ROYAL GOVERNMENT OF CAMBODIA

SOUTH EAST ASIA COMMUNITY ACCESS PROGRAMME

DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

COMPLETION REPORT

SEACAP 019

January 2009

UNPUBLISHED PROJECT REPORT

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COMPLETION REPORT

Prepared for: Project Record:	**SEACAP 19. Development of Local Resource Based Standards**
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ABBREVIATIONS & ACRONYMS

ADB	Asian Development Bank
AusAID	Australian Agency for International Aid
BRCP	Bamboo Reinforced Concrete Pavement
CAFEO	Conference of ASEAN Federation of Engineering Organisations
CBR	California Bearing Ratio
CNCTP	Cambodia National Community of Transport Practitioners
DBM	Dry Bound Macadam
DBST	Double Bituminous Surface Treatment
DCP	Dynamic Cone Penetrometer
DfID	Department for International Development
EIC	Engineering Institution of Cambodia
ENS	Engineered Natural Surface
esa	equivalent standard axles
GIS	Geographic Information System
GMSARN	Greater Mekong Sub-region Academic & Research Network
gTKP	global Transport Knowledge Partnership
GTZ	German Agency for Technical Co-operation
HDM4	Highway Development and Management Model
ILO	International Labour Organisation
IRAP	Integrated Rural Accessibility Planning (Access Program)
ITC	Institute of Technology of Cambodia
JFPR	Japanese Fund for Poverty Reduction
JICA	Japanese International Co-operation Agency
KACE	Khmer Associated Consulting Engineers
km	kilometre
LBAT	Labour-Based Appropriate Technology
LCS	Low Cost Surfacing
m	metre(s)
MERLIN	Machine for Evaluating Roughness using Low-cost Instrumentation
mm	Millimetre(s)
MPa	Mega pascals
MPW&T	Ministry of Public Works and Transport (Cambodia)
MRD	Ministry of Rural Development (Cambodia)
NGOs	Non-Governmental Organisations
NRDP	North-western Rural Development Project

ORN	Overseas Road Note
PDRD	Provincial Department of Rural Development
PRDC	Provincial Rural Development Committee
PRIP	Provincial and Rural Infrastructure Programme
QA	Quality Assurance
RD&RP	Rural Development and Resettlement Project
RED	Roads Economic Decision Model
Ref.	Reference
RFP	Request for Proposal
RGoC = RGC	Royal Government of Cambodia
RIIP	Rural Infrastructure Improvement Project
RRGAP	Rural Road Gravel Assessment Programme (Vietnam)
RRSR	Rural Road Surfacing Research (Vietnam)
SE	South East
SEACAP	South East Asia Community Access Programme
SEILA	Multilateral donors - Government Rural Infrastructure Development Programme
ToR	Terms of Reference
TRIP	Tertiary Roads Improvement Project
TRL	Transport Research Laboratory
UCS	Unconfined Compression Strength
UK	United Kingdom
VOCs	Vehicle Operating Costs
WB	World Bank
WBM	Water Bound Macadam
WFP	World Food Programme
WLC	Whole Life Costs

DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

1 Introduction

1.1 The Project Objectives

The SEACAP 19 project is part of the wider South East Asia Community Access Programme (SEACAP), whose strategic theme is 'livelihoods of poor and vulnerable people in SE Asia improved sustainably'. The core concept in SEACAP was defined at the SEACAP Practitioners Meeting in Phnom Penh in June 2006 as "…maximizing input of local resources, which are materials, labour, enterprise and ingenuity, which ensures affordability".

SEACAP builds on existing knowledge, but also provides a research resource for filling gaps in knowledge, particularly in the local environment. Mainstreaming ensures that these solutions are accepted, adopted and applied on a large scale. This involves a process of participatory workshops, guideline development, demonstrations, dissemination, training and implementation.

SEACAP 19 has contributed to the overall SEACAP theme by continuing the development and mainstreaming of local resource-based standards for rural roads by carrying forward research into cost-saving, sustainable and locally appropriate techniques in road construction, and by contributing to appropriate capacity building.

1.2 Project Structure

Within an overall goal of developing local and sustainable resource-based standards for Cambodia's rural roads, SEACAP 19 is a natural progression to the earlier SEACAP 2 and SEACAP 8 projects, and has consolidated the successes of these and other related projects to improve community access by increasing the capacity of the MRD and the local communities. The project has three main technical components, namely applied research, project development and studies to prepare two rural road development tools. Further details are given below.

1.2.1 Applied Research

To refine and mainstream standards and procedures for rural road works.

This focussed on:

- Strengthening the research capacity of the Institute of Technology of Cambodia (ITC) for the use of local resources.
- Providing an opportunity for ITC students to gain experience by carrying out this research.
- Enhancing cooperation among Ministry of Rural Development (MRD), Ministry of Public Works (MPWT), ITC and the Engineering Institute of Cambodia (EIC).

1.2.2 Project Document Development

The development of five project documents, each on issues relevant to the effective development and management of rural access infrastructure using a local resource based approach and life cycle costing. The five topics were:

- The use of stabilization for the improvement of road materials

- The use of waterbound macadam and other alternative surface options
- Pavement upgrading from gravel to paved surfacings using existing materials and labour based techniques
- Embankment protection measures
- Materials database

1.2.3 Studies to address the development of two specific rural road development tools.

Rural road development is hindered by two specific problems (i) the complexity and cost of providing drainage structures without which access can be severely limited and (ii) providing engineering cost estimates in preparation for the implementation of civil works projects. The studies address these two problems. They are:

- Development of a Low Cost Structures Manual
- Development of a Unit Rate-Costing System

1.3 Capacity building

As well as the technical activities SEACAP19 has capacity building components to:

- Refine and Mainstream Standards and Procedures where they are related to project tasks.
- Strengthen Research Capacity in particular within the Departments of Civil Engineering and Rural Engineering at ITC, but also within Ministries (MRD and MPWT) and in association with and the Engineering Institute of Cambodia. Key issues are seen as the involvement of ITC staff and students in project tasks, offering strategic and operational advice to ITC staff and others on road research and the production of course materials and the development of modules based on project outcomes.
- Enhance ITC Student Cambodian Road Practitioner Experience through participation in project tasks and associated seminars and lectures.
- Enhance Stakeholder Cooperation by working closely with the SEACAP 19 Steering Committee and Working Group

Through the development and association with project partners SEACAP 19 has a positive role in building the capacity of Government sector (MRD and MPWT); the Academic sector (ITC); private practitioners (EIC, CNCTP) and the Donor community.

1.4 Completion report

This project completion report describes the project including the contractual arrangements, the relationships with project partners and summarizes the main activities and outputs from the project.

2 Project Description

2.1 Project Objectives

The project objectives as outlined in Section 1 of this report are summarized in Figure 2.2. The technical tasks are identified in Figure 2.1. These key tasks form the main structure of the project and have guided its implementation.

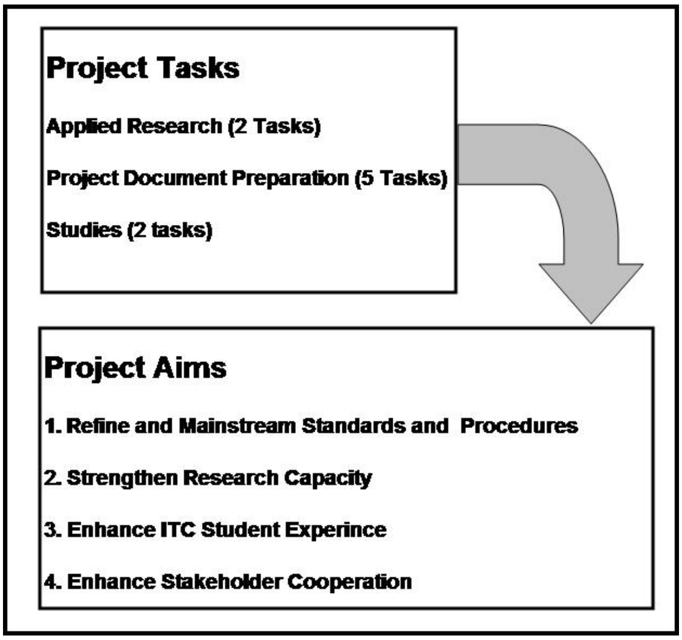

Figure 2.1 Technical tasks and Capacity Building

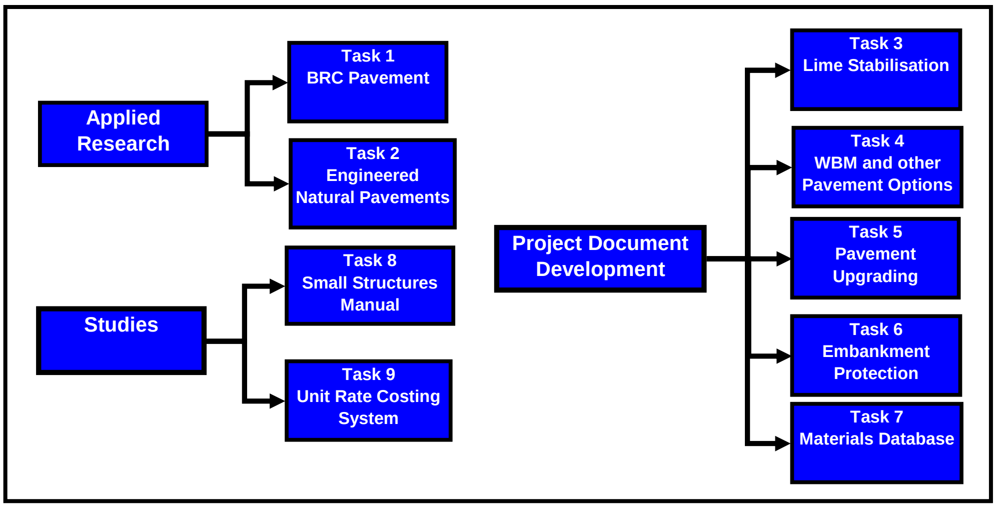

Figure 2.2 Project tasks leading to project objectives

2.2 Contractual arrangements

The Agreement for the project was established under arrangements between the Royal Government of Cambodia and the Department for International Development (DfID), UK. Under these arrangements Crown Agents for Overseas Governments and Administrations Ltd (acting as Contracting Agent for DfID) issued a Request for Proposal (RFP) to a previously identified short list of international consultants. In response, TRL Ltd. submitted a successful technical and financial proposal and subsequently entered into a contractual arrangement with Crown Agents in January 2007.

TRL is supported by associate firms. The principal associate firm is Khmer Associates Consulting Engineers Co. Ltd. (KACE) of Cambodia, which provided comprehensive local consulting services including engineering, translation, liaison, administrative, secretarial and coordination services.

The other associates firms were Intech Associates Consulting Engineers and Living Resources. Intech Associates have worked extensively with TRL on other SEACAP projects in the region and will provide a short-term specialist input. Living Resources supplied the services of John Howell, the bio-engineering specialist.

2.2.1 Core Staff

The specialists given in Table 2.1 were named in the Agreement as key personnel for the project

Table 2.1 List of key personnel

Name	Firm	Role
Jasper Cook	TRL	Project Manager and geotechnical engineer
John Rolt	TRL	Deputy Project Manager and pavement specialist
Dave Weston	TRL	Senior Pavement Expert – Lime Stabilization
Akram Ahmedi	TRL	Senior Training and Costing Specialist
Trevor Bradbury	TRL	IT Specialist & Dissemination Advisor
Rob Petts	Intech.	QA Structures and Technical Review
John Howell	Living Resources	Bio-Engineering Specialist
Heng Kackada	KACE	Senior Research Engineer (local staff)

In April 2007, Crown Agents approved the substitution of Michael O'Connell for duties originally allocated to Dave Weston, as senior pavement expert. In May/June 2008 TRL provided Dr Greg Morosiuk to support the work on unit costing that was being led by Akram Ahmedi.

The original completion date for SEACAP19 was the end of June 2008. In early 2008, a three month extension to the end of September 2008 at no additional cost was sought and approved by Crown Agents. In 2008, an additional but strongly linked contract (SEACAP19/002) in connection with the need to develop a low cost structures manual was agreed, the scope of which is described below.

2.2.2 SEACAP19/002

The scope of SEACAP 19 was extended by project SEACAP 19/002. The task on SEACAP 19/002 was to update the Low Cost Structures Manual. The core staff for this task were:

- Jasper Cook Project Manager

- John Rolt Deputy Project Manager
- Heng Kackada Senior Research Engineer (local staff)

In addition, TRL provided KACE support staff, office and other facilities for the implementation of SEACAP19/002. The work on this extension is reported separately.

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2.3 Mobilisation

The project was mobilized on 2nd April 2007. A temporary office was set up in the Ministry of Rural Development (MRD) while the proposed project office within the Institute of Technology of Cambodia (ITC) was refurbished. The office in ITC was fully occupied on 10th May and has been maintained for the duration of the project.

The initial tasks included developing project working relationships and preparing a detailed work programme. These arrangements are described below.

2.4 Project management and working relationships

Effective cooperation between the SEACAP Project Team and the Project Partners was an essential feature for the successful delivery of SEACAP 19. Figure 2.3 shows the overall structure of the project where the main project partners in Cambodia and DFID were represented by a Steering Committee and a Working Group in hierarchical order. The SEACAP Project Team fully supported the concept of the Steering Committee and a Working Group, and saw these as making a significant contribution to the cooperation necessary for the successful implementation of the project. The Steering Committee's provided guidance on the strategy for the project and monitored progress. The Working Group assisted at the project task level and ensured effective cooperation within and between the stakeholders. Counterparts formed additional essential links between the project team and the Working Group to assist in the flow of project resources, content and information.

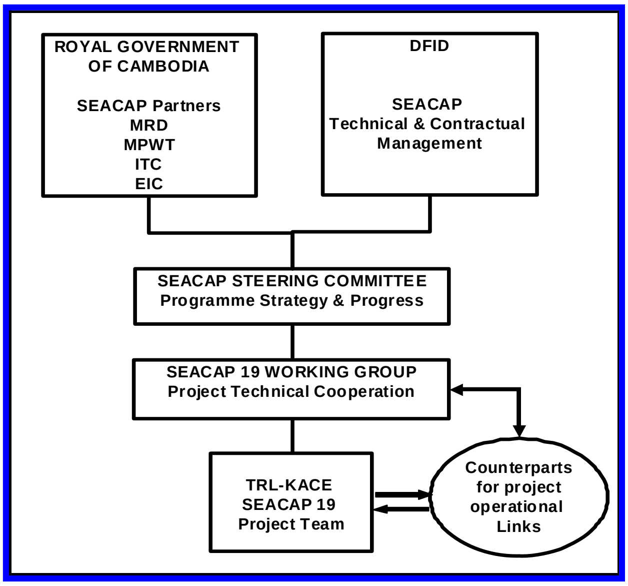

Figure 2.3 Overall SEACAP 19 Project Structure

2.4.1 PWT/MRD and SEACAP management

The Steering Committee was chaired by His Excellency, Suos Kong, Secretary of State. Members of the Steering Committee are given in Table 2.2. The Steering committee comprised representatives from the two Ministries responsible for road infrastructure in Cambodia, The Engineering Institute of Cambodia, EIC, Institute of Technology of Cambodia, ITC, and DfID.

Table 2.2 Members of the Steering Committee

Name	Position	Institution
H.E. Suos Kong (Chairman)	Secretary of State	MRD
H.E. Lim Sidenine (Vice Chairman)	Under-Secretary of State	MPWT
Prof. Prak Min	President	EIC
Dr. Om Romny	Deputy-Director	ITC
David Salter	SEACAP Project Manager	DFID-UNOPS

The Working Group was chaired by His Excellency Chan Darong, Director General of Technical Affairs, MRD.

Table 2.3 Members of the Working Group

Name	Position	Organisation
H.E. Chan Darong - Chairman	Director General of Technical Affairs	MRD
Chhouk Chhay Horng - Vice Chairman	Head of Civil Engineering Department	ITC
H.E. Yoeun Sophal	Director of Rural Road Department Head of Rural Road Committee	MRD EIC
Dr. Yit Bunna	Director of Public Works Research Centre	MPWT
Mrs. Men Nareth	Head of Rural Development Department	ITC
Heng Kackada	Secretary of CNCTP	CNCTP/KACE
Dr. Jasper Cook	Team Leader	TRL

2.4.2 Local stake holders

Local stakeholders including non-Ministry stakeholders have participated at a strategic and working level as members of the Steering Committee and the Working Group during the implementation of SEACAP 19, see Table 2.2 and Table 2.3. Their participation represented the needs of engineering and academic professionals in Cambodia and contributed to the successful delivery of the project.

2.5 SEACAP Relationships

Effective linkages with current, completed and proposed SEACAP programmes was also an essential feature for the delivery of SEACAP 19. Table 2.4 lists the pertinent SEACAP projects and summarises their key features and relevant links to SEACAP 19.

Table 2.4 SEACAP19 linkages

SEACAP	Summary Description	Links to SEACAP 19
1	Development, trialling and monitoring a range of sustainable road surfaces that better use local resources, minimising Whole-life-Costs and supporting the Vietnam Government's poverty alleviation and road maintenance policies.	Technical specifications. Performance of pavement trial & whole-life cost model.
2	Cambodia transport mainstreaming partnership (TMP); support for a range of complementary transport sector initiatives, which assist the aims and policies of the Government of Cambodia, to provide benefits such as improved rural access, lower transport costs and create local employment and enterprise opportunities for rural communities.	Procedures for technical dissemination and co-ordination of research outputs.
3	Development of task or function based Low Volume Rural Road classification and technical standards together with associated training research capacity tasks.	Development of standards and technical specifications.
4	Collection, collation and analysis of field assessments of condition of 276 unsealed road links in Vietnam.	Unsealed gravel road performance.
8	Assessment the performance of low cost (whole life) surfacing trials and associated costs, together with related key issues of maintenance and axle overloading in the rural road sector.	Update Technical specifications. Monitor performance of pavement trial & further develop whole-life cost model.
17	Development, trialling and monitoring a range of sustainable road surfaces that better use local resources in Lao PDR.	Standards and technical specifications.
18	Continued development of sustainable rural road programme in Cambodia through application of appropriate research; support to key institutions and advice on policy.	Support to ITC and CNCTP. Links to sustainable upgrading of rural road network.
20	Assessment of contractor and construction plant related issues within the rural road sector in Vietnam, Cambodia and Lao PDR.	Contractor capabilities and construction plant availability & suitability.
21	The development and application of technologies and approaches for appropriate slope stability management in Lao PDR.	Coordination of embankment erosion concepts.
22 (Complete)	Time and distance studies in Vietnam, Lao and Cambodia representing differing conditions	Background information on travel modes.
27	Monitoring and analysis of existing SEACAP-funded Vietnamese LVVR trials roads	Information of the relative performance of pavement options

2.6 Workshops

A programme of workshops was conducted to present progress on the project, present and discuss any administrative and technical issues that had arisen during the implementation of the project, and to obtain feedback from the Steering Committee and the Working Group. A list of the project workshops is given in Section 7.

