocalamus hamiltonii*, Proceedings of the Fifth International Bamboo Workshop and the Fourth International Bamboo Congress, Ubud, Bali, Indonesia, 19-22 June 1995.

8. Subyakto, *Variation in Specific Gravity and Bending Properties of Dendrocalamus asper Culm Grown in Bogor,* , Proceedings of the Fifth International Bamboo Workshop and the Fourth International Bamboo Congress, Ubud, Bali, Indonesia, 19-22 June 1995.

9. P.N. Balaguru, S.P. Shaw, *Alternative Reinforcing Materials For Less Developed Countries*, International Journal For Development Technology, Vol 3, 87-105, 1985.

10. Dr Pichai Nimityongskul, *Lecture Notes on Use of Bamboo as Continuous Reinforcement in Concrete,* A.I.T., 2001.

11. B.V. Subrahmanyam, *Bamboo reinforcement for cement matrices, in New Reinforced Concretes,* Ed. R.M Swamy, Surrey University Press, U.K. pg 141-194, 1984.

12. J.A. Kankam, S.H. Perry, M. Ben-George, *Bamboo-Reinforced Concrete One-Way Slabs Subjected To Line Loading,* International Journal For Development Technology, Vol. 4, 1-9, 1986.

13. Francis E. Brink, Paul J. Rush, *Bamboo Reinforced Concrete Construction*, U.S. Navy, Port Hueneme, California, February 1966.

14. K.S. Low, *Utilization of Bamboos for Engineering Purposes*, Proceedings of the International Bamboo Workshop held in Cochin, India from 14-18 November 1988.

15. Jules J.A. Janssen, *Building With Bamboo,* Intermediate Technology Publications, 1988.

16. B. Thagesen, 1996, *Highway and Traffic Engineering in Developing Countries*, E&FN Spon, United Kingdom.

17. Overseas Unit, Transport Research Laboratory, 1988, *Overseas Road Note 5, A guide to Road Project appraisal*, Crowthorne, Berkshire, United Kingdom.

18. Robert Petts, May 2001, Rationale for the Compilation of International Guidelines for low-cost

Sustainable Road Surfacing, LCS Working Paper No 1.

19. Khanna and Justo, 1993, Highway Engineering, 7th Edition, India

20. B. Rozemuller et al., February 2000, Traffic Characteristics around Puok Market, Ministry of Rural Development and International Labour Organisation, The Upstream Project, Socio-Economic Series 1, Cambodia.

