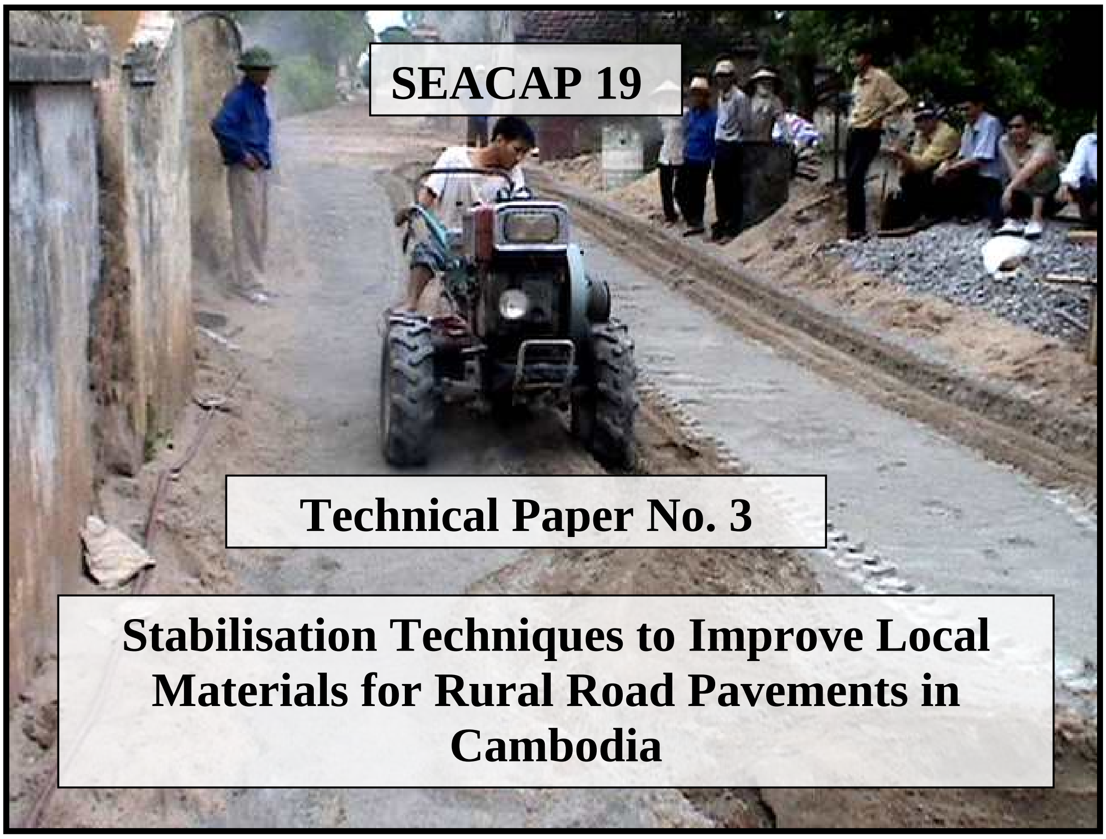
ROYAL GOVERNMENT OF CAMBODIA

SOUTH EAST ASIA COMMUNITY ACCESS PROGRAMME

DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS



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Stabilisation Techniques to Improve Local Materials for Rural Road Pavements in Cambodia

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DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

Stabilisation Techniques to Improve Local Materials for Rural Road Pavements in Cambodia

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Executive Summary

Quality gravels are not readily available throughout Cambodia and are a limited and often low quality resource.

Shortages of materials for road building should cause engineers to consider the stabilisation of those materials available rather than hauling better materials long distances. If suitable materials are available, this can be done most cheaply by mechanical stabilisation which is simply blending two or more materials together to obtain the required engineering properties before using them on the road.

The second alternative is to bind the existing materials together using a hydraulic binder such as cement or lime. The choice of which binder to use depends largely upon the host material. Cement is generally more suitable for soils with a low plasticity, and lime is more suitable for those with a higher plasticity. There is some crossover for those materials with low to medium plasticity where either cement or lime can be used, and sometimes it is suitable to use both either at the same time or in sequence.

Whereas (Portland) cement is only available from large scale industrial production, lime from burning limestone may be produced from small scale industry as well as from large scale production facilities. Small scale production offers livelihood opportunities and the lime produced has a multitude of applications far beyond its use for lime stabilisation of road materials. Agricultural uses for soil improvement is one of the most obvious for Cambodia because one third of the rice growing land is acidic and plants prefer a more neutral environment for abundant growth. Other major uses are as mortars for building works.

There is a concern today about whether or not to promote the use of lime in road construction in Cambodia. There are two reasons for this. Firstly, wood is used to burn the limestone in traditional kilns and this may lead to an unacceptable depletion of reserves. These traditional methods also use up to seven times the fuel used by modern lime kilns. Secondly, the promotion of lime stabilisation in Cambodia without development of a local industry and therefore the use of imported lime is likely to exacerbate the situation elsewhere. In contrast a local industry would benefit the country as a whole.

Expansion of the industry through the development of more efficient local kilns using waste materials or with a connected sustainable supply of wood is desirable. Research using pilot scale kilns to develop the requirements would be beneficial. There is considerable experience in Cambodia in using kilns to make clay bricks. These skills and possibly the kilns themselves with modification as necessary are resources that could be channelled into the development of a local lime industry.

Local contractor experience of stabilisation for road construction is limited and would need to be enhanced by opportunity, training and guidance. The techniques can be readily learned and applied.

Testing requirements for stabilised materials are well defined in the literature and the routine laboratory equipment with some enhancement is suitable.

For local road development, there is a unique opportunity to investigate the performance of stabilised roads without bituminous surfacings. The cost savings in *not* providing the surfacing are considerable. These trials should be monitored and the information disseminated.

Importantly there is a need for a knowledge base to hold experience and data and provide assistance with its dissemination.

Roads must be built using a technically suitable and lowest cost approach based on whole life costs. At the road project development stage the designers should demonstrate that the alternative of using stabilised materials has been explored rather than simply opting for the use of existing techniques using unbound materials.

1 Introduction

1.1 SEACAP 19

Within the framework of SEACAP, and SEACAP 19 in particular, this Technical Paper contributes to the overall development of resource-based rural road standards for Cambodia. It does so by reviewing currently available information and by presenting a clear way forward for the research that is necessary for the development of the technical topic and for mainstreaming.

This document is the formal output from Task 3 of SEACAP 19 and comprises one of a suite of technical papers. This paper is concerned with the techniques of stabilising poor quality materials for road building as a means of providing durable roads at reasonable cost as an alternative to using expensive better quality materials that have to be transported considerable distances from where they are available to where they are needed. It is based on a review of documented experience of using stabilisation techniques for road building both internationally and in Cambodia itself.

Other SEACAP 19 technical papers that are also of relevance to the topics discussed in this paper are,

TP 1. Bamboo reinforced concrete pavements

TP 2.1. Behaviour of engineered natural surfaced roads: a review

TP 2.2. Behaviour of engineered natural surfaced roads: experimental evidence in Cambodia

TP 4. Low volume rural road upgrade options

TP 5. Justification issues for LVRR upgrading

TP 7. Pilot road materials database.

1.2 Document Structure

The paper consists of two principal components namely the main text which comprises a review of the technology as it applies to Cambodia and a concept note outlining the way forward to develop the techniques so that they become standard options for road designers and road builders in Cambodia.

The main text consists of six chapters. Chapter 2 is essentially a brief introduction and summarises key features of the road environment in Cambodia. Chapter 3 describes the technical aspects of all relevant methods of stabilisation and is sufficiently comprehensive to form the basis of a local manual, set of guidelines, standards and specifications. Comments are included where there are any aspects of the Cambodian environment that might influence the techniques. Particular attention is focussed on the issues relating to lime and cement stabilisation. Chapter 4 describes experiences of stabilisation in Cambodia and identifies key issues. Chapter 5 is a summary and Chapter 6 summarises conclusions and recommendations. The concept note details the recommendations and is presented as Appendix A.