2.7 Project activities

2.7.1 Project inputs from the core personnel

The planned and actual inputs from the core specialists are given below in Table 2.5. Allowing for agreed personnel substitutions, the extension of time under SEACAP19, and SEACAP 19/002 inputs these are consistent with the planned inputs. A schedule of the inputs is given in Figure 2.4.

Table 2.5 Planned and actual inputs from the core personnel

Name	**Firm**	**Role**	**Planned**	**Actual**
			person months	
Jasper Cook	TRL	Project Manager and Geotechnical specialist	6.5	7
John Rolt	TRL	Deputy Project Manager and pavement specialist	5.5	5.5
Michael O'Connell	TRL	Senior Pavement Expert – Lime Stabilization	1	2
Akram Ahmedi/ Greg Morosiuk	TRL	Senior Training and Costing Specialist	1	1
Trevor Bradbury	TRL	IT Specialist & Dissemination Advisor	0.5	0.5
Rob Petts	Intech.	QA Structures and Technical Review	1.5	1.5
John Howell	Living Resources	Bio-Engineering Specialist	1.0	1.0
Heng Kackada	KACE	Senior Research Engineer (local staff)	16	19

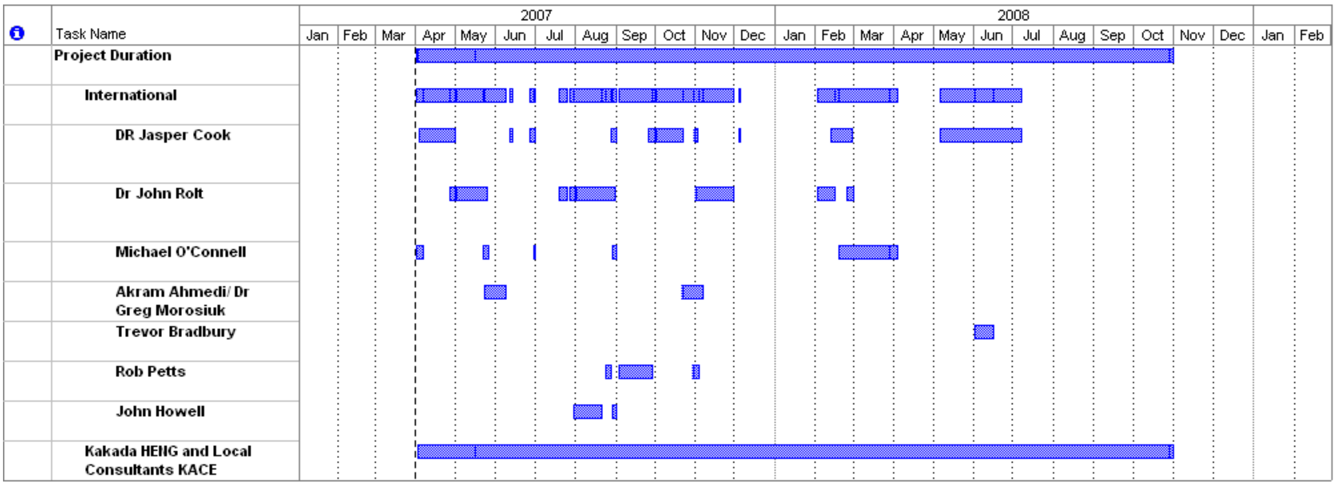

Figure 2.4 Schedule of staff inputs

2.7.2 Project programme

A summary as-completed programme is included as Figure 2.5

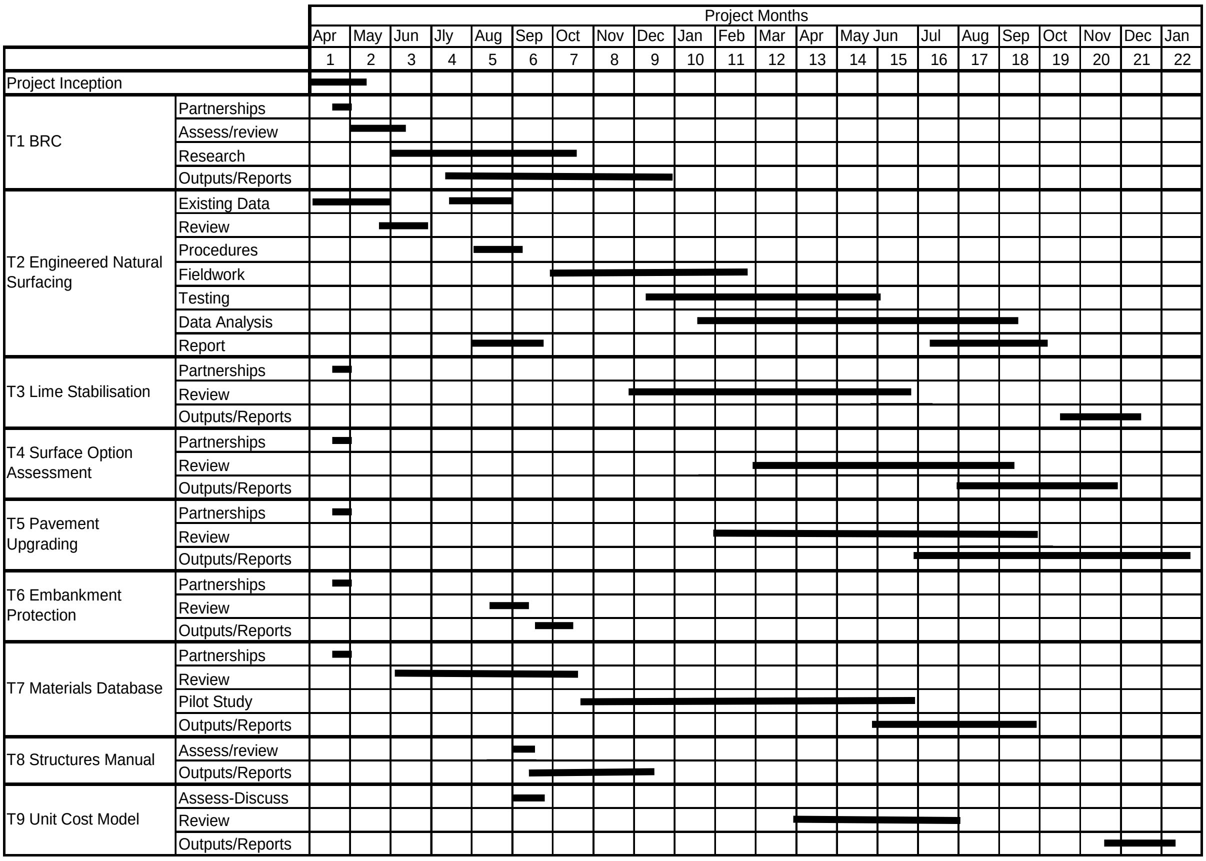

Figure 2.5 Summary Completion Programme

2.7.3 Monthly and Quarterly Progress reporting

Progress on the project was reported monthly. These reports were complemented by quarterly reports which collated progress and created milestones for the next stage of the project. They were usually associated with Steering Committee meetings and their preparation was adjusted accordingly. Quarterly reports were prepared in June 2007 in association with the inception report, December 2007, March 2008, August 2008 and December 2008 in preparation for the project completion report. Further details are given in Chapter 7.

3 Applied Research Tasks

3.1 Introduction

The applied research component of SEACAP 19 contained two Tasks which required a classic research approach (review existing knowledge; undertake field work to fill research gaps, analysis and recommendations, dissemination and mainstreaming), Figure 3.1.

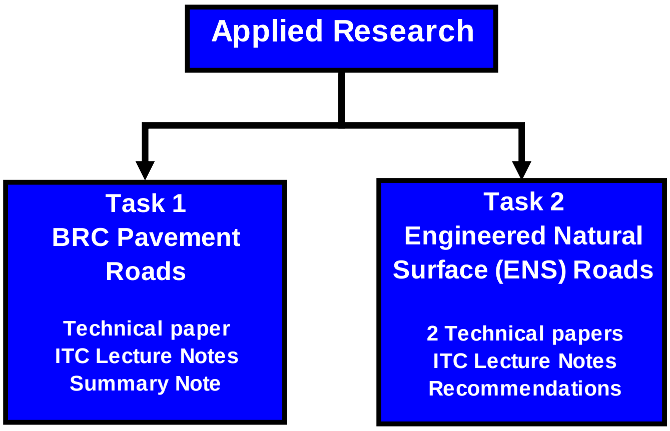

Figure 3.1 Applied Research Tasks

It was intended that these Tasks would provide outcomes that could feed into the upgrading of the Rural Road Standards. The research outcome of the Bamboo Reinforced Concrete Pavement task did not allow this, instead a short summary Technical Note was been drafted for circulation. Outcomes from the Engineered Natural Surface (ENS) Roads task appropriate to the upgrading of Rural Road Standards have been identified in the relevant Technical Paper. These are also included in the more general discussion in Chapter 8 on Recommendations

Details on the individual Tasks are presented in the following sections.

3.2 Task 1: Bamboo Reinforced Concrete Pavement (BRCP) Roads

Requirement

The aim of this Task was to provide advice on the suitability of this pavement option for wider mainstreaming in Cambodia and, if appropriate, to provide guidance on its application.

Output

The review of the role of bamboo as a reinforcement in concrete pavements was completed as SEACAP 19 Technical Paper 1. This paper came to the conclusion that bamboo reinforcement was not adding any noticeable benefit to concrete road slabs and that consequently there was no requirement to provide guidance on its use. The key points noted were:

1. Bamboo cannot prevent load induced cracking in the concrete because its modulus is too low for it to reduce the tensile stresses that might cause cracking.
2. Because of the low modulus, bamboo is unable to keep any cracks that do develop in the concrete from opening more widely than is acceptable. Wide cracks allow access to the bamboo for water, fungi and insects, leading to rotting and disintegration of the bamboo.
3. Pavement quality concrete with properly constructed shrinkage joints and appropriate curing techniques should only crack at the controlled joints. But, in any case, for the same reasons that bamboo cannot prevent load associated cracking, neither can it prevent shrinkage cracking.

4. Even if the modulus of bamboo were high enough, doubts about the allowable stress that bamboo can carry means that the percentage of bamboo in the structure needs to be higher than in the Puok trials if it is to withstand the types of load stress experienced in a pavement.
5. The deterioration of the bamboo within the concrete appears to be quite rapid. Methods of improving this are relatively expensive and unlikely to be sufficiently cost effective in a road pavement.

Technical Paper 1 has been modified as lecture notes as an example of a research programme. They are included within Appendix A to this report.

3.3 Task 2: Engineered Natural Surface (ENS) Roads

Requirement

The aim of this Task was provide information on the feasibility of using Engineered Natural Surface (ENS) roads within a range of Cambodian environments. In the original ToR this aim was defined as being essentially achieved through the construction and monitoring of 5 lengths of Earth Road.

During the Inception Period the SEACAP Team reviewed this task in detail and came to the conclusion, that a statistical approach was required to assess the many variables potentially affecting performance of earth roads. A statistically reliable solution to the problem could only be obtained by assessing the performance of a large sample of such roads covering the practicable range of the key variables. Hence it was proposed by the SEACAP 19 Team and accepted by the Steering Committee that the modus operandi of the task be changed to the following:

1. A review of existing knowledge relating to the performance of Engineered Natural Surface (ENS) roads, followed by:

2. A programme assessing the impacting factors and condition of a range of existing ENS roads in Cambodia to establish a database of information to analyse for the current project and also to be used as basis for further research.

Output

Technical Paper 2.1 “Behaviour of Natural Surfaces for Roads” has been completed which reviews critical factors that affect ENS performance and identifies key data sets required from for a field survey.

The completed Technical Paper 2.2 “Behaviour of Engineered Natural Surfaced Roads: Experimental Evidence in Cambodia” analyses at the results of the ENS survey of 91 road sites. An associated electronic database system containing information recovered from the surveys has been set-up. This will be capable of providing a basis for on going research and of integration with other LVRR databases in Cambodia and the region.

Technical Papers 2.1 and 2.2 have been combined and suitably modified into Lecture Notes on “The Behaviour of Engineered Natural Surfaced Roads with Particular Reference to Cambodia”. These are included within Appendix A to this report

4 Project Document Development

4.1 General Requirements.

The general pattern of work on these five Tasks (Figure 4.1) was defined as following a number of key steps, namely:

1. A review of existing documents and experience (national, regional and international)
2. Pilot studies, field surveys or representative testing (if required
3. Discussion and interaction with relevant stakeholders on the way forward
4. Production of project documents

For reasons of consistency it was decided that the "Project Documents" would comprise a Technical Paper on each of the Tasks and that a Concept Note summarising recommended further research would be included as an Appendix to each paper.

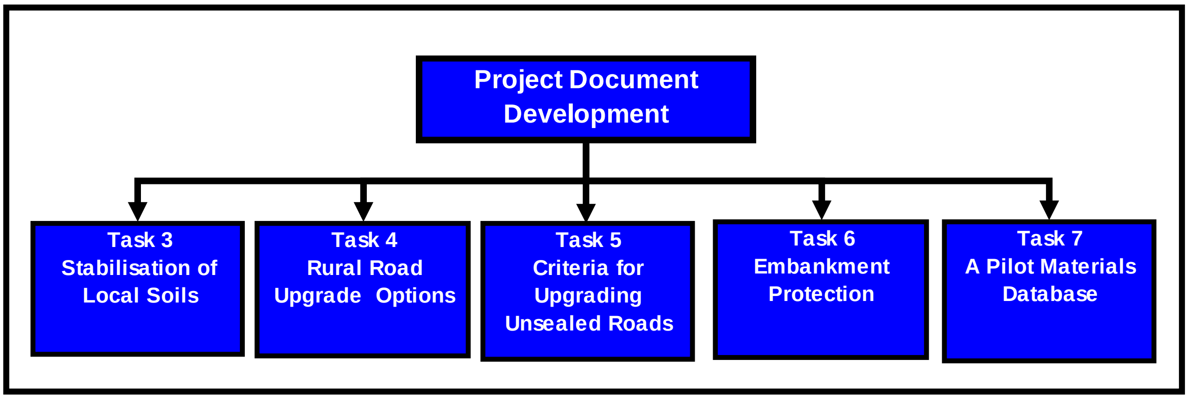

Figure 4.1 Project Development Tasks

4.2 Task 3: Stabilisation Techniques to Improve Local Materials

Requirement

Originally titled "Lime Stabilisation", the initial aim of this Task was to examine the options for the lime stabilisation of local soils for us in Low Volume Rural Roads in Cambodia. In initial discussions, the SEACAP 19 Steering Group requested that this Task be expanded to include other stabilisation options. The SEACAP 19 Team agreed to comply with this request within the existing resource and time constraints.

Output

The completed Technical Paper 3 "Stabilisation Techniques to Improve Local Materials for Rural Road Pavements in Cambodia" discusses the techniques of stabilising poor or marginal quality materials for road building as a means of providing durable roads at reasonable cost as an alternative to expensive better quality materials. It is based on a review of documented experience of using stabilisation techniques for road building both internationally and in Cambodia itself, with particular reference to:

- Mechanical stabilisation
- Emulsion bitumen stabilisation
- Hydrated Lime stabilisation
- Cement stabilisation.

Procedures for selecting and testing the appropriate stabilisation methods testing are discussed and key issues relating to construction procedure are highlighted. Current stabilisation programmes in Cambodia are reviewed and the prospect for increased application of these techniques is summarised. Recommendations for further related research and mainstreaming are included as an Appendix the paper.

4.3 Task 4: Rural Road Upgrade Options

4.3.1 Requirement

Although the ToR originally mentioned Waterbound Macadam (WBM) specifically, the SEACAP 19 Team proposed that this Task should include a wider range of options. The aim of this task was to review LVRR paving and surfacing options that have recently been trialled in Cambodia, Lao and Vietnam and identify those most likely to be appropriate to Cambodia and define the further work required to mainstream them into the Rural Road Standards.

4.3.2 Output

The completed Technical Paper 4 “Low Volume Rural Road Upgrade Options” comprises a review of a range of surfacing and pavement options for possible use in the Cambodian rural road environment. Background information for this review has largely been taken from current SEACAP pavement surfacing research in Cambodia, Lao and Vietnam, Table 4.1.

Table 4.1: Relevant SEACAP Projects

Country	SEACAP Research
Vietnam	SEACAP 1 - design, construction and monitoring of trial roads in a wide variety of physical environments. SEACAP 4 - collection and analysis of condition data on over 200 unsealed road links
Cambodia	SEACAP 8 - assessment of low cost surfacing trials and associated costs, together with related issues of maintenance and axle overloading.
Lao	SEACAP 3 - drafting of LVRR standards and specifications. SEACAP 17 - design, construction and initial monitoring of trial roads in hill terrain.

Although a number of LVRR pavement trials programmes have been undertaken in the last few years in Cambodia, Lao and Vietnam, only one so far in Cambodia has involved performance monitoring and hence there has been limited input to determining appropriate pavement upgrade options for Cambodia. This paper therefore relies heavily on the extensive SEACAP trials of over 140 km of roads in Vietnam for regional input to this review of Cambodian upgrade options

Upgrade options are reviewed under the following groupings:

- Bitumen emulsion surfacing
- Hot bitumen surfacing
- Stabilised pavement layers
- Non-stabilised pavement layers
- Block paving
- Concrete pavements

Upgrade options are assessed in relation to key construction, performance and sustainability criteria and to some typical Cambodian road environments.