21. Robert Petts, May 2002, Costing of Roadworks, LCS Working Paper No 3.

Appendix 1: Table 1- Strength of Bamboo

Author, species and location	Age, moisture content and splint or full culm	Tensile A	Tensile B	Flexural A	Flexural B	Compressive A	Compressive B
(a.) Narayana *et al.* (b.) *Dendrocalamus strictus* (c.) Roorkee, India	(d.) NA (e.) NA (f.) NA	102.5	13.3-24.6	70.8-134.1	NA	NA	NA
(a.) Limaye (b.) *Dendrocalamus strictus* (c.) Dehradun, India	(d.) 1-8 (e.) Green (98.9) (f.) Full	NA	NA	101.4	17.1	36.5	NA
(a.) Limaye (b.) *Dendrocalamus strictus* (c.) Dehradun, India	(d.) 1-8 (e.) Kiln-dry (f.) Full	NA	NA	163.3	22.1	63.4	NA
(a.) Espinosa (b.) *Dendrocalamus strictus* (c.) Phillipines	(d.) NA (e.) Air-dry (f.) Splint	NA	NA	115.8	NA	52.5	NA
(a.) Mehra et al. (b.) *Dendrocalamus strictus* (c.) Delhi, India	(d.) NA (e.) NA (f.) NA	89.9	16.6	NA	NA	NA	NA
(a.) Datta (b.) *NA* (c.) West Germany	(d.) NA (e.) NA (f.) NA	172.8	17.3	68.1-254.4	NA	72.6	NA
(a.) Cox *et al.* (b.) *Arundinaria tecta* (c.) U.S.A.	(d.) NA (e.) 9.9 - 18.7 (f.) NA	76.5-172.7	14.4-27.7	NA	NA	NA	NA
(a.) Ali *et al.* (b.) *Thyrosostchya Olivery* Gamble (c.) Thailand	(d.) NA (e.) NA (f.) Splint	2170-354.7	21.7-27.2	NA	NA	NA	NA
(a.) Fang (b.) *Arundinaria tecta* (c.) U.S.A.	(d.) NA (e.) NA (f.) NA	NA	NA	NA	NA	23.2-27.3	7.95-9.5
(a.) Cook *et al.* (b.) Thyrosostchya Olivery Gamble (c.) Thailand	(d.) NA	82.8*	9.65*	NA	NA	55.3	19.35
	(e.) Seasoned (f.) NA	109.3+	NA	NA	NA	NA	NA
(a.) Cook *et al.* (c.) Taiwan	(d.) NA (e.) Seasoned (~ 14%) (f.) NA						
(b.) *Phyllostachys pubescens* Mazel		NA	NA	156.2-171.9	12.1-13.5	72.0-82.5	NA
(b.) *Phyllostachys makinoi* Hayata		NA	NA	185.3-205.9	16.3-17.2	84.8-9.7	NA
(b.) *Bambusa dolichocalada* Hay		NA	NA	199.1-214.0	14.1-17.4	79.1-91.2	NA
(b.) *Dendrocalamus latiflorus* Munro		NA	NA	128.1-140.8	9.3-10.7	60.2-68.0	NA
(b.) *Bambusa stenostachya* Hackel		NA	NA	136.6-140.2	10.1-10.5	71.1-73.1	NA
(b.) *Bambusa oldhamii* Munro		NA	NA	152.9-166.9	12.2-13.9	68.2-69.7	NA
(a.) Youssef (b.) *Arundinaria gigantean* (c.) Egypt	(d.) >4 (e.) Green (39%) (f.) Full	114.8* 161.4+	11.3* 12.4+	NA NA	NA NA	29.0* 31.7+	4.6* 5.8+
	(e.) Green (39%) (f.) Splint	NA NA	NA NA	59.1* 67.0+	6.5* 8.1+	NA NA	NA NA
	(e.) Seasoned (f.) Full	188.4* 256.0+	18.6* 22.2+	NA NA	NA NA	87.3* 91.6+	6.7* 9.6+
	(e.) Seasoned (f.) Splint	NA NA	NA NA	57.0* 206.0+	15.1* 18.6+	NA NA	NA NA

Notes: (a.) Author; (b) Species; (c.) Location; (d.) Age in years; (e.) Moisture content(per cent); (f.) Splint or full culm. Letter A denotes sttrength in N/mm^2, and B denotes modulus in kN/mm^2. * = At node + = At inter-node

Table 2: Bond strength of bamboo with Portland Cement Concrete

Source	Treatment	Moisture absorpion (%) after treatment	Bond Strength (N/mm^2)	Remarks
Narayana and Reyman	Untreated	43	NA	Seasoned whole bamboo
	Bitumen-kerosene (1: 0.25)	13	NA	Seasoned whole bamboo
Cox and Geymayer	Untreated	NA	0.34 - 0.38	Seasoned split bamboo
	Wound with steel wire	NA	0.52	
	Polyester - sand	NA	>0.56[a]; 0.81	Only two results
	Epoxy - sand	NA	1.13; >1.15[a]	Only two results
Murthy *et al.*	Bitumen - sand	NA	NA	Considerable improvement and succuess claimed
Youssef	Untreated	35	0.56[b] 0.68[c]	Split bamboo
	Varnish (2 coats)	11	1.11[b] 1.27[c]	
Gupchup *et al.**	Untreated	37.5	0.29	
	Bitumen	9.8	0.84	
	Epoxy	0.4	1.13	
Fand and Mehta.*	Untreated	NA	3.2 - 12.8[d]	Whole bamboo
	Sulphur-sand	NA	10.3 - 13.8[d]	
Cook *et al.**	Untreated	NA	0.24 - 1.47	Seasoned bamboo

(a) tension failure; (b) Cement content = 250 Kg/m3 and w/c = 0.6; (c) Cement content = 350 Kg/m3 and w/c =0.4; (d) Total pull-out force in kN.

Appendix 2 - Work Norms

Task	Method	Unit	Work Norm Unit/day	Remarks

Table: Work norm summary

Appendix 3 - Site Control Sheet

Item	Activities	Unit	Chainage		Qty	Workdays			Remarks
			Start	End		Male	Female	Total	

Appendix 4 – Pavement Design to Be Added

Appendix 5 – Drainage Design to Be Added