Although the project is concerned with low volume rural roads, the basic technology of stabilisation that is the subject of this report is also applicable to roads carrying much higher levels of traffic. For LVRR roads the application of the technology will necessarily differ, construction methods for example, but, for completeness, aspects of the technology that are only applicable to higher level traffic roads have been retained in the text.

2 The Road Environment in Cambodia

Cambodia lies in the south western part of the East Asia peninsula and has a land area of 181,035 km^2. A map of Cambodia is shown in Figure 2.1. It is divided into three distinct parts (i) the central plains (ii) the flat coastal areas, and (iii) the mountain ranges and the high plateau. The central plains cover 75% of the country, and consist of the alluvial plains of the Mekong River and the Tonle Sap basin. These are Cambodia's two dominant topographical features.

The climate of Cambodia is dominated by the monsoon which causes distinct wet and dry seasons. The southern part of the country has a two-month dry season whereas the northern areas have a four-month dry season. The annual mean rainfall is 1,400 mm in the central low regions but can reach more than 4,000mm in coastal and mountainous areas. The relative humidity is high throughout the year, usually exceeding 90% and rarely falling below 50%.

Temperatures are fairly uniform throughout the country, with only small variations from the average annual temperature of around 28°C. The monthly average temperature is about 34°C with daily temperatures of up to 38°C. It seldom falls below 24°C.

Figure 2.1 Map of Cambodia

The road network was weakened considerably during the years of civil strife and, in recent years, considerable efforts have been made to strengthen the road links. Today the total network consists of about 30,200kms of roads of different standards. There are 4,700kms of primary and secondary national roads of which only about 2,250km are paved and the remainder are gravel-surfaced. A further 6,600kms are provincial highways and the remainder (18,900kms) are rural roads. The rural roads are either gravel or earth-surfaced. The road density in Cambodia is 0.17 km/km^2 which is about half of that in Vietnam or Thailand. The Government is committed to improving the road network as a primary means of reducing poverty by increasing access to markets and services.

Cambodia’s lowland provinces can be generally characterized as having extensive regions of fine soils ranging from silty sand to sandy clays and clays with varying plasticity, with very few sources of good quality road building materials. There are outcrops of limestone, in Battambang and in Kampot for example, and there are infrequent sources of gravel, usually of uncertain quantity and relatively low quality for road building. For example, a study carried out in 2001 in two provinces showed that the haul distances for gravel for roads in Battambang Province varied from 27 to 75 km with an average of 48 km. In Banteay Meanchey Province the haul distances were less, ranging from 2 to 15 km but in both provinces the gravel sources were of only medium or poor quality. The gravel contained excessive amounts of clay and the roads surfaced with them performed poorly. Despite low levels of traffic loading, gravel loss ranged from 50 to 180 mm in less than three years. The study serves to highlight the shortage of good road-building material and relevance of seeking to improve local road construction materials by stabilisation methods.

The wet climate, intensity of rainfall and the large areas of low lying ground, often subject to flooding, coupled with the frequent lack of locally available materials all create difficult circumstances for road building.

3 Stabilisation for Road Building

Stabilisation is carried out to achieve the following main objectives:

- To increase strength and bearing capacity.
- To control volume change when moisture content changes.
- To increase the resistance to erosion, weathering or traffic usage.
- To reduce the permeability of the stabilised soil.

Many natural materials can be stabilised to make them suitable for road pavements but this process is only economical when the cost of overcoming a deficiency in one material is less than the cost of importing another which is satisfactory without stabilisation.

There are three primary types of stabilisation used for improving the engineering properties of soils and gravels for road building. These are; mechanical stabilisation (compaction, and blending sources of aggregates with different particle size distributions); bituminous stabilisation (using bitumen in one form or another); and chemical stabilisation using cement, lime or pozzolans (often called hydraulic stabilisers because water is a necessary reagent in the process). The principles of the use of these stabilisers are described in this report.

Over the years, other products have been developed or have appeared in the market place, often as by-products of other processes. Many of these are sold as propriety products and hence their exact composition is not known. They are not often recommended by national authorities hence they are not dealt with in detail in this report. However, they are included for completeness and referred to as ‘other stabilisers’.

3.1 Mechanical Stabilisation

3.1.1 Compaction

Compaction is the simplest method of stabilisation. Well-graded soils can be compacted to high densities at the optimum moisture content that can be determined using standard compaction tests. BS 1924: Part 2: 1990 describes four such tests, each has its merits and the one that is most closely related to field conditions will depend on the type of material that is being compacted.

At a particular compactive effort, as the fines content of a soil increases the maximum dry density that can be obtained decreases with a consequent increase in the optimum moisture content.

Merely compacting a soil does not necessarily produce a material that is strong enough. The particle size distribution is also important. For example, uniformly graded sand has a high void content at the optimum moisture content because there are insufficient fines to fill the voids. A denser and stronger material could be obtained by blending the sand with another suitable soil, a second method of mechanical stabilisation.

3.1.2 Blending

Blending of materials is carried out for two main reasons namely to

(a) improve the stability of cohesive soils of low strength by adding coarse material or

(b) improve the stability of otherwise unstable granular materials by adding a fine material

The original processes of making water-bound macadam and dry-bound macadam are both pragmatic methods of achieving a high degree of mechanical stabilisation using aggregates of different particle size distributions. Knowledge of the exact grading (or particle size distribution, psd) of the finished product was not originally required in these processes but subsequent research has shown how to achieve good mechanical stabilisation. Knowledge of the grading of the final product is essential for this purpose and it is important to ensure that, after compaction, the air void content is low (<5%). The aim is to try to change the grading of the original material so that it more closely approximates to the maximum density grading given by an equation originally derived by Fuller (1952) and so gives a higher stability and strength. The maximum density grading is

$$P = 100(d/D)^{0.5}$$

Where

P = Percentage by weight of the total sample passing any given sieve size
d = Aperture of that sieve (mm).
D = Size of the largest particle in the sample (mm).

Mechanical stabilisation of fine grain soils, by the addition of non-cohesive granular material, requires sufficient granular material to be added to ensure that the granular fragments are in contact forming a matrix with particle-particle contact throughout.

Plate 1 Laterite gravel blended with graded crushed stone as base overlying unblended laterite sub-base

Mechanical stabilisation is usually carried out to produce sub-base and base materials but might occasionally be carried out to produce an improved upper fill or capping layer, Plate 1. Care must be taken to ensure that the plasticity of the fines fraction is controlled. The strength of a blended material must always be determined by testing samples that are representative of the field-mixed product and not on well-mixed laboratory samples. Once mechanical stabilisation has been achieved it can be expected to remain unchanged for the life of the road.

Mechanical stabilisation is usually found to be the most cost-effective process for improving poorly graded materials, however, this cannot always be achieved. It is important to consider the practical limits of this type of processing. For example, production of a uniform mixture by the addition of granular material to a clay-rich one may produce a uniformly graded material, but one in which the clay may still play the dominant role in determining the properties of the material. In this case lime modification could be considered in order to allow adequate processing of the clayey material (see Section 3.3). This double processing is unlikely to be an economically viable solution in LVRR projects, except in exceptional circumstances where there is complete lack of alternative materials.

3.2 Bituminous Stabilisation

3.2.1 Description

Bitumen is a solid or viscous liquid that occurs naturally or can be refined from crude oil. It has strong waterproofing and adhesive properties and these properties make it an ideal material for use in road building. To be used in stabilisation it needs to be diluted, either cut-back with a solvent such as kerosene or diesel, or emulsified with water. Given the cost of solvents, emulsification is often preferred. However, as the emulsion 'breaks' during or shortly after processing (the water and bitumen separate), and the bitumen becomes an adhesive.

The action of the residual bitumen emulsion is as a binder adding cohesive strength as well as inhibiting water penetration (Ingles and Metcalf, 1972) and hence reducing erosion, potential dimensional change (Spence and Cook, 1983) and loss of strength associated with wetting-up of soils. The process is most suitable in hot and reasonably dry weather that ensure rapid evaporation of the solvents or the water. Bitumen is especially useful for the stabilisation of fine materials with low plasticity characteristics such as sands, especially if they tend to be uniform in particle size. Materials with higher plasticity characteristics may be pre-treated with lime, but this two-stage process will tend to be relatively expensive in the case of low volume sealed roads.