Proposals for addressing the identified knowledge and application gaps are contained in a concise Concept Note attached as Appendix A to this Technical paper. This Concept Note summarises a possible way forward through a number of Modules that could be adopted singly or in combinations

4.4 Task 5: Criteria for Upgrading Unpaved Roads

4.4.1 Requirement

In discussion with stakeholders the definition of this Task has undergone a change in emphasis from that originally described in the ToR. With the objective of closer linkages with Tasks 2, 4 and 7 the main thrust has been on assessing the financial and economic criteria relevant to gravel road upgrade.

The initial inception work indicated that Task 4 and Task 5 had close links. Following inception meeting, it was decided to expand the scope of Task 4 to address issues relating pavement options while Task 5's scope was redefined to focus on knowledge related to economic evaluation of LVRR upgrading and indicate key decision making processes.

4.4.2 Output

Technical Paper 5 reviews the approaches available for the economic appraisal of LVRR upgrading and puts this in the context of current regional research. Economic valuation is noted as being important to make sure that the pavement or surfacing options with the greatest economic impact are selected. Some current methods of economic appraisal require substantial amounts of data that may not be readily available, would be costly to collect, would be difficult to analyze with confidence, and may not be justified at the levels of investment funding available, especially for smaller projects. The paper includes a discussion on key decision making processes for pavement upgrade.

There are significant relevant information gaps in the Cambodian rural road knowledge base and the associated Concept Note outlines the outline steps to address them.

4.5 Task 6: Embankment Erosion

4.5.1 Requirement

This Task was primarily aimed at reviewing key technical issues associated with the prevention of embankment slope deterioration by the erosive action of rainfall and canal and river flooding. The Task also aimed to identify possible solutions appropriate to the Cambodian environment and specify suitable trials to carry this work forward.

4.5.2 Output

The completed Technical Paper 6, "A Study of Road Embankment Erosion and Protection" comprises an in-depth review of the subject background. It provides an assessment of the rural road environment in the lower flood plains of Cambodia. Two principal situations are identified and discussed:

- The periodic damage caused to the extensive lengths road embankments at a considerable distance from rivers, but crossing land subject to seasonal flooding, Figure 4.2.
- Where the eroding banks of major river channels (particularly the Mekong and Bassac) are undercutting roads where they happen to run close to the main channels, Figure 4.3.

Figure 4.2 Local Roads within Flood Areas

Figure 4.3 River Bank Erosion

A summary of site investigations undertaken as part of the SEACAP 19 Task 6 programme is also included.

Proposals covering the perceived need for research and an outline of how this might be done through suitable trials to develop technical solutions appropriate to the Cambodian environment are included in a Concept Note attached as an Appendix to the paper. The techniques proposed are low cost and innovative, using bio-engineering as their basis.

4.6 Task 7: A Pilot Materials Database

4.6.1 Requirement

This Task was aimed at establishing a methodology for assembling and managing a database of naturally occurring Cambodian road construction materials. Procedures for the formation of the database were required to be trialled in pilot studies within 3 districts in 2 provinces.

4.6.2 Output

A relational Pilot Road Materials Database (PRMD) has been set up; procedures developed for data capture; and a representative suite of data has been collected and entered into this structure. The two provinces of Siem Reap and Kandal were selected as the principal trial areas containing a suitable selection of materials sources, from sub-grade soil borrow pits to hard rock quarries. Data from a representative sample of materials resource types from 13 districts within these provinces have been collected.

The PRMD records the location and details of quarries, the types of material available and the products derived from these materials, along with details of samples taken for testing and the results of the tests, Figure 4.4. The PRMD is based on the Microsoft Access® database platform which has advantage of being simple to develop and is widely available as a desktop application. The structure allows the easy entry and reporting of materials information relevant to rural infrastructure engineers. The current SEACAP 19 PRMD is available on CD.

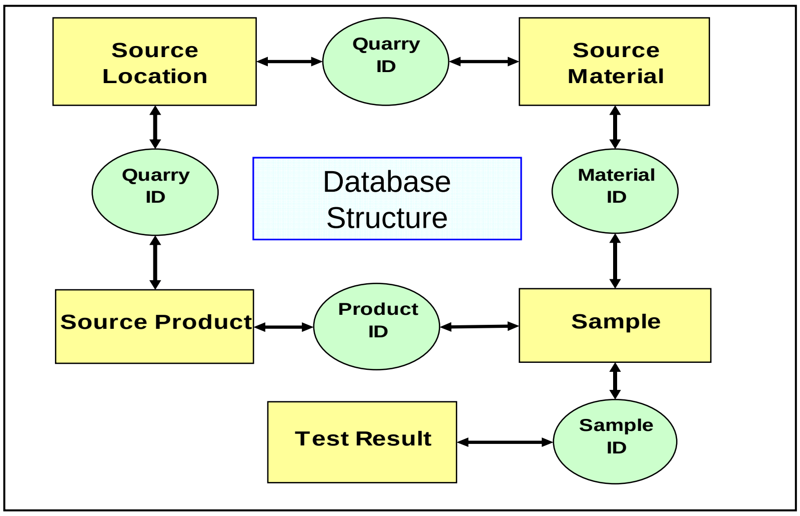

Figure 4.4 Linked Data Sets within the PRMD

The completed Technical Paper 7 "Pilot Road Materials Database" reviews the background to road materials management in Cambodia as well as containing details on the procedures developed for the PRMD.

A Concept Note describes the options for the way forward firstly of a full-scale National Road Materials Database (NRMD) and then possibly to a National Road Materials Information System (NRMI).

5 Studies

5.1 Task 8: Low Cost Structures Manual

5.1.1 Requirement

The defined aim of this task was to review a Low Cost Structures Manual previously developed to a preliminary draft stage using previous DfID funding and to assess firstly its status and secondly its potential usefulness within the Cambodian rural road context in particular and the regional environments in general.

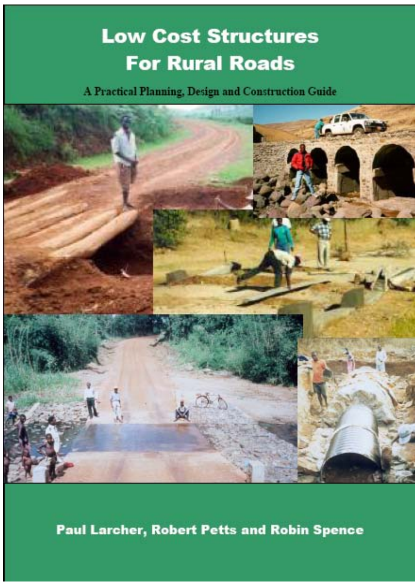

Figure 4.5 The Original Draft LCSM

5.1.2 Output

Technical Paper 8 "A review of the Low Cost Structures Manual (LCSM)" has been completed together with annotated electronic copies of the 2 volumes of the LCSM in pdf format. The production of a final draft of the LSCM based on the Technical Paper is the subject of the separate but associated SEACAP 19.02 project. The outputs from the extension are reported in separate document.

5.2 Task 9 Unit Rate Costing System

5.2.1 Requirement

This Task was initially aimed at the review of existing costing systems both regional and international, followed by recommendation as to the most appropriate elements to be incorporated into a draft Cambodian system. During discussions with the MPWT it became clear that a review of an already existing document was a priority. The task was therefore re-oriented towards making comment on this document together with recommendations on its improvement for use in the LVRR environment

5.2.2 Output

At the start of this assignment it was noted that a unit rate costing system had in fact already been prepared by the Ministry of Public Works and Transport (MPWT). The costing system relates to materials, equipment and labour used for road works. This document in turn relates to the MPWT's Cambodian Construction Specification.

Following discussions with the Ministry this Task therefore focused on the review of the system. Essentially this constituted reviewing the "Construction Cost Analysis" - (CCA) document proposed by the Ministry of Public Works and Transport (MPWT).

A review of the proposed MPWT document has been completed as Technical Paper 9. Comments are made in this paper on the existing unit rate cost system which, in summary, was seen as being quite comprehensive and potentially very useful in preparing costs estimates of projects at all levels including in preparing departmental budgets. The paper includes recommendations on further work required if the MPWT document is to be applied to LVRRs. Effective dissemination was also noted as being a required task.

6 Capacity Building

6.1 Refine & Mainstream Standards & Procedures

The process is related to the outcome of the Applied Research project Tasks 1 and 2 and was not seen as a comprehensive redrafting of the rural road standards as a whole. Tasks 3-7, which were, by definition, largely interim activities, did not contribute to this process.

The Technical Paper 1 (BRCP) clearly indicated that there was no benefit to be gained from using bamboo reinforcement in concrete road slabs. Well constructed non-reinforced concrete is a better option. It follows that no changes to relating to bamboo reinforcement standards and procedures are required other than to circulate a summary document to highlight the Technical Paper findings.

Task 2 resulted in some recommendations on the Standards and Procedures for ENS roads on the following issues:

- Sustainable gradients
- The use of Plasticity Product to define suitable surfacing materials
- Minimum strength for surfacing material

There is a general recognition that the available Standards and Specifications for LVRR in Cambodia would benefit from a comprehensive review. (See Section 8.2)

6.2 Strengthen Research Capacity

This process was aimed particularly at the Civil and Rural Engineering Departments of ITC, although Ministry staff and the EIC were also be involved in this process. In practice the principal beneficiary was ITC whose staff were associated with:

- The research into BRC (Task 1)
- The research and materials testing for ENS (Task 2)
- The development of the materials testing programme for Task 7 database.

6.3 Enhance ITC Student Experience

Significant difficulties have been experienced in coordinating the ITC academic programme with that of SEACAP 19. This is discussed further Section 8.3

The following 3 lectures by Dr John Rolt were made available by the project for presentation to students and staff:

- Empirical Pavement design
- The Pavement Design Revolution
- An HDM 4 Overview

6.4 Enhance Stakeholder Cooperation

This has been successfully achieved by working closely with the SEACAP 19 Steering Committee and Working Group which, by their very make-up, played a key role in enhance cooperation between the Government sector (MRD & MPWT),the Academic sector (ITC), private practitioners (EIC, CNCTP) and the Donor community.

7 Outputs

7.1 Report and Technical Papers

The SEACAP19 project has delivered a significant body of research, applied research and reviews in the form of Technical Papers, Table 7.1

Table 7.1: Technical Paper Titles for SEACAP 19

Reference	Title
TP1	Bamboo reinforced concrete pavements
TP2	Behaviour of engineered natural surfaced roads
TP2.2	Behaviour of engineered natural surfaced roads: experimental evidence in Cambodia
TP3	Stabilisation Techniques to Improve Local Materials for Rural Road Pavements in Cambodia
TP4	Low volume rural road surface and pavement for Cambodia
TP5	Low volume rural road upgrading in Cambodia
TP6	A study of road embankment erosion and protection
TP7	A road construction materials database for Cambodia
TP8	Review of a draft low cost structures manual
TP9	Unit rate costing system review

In addition, a substantial amount of progress reporting, both monthly and quarterly, was delivered during the project; as listed below:

SEACAP 19 Progress Report 1: April 2007

SEACAP 19 Progress Report 2: May 2007

SEACAP 19 Progress Report 3: June 2007

SEACAP 19 Progress Report 4: July 2007

SEACAP 19 Progress Report 5: August 2007

SEACAP 19 Progress Report 6: September 2007

SEACAP 19 Progress Report 7: October 2007

SEACAP 19 Progress Report 8: November 2007

SEACAP 19 Progress Report 9: December 2008

SEACAP 19 Progress Report 10: January 2008

SEACAP 19 Progress Report 11: February 2008

SEACAP 19 Progress Report 12: March 2008

SEACAP 19 Progress Report 13: April 2008

SEACAP 19 Progress Report 14: May 2008

SEACAP 19 First Quarterly Report: August 2007

SEACAP 19 Second Quarterly Report: December 2007

SEACAP 19 Third Quarterly Report: March 2008

SEACAP 19 Fourth Quarterly Report August 2008

SEACAP 19 Fifth Quarterly Report December 2008

7.2 Workshops and Presentations

During the inception period it was agreed that it would be more effective to hold a limited number of multi-task progress workshops rather than to hold individual task workshops. The following Table 7.2 summarises these key workshops and their presentations

Table 7.2 Project Workshops

Date	Designation	Main Task Presentations
17th June 2007	Inception and Progress	Inception Report
30th August 2007	Progress	Overall progress Tasks 1-9 Technical cooperation Task 1 BRCP Task 2 ENS Roads Task 7 Materials Database
1st November 2007	Progress	Overall progress Tasks 1-9 Technical cooperation Task 2 ENS Roads Task 6 Embankment Erosion Task 8 LCSM
27th February 2008	Progress	Overall progress Tasks 1-9 Task 1 BRCP (Task 1) Concrete Roads in the Philippines (Task 1) RRST Concrete Roads in Vietnam Task 2 + 7 Data Collection
26th August 2008	Progress	Overall progress Tasks 1-9 Task 2 ENS roads Task 7 Materials database
February-March 2009	Final Workshop	To be detailed

In addition a number of external presentations associated with SEACAP 19 were made at the following meetings and workshops:

1. SEACAP Practitioners' Meeting; Hanoi, September 2007

2. Regional Workshop on Natural Resources and Materials for Sustainable Development of ASEAN. AUN/SEES Regional Meeting at ITC August 2008
3. gTKP Government Theme “Mobilising civil society to improve governance in transport” Manila June-2008
4. ADB Transport Forum, Manila, September 2008: 1 Presentation
5. SEACAP Practitioners’ Meeting; Vientiane, November 2008: 1 Presentation

During the implementation of SEACAP19 the project team have also contributed consistently to management activities of CNCTP for the furtherance of SEACAP objectives.

8 Conclusions and Recommendations

8.1 Assessment of Project Completion

This completed project task work is briefly summarised below in relation to the original ToR and their agreed amendment.

Table 8.1 Conclusion on Task Achievements

Task	ToR Objective Summary	Conclusions on Task Achievements
Applied Research		
1. BRCP	Increase the appropriate utilization of local species of bamboo in Bamboo Reinforced Concrete Pavements (BRCP)	The technical review indicated that there was no advantage in using BRCP over non-reinforced concrete pavement. The Technical Paper and associated presentations successfully achieved a modified objective of advising the Ministries on this.
2. ENS Roads	Improve community access by increasing the capacity of the MRD and local communities to develop and manage the earth roads.	The two Technical Papers have provided a substantial body of knowledge to the MRD on the effective application of the ENS road option. Limitations in terms of materials, traffic, and road geometry have been indicated. An important database has been established for the use in the continuation of this work .The two papers constitute a successful step to achieving the declared task objective
Project Document Development (all these tasks in addition include a requirement to identify and define further work)		
3. Stabilisation	Review of existing knowledge base. Survey availability, suitability and cost of lime products in Cambodia. Carry out a feasibility study for application of the technique in Cambodia	As agreed during the inception phase the Task was altered to include a broader look at stabilisation techniques in general in terms of their application in Cambodia. Technical Report 3 has achieved this modified objective. Knowledge gaps have been identified and further applied research modules defined
4. Waterbound Macadam and Other Surface Options	Identify the current knowledge gaps for expanding the use of waterbound macadam and other local resource based surfacing techniques in the various regions of Cambodia. Elaborate a project document for further research trialing and demonstration of techniques.	The objective has been achieved through Technical Report 4 which summarises the principal advantages and disadvantages of a wide range of pavement and surfacing options within Cambodian LVRR environments. Recommendations are made as to further trials and long term monitoring.
5 Pavement Upgrading	Review of existing knowledge base. Review experiences in Cambodia. Survey the current condition of a representative sample of the roads developed in recent programs. Carry out technical, financial and economic analysis of favourable alternatives for upgrading.	Modified objectives have been achieved through Technical Paper 5 which reviews the approaches available for the economic appraisal of LVRR upgrading and puts this in the context of current regional research. Key decision making processes are also reviewed and related knowledge gaps are identified. Technical Paper5 and close links with Technical Paper 4 in achieving joint objectives

Table 8.1 (Continued)

6. Embankment Protection	Carry out a literature review of the knowledge base for embankment protection of rural roads. This would include embankment stability and erosion control under flood/emersion conditions. Identify the knowledge gaps in methods of embankment protection appropriate for Cambodian conditions.	Technical Report 6 contains a comprehensive review of the problems of river bank and embankment erosion within the Lower Mekong area of Cambodia. Particular issues are identified based on this review and associated field studies and potential bioengineering solutions are proposed. Previous bioengineering solutions used in Cambodia are assessed and knowledge gaps identified. Further applied research and associated trials are defined. It is considered that the Task objectives have been achieved.
7. Materials Database	Review the IRAP maps and resource inventories developed by the ILO/NRDP in three districts in NW Cambodia. Prepare a materials database, which is GIS based. Pilot a study in 3 districts. Elaborate an IRAP component that identifies the material locations and registers them in the IRAP database.	A Pilot Road Materials Database (PRMD) has been designed and data from several districts in two provinces have been collected and entered. Existing information from IRAP maps has been incorporated and the database is GIS based to allow compatibility with the IRAP information. Technical Paper 7 reviews the requirement for the effective management of construction materials in Cambodia as well as describing the PRMD and providing guidance on its use and further expansion on a National basis. It is considered that the Task objectives have been achieved
Studies		
8. Low Cost Small Structures Manual	Assess the status of the unfinished small structures manual. Estimate the work and resources required to complete the manual and to undertake trials. Make any other recommendations as to its further development.	The existing LCSM has been reviewed and extensive amendment notes have been attached to the document on a chapter-by chapter basis. These allow the updating of the LCSM to be undertaken (by the separate SC19.02 contract). Technical Paper 7 assesses the status of the LCSM; summarises the review and outlines the way forward with identified resources, thus achieving the Task objectives.
9. Unit Rate Costing System	Prepare a unit rate-costing system which relates to materials, surface options and expected maintenance costs. Prepare the computer program to do this with supporting guidelines for operation.	Following discussion with and agreement from the MPWT, Technical Paper 9 has concentrated on a review of an existing MPWT document on a Unit Rate Cost System rather than developing a new procedure. This paper includes recommendations on further work required if the MPWT document is to be applied to LVRRs.

8.2 Continuation

Most of the Technical Papers make recommendations as to further work and in the case of the Project Development Talks (Nos 3-7) there are specific programmes defined. The following Tables 8.2 and 8.3 summarise these recommendations and indicate where opportunities exist for cost-effectively combining resources.

Table 8.2 Summary of Further Works Recommendations

Tasks		Recommended Continuation
2.	ENS Roads	1. Continuation of monitoring 2. Specially constructed ENS trials
3.	Stabilisation	3. Laboratory Studies 4. Quality of available limestone 5. Field trials 6. Contractor capabilities 7. Whole life costing 8. Appropriate Standards 9. Dissemination
4.	Upgrading Options	1. Monitoring of existing trials/roads 2. New trial roads 3. Data analysis 4. Dissemination and mainstreaming 5. Training
5	Upgrading Criteria	1. Cost data from trials 2. Whole life costing on existing roads 3. Economic data analysis 4. Training
6.	Embankment Protection	1. Trials for riverbank erosion protection 2. Trials for embankment protection 3. Guideline
7.	Materials Database	1. Training 2. Data collection 3. Database management

Table 8.2 Possible Combined Programmes

Programme	Combined Tasks
A. Monitoring and Data analysis	Elements of Tasks 2, 3 and 4.
B. Trials Construction	Elements of Tasks 2, 3 and 4 for LVVR trials could be effectively combined with the embankment erosion trials.
C. Training and Dissemination	Most of the proposed additional tasks contain a training or dissemination element. See section 8.3 for specific recommendations of training and dissemination
D. Economic analysis	Key recommendations in Task 5 could be combined elements in Task 2, and 3.
E. Materials Database	A road construction materials based programme could include additional elements of Tasks 2, 3 and 4 as well as the central task 7 theme.
F Standards and Specifications	Includes elements of Tasks 2, 3, 4, 6 and 7 – as well as having links with A and B above

In the light of the accumulated Cambodian and regional research by SEACAP, we consider it is appropriate now to propose an overall review of the LVRR Standards and Specifications rather than attempt a partial upgrades and amendments. Recent opinions expressed by the MRD are in agreement with this view. We agree with suggestions that the SEACAP 3 Standards and Specifications could be used a model to be adapted to suit Cambodian requirements. The SEACAP 3 output was arrived at by working through a logical series of key steps which are also applicable to Cambodia, namely:

1. Define road tasks.
2. Define geometric standards.
3. Identify available construction materials.
4. Identify suitable standard road designs.
5. Draft construction specifications

8.3 Recommendations on Approaches to Future Work

The following points are based on the experience not only of SEACAP 19 and its predecessors in Cambodia but also on the related projects in Vietnam and Lao PDR.

Resourcing: It is difficult to predict the extent and direction of research programmes, as opposed to review, training or dissemination projects. There were some aspects of SEACAP where it was necessary to expand the work beyond that originally intended in order for the research to reach a logical conclusion. For example Task 2 and Task 7 expanded in this way beyond initial expectations and this had had a significant knock-on effect for the overall completion programme. A fixed ceiling budget approach adopted for SEACAP is not, in our opinion, the ideal approach to genuine research. In addition, and in retrospect, we feel that SEACAP 19 was significantly underfunded.

Project Structure: Competitively bid research programmes need to have a single central cohesive core with clearly defined end products (For example SEACAP 3 or SEACAP 27). SEACAP 19 in many ways grew out of a range of issues raised during SEACAPs 2 and 8 and whilst we acknowledge the excellent work done in drawing the various strands together into a comprehensive ToR, it remained a difficult and complex project both to cost and to manage.

Capacity Building in the Academic Sector: Whilst there has been good cooperation with ITC at administrative level and in the development of general strategic aims there has been less success in developing sustainable working relationships at the grass-roots level with academic staff and students. This experience on SEACAP 19 is similar to that on SEACAP projects in Vietnam where it has taken a number of years to gain the confidence of individual academics and establish involvement with students. There a number of possible reasons for this, including:

- The need for long periods of sustained contact with the relevant academics to show sustainable commitment – the intermittent nature of the specialist input into SEACAP 19 precluded this.
- The difficulty of fitting fieldwork and lectures into an established academic year given the time constraints on projects such as SEACAP 19
- The need to have a high level of compatibility between the research aims of the academics and the project – while this was achieved to an extent in Task 1 (BRCP) it was probably not true for many other SEACAP 19 Tasks.

Training and Mainstreaming: The importance of training and mainstreaming of research outputs from programmes such as SEACAP are rightly described as key priorities. However, in most projects these are included activities that follow-on from the research within what are usually tight programmes. The consequence is that they tend to become subject to very compressed schedules, usually at the end of projects. Our recommendation is that priority should be given to providing specialist training or mainstreaming projects, with necessary links to, but separate from, the associated research programmes. The success of DF55-SEACAP 1 link is good example of this approach.

Steering Group/Committee: All the SEACAP experience has indicated the essential need to continue with the Steering Group or Committee concept as means of bringing all major stakeholders together under sound leadership.

DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

COMPLETION REPORT

APPENDIX A

Teaching Modules

M1: An Assessment of Bamboo Reinforced Concrete Pavements

M2: A Review of Engineered Natural Road Surface Roads

SEACAP 19

Teaching Modules

M1: An Assessment of Bamboo Reinforced Concrete Pavements

Introduction

Bamboo has been used in many applications in construction works for hundreds of years because of its high strength-to-weight ratio and its relative ease of use. Its properties are such that it has potential for reinforcing weaker materials and perhaps it was inevitable that engineers should try to use it for reinforcing concrete. Gleeson (2002) has reviewed the use of bamboo for this purpose and it is clear that although bamboo has potential for reinforcement in specific circumstances, it is by no means the easiest material to use and considerably more (successful) research is needed if its potential is to be realised. For example, Datye et al. (1978) state that, *'Bamboo reinforced cement concrete has not met with any degree of success mainly due to the low elastic modulus of bamboo, its poor bond with concrete and its tendency for volume change due to moisture absorption'*. On the other hand, after discussing all the problems in considerable detail, Subrahmanyam (1984) concludes that '… *notwithstanding the future requirements (of research), bamboo reinforced cement composites can be effectively used on the basis of existing knowledge.* In general, the greatest successes have occurred with bamboo reinforcement of materials weaker than pavement quality concrete and in situations where bamboo has been treated to provide durability (and improve bond) and where cracking can be tolerated. Thus it is important to note the limitations of bamboo reinforcement and, in particular, its low elastic modulus is a limiting factor in many reinforcement uses.

Azam et al. (2002) have described a demonstration project in Cambodia, constructed as part of the overall 'ILO Upstream Project' in cooperation with the LCS (Low Cost Surfacing) initiative, where bamboo reinforcement was used in the construction of a concrete road pavement at Puok Market near Siem Reap. Subsequently a number of trial sections of other pavement designs were constructed along the same road as part of the LCS initiative. Also, as part of a related DfID/SEACAP initiative, several trial sections of bamboo reinforced concrete (BRC) were also constructed in Vietnam (Intech, TRL and ITST, 2006).

Despite the fact that the report by Azam et al. (2002) refers to research on bamboo reinforced concrete pavements (BRCP) carried out at Chiang Mai University in Thailand, the report does not reference any documents from that source, nor does it describe how the design of the reinforcement was carried out. It appears that a report was submitted to ILO by the University but was never published (see Appendix A). A review by Gleeson (2002) identifies a key reference by Brink and Rush (1966) which was placed on the worldwide web in 2000 by the originating organisation because of its historical interest. However, the definitive paper on the topic is probably that by B V Subrahmanyam in 'New Reinforced Concretes' published by the University of Surrey in the UK. Typical properties of bamboo quoted in this paper are shown in Table

Table 1 Mechanical properties of bamboo reinforcement

Mechanical Property	Range of values (MN/m^2)	Typical value (MN/m^2)	Typical value (psi)
Tensile strength[1]	75 – 350[2]	130	18,850
Poison's ratio	0.25 – 0.41	0.32	0.32
Modulus of elasticity	10,000 – 28,000	18,000	$2.6x10^6$

Notes
1. This is not quite the same as the modulus of rupture which is now the preferred test.
2. This value is unusual. A more realistic maximum is 250 MN/m^2.

Reinforcement is not normally used in concrete road pavements designed for relatively low levels of traffic. This is considered unusual by engineers more familiar with the design of concrete beams used in engineered structures such as bridges and buildings. The reason is that the tensile strength of concrete is very low in structural terms (it is normally assumed to be zero for the purposes of beam design) and therefore, in structural engineering, all concrete that is expected to be in tension is always reinforced, preferably with a material that has a high elastic modulus and high tensile strength (e.g. steel).

The principles of rigid pavement design are somewhat different and this has led to some misunderstanding. Therefore, before reviewing the use of bamboo for reinforcing road pavements, it is worthwhile reviewing the principles of reinforcement for structural purposes and the factors that need to be taken into account when bamboo is used for this.

Bamboo Reinforcement

Bamboo reinforcement has been well documented by Subrahmanyam (1984). The properties of bamboo are not consistent but cover a wide range as shown in Table . This is because they depend on a considerable number of variables including such obvious ones as,

- Species of bamboo
- Age of the bamboo culm
- Moisture content
- Pre-treatment (i.e. how the bamboo is stored and weathered)

But also on less obvious factors such as…

- Time of harvest
- Method of harvesting
- Soil in which it is grown

As a result, the properties of bamboo vary a great deal. Much academic research has been devoted to measuring the properties of bamboos under a very wide range of conditions but, despite this, the detailed situation is not very clear because test methods have not been standardised and insufficient research has been done. Nevertheless, the broad range of likely values for the key variables of elastic modulus and tensile strength are well documented and therefore, for design purposes, realistic and safe values can probably be assumed, subject to checks made on samples of bamboo that it is proposed to use.

Interaction with Water

In use, the interaction of bamboo with the water in the concrete is responsible for several problems. First of all, when the concrete is curing, the wet environment causes bamboo to expand, especially in the transverse direction (i.e. perpendicular to the direction of the culm). This can cause premature cracks in the concrete. Later, the bamboo shrinks back and the bond between the concrete and the bamboo is broken. Methods of dealing with these problems usually involve treating the bamboo in some way and are likely to be expensive. Such treatments should also improve the durability of the bamboo, which is normally very poor in an aggressive or in a wet environment.

Bonding with Concrete

The modulus of bamboo is low compared with that of the concrete and therefore the strain in the bamboo is correspondingly high. Thus, when the concrete cracks, the bamboo allows the cracks to widen considerably. Bamboo is also inherently smooth and does not bond well to concrete. Failure of the bond will allow the cracks to widen even more than they would if the bond was good. Under service loads these cracks can be greater than one millimetre wide. This is far in excess of the width that is normally considered tolerable. Methods of improving the bond include (i) coating the bamboo to increase the cohesion, (ii) constructing anchors of various kinds, and (iii) attempting to minimise the problem by minimising the volume changes in the bamboo that are the primary cause. This can be done by controlling the initial moisture content of the bamboo and using high grade cement that cures quickly and requires a low water content. None of these solutions are likely to be suitable for local, rural, resource-based construction projects.

A related problem is that the thermal expansion of bamboo in the radial direction is very high compared to that of concrete (3-5 times greater). This property has a considerable effect on the bond between the two if temperature changes are significant.

Response of Bamboo to the Load Regime

It has been observed that the response of bamboo to sustained loads is a reduction in strength by as much as 50%, but little is known about this effect (Subrahmanyam, 1984). The response of bamboo to *repetitive* loads is relatively unknown and there is little or no information about the fatigue behaviour of bamboo reinforced beams.

Consequences

These unknown factors, combined with the variability in the basic properties of bamboo, imply that, until further research has been carried out, large, pragmatic safety factors need to be incorporated in structural design. The allowable tensile stress may therefore be as low as 20% of the tensile strength. For concrete slabs, values of allowable stress in the bamboo of between 20 and 40 N/mm^2 have been proposed with most being at the lower end of this range.

Although the tensile strength of the bamboo is quite high, it is relatively low compared with steel, therefore the allowable stress is much lower and a great deal more reinforcement is needed to carry the same loads. If the safety margins are taken into account, some observers have concluded that ten times more bamboo is needed than mild steel for comparable performance *in strength terms*. But from a practical point of view the maximum amount of bamboo that can be used is 3 to 4 percent. Indeed, higher quantities have been shown to have an adverse effect. Thus, in principle, it may not be possible to provide as much reinforcement as required and this limits its use in comparison with steel.

Of greater importance is the fact that because the elastic modulus of the bamboo is low, the cracks in the concrete can widen under load to unacceptable levels. Also, since the initial cracks in the concrete are likely to be wider than those that occur when steel reinforcement is used (see above), the situation is further exacerbated. Wide cracks are serious in steel-reinforced structures because of subsequent lack of interlock of the concrete across the crack and the accelerated deterioration that occurs when steel is exposed. The situation is a great deal worse when bamboo is used because the cracks are much wider and bamboo deteriorates very rapidly, especially when fully exposed to air, water, fungi and insects. Indeed, the research evidence indicates that unless the bamboo is suitably treated, it is also likely to rot and disintegrate *within* the concrete, not only at the exposed cracks. Thus the life of a structure that relies on bamboo reinforcement can be very short in normal engineering terms.

These problems are serious for structural design using bamboo, but the design of road pavements is based on slightly different principles.

Principles of Rigid Pavement Design

Cracking in concrete pavements cannot, in general, be tolerated, but cracking is an inevitable result of the natural shrinkage of concrete. Therefore a concrete pavement is designed in such a way that the shrinkage cracks are controlled so that they occur at a pre-defined spacing, usually between 3.5 and 4.5 metres. The cracks are controlled so that they are straight and perpendicular to the direction of the carriageway. After construction, they are sealed to prevent water from the surface of the road from entering the underlying pavement structure. No other cracking from shrinkage or thermal stresses normally occurs. If construction is not continuous (e.g. if mixing is done in small mixers) then joints can be constructed at the appropriate intervals and cracking can be eliminated.

Although the tensile strength of concrete is low, it is usually strong enough under traffic loads to resist cracking in a road pavement. This is because a road pavement is designed to be uniformly supported by the sub-base underneath and therefore the stresses induced by vehicle loads are normally lower than the critical tensile strength. Also, concrete is brittle. This means that as long as a critical stress is not exceeded, the concrete should not fail through fatigue and should therefore have a very long life. *The key to success is the uniform support*. Roads of this kind have been constructed worldwide and usually perform successfully. In the Philippines, for example, concrete roads of this type make up 63% of the paved national road network of about 20,000km and there are many more such roads that are not classed as national roads. Concrete pavements such as this are also used for spot improvements where conditions are too severe for gravel or unsurfaced roads.

The Role of Steel Reinforcement in Road Pavements

For relatively heavily trafficked concrete roads (cumulative traffic > 8 million equivalent standard axles (mesa)), reinforcement is often used. When bonded properly, it is the tensile *strain* that is the same in both the steel and in the concrete and it is the stress that is different. Thus, for every small increment of strain, the steel will develop a much greater tension than the concrete such that when the tensile forces in total are enough to support the load, there will be a much lower strain (in both the concrete and the steel) and therefore a correspondingly much lower stress in the concrete than there would be without the steel. In other words the steel prevents possible cracking from the tensile forces because it greatly reduces those tensile forces. For this to work, the steel must remain bonded to the concrete. Also, there must be enough steel because, in this use, the steel carries all of the tension. In contrast to the use of reinforcement in other structures, the role of the reinforcement in road pavements *is* mainly to *prevent* cracking.

The alternative to the use of reinforcement is to reduce the critical stress in the concrete by making the concrete slab thicker (conversely, the use of steel reinforcement allows reductions in thickness). The most vulnerable areas of a concrete slab to cracking are at the corners and at the longitudinal edges. A theoretical approach to thickness design using Westergaard's approach can be used, however, it should be noted that the details of concrete road designs are based almost entirely on empirical research (i.e. what is known to work). In the UK, for example, concrete slabs of less than 150mm are no longer permitted, even for low traffic levels, but, for high traffic levels where the required thickness of unreinforced concrete is considerably greater than 150mm, reductions in concrete slab thickness of between 20 and 50mm are allowed depending on the quantity of reinforcement used. For relatively low traffic (< 8.0 mesa) no reinforcement is recommended. This traffic level is very high compared to the traffic on most of the rural roads in Cambodia.

The exception to these principles occurs in the case of Continuously Reinforced Concrete Pavements (CRCP). In such pavements there are no contraction joints and therefore cracks might occur just as in normal structural concrete. The reinforcement therefore performs exactly the same role as in other structures and bamboo is not suitable for such reinforcement; it will simply allow wide cracks to develop and will, itself, deteriorate quickly.

The Use of Bamboo as Reinforcement for Pavements

In view of the foregoing discussion of principles, how is it expected that bamboo can be used instead of steel for reinforcing road pavements? Can it reduce the thickness of concrete required? And, given that reinforcement is not normally used for concrete roads carrying light traffic, is reinforcement necessary at all?

Anomalous Design Principles

It is first necessary to correct a fallacy relating to the design of concrete roads that occurs in many design methods, a notable exception being the Portland Cement Association method that is often used in the USA. In this method a proper fatigue law is used and cumulative damage calculated using Minors assumption concerning accumulated fatigue damage. Concrete is brittle and therefore the number of times that a load can be repeated before fatigue failure occurs is very sensitive to the magnitude of that load. Below a critical level (typically 50% of the tensile strength, although 75% has also been quoted) the concrete should not fail through fatigue. The repetitions of load do practically no damage at all and the life of the concrete is long. However, above the critical stress level, the life of the concrete before it cracks can be very short. This means that it is not correct to assess traffic load using the standard 4.5 power law to convert axle loads into an equivalent number of standard axles, as is done for flexible pavements; the effective power law is much higher. Also, because concrete is brittle, there is little or none of the 'healing' effect that occurs with bituminous materials. Thus it is vital to make sure that very heavily overloaded vehicles do not use the concrete pavement or that the safety margin is high enough to prevent failure under such circumstances. This is one of the potential benefits of reinforcement. Provided the reinforcement has the appropriate properties, cracking caused by excessive loads can be prevented and concrete thickness can be reduced.