Bitumen emulsion stabilisation of gravelly to silty sands may sometimes be a viable alternative to cement treatment, particularly in cases when bitumen is favourably priced with respect to cement. It may also be favoured in situations where resistance to cracking is required.

An alternative method of mixing the bitumen with the aggregate is a foaming technique in which water is added to hot bitumen and disperses it in a fine foam. Special equipment is required for this so it is unlikely that this method will be suitable for low cost rural roads at this time.

3.2.2 Materials and testing

Slow setting (SS) anionic or cationic emulsion grades are recommended for soil stabilisation rather than medium (MS) or rapid setting (RS) types, which are considered unsuitable.

Standard strength testing of emulsion stabilised materials by CBR or Unconfined Compressive Strength (UCS) methods is not a valid option. Research on the testing of bitumen stabilised sands (Hitch and Russell, 1975) indicated the inappropriateness of these tests and recommend either Marshall Stability procedures or the use of the Hubbard-Field stability test. Recent SEACAP research in Vietnam on emulsion stabilisation used the former to ascertain the optimum residual bitumen contents, (Intech-TRL, 2006).

3.2.3 Construction issues

A limited trial of bitumen emulsion stabilised sand has recently been undertaken in the central coastal region of Vietnam and in addition to standard good construction practice the following issues were highlighted in the resulting guideline (Intech-TRL, 2007):

a) Bitumen stabilisation work cannot be carried out in wet weather, on wet surfaces, or when rain is expected before the completed work can be covered and protected.

b) The soil to be treated must be processed by breaking up and pre-mixing using approved single axle tractor rotovators or 2-axle tractor driven rotovators. Hard soil must be loosened initially by hand tools or scarifying equipment.

c) The target soil moisture content should generally be just below the standard optimum content, with a satisfactory moisture distribution over the full depth, width and length of the section being treated.

d) It is recommended that for labour based operations the required amounts of bitumen emulsion should be added to short 10-25m lengths of pavement at a time and then thoroughly mixed with the approved rotovator assisted by hand raking, Plates 2 and 3.

Plate 2 Adding and rotavating bitumen emulsion in short length panels

Plate 3 Final hand raking of bitumen emulsion-sand mix

e) Consideration should be given to diluting the emulsion in hot dry conditions in order to achieve adequate mixing in sand materials.

f) It is recommended that a small percentage of the emulsion be retained for final topping up of patches that become apparently deficient in emulsion during mixing.

g) Final compaction and shaping should begin when the emulsion mixture begins to break and must be completed within 6 hours of mixing, before hardening of the stabilised soil. The finished layer must be cured for a period of 7 days and traffic or any other equipment, other than that involved in the curing process, must not be allowed onto the treated material for the first seven days after compaction.

h) In the case of a 2-layer construction the second layer construction may be carried out immediately after compaction of the first layer is completed.

The process is essentially a method specification (Box 2) as in situ testing techniques such as DCP or sand replacement density require careful correlation. The DCP-CBR standard correlations are, in particular, reported as not being suitable for bitumen emulsion stabilised materials. Visual assessment of the quality of the finished product allied to a close observation of the key procedures and material specifications is therefore essential

Box 1 Method Specification

There are advantages and disadvantages to both 'method' and to 'end-product' specifications but it is outside the scope of this report to discuss this in detail. Method specifications require extremely reliable site inspectors to ensure that the 'methods' are carried out correctly but they are relatively independent of laboratory testing provided that the methods themselves are reliable. Such methods may need to be set up for each type of material. However, every effort should be made to develop reliable laboratory testing because end-product specifications are more versatile and auditable

3.3 Hydraulic Stabilisers

Stabilisation of road materials by the addition of a chemical additive can enhance the properties of the materials and give pavement layers the following attributes:

- A substantial proportion of the strength is retained when they become saturated with water.
- Surface deflections under traffic are reduced.
- Resistance to erosion is increased.
- Materials in the supporting layer cannot contaminate the stabilised layer.
- The elastic moduli of granular layers constructed above stabilised layers are increased.
- Lime-stabilisation can be used to produce a capping layer or working platform with wet or unsuitable in situ materials.
- Characteristics such as plasticity, compressibility and permeability can be reduced.

Additives can also be used to waterproof a material rather than to directly increase its strength.

The common features are that the natural materials are bound together using a low percentage of the chosen stabiliser. The choice of stabiliser is largely dependent on the properties of the unstabilised material. Materials with a low plasticity, and therefore a low clay content, are more suitable for cement stabilisation. Materials with higher plasticity and a more cohesive nature are better stabilised with lime. For lime, it is also possible to merely modify the soil instead of stabilising it. In other words the amount of stabiliser is less than that required to bind the soil together but, instead, the plasticity is greatly reduced, making it more workable.

It is not unusual for designers to achieve stabilisation by using both cement and lime for a particular job. Everything depends upon achieving the desired strengths and other engineering properties at the lowest cost. The particular features of each of these stabilisation methods are given below.

3.3.1 Cement stabilisation

Cement is a product consisting mostly of calcium silicates and aluminates and calcium oxide. In the presence of water, these form hydrated compounds which crystallise and harden over time, bonding the material particles together and producing a strong cemented matrix.

Cement is obtained by heating, to partial fusion, a pre-determined and homogeneous mixture of materials containing principally lime (CaO) and silica (SiO_2) with a small proportion of alumina (Al_2O_3) and iron oxide (Fe_2O_3) (BSI 1978). The CaO is obtained from calcareous materials, typically limestone, and argillaceous materials such as clay and shale provide the SiO_2, Al_2O_3 and Fe_2O_3.

Cement should be made to recognised standards (e.g. BS 12: 1978; ASTM C595-77). The process is not suitable for local or small scale industries hence it is produced in commercial factories. Usually

Ordinary Portland Cement is used for stabilisation, although other types of cement may be used if they produce the desired properties. The types of cement available are given in the ASTM standards, for example.

The amount of cement added is usually less than 5%. The initial chemical reactions occur quite quickly hence the processing of the materials has to be completed in a fairly short time; construction must be completed within two hours. The cement is then allowed to cure for a period of, usually, 7 days. Although not essential, use of a batching plant to blend the cement with the host material and water rather than mixing on the road gives a more consistent mix and a better result.

Cement can be used to stabilise most soils. The exceptions are those with a high organic content, which retards the hydration process, and those with a clay content outside the normal specification range and where it is difficult to mix the soil/cement mixture evenly. Addition of cement to base materials results in a reduction in plasticity and swell, and an increase in strength and bearing capacity. CBR values well in excess of the minimum requirement for unstabilised gravels (usually 80 per cent, soaked at the required field density) normally result.

3.3.2 Lime stabilisation

Lime may be in one of the following forms;

(a) quicklime: calcium oxide (CaO),

(b) slaked or hydrated lime: calcium hydroxide ($Ca(OH)_2$)

(c) calcium carbonate ($CaCO_3$).

Calcium carbonate has no cementing properties and only quicklime and hydrated lime are used as stabilisers in road construction. They are produced by heating calcium carbonate to more than about 900°C to drive off carbon dioxide. The reactions are represented by the following equations:

(a) $CaCO_3 + heat = CaO + CO_2$ (reversible in the presence of carbon dioxide)

(b) $CaO + H_2O = Ca(OH)_2 + heat$

(c) $Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$

The most common form of commercial lime used in stabilisation is hydrated (high calcium) lime, $Ca(OH)_2$, but limes can also be produced from dolomitic limestone where magnesium replaces some of the calcium; as in monohydrated dolomitic lime, $Ca(OH)_2$-MgO, and dolomitic quicklime, CaO-MgO.

ASTM or AASHTO standards are commonly used to determine the physical and chemical properties of lime (Appendix B). Using the ASTM series as an example, the quality of lime itself is specified in terms of its chemical properties in ASTM C25 and its physical properties in ASTM C110. The purity of lime for sale also varies considerably.

For hydrated lime the majority of the free lime (i.e. $Ca(OH)_2$that is not combined with other constituents) should be present as calcium hydroxide. For example, in the UK, lime for building purposes is required to be 95% pure calcium hydroxide while agricultural lime may be only 65% pure. The quantity is often also referred to as the 'available lime'. For a particular application it is important to carry out laboratory tests with the same lime as will ultimately be used for the project.