Reinforcing Action of Bamboo

The modulus of bamboo is considerably less than that of concrete; therefore it cannot reinforce concrete in the conventional sense. The purpose of reinforcement is to provide some tensile strength to a material that lacks tensile strength. In order to fulfil this function, the reinforcing material needs to have sufficient tensile strength and a high elastic modulus so that the greatest amount of tension can be borne by the reinforcement rather than the matrix in which it resides. Bamboo has a relatively high tensile strength but its modulus is too low. To demonstrate this, the following model has been analysed.

A full sheet of material with the characteristics of bamboo has been placed within the concrete slab and bonded to it as shown as model A in the Figure. The results of the analysis of this model are to be compared with the results obtained without the bamboo sheet (model B).

1. The assumptions are shown in Table and the stresses at the two critical points at the underside of the concrete, calculated using multilayer elastic theory, are shown in Table 2.

2. The stress in the bamboo is very much less than the allowable stress (~ 2% of it assuming a design safety limit of, say, 30 MPa), but it should be remembered that this is a complete layer of material with the properties of bamboo. The stress in bamboo strips would be higher but not so high that it would constitutes a problem.

Table 2 Assumptions

Property	Value
Thickness of concrete	140 and 150 mm
Elastic modulus of concrete	30,000MPa
Poison’s ratio of concrete	0.30
Thickness of bamboo	10mm
Elastic modulus of bamboo	15,000MPa
Poison’s ratio of bamboo	0.35
Modulus of subgrade	10, 20, 50, 100, 200 and 300MPa
Load	Standard dual-wheel carrying 40 KN

Table 3 Tensile stress at base of concrete

Subgrade modulus (MPa)	Tensile stress in bamboo MPa	Tensile stress in the concrete (MPa)		
		Model A	Model A	Model B
		Above bamboo	Bottom	Bottom
10	0.64	0.91	**2.64**	**2.58**
20	0.57	0.82	**2.37**	**2.32**
50	0.47	0.69	**2.01**	**1.97**
100	0.40	0.60	**1.74**	**1.70**
200	0.33	0.50	**1.47**	**1.44**
300	0.29	0.44	**1.31**	**1.28**
500	0.23	0.37	**1.10**	**1.09**

It can be seen that the maximum stress in the concrete occurs at the bottom of the overall slab. Although the stress in the concrete is almost identical in both models, the stress in Model A (i.e. with ‘reinforcement’) is slightly larger than in Model B. This is simply because the modulus of bamboo is less than that of concrete and the thickness of the overall pavement slab is the same in both cases. The small differences that are shown in the Table will all but disappear if the solid bamboo sheet is replaced with thin strips. This is because such strips will occupy only about 10% of the volume of the complete sheet (or about 0.5% of the total area of the slab). Additional layers of bamboo could be added but the Table indicates that the difference in stress will be negligible for any realistic amounts of bamboo (up to 3.5% area). Thus it is not surprising that bamboo reinforcement will make no significant difference to the stress carried by the concrete when under traffic loading.

The effect of increasing the elastic modulus of the reinforcement is shown in Figure 1. Only when the modulus of the reinforcement is greater than that of the concrete (very unlikely for bamboo) is there any reduction in the critical stress. To achieve a worthwhile level of stress reduction requires both a much greater quantity of reinforcement and a much higher modulus.

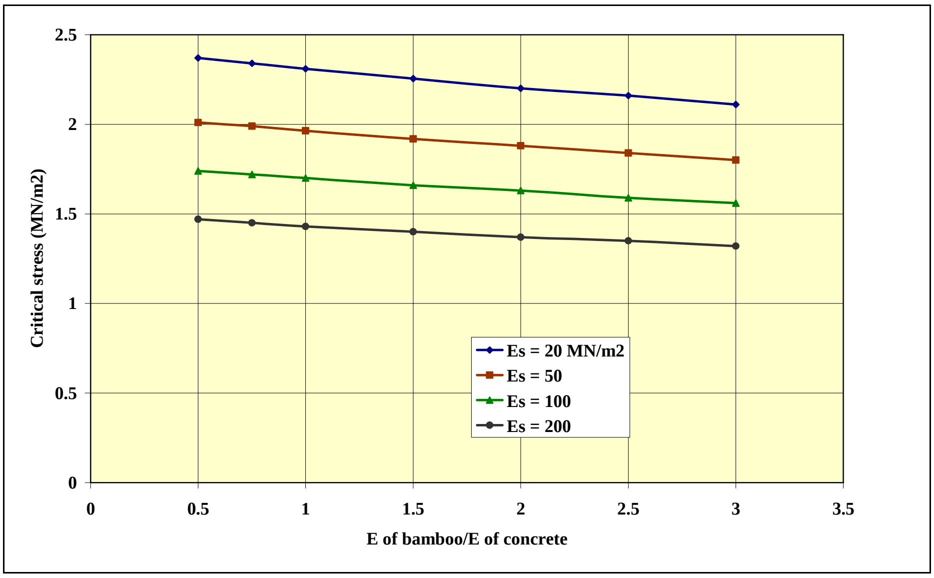

Figure 1 Relationship between critical stress in the concrete and bamboo modulus

However, to keep the stresses in the concrete to acceptable levels, the supporting layer beneath the concrete is of vital importance. The tensile stress in the concrete depends very strongly on the modulus of the supporting layer; this is why a good sub-base is required. The rule of thumb for calculating the tensile strength of concrete is that it is between 0.4 and 0.7 times compressive strength. This gives a very wide range (1.7 – 4.2 MPa, typically) and is really not much use for calculation purposes. However, it does indicate that a sub-base of elastic modulus greater than 100MPa is normally required. The tensile strength of the concrete from the Puok trials has been measured and found to be an average of about 3.7 MN/m^2 but this is after five or more years. A reasonable estimate of its value at 28 days is difficult to obtain accurately but is likely to be at least 3.0 MN/m^2.

Shrinkage Cracking

It has been suggested that the introduction of bamboo reinforcement may prevent or control shrinkage cracking as the concrete cures. Using the eventual (long-term) values of the elastic and the strength properties of concrete and bamboo, it is clear from the foregoing that this cannot occur. However, the curing process is very complex. Initially the elastic modulus of the concrete and its strength will be very low (i.e. much less than that of the bamboo). As the concrete cures, both its elastic modulus and its tensile strength increase, but not necessarily at the same rate. At the same time, the concrete begins to bond with the bamboo and shrinkage stresses also begin to develop in the concrete matrix. Thus a great deal is going on, all at different rates and dependent on different factors. It may be that, at the point when the concrete would normally crack, the modulus and strength of the concrete compared with bamboo are such that true reinforcement does occur and cracking is prevented or, at least, controlled, as it would be if steel reinforcement is used.

With no reinforcing, a concrete slab is expected to suffer shrinkage cracks if it is longer than about 4.5m. The exact figure depends, of course, on many variables but the practical size of an unreinforced pavement slab is usually between 3.5 and 4.5m. There is also a safety factor associated with this so, undoubtedly, longer slabs can be manufactured that may not suffer shrinkage cracking. The process is too complicated to calculate accurately but it can be tested by experiment. Indeed, this was one of the main purposes of the experiments that were carried out at Chiang Mai University in the mid-1980s. The results showed that slabs as long as 6.0m could be made without shrinkage cracking occurring and therefore indicated that some reinforcing effect may have been taking place during curing of the concrete, but the effect was small (A Thongchai, 2007).

The control of shrinkage cracks in continuously-laid unreinforced concrete slabs by inducing the cracks at preset intervals is a very well known and relatively easy technique (introducing dowels for load transfer is, however, more difficult). For local resource-based construction, concrete slabs are automatically made with the correct dimensions without the need to induce cracks. Therefore the slight benefit that arises by increasing the slab length from, say, 4.0m to 6.0m (i.e. reducing the number of joints) seems to be outweighed by the complexity of adding bamboo reinforcement to achieve this. Furthermore the experiments at Chiang Mai University were not sufficiently comprehensive to be certain that a 6.0m slab would be satisfactory in all likely situations. Indeed, this was one reason why the results were not published more widely at that time. The public works authority in Thailand adopted bamboo reinforcement for use in LVRRs but did not adopt the 6.0m slab, reverting to the traditional 4.5m slab in their designs. The reason that reinforcement was used at all for such roads appears to be because the underlying existing road or track was not being fully reconstructed, reshaped and re-compacted. Thus, despite a sand levelling layer, the expectation was that the support for the concrete would not be uniform and that some cracking would occur. It was therefore important to minimise the adverse effects of such cracking as discussed in the following section. Under different circumstances, the arguments above, and practices in other countries, imply that reinforcement is not normally necessary.

Belts and Braces

The way that reinforcement *will* affect behaviour is if the concrete slab does crack for any reason (e.g. severe overloading, partial loss of underlying support caused by erosion, pumping, subgrade volume changes, etc). Without a connection between the two parts of the cracked slab, differential vertical movement of the two parts of the slab occurs, especially if there is poor support from the sub-base layer and interlock across the crack is lost. Thus, under these conditions, reinforcement will hold a cracked slab together and allow it to carry traffic for considerably longer. This is a belt and braces approach. Bamboo, however, will not fulfil this function for very long because it is then exposed to water and attack by insects and will surely decay quickly. If steel is used, the eventual disadvantage is the added difficulty in the future of reconstructing a pavement which contains strong reinforcement.

The literature also mentions the problem of thermal cracks caused by the shrinkage and expansion of the concrete slab as a result of temperature changes. The friction between the supporting layer and the slab itself is an important element of this and in some designs a layer with low friction is introduced to prevent such cracking. However, the temperature changes that occur in Cambodia are small and this form of cracking is unlikely.

Samples Extracted from the Puok Market Road

Inspection of the road after six years indicated no serious cracking had occurred. Blocks of the BRC road at Puok market, suitable for strength testing in the laboratory, were cut from the trial road using a pavement saw. Cuts were made in such a way that blocks were extracted with and without bamboo running longitudinally down the centre of the specimen, one of the intentions being to compare the strength of the two to determine the effectiveness of the reinforcement. However, much of the bamboo was found to have disintegrated, as shown in the following photographs.

Beams cut from the road at Puok showing bamboo

The condition of the bamboo after six years within a cut block (No 3)

The condition of the bamboo after extraction from crushed block (No 3)

The flexural strength of the concrete was tested using 3-point bending (now called the centre-point loading method) (BS EN 12390-5:2000).and the results summarised in Table 4. The compressive strength was also measured on 100mm cubes.

Table 4 Strength of the concrete samples from Puok market trial road

Block Sample Identifier	**Condition of bamboo**	Flexural Strength MN/m2	Compressive Strength MN/m2
01	Fair	3.01	36.3
03	Rotten	3.94	40.5
04	None present	3.16	48.0
05	None present	3.60	51.2
06	Fair	4.77	43.6
07	Rotten	3.94	27.3
08	Rotten	3.25	28.5
	Mean	**3.67**	**39.3**

The sample size was too small and the standard deviation too large to detect any statistically significant effect on the *flexural* strength of the concrete caused by the presence or absence of bamboo or the condition of the bamboo.

However, and in contrast, the *compressive* strength of the concrete which contained no bamboo appears to be significantly higher than that of the concrete containing bamboo. Nevertheless the compressive strengths are high and should not be a problem.

Conclusions

It is concluded that bamboo reinforcement in pavement slabs fulfils no useful purpose. There are three main reasons,

1. Bamboo cannot prevent load induced cracking in the concrete because its modulus is too low for it to reduce the tensile stresses that might cause cracking.
2. Because of the low modulus, bamboo is unable to keep any cracks that do develop in the concrete from opening more widely than is acceptable. Wide cracks allow access to the bamboo for water, fungi and insects, leading to rotting and disintegration of the bamboo.
3. Pavement quality concrete with properly constructed shrinkage joints and appropriate curing techniques should only crack at the controlled joints. But, in any case, for the same reasons that bamboo cannot prevent load associated cracking, neither can it prevent shrinkage cracking.

These three conclusions are sufficient to show that bamboo reinforcement in concrete pavements is not a viable engineering solution. But there are two more conclusions that should also be considered.

4. Even if the modulus of bamboo were high enough, doubts about the allowable stress that bamboo can carry means that the percentage of bamboo in the structure needs to be higher than in the Puok trials if it is to withstand the types of load stress experienced in a pavement.
5. The deterioration of the bamboo within the concrete appears to be quite rapid. Methods of improving this are relatively expensive and unlikely to be sufficiently cost effective in a road pavement.

Fortunately, as a consequence of point 3 above, reinforcement is not necessary in pavements designed for low levels of traffic. Furthermore, the use of any reinforcement (steel reinforcement, for example) is normally not recommended for such pavements, presumably because it is not cost effective even though small reductions in slab thickness (below the normal minimum of 150 mm) are theoretically possible.

However, there is one proviso; concrete is brittle and therefore it can be cracked by a single excessive load. Calculating the critical load accurately is not straightforward but it is relatively easy to apply suitable safety factors to derive a practicable value. This is usually done by assuming that the allowable stress is 50% of the strength obtained in the modulus of rupture test. However, except in exceptional circumstances, the pavement designer will not need to make use of this provided that the quality of the concrete meets normal specifications and the common minimum thickness of slab of 150mm is used. Nevertheless, preventing excessively heavy vehicles from using lightly designed rural roads in developing countries is a problem in all countries and for all types of road and efforts to do so should continue.

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SEACAP 19

Teaching Modules

M2: A Review of Engineered Natural Road Surface Roads

INTRODUCTION TO SOME BASIC CONCEPTS

A road surface must withstand the loads imposed by traffic and the effects of climate, principally rain (precipitation) but possibly including the effects of the level of the water table and flooding. The ability of a soil to support traffic can be related to the shear strength of the soil and this, in turn, is traditionally related by road engineers to the **California Bearing Ratio** (CBR) of the soil, which depends on the soil itself, its level of compaction and the moisture conditions.

Many soils will not be strong enough to support even moderate levels of traffic when they are too wet, it is necessary to define the level of access that we require of a road fairly carefully. In practice it has been quite difficult to define the **'passability'** of a road in a clear and unambiguous way. Table.1 provides an accepted set of characteristics which define **basic access**. This is the highest level of service likely to be achieved by means of an Engineered Natural Surface Roads (ENSR).

The choice of **standard vehicle** depends on the use of the road and is normally the common vehicle that makes the most demands on the road in terms of engineering standard. For example, a standard vehicle for a road carrying considerable agricultural produce might be a 3-tonne truck, but a pick up or even a motor tricycle might be the standard vehicle for a road where heavier vehicles are rare.

The **standard speed** is <u>not</u> used to define the speed that the standard vehicle can travel along the road but the speed at which the standard vehicle travels through the **critical sites** along the road. For most ENSRs there will be places where an ENS is not good enough and therefore localised improvements will be required. These are often first identified where the standard speed becomes too low.

Table.1 Definitions of basic access service levels for ENSRs

		Criteria
A road provides basic access if all of these criteria are met.	A	The *standard vehicle* can pass all year round except for a period of up to 24 hours following rain
	B	The *standard vehicle* does not need to travel slower than the *standard speed*
	C	The *standard vehicle* can pass safely without risk of injury to the driver, passengers and other road users
	D	The *standard vehicle* can pass without being damaged and without damaging its cargo beyond normal wear and tear
	E	The *standard vehicle* can pass without damaging the road beyond normal wear and tear, even when it is raining
	F	It is unlikely that the road will deteriorate at a rate in excess of a predefined standard

From TRL (2006) *Spot Improvement Manual for Basic Access*

BEHAVIOUR OF ENGINEERED NATURAL SURFACES

General

The deterioration of ENSRs is governed by the combined actions of traffic and the environment and, most of the time; it is at the surface itself that deterioration occurs. However, although by definition a length of road comprises only one type of material, the surfacing may be relatively dry and strong for much of the time whereas the underlying material may be wetter, less compacted, and consequently weaker. If this weaker material is too close to the surface it may be at risk of failure. For example, this can occur if the embankment height in low lying areas is inadequate. Under these circumstances it may sometimes be necessary to consider the pavement as a layered structure in much the same way as is done for normal multilayered pavements and to consider likely failures at depth, but under most circumstances this will not be necessary.

The surface of an ENSR is usually permeable although, in some cases, the permeability may be very low; thus material properties, rainfall, and surface drainage influence the behaviour of the surfacing itself. On the other hand, surface water run-off and side drainage usually affect the moisture penetration into the underlying layer (roadbed) and thus it's bearing capacity.

There are three principal mechanisms of deterioration namely:

(i) Deformation of the surface (and possibly the roadbed material) under the stresses induced by traffic loading.

(ii) Wear and abrasion of the surface material under traffic.

(iii) Erosion of the surface by traffic, water and wind.

The modes of deterioration in dry weather and in wet weather are different. Dry weather deterioration.

Dry Weather

Under dry weather conditions, the most prominent deterioration mechanisms are:

(i) Wear and abrasion of the surface material (thereby generating loose material and promoting ruts).

(ii) Loss of the surfacing material as dust and through 'whip off' by traffic.

(iii) Movement of loose material under traffic action to form corrugations.

These mechanisms result in roughness and material loss, with the rates of deterioration being primarily a function of the properties of the surfacing material and traffic.

Wet Weather

Under wet weather conditions the shear strength of the materials determines the pattern of deterioration. When the shear strengths of the surfacing and roadbed materials are adequate for the stresses induced by traffic, deterioration occurs only at the surface. The major modes of deterioration under these conditions are:

(i) Environmental and traffic influences on surface erosion.

(ii) Wear and abrasion of the surface by traffic causing rutting and loss of the surfacing material.

(iii) Formation of potholes under traffic action. Free water on the surface accumulates in any depressions. The passage of a vehicle tyre stirs up the water causing fine material to pass into suspension. Water, with the suspended fine material, is also forced out of the depression. Under the action of many wheel passages and sufficient water, this is a rapidly accelerating phenomenon.