Stabilised materials (and concrete) may deteriorate in the presence of salts. The percentage of sulphates in the soils and soil water is a common source of problems in some regions. It is always important to detect the presence of such compounds. However, it has been established that Cambodia has a relatively low risk (Cambodia Bridge Design Standard; MPWT, 2003).

The reaction between lime and soil causes calcium ions to replace sodium ions until the soil becomes saturated with calcium ions. The pH increases to a desirable value in excess of 12 after which soil strengthening can take place. For adequate stabilisation with lime, sufficient lime needs to be added to give rise to an excess after the replacement reactions have been completed i.e. the Initial Consumption of Lime (ICL) of the soil should be satisfied and an excess of lime provided. The ICL test developed by Eades and Grim (1966) can be used to give a rapid indication of the minimum amount of lime that needs to be added to a material to achieve a significant change in its properties. The principle of the test is based on the fact that a saturated solution of lime (calcium hydroxide) in distilled water that is completely free of carbon dioxide has a pH value of 12.4 at 25°C. This pH is required to maintain the reaction between the lime and any reactive components in the material to be stabilised. Samples of the material are therefore mixed with water and different proportions of the lime being used. The minimum amount of lime needed to give a pH of 12.40 is expressed as the ICL of the material.

The original test was improved by Clauss and Loudon (1971) and details of the test are included in the latest edition of BS 1924 (BS 1924: Part 2: 1990b). The test can be completed in one hour and is thus a rapid means of establishing the minimum amount of lime required for stabilisation. However, it does not dispense with the need to carry out strength determinations because it does not establish whether the soil will react with lime to produce a substantial strength increase. Research has also suggested that the lime percentage obtained from the test does not necessarily produce the maximum cured compressive strengths for tropical and sub-tropical soils (TRB 1987).

Quicklime has a much higher bulk density and is less dusty than hydrated but is generally not used in LVRR projects due to its caustic nature and consequent health and safety issues.

When lime is added to a plastic material, it first flocculates the clay and substantially reduces the plasticity. The reduction of plasticity is time dependent during the initial weeks and has the effect of increasing the optimum moisture content and decreasing the maximum dry density in compaction. The workability of the soil also improves as the soil becomes more friable. If the amount of lime added exceeds the ICL the stabilised material will generally be non-plastic or only slightly plastic.

Typically 3 to 5 per cent of stabiliser is necessary to gain a significant increase in the compressive and tensile strengths. The gain in strength with lime stabilisation is slower than that for cement and a much longer time is therefore available for mixing and compaction. Lime has a much lower specific gravity than cement so, for a given percentage mass, a higher volume is available and it is therefore easier to achieve uniform mixing.

The production of cementitious compounds can continue for ten years or more but the strength developed will be influenced by the materials and the environment. The elastic modulus behaves similarly to the strength and continues to increase for a number of years. Between one month and two to three years after compaction there can be a four-fold increase in the elastic modulus.

In many parts of the world, lime has been produced on a small scale for many hundreds of years to make mortars and lime washes for buildings. Different types of kilns have been used and most appear to be relatively effective. Trials have been carried out by TRL in Ghana to determine the output possible from these small kilns and to assess the suitability of the lime for stabilisation, Ellis (1974). Small batch kilns have been used to produce lime for stabilised layers on major road projects. The use of such kilns in Cambodia is discussed in Section 4.5 below.

3.4 Secondary Stabilising Agents

There are a number of materials which in themselves do not produce a significant stabilising effect but do so when used in association with lime or cement. They are normally waste products that are cheaper than cement or lime and therefore, when they are mixed with cement or lime and 'activated', the overall product should be cheaper per unit of cementitious material than either lime or cement separately. They are often blended before use in which case the blended mixture assumes the role of a primary agent.

Box 2 Pozzolans

A pozzolan is defined in ASTM 1976 as 'a siliceous, or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with the calcium hydroxide produced in the hydration reaction at ordinary temperatures to form compounds possessing cementitious properties'. The reaction between clay and lime is a reaction of this type. Natural pozzolans are mainly of volcanic origin.

Artificial pozzolans (Box 2) are mainly obtained by the heat treatment of clays, shales and certain siliceous rocks. One of the primary sources of pozzolan in Europe is pulverised fuel ash (PFA) collected from the boilers of coal-fired electricity generating stations.

PFA is usually mixed with lime in the proportions of 1 of lime to 3 or 4 of PFA but ratios of 1 to 2 up to 1 to 10 are used. The proportion depends on the reactivity of the particular fly ash and this varies substantially from source to source. Lime and fly ash treated layers have a similar performance to cement treated layers constructed from the same aggregate material. The final mixtures should be chosen after a series of laboratory tests carried out after 21 days of moist cure and 7 days of soaking to determine the optimum ratio of lime to fly ash and the optimum lime content (expressed as a percentage of dry soil).

Ash from burnt plants, especially rice husks, rice straw and bagasse (from sugar cane) can have a high enough silica content to provide an excellent pozzolana (Mehta 1979, Spence 1980), (Cook and Suwanvitaya (1982). Lime and rice husk ash mixtures gain strength quickly during the curing but little additional strength is obtained after 28 days of moist curing. The long-term strength depends on the stability of the calcium silicate hydrates. Under certain conditions, lime leaching can occur and eventually the strength will decrease, but the presence of excess lime (free lime) can stabilise this calcium silicate hydrate. Mixtures of lime and rice husk ash in the proportions 2:3 are the most stable and have the highest strength but the durability may be improved by increasing the lime content to give a 1:1 mixture.

Many pozzolana can be used in the manufacture of Portland-pozzolan cements (ASTM C595-76). Specifications exist for both the properties of pulverised fuel ash used in cement (BS6588: 1985a), in concrete (BS 3892: 1982 and 1985) and for Portland pulverised fuel as cement (ASTM C595-76 and BS 6588: 1985b).

3.5 Other Stabilisers

The use of other stabilisers is problematic. There are many products on the market but they all tend to be high cost additives with advertised properties that are onerous to verify, therefore the products have no proven applicability. Where such materials are marketed, road trials should be encouraged at the cost of the supplier and comparative control trial sections must also be constructed. These should then be monitored over a long period to prove that their application is economically and technically viable. Given the suitability of conventional stabilisers for Cambodia, and unless the 'other' stabilisers are low cost waste products, they are unlikely to find significant application in the short to medium term.

3.6 Application of Hydraulic Stabilisation

3.6.1 Strength of cement and lime stabilised materials

There are three main types of cement-stabilised materials, 'Soil-Cement', Cement Bound Granular Material, and Concrete.

The addition of more than 15% cement usually produces a conventional concrete. Granular materials can be improved by the addition of generally less that 10 per cent of Portland cement. Cement-bound natural gravels and crushed rocks will have high moduli in the range of 2,000 to 20,000 MPa compared to 200-400 MPa for the unbound material.

Lime (typically 1-3 percent) or small quantities of cement are often used to modify soils simply to improve their engineering characteristics. Australian (NAASRA 1986), New Zealand (Dunlop 1977) and South African (NITRR 1986) specifications all make a distinction between a stabilised soil ‘modified’ for subgrade improvement and ‘cemented’ for use as sub-base or roadbase where higher compressive strengths are required.

A 7-day unconfined compressive strength of 0.8 MPa and an indirect tensile strength of 0.08 MPa have been suggested to represent the boundary between modification and cementation (NAASRA 1986). Table 3.1, after Ingles and Metcalf (1972), summarises the distinction between lime modification and cementation and the principal uses of both types of treatment.