When the surfacing layer has inadequate shear strength to sustain the stresses applied by traffic loadings, shear failure and deformation occur. The road surface will be soft and even slushy under wet conditions so that, while it may be possible for a few light vehicles to pass, the road will become impassable after a relatively small number of vehicle passages. Traditionally, index tests such as the California Bearing Ratio (CBR) have been used in road engineering to identify materials that resist shear failures, but material properties such as plasticity and fineness, also influence the behaviour under these conditions. More fundamentally, the mineralogy and structure of a material are also likely to have an influence in some soil groups. There are some materials, principally fine-grained with very low wet shear strength, for which loss of wheel traction is a primary cause of impassability rather than pavement deterioration.

Required Characteristics

The ideal ENS will therefore have the following characteristics. It will be:

- strong - to support traffic,
- impermeable - to shed water quickly,
- erosion resistant (by having a suitable particle size distribution)
- smooth - so that the ride quality will be good,
- durable - so that these qualities last a long time,
- easy to maintain.

Many of these characteristics are conflicting. For example, a coarse soil with a relatively large maximum particle size may be strong and will resist erosion but the ride quality may be poor and carrying out maintenance may be relatively difficult. It is useful to discuss all the conflicting requirements of an ENS to help define the kind of soils that are likely to be acceptable.

In Cambodia it is thought that some soils will have an acceptable mixture of properties, but this is not guaranteed. Furthermore it is not expected that such a soil will form a suitable surface for the complete length of a road. Some sections, for example, on gradients or water crossing points, will need more robust surfacings. This is the principle of ‘spot’ design whereby the optimum choice of design is based not on the properties of the whole road but on an assessment of the properties and individual design of separate but uniform sections within it.

BEARING CAPACITY

Strength of soil

In Cambodia soils are likely to become wet throughout a sizeable proportion of the year, thus the behaviour of a soil in a wet or a saturated state is an important factor for determining the likely service level of the road.

The US Army carried out a great deal of research into problem of wet strength and much of the knowledge concerning the relationship between soil strength, wheel loads, tyre pressures, and traffic carrying potential of soils derives from this research. Unfortunately most of it was carried out a relatively long time ago (from 1947 to circa 1975) and it is therefore often overlooked. A short paper by Ahlvin and Hammitt (1976) has summarised much of this work and is the basis for the following calculations (Figure 1) showing the relationships between soil strength, tyre pressure, axle load and vehicle passages for a failure **rut depth of 75 mm**. Although this rut depth is not excessive, surface run off is severely impeded and deterioration progresses rapidly hereafter if rain occurs.

Figure shows the relative small effect of axle or wheel load compared with tyre pressure and the very sharp rise in traffic carrying capacity as soil CBR increases. To put the data into perspective, if we assume that in Cambodia the rainy season lasts for 5 months then the number of wet days per year will be about 150. It is only in the wet season that the soil is weak and we assume that in the dry season bearing capacity is not a problem. Thus 25,000 passages represents the equivalent of 167 vehicles per day for 1 year, 83 vpd for 2 years, 56 vpd for 3 years, 42 vpd for 4 years , 33 vpd for 5 years and so on. These are realistic or even conservative estimates of traffic considering that the standard vehicle being considered has an axle load of 80 KN and a tyre pressure of 75 psi (0.52 MN/m^2) - it is typically a 10-tonne truck. In addition, the road will also carry many more lighter vehicles.

Figure shows a critical CBR of about 13% for this **standard 10-tonne vehicle**; at this point the traffic carrying potential of the road is increasing very quickly as CBR increases. The importance of tyre pressure rather than wheel load is illustrated by the right hand curve in the Figure. If the tyre pressure is increased to 0.69 MN/m^2, then the critical CBR increases to about 18%. This is a considerable increase. In terms of shear strength it is approximately an increase from 400 to 550 KPa, equivalent in soil mechanics terms to a hard clayey soil.

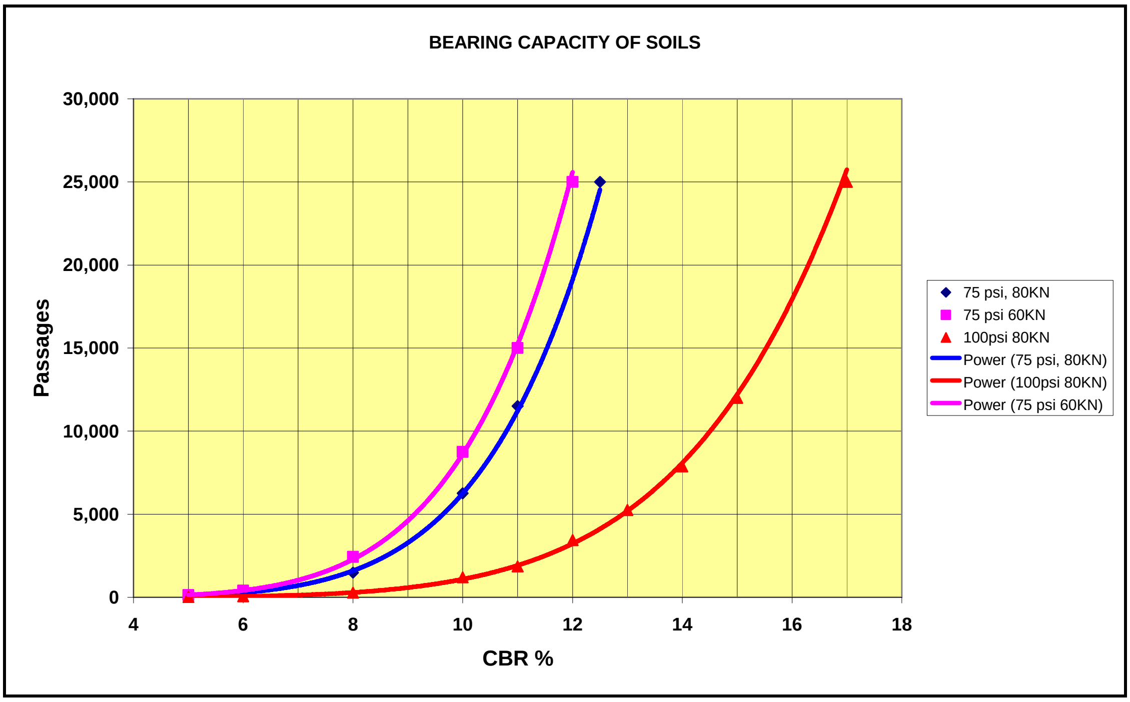


Figure 1   Bearing capacity of soils (from Ahlvin and Hammitt, 1976)

It should be noted that roads with surfacings of these strengths will be capable of carrying far more vehicles with lower tyre pressures, many hundreds per day in fact. However, non-pneumatic or solid wheels may impose higher stresses because of their small contact area. In some places this is a potentially serious problem.

More recent empirical studies by Visser (1981) also showed that the soaked CBR of the surfacing material was a reliable indicator of passability. The criterion proposed by Visser for ensuring that a road remains passable during a wet season (providing that there is no flooding) is:

$$SFCBR > 8.25 + 3.75 \log_{10}(ADT)$$

where,

SFCBR = soaked CBR at standard AASHTO compaction (%)

ADT = average daily traffic in both directions, in vehicles per day.

Thus if SFCBR exceeds this value, the road should remain passable all through a rainy season. Visser's experiments took place on normal roads under typical traffic conditions and so the effects of tyre pressure and wheel loads could not be measured separately. The average daily traffic on the test roads contained differing numbers of trucks and a variety of axle loads and tyre pressures. However, if we assume that 10% of the vehicles were trucks and that they were almost certainly overloaded, we can draw a rather approximate comparison with the US Army data. With these assumptions, an ADT of 400 is equivalent to about 40 trucks and the Visser criterion (equation above) suggests that SFCBR must exceed about 18%. This is similar to the criterion derived above from the US Army data for trucks with a degree of overload (e.g. tyre pressures of 100 psi). This agreement is encouraging.

The degree of saturation that occurs during a typical rainy day in the wet season depends on the permeability of the soil, the camber or slope of the road and the opportunities for evaporation and drying. Low permeability is associated with fine-grained soils which tend to have higher plasticity and to be relatively weak when wet so the ideal soil will be a compromise between low permeability (low wet strength) and high wet strength (high permeability). It is worth noting as an example that a good quality, true laterite gravel will generally meet this compromise objective.

There is one interesting aspect of this trade-off. Many relatively impermeable soils are extremely slippery when wet. Thus, although they are very weak when wet, the weak layer is very thin (because the permeability is low) and the slipperiness ensures that traffic cannot actually travel on them until they have dried sufficiently. They are therefore 'self-protecting' and generally have good performance in terms of a low deterioration rate. Note that the criteria discussed above do not explicitly take this into account.

Other soil characteristics influencing bearing capacity

Studies of the performance of unpaved roads have often focussed on the effects of particle size distribution (PSD) and plasticity rather than the basic strength of the soil. This is because the strength depends on compaction level and current moisture content, both of which are always changing and hence difficult to measure or quantify adequately, whereas it was thought that particle size distribution and plasticity were relative constants.

Thus, in principle, models could be developed relating the performance of a variety of surfacing, each with different values of these and other 'constant' parameters such as gradient and width, to the independent variables of traffic and rainfall, variables that could be measured relatively easily. Such models would be capable of taking into account the deterioration caused by environment as well as traffic because, for example, erosion effects will also depend on PSD, plasticity, rainfall, road geometry and so on.

Clearly soil strength is also highly correlated with PSD and plasticity but it is difficult to compare the two approaches unless ALL the required data have been collected for the test sites so that strength can also be related to the other variables. To our knowledge this has not been done for roads in environments similar to those in SE Asia.

Tropical Soils

One significant issue with regard to understanding the behaviour of soils in SEA is that they are likely to have been formed by tropical weathering processes (where chemical alteration is dominant) as opposed to the more traditional soils from European and similar climates where physical weathering is more dominant in soil formation.

In the field of geodetics it is now recognised that many of the traditional empirical relationships derived for classifying soil may not hold true for tropical soils and that great care has to be taken in the use of traditional soil testing and interpretation (GSL, 2000). The influence of mineralogy together with soil structure and its destruction have a more widespread influence on the behaviour of tropical soils than on that of temperate soils. With respect to the more robust gravelly materials normally associated with pavement construction, this contrast in behaviour is not generally relevant; however, weaker, non-standard soils used in ENSRs may well be outside the envelope of established pavement engineering assumptions on material behaviour.

The above concept can be briefly illustrated by two examples. Firstly, there is an assumed relationship between Linear Shrinkage (LS) and Plasticity (Ip) , where Ip = 2.13 x LS. Table shows variations in this relation for tropical soils of different mineralogy along a single road alignment. Secondly, the influence of fabric and the effect of total destructuring and wetting up is shown in Figure.2, where moisture content is plotted against shear strength for both slurried and normally remoulded materials.

Table 2 Plasticity-Linear Shrinkage for Some Tropical Soils (West Java Toll Road)

Material	Mineralogy	Average Ip	Average Ip/LS	No of samples
Tropically weathered silty mudstone	Kaolinite; Smectite	44	3.06	13
Tropically weathered mudstone	Smectite dominant	59	5.18	26
Tropically weathered volcanic ash	Kaolinite-Halloysite	36	1.59	120

Source: (Cook, 1997)

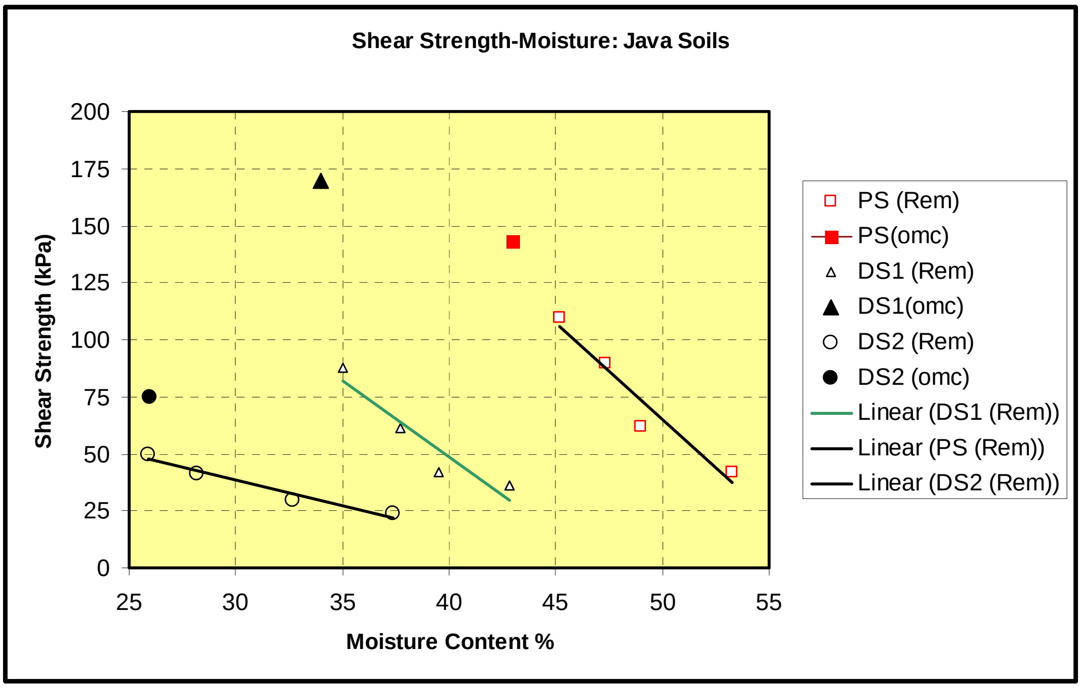


Figure.2 Effect of moisture content on shear strength (Cook, 1997)

D: Poorly structured volcanic soil   S1: Distinctly structured volcanic soil

S1: Distinctly structured residual mudrock soil

(Rem): Completely destructured condition   (omc) Remoulded only by compaction

The distinctly structured soils (DS1 and DS2) indicate a change in strength behaviour between normally remoulded and totally destructured conditions, whilst the poorly structured soil (PS) does not.

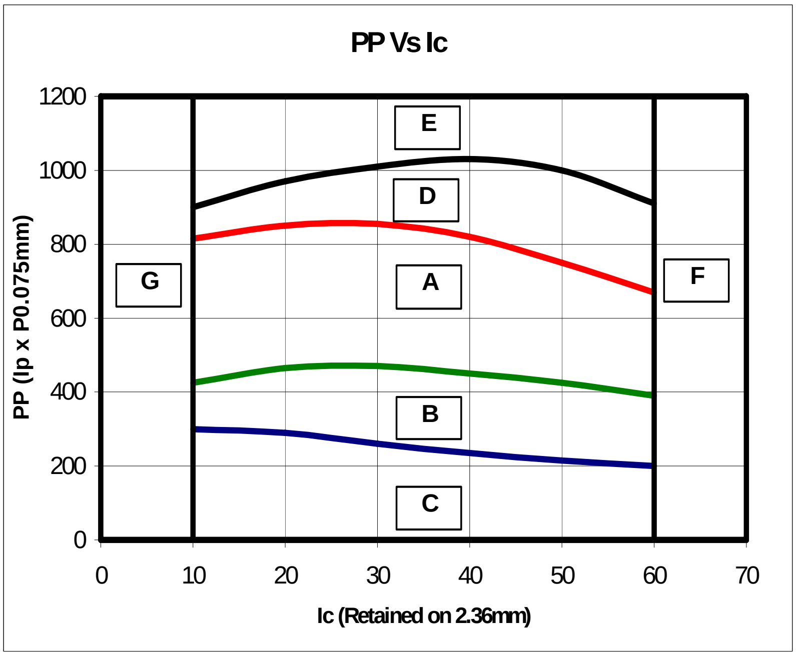
The concept of varying levels of disturbance behaviour is important when considering sample test condition (i.e. normally remoulded) as against total destructuring as is likely to happen under wheel-spin conditions on an earth road. Some structured soils for example, even when normally remoulded, retain a residual fabric which, on destructuring, can release previously held water and further weaken the material; hence the commonly observed slurrying of material under the spinning wheels of a stuck vehicle; as modelled by soils DS1 and DS2 in Figure 2 .

In summary, care needs to taken in using standard behaviour assumptions based on "traditional" soils when dealing with tropically weathered soils such as, for example, latosols (lateritic red clays)..

DETERIORATION TRENDS

General trends with PSD and plasticity

The chart shown as Figure 3 illustrates the general trends that occur as the PSD and plasticity characteristics of soils are changed. The chart was developed primarily for gravels but the area on the left of the diagram covers the finer-grained materials that include most natural soils. It can be seen that there is considerable scope for such soils to fall into categories A and B, where good performance as road surfaces is expected, although many will also fall into the unsatisfactory categories, particularly category G where particles of sand size and above are largely absent and category C, which comprises silty sands lacking cohesion.



A: Good performance under wet and dry conditions
B Good performance under wet conditions; corrugates in dry conditions
C Lacks cohesion: rapid deterioration with trafiic
D Good in dry conditions; slippery in wet; potholes/erosion
E Poor in both wet and dry conditions
F Too coarse: erodes badly; difficult to maintain
G Too fine; trafficability problems in wet and very dusty when dry

Figure 3 Performance trends with PSD and Plasticity Product

A similar chart based on Shrinkage Product and Grading Coefficient has been developed from extensive research in southern Africa. This chart is shown in Figure 4 P Two versions of the chart exist depending on whether the test methods used are the British Standards or the American ASTM standards (P Paige-Greene, 2007); the chart appropriate to the British Standards is shown. Shrinkage Product is defined as the product of Linear Shrinkage and the percentage of material passing the 0.425 mm sieve (i.e. the fraction of material used for the test itself). The Grading Coefficient is defined as follows,

$$GC = P4.75*(P26.5 - P2.0)/100$$

where P4.75, P26.5, P2.0 are the percentages passing the 4.75, 26.5 and 2.0 mm sieves respectively. Sometimes the 5.0 mm and 28 mm sieves are used instead of the 4.75 and 26.5 mm sieves.

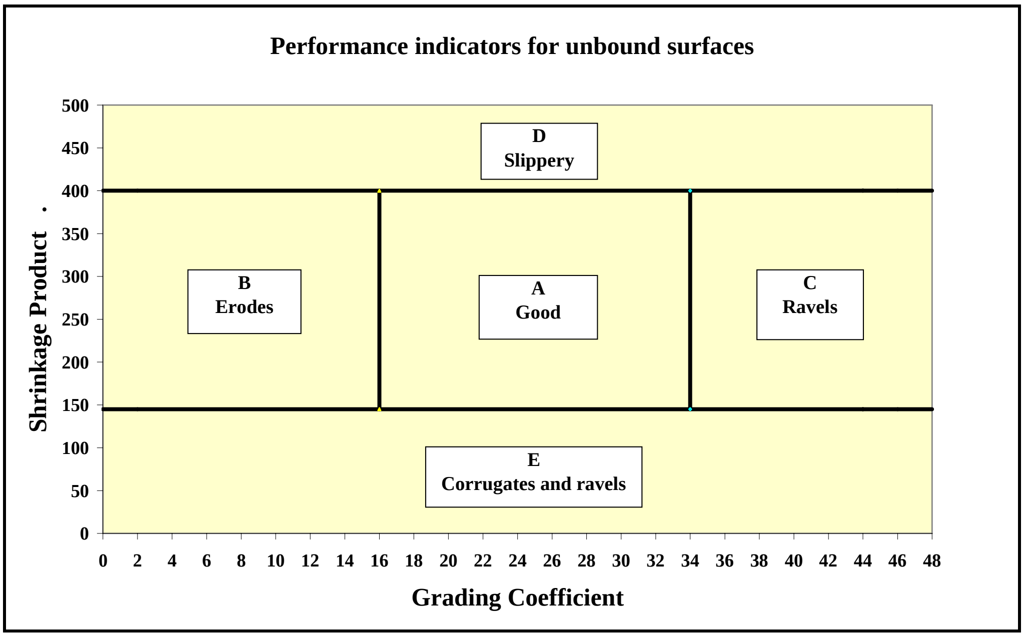


Figure 4 Performance trends with Shrinkage Product and Grading Coefficient (Source: P Paige-Greene, 2007)

These two charts are based on research in drier environments and on largely different (non-tropical) materials to those found in SEA, therefore exact agreement with performance trends observed in Cambodia is not expected. Therefore, although the general trends will be similar, and taking into account the fact that the boundary lines between the different regions of the charts are based on considerable engineering judgement, the differences may be sufficient for new charts specific to Cambodia or S E Asia to be devised.

Erosion

As well as the traffic effects the other major cause of surface deterioration is erosion. Erosion has been studied extensively for agricultural purposes, where soils are loose (uncompacted). Much less data are available concerning engineered surfaces although it is reasonable to expect that the same variables are involved.

Lack of cohesion is associated with an absence or deficiency in the clay fraction. In a gravel material with plenty of medium and coarse gravel sizes present, lack of clay is not so critical because mechanical interlock will help prevent erosion. In fine-grained material, lack of clay means lack of cohesion. Thus materials that are predominantly silt and sand-sized are extremely prone to erosion (category C in Figure 3).

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Predicting deterioration or performance

Although the performances of unpaved roads have been studied extensively, most of the studies have concentrated on gravel-surfaced roads and have tended to focus on the behaviour of roads carrying relatively high levels of traffic. The reason for this is that large economic penalties occur, in whole life cost terms, if high levels of traffic travel on rough surfaces because the cost of operating vehicles on such roads can rise rapidly as roughness increases. Hence it is important to identify the conditions that justify upgrading gravel roads to a sealed surface standard and to determine optimum maintenance policies.

Thus tools such as the HDM III and HDM 4 computer models have been developed to help engineers, economists and planners to make these investment decisions. The best of these models include equations for predicting the performance of unpaved roads based on all the factors that come into play. These include traffic factors, environment factors and material properties as discussed above.

Roughness

The model form adopted in HDM constrains the roughness to a high upper limit, or maximum roughness (RI_{max}), by a convex function in which the rate of increase in roughness decreases linearly with roughness to zero at RI_{max}.

From the results of the Brazil UNDP study, which led to HDM III (Paterson, 1987), the maximum roughness was found to be a function of material properties and road geometry, and the rate of roughness progression to be a function of the roughness, maximum roughness, time, light and heavy vehicle passes and material properties. The HDM-III roughness progression relationship is given by:

$$RI_{TG2} = RI_{max} – b\,[RI_{max} – RI_{TG1}]$$

where,

RI_{max}	=	$\max\{[21.5 – 32.4(0.5 - MDR)^2 + 0.017(HC) – 0.764(RF)(MMP/1000)], 11.5\}$
b	=	$\exp[c(TG_2 – TG_1)]$ where $0 < b < 1$
c	=	$\{-0.001[0.461 + 0.0174(ADL) + 0.0114(ADH) - 0.0287(ADT)(MMP/1000)]\}$
and		
RI_{TG1}	=	roughness at time TG1, in m/km IRI
RI_{TG2}	=	roughness at time TG2, in m/km IRI
RI_{max}	=	maximum allowable roughness for specified material, in m/km IRI
TG1, TG2	=	time elapsed since latest grading, in days
ADL	=	average daily light traffic (GVW < 3500kg) in both directions, in vpd
ADH	=	average daily heavy traffic (GVW ≥ 3500kg) in both directions, in vpd
ADT	=	average daily vehicular traffic in both directions, in veh/day
MMP	=	mean monthly precipitation, in mm/month
HC	=	average horizontal curvature of the road, in deg/km
RF	=	average rise plus fall of the road, in m/km
MDR	=	material gradation dust ratio:
	=	P075 / P425 if P425 > 0
	=	1 if P425 = 0
P425	=	amount of material passing the 0.425 mm sieve, in per cent by mass

P075 = amount of material passing the 0.075 mm sieve, in per cent by mass

Figure illustrates the predicted increase in roughness with time for roads carrying different levels of traffic. In this example the input variables are as follows,

RI_{TG1}	=	5 m/km IRI
ADH	=	10% x ADL in vpd
ADT	=	ADH + ADL in vpd
MMP	=	150 mm/month
HC	=	180 deg/km
RF	=	50 m/km

The models can be calibrated for local conditions but it is unlikely that they will be able to discriminate between the performances of the different soils with sufficient precision for the purposes of ENSRs. This is because the models contain too few parameters. For example, the only material factor in the roughness performance models is the ratio P075/P425 where P075 and P425 are the percentages of material passing the 0.075 and the 0.425mm sieves. The effect of changing this from 0.5 to 0.75 (i.e. more fine material) is to increase the rate of deterioration slightly as shown in Figure

Thus if the critical level of roughness is defined as, say, 14 IRI, the time to reach this value decreases from 3.5 years to 2.5 years (in this example). The optimum performance occurs when the P075/P425 ratio is equal to 0.5. This broadly agrees with Figure 3 , corresponding reasonably well to the area labelled A if it is assumed that the P075 material has a moderate plasticity to provide cohesion. Nevertheless, the P075/P425 ratio alone is generally inadequate to explain all the effects of PSD and plasticity hence the power of the model to discriminate between materials is limited.

However, the HDM equations also provide insight into the effect of road gradient on deterioration.

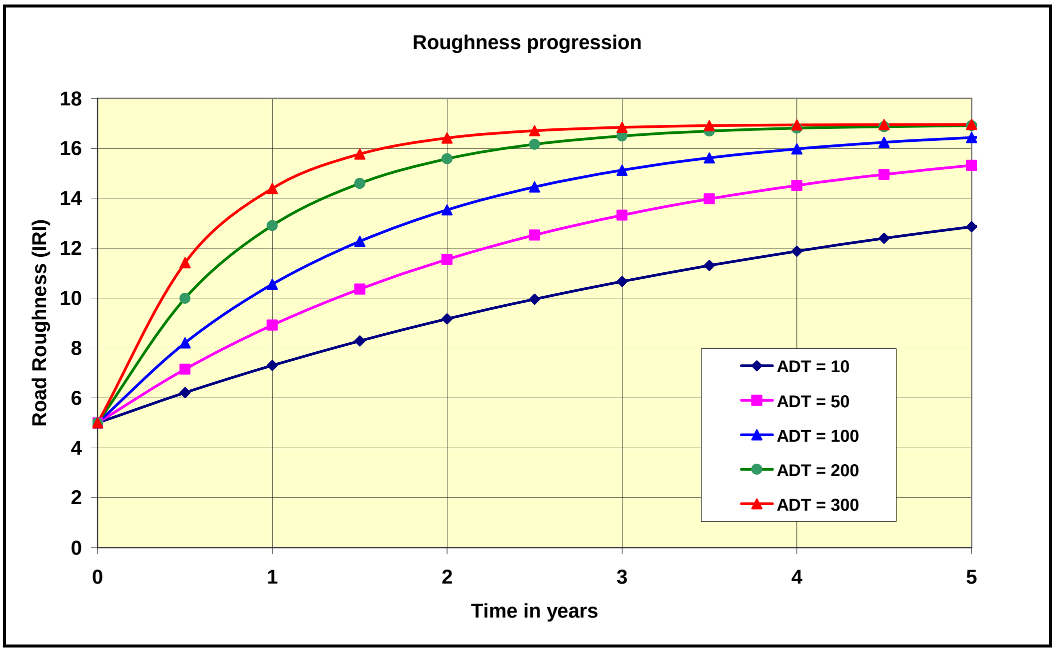

Figure 5 Roughness deterioration with time

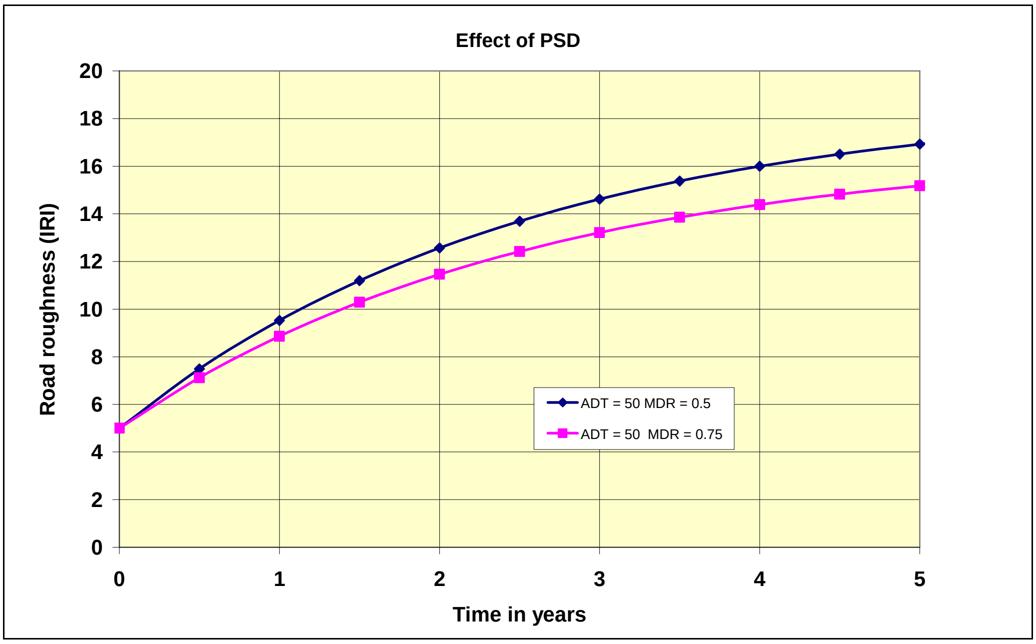

Figure 6 The effect of changing the PSD

The effect of compaction at the surface of the ENSR on the rate of deterioration is considerable. It should be noted that the unsealed road models in HDM were based on the behaviour of gravel roads which were maintained by grading but with no associated compaction. The process of grading loosens the material and hence relatively high rates of deterioration occur compared with the rates that would be obtained if the surfacing is also re-compacted at each grading operation.

In our case, modelling the performance from 'newly constructed' (when compaction would have been carried out), but with no subsequent maintenance grading operations, is equivalent to having a compacted surfacing and so the rate of deterioration will be initially lower than shown in the Figures above. Figure shows the predictions of HDM 4 for the same conditions as in Figure 5 but with a well-compacted surface. The lower rate of initial deterioration is apparent.

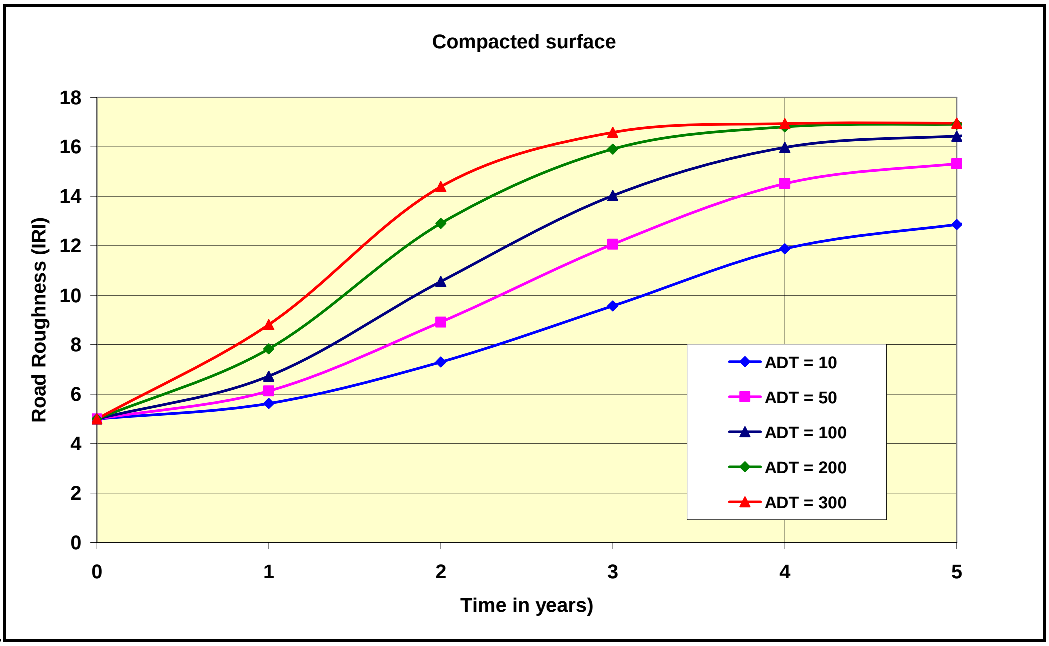

Figure 7 Roughness deterioration with compacted surface

Corrugations

Under some circumstances unpaved roads are prone to the phenomenon of corrugations. Material in the surfacing moves longitudinally to form waves of about 1 to 1.5 metres wavelength and up to 50mm amplitude. The materials that are prone to corrugations have PSDs within quite a broad range but corrugations form only under dry conditions and require moderate traffic levels. Corrugations are unlikely to be a major issue in the behaviour assessment of Cambodian low volume ENSRs.

Loss of surfacing material

The loss of material from the surface of a *gravel* road is a major concern and usually dictates the maintenance and upgrading strategy. In the HDM models the loss of surface material is caused primarily by the action of traffic. The models for predicting this in HDM include the plasticity of the material as the only explanatory *material* variable. However, rainfall and geometry are also important. The equations are as follows;

$$MLA = K_{gl}\ 3.65[3.46 + 0.246(MMP/1000)(RF) + (KT)(AADT)]$$

where,

$$KT = K_{kt} \max [0,\ 0.022 + 0.969(HC/57300) + 0.00342(MMP/1000)(P075) - 0.0092(MMP/1000)(PI) – 0.101(MMP/1000)]$$

and

MLA	=	annual material loss, in mm/year
KT	=	traffic-induced material whip-off coefficient
AADT	=	annual average daily traffic, in veh/day
MMP	=	mean monthly precipitation, in mm/month
RF	=	average rise plus fall of the road, in m/km
HC	=	average horizontal curvature of the road, in deg/km
PI	=	plasticity index of the material, in per cent
K_{gl}	=	calibration factor for material loss
K_{kt}	=	calibration factor for traffic-induced material whip-off coefficient

As an example Figure shows that, in hilly terrain, as rainfall increases from 100 to 200mm/month, the loss of material loss increases by 10 - 15 mm/year. The effect of increasing the traffic by about 150 vpd gives a similar increase in material loss. In rolling terrain rainfall has less effect, material loss increasing by about 5 - 7 mm/year as rainfall increases from 100 to 200 mm/month. In flat terrain the effect of rainfall is predicted to be even less.

For a much finer and more plastic material the trends are similar to those for the coarser, non-plastic material but, perhaps surprising, the magnitude of the loss of material is only slightly greater.

In general, the data were not derived from roads carrying a large number of motorcycles, motorcycle trailers and bicycles. For such roads the models are not expected to give accurate values but the trends with each variable ought to be similar.