Table 3.1 Application of stabilised mixtures (after Ingles and Metcalf, 1972)

Process	Purpose	Requirement
Modification	Improvement of access to sites Improvement of workability and pulverisation	Large increase in PL on wet sites. Rapid increase in bearing strength. Large and rapid decrease in plasticity, increased proportion passing 5 mm sieve
Cementation (Stabilisation)	Improvement of sub-grade material Improvement of sub-base and base material	Increase in bearing capacity and durability. Reduced swell Decrease in moisture susceptibility Decrease in plasticity Decrease in swell. Increase in shear, compressive and tensile strength and bearing capacity (CBR >100)

3.6.2 Soil Cement

Soil cement usually contains less than 5% cement (Lay, 1986). This can either be mixed in situ (usually up to 300mm layer at a time) or mixed using plant such as a pulverisor. The technique involves breaking up the soil, adding and mixing in the cement, then adding water and compacting in the usual way.

3.6.3 Cement Bound Granular Material (CBM)

This can be regarded as a stronger form of soil-cement but using a granular aggregate rather than a soil. The process works best if the natural granular material has a limited fines content. This is almost always mixed in plant and the strength requirement is usually in the range 3-6 MPa (7-day cube crushing strength). Layers with the strength of CBM are rarely required in LVRR construction.

3.6.4 Strength requirements for pavement layers

The minimum acceptable strength of a stabilised material depends on its position in the pavement structure and the level of traffic. It must be sufficiently strong to resist traffic stresses but upper limits of strength are usually set to minimise the risk of reflection cracking. The strengths for three types of stabilised layer given in Overseas Road Note 31 (TRL, 1993) are shown in Table 3.2. Such material is included in the Cambodian road design manual (Section 4.1).

Table 3.2 Recommended strengths of stabilised materials (ORN31, 1993)

Code	Description	Unconfined compressive strength* (MPa)
CB1	Cemented roadbase	3.0 - 6.0
CB2	Cemented roadbase	1.5 - 3.0
CS	Stabilised sub-base	0.75 - 1.5 or minimum CBR of 70% (after 7 days moist curing and 7 days soaking)

- Strength tests on 150 mm cubes

The overall design recommendations take account of the likelihood of shrinkage cracking from the stabilised layer reflecting through to an overlying asphalt surfacing. Thus, if a bituminous running surface is required, then this should be a thin seal if the surfacing is placed directly onto a stabilised roadbase.

3.6.5 Two-stage stabilisation

Although lime used in equivalent amounts generally produces lower strengths than cement it is very effective in breaking down heavy soils and clods. A first treatment of the soil with lime makes it much easier to achieve stabilisation with cement.

Early work in the UK using two-stage stabilisation with lime and cement was disappointing (Metcalf 1959, Cruchley 1956, Sherwood and Covell 1959 and Lea 1970). However, more recently the alkali content of British cements has increased and this may well explain why there have been several recent examples of the successful use of lime and cement. Tesoriere et al (1980) found that a heavy clay soil of high pozzolanic activity attained higher strengths when stabilised with lime and cement than it did with equivalent amounts of lime or cement used alone.

In tropical climates, lime and cement-stabilised soils often develop strengths at a similar rate and attain similar ultimate strengths. However, economic reasons and difficulties in mixing in the stabiliser are likely to determine whether or not two-stage stabilisation will be appropriate.

3.7 Testing for Hydraulic Stabilisation

3.7.1 ICL and ICC testing

It is recommended that during any assessment of the suitability of materials for stabilised base or sub-base, the first test to be carried out should be the Initial Consumption of Lime (ICL) or the Initial Consumption of Cement (ICC). The inclusion of the gravel ICL/ICC test into specifications should alleviate most of the durability problems presently experienced, for example with basic igneous materials.

A significant amount of work on the ICL test and its interpretation has been carried out by the KwaZulu Natal Roads Department. They now recommend that the one-hour ICL test should be supplemented by a delayed 28-day ICL test on the same material, sealed after the original one-hour test has been carried out. Calculation of the ICL value is then made from the breaking point of the graphs of the two test results as follows:

ICL (%) = a + (b - a) / 3

Where a = one-hour ICL breakpoint

b = 28-day ICL breakpoint

While this method may give a more accurate ICL value, it is time consuming to obtain a result. For the purposes of evaluating stabiliser contents for other durability tests, the gravel ICL value is considered suitable.

3.7.2 Strength testing

Cement or lime stabilised materials are usually approved on the basis of strength tests carried out on the materials after the stabiliser has had sufficient time to cure. The most commonly used methods are the Unconfined Compressive Strength (UCS) Test, for cement stabilised materials, and the California Bearing Ratio (CBR) Test for lime stabilised or modified materials.

Methods of testing the strength of cement and lime stabilised materials usually depends upon the type of soil being stabilised and its intended position in the road structure. Three classes of stabilised material are defined in BS 1924 (Part 1:1990) together with recommended sizes for test samples for testing purposes, the details of which are given in Table 3.3.

Both BS and ASTM standards specify cylindrical specimens with a height/ diameter ratio of 2:1 and this is generally the same with other standards. The notable exception is a cylindrical specimen which has the same dimensions as a CBR mould i.e. 152 mm high and 127 mm diameter.

If cubical moulds are not available, Overseas Road Note 31 (1993) in common with the South African standard (NITRR 1986) recommends the use of CBR moulds. Other cylindrical moulds of suitable size may also be used. Material strength determined with different sizes of sample will vary and for the materials normally used in road building the correction factors given in Table 3.3 Definition of soil granularity and size of sample for determining stabilised strength

Description of soil	Amount retained on a BS test sieve	Shape of test sample	Dimensions of test sample
Fine-grained	<1% on 2 mm	Cylindrical: Cubical:	100mm high, 50mm diameter 150 mm cube
Medium-grained	<10% on 20mm	Cylindrical Cubical	100mm high, 50mm diameter 150 mm cube
Coarse-grained	<10% on 37.5 mm	Cubical	150mm cube

Table 3.4 should be used to calculate the approximate equivalent strength of a 150 mm cube.

Table 3.3 Definition of soil granularity and size of sample for determining stabilised strength

Description of soil	Amount retained on a BS test sieve	Shape of test sample	Dimensions of test sample
Fine-grained	<1% on 2 mm	Cylindrical: Cubical:	100mm high, 50mm diameter 150 mm cube
Medium-grained	<10% on 20mm	Cylindrical Cubical	100mm high, 50mm diameter 150 mm cube
Coarse-grained	<10% on 37.5 mm	Cubical	150mm cube

Table 3.4 Correction factors for size and shape of test samples

Specimen size	Correction factor for 150 mm cube
150 mm cube	1.00
100 mm cube	0.96
200mm x 100 mm dia. cylinder	1.25
142mm x 71mm dia. cylinder	1.25
155mm x 105 mm dia. cylinder	1.04
127 mm x 152 mm dia. cylinder	0.96

Unconfined Compressive Strength

The UCS Test is carried out on cylindrical or cubical samples by mixing the material at the desired moisture and stabiliser content and then compacting the material into a mould to either a pre-determined density or a given compactive effort. As the increase of strength of stabilised materials occurs over relatively long periods of time, samples are cured for 7, 14 or 28 days prior to testing. A 7-day curing period, although arbitrary, is often chosen as a convenient reference for cement-treated materials, whilst a longer 28-day period is chosen for lime-treated materials to take into account their slower strength gain.

California Bearing Ratio (CBR)

Whilst the CBR test is permitted for testing sub-base materials, it is still preferable to use the UCS test wherever possible. This is partly for consistency with testing stronger stabilised materials and also because the relationship between CBR and UCS is not unique but depends very strongly on the grading of the material, amongst other things, hence it is difficult to relate a CBR value to a corresponding UCS value.

3.8 Durability Tests

Neither the standard UCS nor CBR tests used by themselves are considered to reflect the stability of a chemically stabilised material in terms of durability against wetting and drying (Sherwood, 1993). A number of countries therefore employ additional tests to assess durability namely:

(a) Wetting and drying test – ASTM D559

(b) Wet/dry brushing test - A19 of TMH 1 (NITRR, 1986)

(c) Residual UCS test - The original residual UCS test described by De Wet and Taute (1985) included a UCS after 12 cycles of wetting and drying and a UCS after vacuum carbonation. Research has shown that only the residual, vacuum-carbonated, 7-day UCS need to be satisfied.

3.9 Selection of Hydraulic Stabilisation Method

3.9.1 Selection of stabilisation type

Figure 3.1 and Figure 3.2 summarise the general approach to assessing material suitability for stabilisation and the selection of stabiliser type.

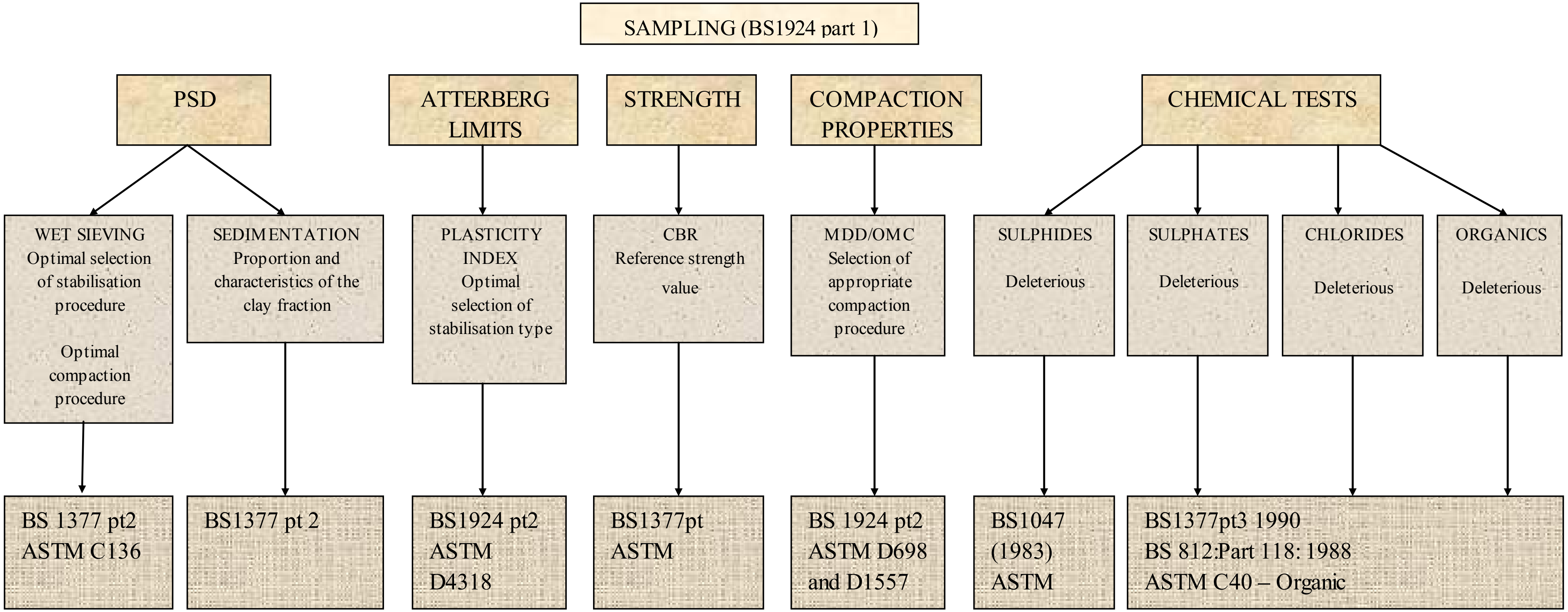
The selection of the stabiliser is based on the plasticity and particle size distribution of the material to be treated. The appropriate stabiliser can be selected according to the criteria shown in Table 3.5 adapted from NAASRA (1986).

Table 3.5 Guide to the type of stabilisation likely to be effective

Type of stabilisation	**Soil properties**					
	More than 25% passing the 0.75mm sieve			Less than 25% passing the 0.75mm sieve		
	PI ≤ 10	10 ≤ PI ≥ 20	PI ≥ 20	PI ≤ 6 PP ≤ 60	PI ≤ 10	PI ≥ 10
Cement	Yes	Yes	*	Yes	Yes	Yes
Lime	*	Yes	Yes	No	*	Yes
Lime - pozzolan	Yes	*	No	Yes	Yes	*

Notes: 1 * indicates that that stabiliser will have marginal effectiveness

2 PP = Plasticity Product (PI x the percentage passing the 0.075mm sieve)



NB: 1. FOR WASTE MATERIALS AND INDUSTRIAL BY PRODUCTS REFER TO BS 6543

Figure 3.1 Suitability of natural soils for chemical stabilisation

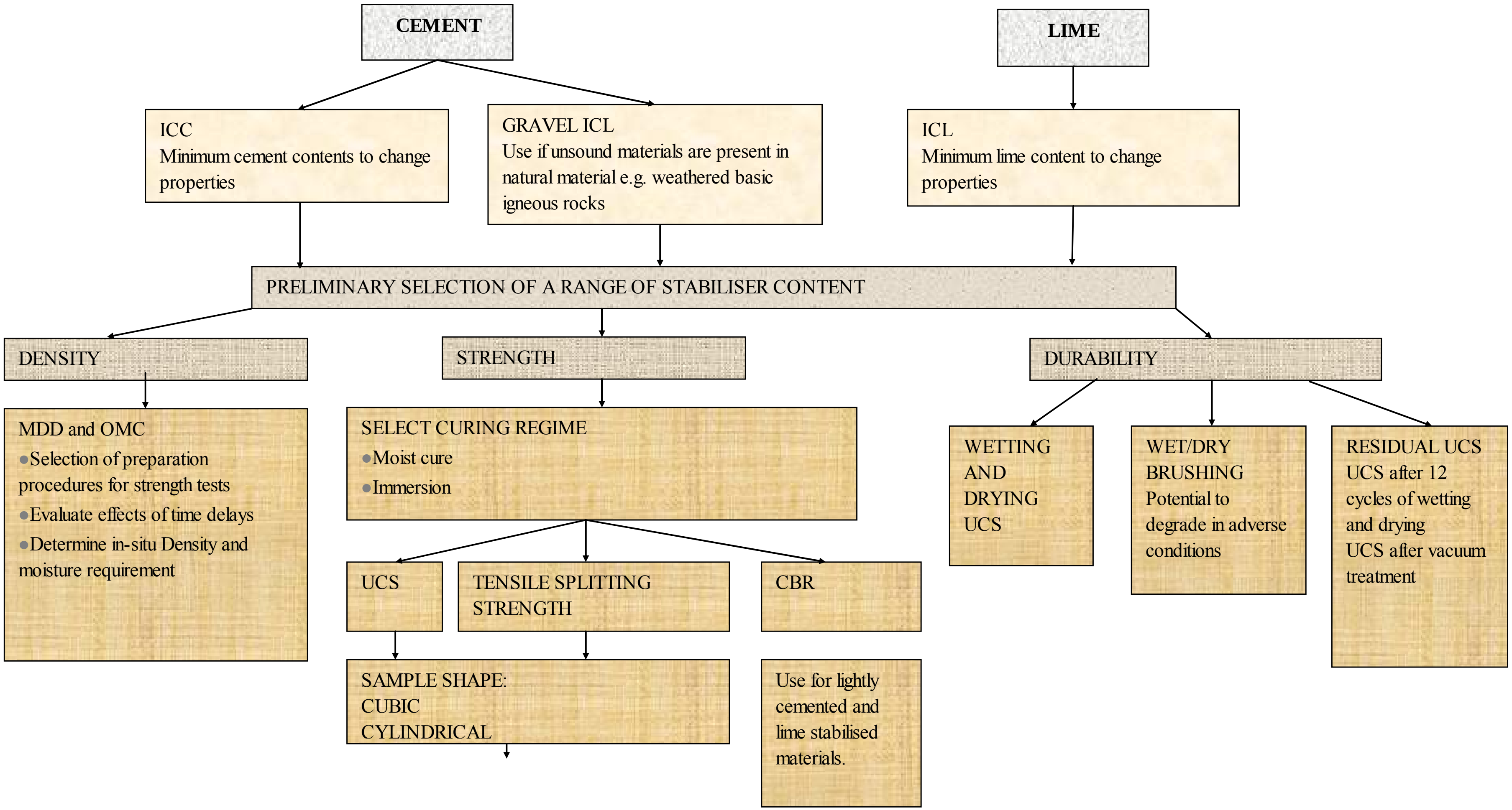


Figure 3.2 Determination of stabiliser content

Some control over the grading can be achieved by limiting the coefficient of uniformity to a minimum value of 5. If the coefficient of uniformity lies below this value the cost of stabilisation will be high and the maintenance of cracks in the finished road could be expensive. Except for materials containing amorphous silica (e.g. some sandstones and chert), material with low plasticity is usually best treated with cement. However, reactive silica in the form of pozzolans can be added to soils with low plasticity to make them suitable for stabilisation with lime. If the plasticity of the soil is high there are usually sufficient reactive clay minerals which can be readily stabilised with lime. Cement is more difficult to mix intimately with plastic materials but this problem can be alleviated by pre-treating the soil with approximately 2 per cent of lime to make it more workable.