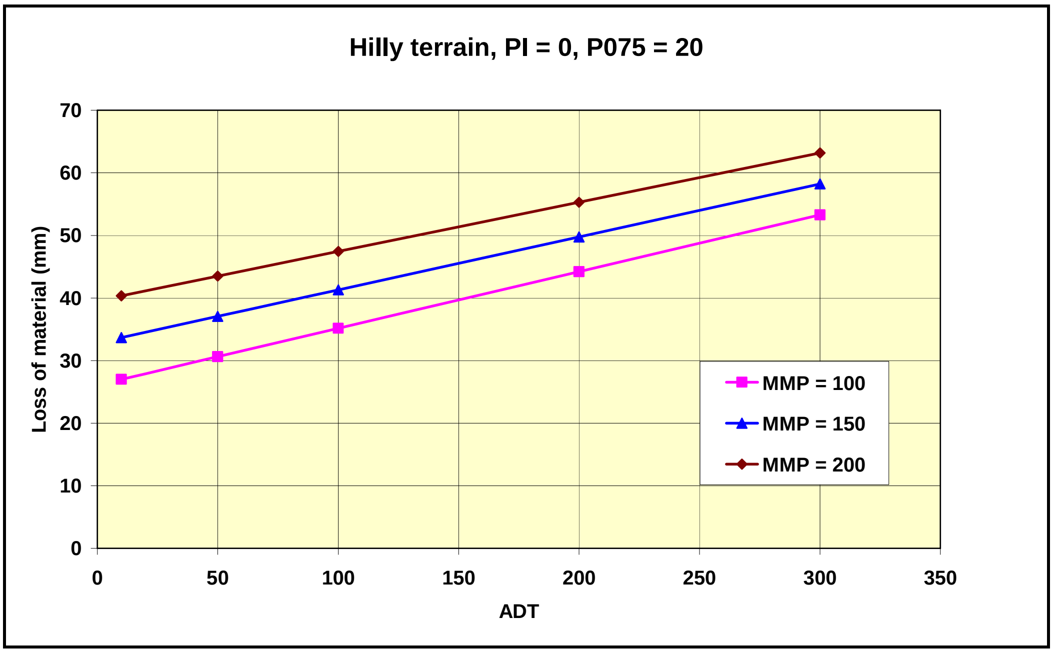

Figure 8 Loss of material (PI = 0, P075 = 20%) in hilly terrain

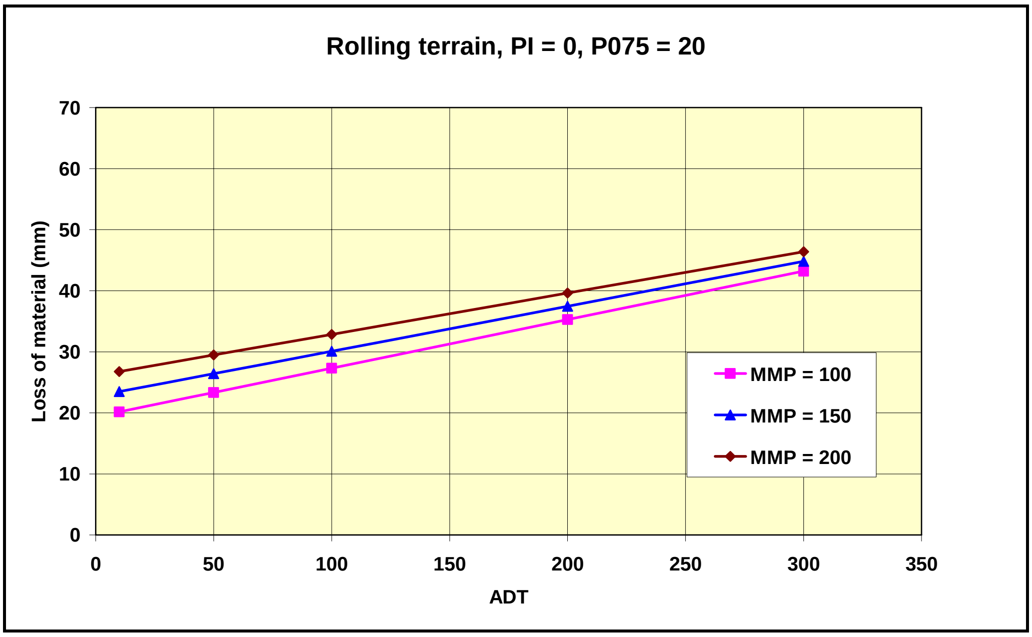

Figure 9 Loss of material (PI = 0, P075 = 20%) in rolling terrain

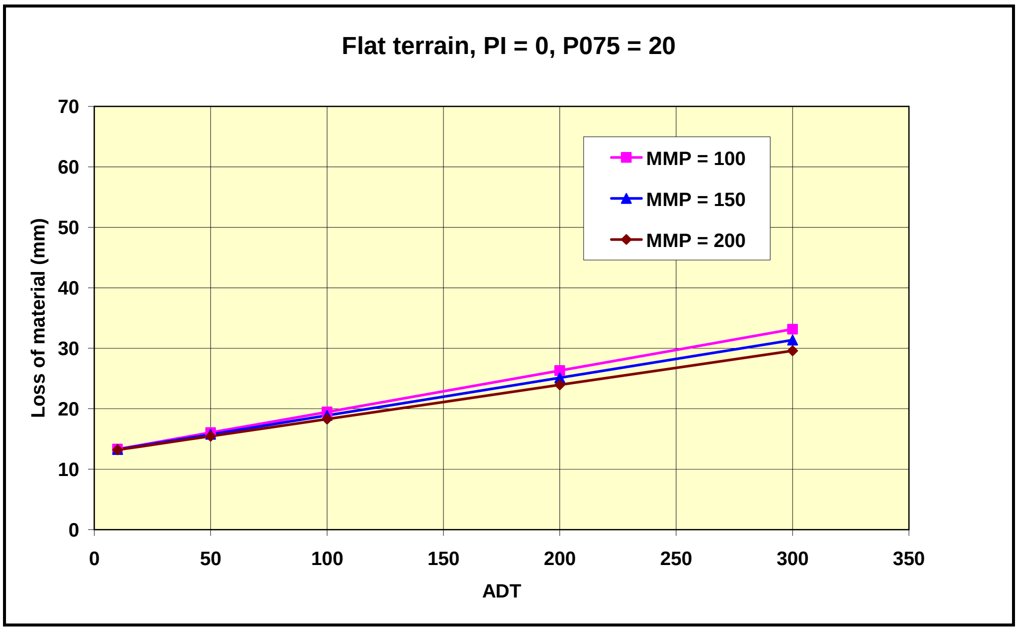

Figure 10 Loss of material (PI = 0, P075 = 20%) in flat terrain

Experiences in Vietnam (SEACAP 4) have shown that rates of gravel loss can be considerably higher than predicted by HDM 4 and were generally related to such factors as high rainfall, flooding, material type and terrain rather than predominantly to traffic. There are several probable reasons for this. First of all the HDM equations are based on empirical evidence from more moderate climates and less severe topography where erosion effects were much less important than the traffic effects caused by generally heavier traffic than that which runs on LVRRs in S E Asia. Secondly, inadequate maintenance was also identified as a factor in the SEACAP 4 study and contrasts with active road maintenance on many of the roads whose performances are described by the HDM4 relationships. Models for predicting the gravel loss from the sites in Vietnam remain to be developed from the SEACAP 4 database, although general regional gravel loss figures have been derived for whole life costing purposes, Table (Cook and Petts, 2004)

For ENSRs it is assumed that loss of any surface material can also be high although it is doubtful whether these losses can be predicted using the 'gravel' equations in HDM. Furthermore the effects of erosion are likely to be much greater. For gravel surfaces, the loss of gravel results in the need to import more gravel. Similarly, it is necessary to restore the height of the running surface of ENSRs and to maintain adequate camber using the available material at that location. Failure to do this results in 'sunken' road profiles that begin to act like drainage channels.

Effect of road geometry

Road geometry has a considerable effect on the performance of unsealed roads. Unfortunately much of the research on performance has been based on the behaviour of roads in relatively flat terrain. The reason for this is that it was important to carry out such research first but, partly because of the complexity of the problem, insufficient effort has been devoted to more extreme conditions. Thus the models in HDM may not reflect the conditions in much of S E Asia and the models may be therefore be inadequate.

Table 3 Vietnam Gravel Loss (no maintenance)

Terrain Region	**Low delta/coast. Subject to flood**	**Low delta/coast. Minimal flood**	**Inland flat**	**Rolling small hills**	**Hilly and mountaineous**
Basic Gravel Loss (mm/year)	40	25	30	20	35
Key Regional Factors	Poor quality material	Poor quality material	Poor quality material	Gradient	Sheet erosion See Note
Adjustment to basic loss for regional factors	Add 15mm/year	Add 5mm/year	Add 10mm/year	2-4% add 5mm/year 4-6% add 10mm/year	A: add 5mm/year B: add 15mm/year C: add 30mm/year

Notes: Sheet erosion definition; A = Gradient < 2% subject to minor sheet flooding

B = Gradient 2-4% subject to regular sheet flooding

C = Gradient > 4% subject to regular sheet flooding

Sheet flooding means that water covers the road surface due to flooding from surrounding ground and not just the rainwater that falls directly on the road surface.

Sector ‘rules of thumb’ recommend that gravel roads are not constructed at longitudinal gradients of more than 6% (e.g. R Millard (1993) *Road making in the tropic: materials and methods*). At higher gradients the longitudinal gradient is substantially steeper than the crossfall and the general direction of the water runoff is along, rather than off, the surface. Any irregularity in the surface can accentuate this effect and the water picks up any loose material to rapidly erode the surface into roughly longitudinal channels. It is likely that more stringent restrictions should be placed on certain combinations of rainfall and gradient for ENSRs in S E Asia pending local research into this issue.

Crossfall is an important feature of the geometry of ENSRs. At below about 2% there is a risk that water will pond locally and pothole development will be initiated. At above about 7%, lateral erosion and the safety and stability of vehicles become issues. The usual recommendation is to construct and maintain unsealed surfaces at between 4 and 6% crossfall.

Loss of traction or slipperiness

Low traction, lack of friction or slipperiness is not specifically associated with deterioration but for ENSRs it is a critical parameter which determines the number of days that a road can be trafficked. Table.1 Definitions of basic access service levels for ENSRs shows the conditions for defining basic access. Condition A is concerned with this but was specifically aimed at the time required for water levels to fall sufficiently for all water crossings to be trafficable. However, in the wet climates of S E Asia there are periods of the year when rainfall can occur so frequently that roads can be too slippery for traffic for much longer periods than 24 hours. Here we are discussing roads with adequate camber and good overall shape; in other words roads that are newly constructed. This behaviour can be associated with inherent characteristics of the road materials which may be related to a combination of mineralogy and fabric. Such roads may not be viable if they are too slippery for too long.

In general, many old roads have deteriorated so much that they lack camber and shape. At this level of deterioration, water ponds for many days in vulnerable places. Such spots deteriorate quickly and the affected area can become impassable. This is a maintenance issue and not directly related to the viability of the basic design unless, of course, such deterioration occurs too quickly after construction because of inadequate materials, too much traffic or some other design fault.

Research has shown that impassability resulting from loss of traction between vehicle wheels and the road on a well-shaped ENSR will occur on all roads whose surfacing comprises predominantly clay material whenever a minimum depth of rain falls onto the surface. This level of rainfall is typically the amount that would fall in an average intensity storm of more than about 30 minutes duration, although the precise impact will be a function of mineralogy, fabric and structure. Thus the number of days each year that such a road will be impassable for some of the time depends simply on the number of days that such a storm occurs. If such storms occur too frequently then there will be insufficient time for the road surface to dry and so the period of impassability will be correspondingly longer.

Experience with an ENSR maintenance programme in East Africa found that within three hours of rain ceasing on a well-cambered lateritic clay soil, the surface was usually drained and dried out sufficiently to bear medium truck traffic. Investigations would be informative relating to the local soils, climate and traffic conditions in Cambodia.

Maps showing contours of equal rain days superimposed on a soil map are helpful in evaluating the potential loss of access for roads in different areas of the country.

Maintenance

The HDM models also concentrate on the effects of grading the unsealed roads to improve roughness and to minimise gravel loss. On the unsealed roads in Cambodia grading is not being considered as a regular maintenance option at the moment. The viability of ENSRs are being considered in terms of the length of their likely durability without periodic maintenance, but the type of maintenance that can be done in the provincial areas will need to be assessed and its effectiveness evaluated during field surveys.

Important issues to be addressed in developing an effective maintenance strategy for ENSRs in the Cambodian environment are:-

- The types of vehicle that require access and their characteristics with respect to road deterioration
- Acceptable interruptions of access through the year (social and economic)
- The types of soil and the rates of deterioration of the key characteristics that affect access
- Suitable maintenance intervention criteria
- The technical options for carrying out the maintenance (including labour and intermediate equipment)
- Organisational options and possible responsibilities for road maintenance
- Resources and funds required for ENSR maintenance
- Acceptable and achievable levels of service

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THE SEACAP 19 FIELD RESEARCH

The Approach

A “slice-in-time” survey procedure was adopted for gathering ENS data. This was a development from the SEACAP 4, Gravel Study procedure used in Vietnam. In this way a reasonably large sample of roads could be studied with the resources available.

In total, 91 sites were surveyed in late 2007; 21 sections in Kampot, 17 sections in Kandal, 35 sections in Ratanakiri and 18 sections in Siem Reap. A second survey was made of 66 of the sections in March/April, 2008. More than 45 factors associated with each site were measured or recorded for use in the performance analysis.

The study adequately quantified the way that the deterioration of the sites in terms of physical damage such as potholes, erosion and rut depth develops with time and with engineering design factors. The mathematical performance models that were derived allow the predicted behaviour of an ENS to be calculated provided that the conditions are similar to the conditions covered in the survey. By defining limiting criteria it was possible to determine the properties of an ENS road that would provide satisfactory performance and to derive specifications.

Performance of ENS roads

The study illustrated the complexity of performance of ENS roads and highlighted the reasons why deriving generally agreed specifications has proved elusive and confirmed the need for locally derived flexible specifications that are relevant to the local materials and the road tasks. Nevertheless the results have been encouraging and have indicated that, with longer term monitoring, the outstanding questions could be resolved.

Despite the size of the survey, there are many materials and conditions that could not be included and it is important to remember that the results of any experimental study are only valid within the range of the variables. For example, all the surfacing materials in the study were finer than 26.5mm maximum particle size. The range of all the variables is summarised in Chapter 3.

Although the effect of some of the factors (and their interactions) that affect performance could not be quantified in the performance models, much of the ‘unexplained’ deterioration was quantified in the ‘age’ term in the models. This term captures all the time dependant deterioration that always occurs and which is usually ascribed to a cumulative traffic variable (e.g. cumulative commercial vehicles or cumulative equivalent standard axles), but it is equally likely to depend also on cumulative rainfall, number of cycles of inundation, or any other time dependant effects or combinations thereof.

Since traffic itself did not prove to be a strong determinant of performance (although age did), the results are only valid where traffic has similar characteristics to those observed in the study. In particular, heavy trucks were largely absent and most motorised vehicles would have had relatively low tyre pressures. This has important implications for design; the designer must be confident that heavy traffic will not use his road, or effective methods must be devised to guard against it.

The study adequately quantified the deterioration of the roads in terms of physical damage such as potholes, erosion and rut depth and therefore limiting values of these could be set for design purposes and suitable specifications developed. However the study was not able to quantify lack of accessibility caused by slipperiness, flooding or any other reason that was not measurable by the survey staff during the survey itself. In other words *quantitive* information that had to be obtained by interviewing local residents or engineers tended to be unreliable (e.g. 'how many days per year is your road impassable?'). Although not ideal, any specifications designed to cope with these problems must be adapted or copied from specifications derived elsewhere.

The study did not address the issue of dustiness and the problems that this causes to local people. In general all soils that contain sufficient fine material will cause dust and this problem gets worse very quickly as vehicle speeds increase and as materials dry out.

Although drainage factors were not as dominant as expected it was concluded that the main reason for this was that they tend to form a critical path comprising, camber, longitudinal slope, ease of run-off, crown height and good side drains. Any one of these could be sufficiently deficient to cause drainage problems and in that case the others would not appear to be significant in a statistical analysis. The study contained examples of each of these individually being the likely cause of problems. However the most significant was the run-off factor. Admittedly this is subjective and was almost certainly influenced by other factors, but it is something that can be corrected relatively inexpensively by local, regular maintenance and, if necessary, spot improvements.

Implications for specifications for LVRR

The models derived from the survey allow the predicted behaviour of an ENS to be calculated provided that the conditions are similar to the conditions covered in the survey. By defining limiting criteria it is possible to determine the properties of an ENS road that would provide satisfactory performance. For example, a reasonable criterion is that a road should remain in a satisfactory condition for 7 years. The criteria for satisfactory performance are as shown in Table 4.

This Table presupposes that there is sufficient maintenance to ensure that the run-off of water remains unimpeded. Under the current maintenance regime for rural roads in Cambodia this is unrealistic and therefore a more relevant assumption is that run-off will be impeded for some of the time, as it was on the roads in this study. In this case Table shows more conservative criteria that should ensure satisfactory performance.

Table 4 Minimum Grading Coefficient when maintenance is adequate

Gradient %	Low rainfall 1000mm/yr	Medium rainfall 2000mm/year	High rainfall 3000mm/year
0 - 4	10	15	20
4 - 6	15	20	25
6 - 8	20	25	30
8 - 10	25	30	35
10+	30	40	NA

Table 5 Minimum Grading Coefficient when maintenance is poor

Gradient %	Low rainfall 1000mm/yr	Medium rainfall 2000mm/year	High rainfall 3000mm/year
0 - 4	25	30	40
4 - 6	30	35	45
6 - 8	35	40	NA
8 - 10	40	NA	NA
10+	NA	NA	NA

Current advice on unsealed roads in the S E Asian region (Intech-TRL, 2006, TRL-LTEC,2008) is that unsealed gravel roads become unsustainable in terms of erosion and gravel loss above 6% gradient. Below this gradient the limiting factor is that rainfall must be below 2000mm per year.

The surface material will also benefit from some plasticity. Changing the Plasticity Product over a practical range does not affect the criteria in these Tables because the maximum range of PP is equivalent to a change in Grading Coefficient of less than 5.

The study has not been able to measure performance criteria based on ‘slipperiness’, however, slipperiness is likely to be a problem if the Plasticity Product exceeds about 550.

The strength of the material was not a significant factor in the performance analysis. Despite the weakness of a considerable number of the soils in the wet season, the nature of the traffic has meant that *serious* traffic-related deterioration has not occurred, although time-related deterioration, which is largely traffic related, is a feature of all the models and accounts for about 40% of the deterioration that occurs.

It would therefore be prudent to include a strength criterion in the specifications. The information in Technical Paper No 2.1, ‘*Behaviour of engineered natural-surfaced roads*’, indicates that a minimum soaked CBR of 15% at 95% of Proctor compaction is more than adequate to cater for the types of vehicles using the surveyed roads However, almost all soils with a Grading Coefficient meeting the specifications described above will exhibit a soaked CBR in excess of 15% (in this study 90% of the soils did so) hence although a strength criterion is recommended, it is primarily a safety precaution.

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