Table 3.6 summarises the desirable grading characteristics for materials to be stabilised. Stabilised layers constructed from these materials are more like to perform satisfactorily even if they are affected by carbonation (Box 3) during their lifetime.

In LVRR design the objective is to use locally available materials rather than to seek out ideal materials. In this context materials which do not comply with Table 3.6 can sometimes be stabilised but more additive may be required and the cost and the risk from cracking and carbonation may also increase. Some aspects of construction must also be considered in selecting stabiliser. It is not always possible to divert traffic during construction and the work must then be carried out in half-widths. The rate of gain of strength in the pavement layer must be rapid so that traffic can be routed over the completed pavement as soon as possible. Under these circumstances, cement stabilisation, with a curing period of seven days, is likely to be more suitable than lime stabilisation which requires a much longer curing period.

Box 3 Carbonation

As with the many chemical reactions, the process of lime formation is reversible, depending on the environmental conditions. Both the oxide and hydroxide forms of lime can react with carbon dioxide on long-term exposure to form calcium carbonate.

The reactions with cement are more complex, but the cemented products, primarily hydrated calcium silicates (CSH) and hydrated calcium aluminates (CAH), are also susceptible to carbonation.

Table 3.6 Desirable properties of material before stabilisation (ORN 31, TRL, 1993)

BS test sieve (mm)	Percentage by mass of total aggregate passing test sieve		
	CB1	**CB2**	**CS**
53	100	100	-
37.5	85 – 100	80 - 100	-
20	60 – 90	55 - 90	-
5	30 – 65	25 - 65	-
2	20 – 50	15 - 50	-
0.425	10 – 30	10 - 30	-
0.075	5 – 15	5 - 15	-
Plasticity			
LL	25 max	30 max	-
PI	6 max	10 max	20 max
LS	3 max	5 max	-

Note: It is recommended that materials should have a coefficient of uniformity of 5 or more.

Certain types of organic compounds in soils can affect the hydration of cement and inhibit the gain in strength. It is recommended that the effects of organic matter are assessed by strength tests as outlined below.

3.9.2 Selection of cement content

The cement content determines whether the characteristics of the mixture are dominated by the properties of the original soil (grain interlock) or by the hydration products (cemented matrix). As the proportion of cement in the mixture increases, so the strength increases. Strength also increases with time. During the first one or two days after construction this increase is rapid. Thereafter, the rate slows down although strength gain continues provided the layer is well cured. The choice of cement content depends on the strength required, the durability of the mixture, and the soundness of the aggregate.

The minimum cement content, expressed as a percentage of the dry weight of soil, should exceed the quantity consumed in the initial ion exchange reactions. Until research into the initial consumption of cement (ICC) is completed it is recommended that the percentage of cement added should be greater than the ICC If there is any possibility that the material to be stabilised is unsound e.g. weathered basic igneous materials, then the Gravel ICL Test (NITRR, 1984) is preferred.

Additional stabiliser is normally incorporated to take account of the variability in mixing which occurs on site. If good control is exercised over the construction operations, an extra one per cent of stabiliser is satisfactory for this purpose.

The durability of the stabilised mixture which satisfies the strength requirements for the particular layer should also be assessed. Mixtures produced from sound materials complying with the minimum requirements can be assumed to be durable if they achieve the design strength. Mixtures produced from other materials can be checked using the wet-dry brushing test (ASTM 1987).

3.9.3 Selection of lime content

The procedure for selecting lime content follows the steps used for selecting cement content and should, therefore, be carried out in accordance with British Standard 1924 (1990). The curing period for lime-stabilised materials is 21 days of moist cure followed by 7 days of soaking. In tropical and sub-tropical countries the laboratory curing temperature should be maintained at 25°C.

3.10 Construction Issues: Hydraulic Stabilisers

3.10.1 Construction methodologies

Construction methods will differ between LVRR and roads carrying high levels of traffic. For completeness this section of the report deals with both.

The construction of hydraulically stabilised layers for LVRRs is generally a mix-in-place operation and follows the same general procedure whether the stabilising agent is cement, lime or mixtures of lime-pozzolan. After the surface of the layer has been shaped, the stabiliser is spread and then mixed through the layer. Sufficient water is added to meet the compaction requirements and the material mixed again. The layer must be compacted as soon as possible, trimmed, re-rolled and then cured.

Good curing and construction practices are the best means of preventing problems such as carbonation in a cement or lime stabilised layer. The precautions to be taken are;

(a) Keep the material continuously moist during curing and avoid wet/dry cycles. Wet sand or polythene sheeting should be used if possible;

(b) Keep out carbon dioxide by minimising the exposure of the layer to the atmosphere i.e. seal as soon as possible, and encapsulate in potentially severe cases;

(c) Compact at the correct optimum moisture content for the soil-stabiliser mix and to a low air void content (e.g. <5%) rather than to a prescribed percentage of a compaction test;

(d) Test the density-strength-delay time relationship in the laboratory and revise the construction procedures if necessary;

(e) Avoid over-compaction of the roadbase layer which leads to micro-cracking on the surface and loose material

(f) Brush the surface to remove loose material and probably carbonated material which may affect the penetration of a prime coat and adherence of the seal

(g) Seal the roadbase with a surfacing as soon as possible after compaction to exclude carbon dioxide

(h) Reduce the possibility of reflection cracking by proper curing during construction

(i) Where cracking occurs, if lower pavement layers are moisture sensitive, seal the cracks as soon as possible,

Spreading the stabiliser

With lime or cement the stabiliser can be spread manually by "spotting" the bags at predetermined intervals, breaking the bags and then raking the stabiliser across the surface as uniformly as possible, Plate 4. Lime has a much lower bulk density than cement and therefore higher volume per unit weight. Therefore, when stabilisers are spread manually, it is possible to achieve a more uniform distribution with lime than with cement. Alternatively, mechanical spreaders can be used to gauge the required amount of stabiliser onto the surface.

Plate 4 "Spotting" and then breaking bags prior to spreading

Mixing.

Robust mixing equipment of suitable power for the material being processed is best able to pulverise the soil and blend it with the stabiliser and water. The most efficient of these machines can carry out the operation in one pass, enabling the layer to be compacted quickly and minimising the loss of density and strength caused by any delay in compaction. Multi-pass machines are satisfactory provided the length of pavement being processed is not excessive and each section of pavement can be processed within an acceptable time. For LVRRs mixing is often carried out with agricultural equipment, Plate 5. Care is required to achieve good mixing to the full depth required and to complete the processing inside the recommended time limit. Graders have been used to mix stabilised materials but they are inefficient for pulverising materials and a number of passes are needed before the quality of mixing is acceptable. Graders should only be considered for processing lime-stabilised layers or well graded granular materials which can be mixed very quickly.

Plate 5 Agricultural rotavator that may be used for mixing lime or cement stabiliser

Compaction

A stabilised layer must be compacted as soon possible after mixing has been completed in order that the full strength potential can be realised and the density can be achieved without overstressing the material. If the layer is overstressed, shear planes will be formed near the top of the layer and premature failure along this plane is likely, particularly when the layer is only covered by a surface dressing.

Care should be taken to reduce the density gradient in the layer because permeable material in the lower part of the layer makes it more susceptible to carbonation from below. If necessary, two-layer construction can be employed to ensure effective compaction throughout the stabilised material.

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Curing

Proper curing is very important for three reasons:

- It ensures that sufficient moisture is retained in the layer so that the stabiliser can continue to hydrate.
- It reduces shrinkage.
- It reduces the risk of carbonation from the top of the layer.

In a hot and dry climate the need for good curing is very important but the prevention of moisture loss is difficult. Curing by water spraying can be an efficient curing system if a layer of sand from 30 to 40mm thick is first spread on top of the stabilised layer. After seven days the sand should be brushed off and the surface primed with a suitable cutback bitumen.

A prime coat cannot serve as a curing membrane. Research has shown that a prime penetrates too far into the layer and insufficient bitumen is retained on the surface to provide the necessary continuous film (Bofinger, 1978).

3.10.2 Control of shrinkage/reflection cracks

There is no simple method of preventing shrinkage cracks occurring in stabilised layers. However, design and construction techniques can be adopted which go some way to alleviating the problem.

Shrinkage, particularly in cement-stabilised materials, has been shown (Bofinger et al., 1978) to be influenced by,

- Loss of water, particularly during the initial curing period.
- Cement content.
- Density of the compacted material.
- Method of compaction.
- Pre-treatment moisture content of the material to be stabilised.

Proper curing is essential, not only for maintaining the hydration reactions but also to reduce volume changes within the layer. The longer the initial period of moist cure the smaller the shrinkage when the layer subsequently dries.

When the layer eventually dries, the increased strength associated with a high stabiliser content will cause the shrinkage cracks to form at increased spacing and have substantial width. With lower cement contents, the shrinkage cracks occur at reduced spacing.

In order to maximise both the strength and durability of the pavement layer, the material is generally compacted to the maximum density possible. However, for some stabilised materials it is sometimes difficult to achieve normal compaction standards and any increase in compactive effort to achieve them may have the adverse effect of causing shear planes in the surface of the layer or increasing the subsequent shrinkage of the material as its density is increased. If it proves difficult to achieve the target density, a higher stabiliser content should be considered in order that an adequately strong and durable layer can be produced at a lower density.

Shrinkage problems in plastic gravels can be substantially reduced if air-dry gravel is used and the whole construction is completed within two hours, the water being added as late as possible during the mixing operation. It is generally not possible to use gravel in a completely air-dry condition, but the lower the initial moisture content and the quicker it is mixed and compacted, the smaller will be the subsequent shrinkage strains.

When cemented material is used as a roadbase a flexible surfacing such as a double surface dressing is recommended. Experience in a number of countries has shown that a further surface dressing applied after 2-3 years can partially or completely seal, or arrest, any subsequent cracking, particularly where lime is the stabilising agent.

3.10.3 Quality Control

A high level of quality control is necessary in the manufacture of cement and lime-stabilised materials, as with all other materials used in the road pavement, but several factors need special consideration.

Storage and handling of stabiliser

Unless cement and lime are properly stored and used in a fresh condition it will not be suitable. Even if cement is properly stored, the following losses in strength will occur:-

After 3 months	20% reduction
After 6 months	30% reduction
After 1 year	40% reduction
After 2 years	50% reduction

Lime should be packed in sealed bags, tightly stacked and stored under cover, or at least under a watertight tarpaulin. If it becomes contaminated or damp, it will no longer be an effective stabiliser and can only be used as a filler. Lime which is older than 6 months should also be discarded.

Distribution of stabiliser

After the layer has been properly processed samples should be taken for determination of the stabiliser content.

Opening to traffic

Insufficient research has been carried out to determine the precise effects of opening a road to light traffic before the completion of the curing period but it is considered that allowing traffic on the pavement during the first two days can be beneficial for some stabilised layers provided the traffic does not mark the "green" surface and all traffic is kept off the pavement from the end of the second day until one week has elapsed (Williams, 1986). Early trafficking has the same effect as pre-cracking the layer by rolling within a day or two of its construction. The purpose of this is to promote more but narrow cracks rather than allow few but very wide shrinkage cracks to develop.

Layers which are pre-cracked or trafficked early must be allowed to develop sufficient strength to prevent abrasion of the edges of each crack before the layer is opened to general traffic. The slab strength of these layers is effectively destroyed and it is recommended that early trafficking is only acceptable for layers of cemented roadbase type CB2.

Multi-layer construction

When two or more lifts are required to construct a thick layer of stabilised material, care must be taken to prevent carbonation at the surface of the bottom lift. It is also very important that the stabiliser is mixed to the full depth of each layer. A weak band of any type can cause overstressing and premature failure of the top lift followed by deterioration of the lower section. In general the thickness of a lift should not be greater than 200mm or less than 100mm after compaction.

4 Review of stabilisation for LVRRs in Cambodia

The shortage of good road-building materials in many areas of Cambodia is not in dispute, hence nor is the need for stabilisation techniques for making use of locally available soils and poor quality gravels to provide affordable and sustainable LVRRs. Chapter 3 has summarised the technology of stabilisation. It is suggested that cement and lime stabilisation are likely to be the most appropriate methods but the design process for any particular soil or material is too complex to be used on every LVRR project. Fortunately the number of basic soil types is not large hence generic studies can be carried out to determine guidelines for each basic soil type.

4.1 Standards and Specifications – the Cambodian Road Design Manual

The use of any method or technique usually requires that it is incorporated in National Standards and Specifications. In many countries this is a major hurdle to introducing new methods because the process of doing so often takes a great deal of time, often many years, because such methods have to be demonstrated and proven comprehensively. There is no such problem associated with the use of most stabilising techniques for road materials in Cambodia.

The Cambodia Road Design Manual which is similar in flexible pavement design to ORN 31 (TRL, 1993) permits and gives guidance on the use of hydraulically stabilised materials in road pavements. Guidance is given on the use of a stabilised roadbases of two types, CB1 and CB2. Application of either CB1 or CB2 depends upon the pavement design chart that will be used. The strength of CB1 ranges from 3 MPa to 6 MPa and CB2 ranges from 1.5 MPa to 3 MPa. The tests are carried out on cube specimens. The range of host materials that can be used is more stringent than those required for sub-base, requiring a better grading in the host material.

There is a requirement to modify guidance in this document for LVRR use and to focus on the low volume traffic and small contractor environment where the use of locally available soils is important.

4.2 Local Materials Suitable for Stabilisation

Samples of the natural soils in Cambodia have been tested as part of the study that comprised Task 2 of this project namely the study of Engineered Natural Road Surfaces (ENS) which focussed on the provinces of Kandal, Kampot, Siem Reap and Ratanakiri. Although the soils were not tested specifically for their potential for stabilisation, their suitability can be inferred from the tests that were carried out. The visual descriptions of the materials are listed in Table 4.1 together with the number of occurrences. Gravel materials have been recorded at 44 of the sites and the remaining 50 sites were soils of various types.

They are all potentially suitable for stabilisation using varying quantities lime or cement. The silty sand and sandy soils may be suitable for stabilisation using bitumen. It should also be noted that the gravels, whether they are in situ or imported for use as a gravel wearing course, may also be suitable for improvement by either mechanical means or stabilised as necessary using lime or cement. Under the ENS component these materials have been tested in the laboratory to determine their engineering properties and classification.

Table 4.1 Soil types encountered in the ENS studies

Visual description	Number of sites
Laterite gravel	36
Hill gravel	7
Alluvial gravel	1
Sandy clay	23
Sand	1
Gravel and clay	3
Silty clay	8
Silty sand	8
Clay	7

Table 4.2, from ORN 31 (TRL, 1993) has been reproduced below together with the number of soils tested under the ENS study that fall into the various categories. The Table shows the number of cases where each of the stabiliser types are likely to be effective. Considering either cement or lime as the stabiliser, the data show that cement is likely to be most effective in 32 cases, lime is likely to be most effective in 11 cases, and that either cement or lime may be effective in a further 20 cases.

Table 4.2 Guide to the type of stabilisation likely to be effective

Type of stabilisation	Soil properties					
	More than 25% passing the 0.75mm sieve			Less than 25% passing the 0.75mm sieve		
	PI ≤ 10	10 ≤ PI ≥ 20	PI ≥ 20	PI ≤ 6 PP ≤ 60	PI ≤ 10	PI ≥ 10
Cement	Yes	Yes	*	Yes	Yes	Yes
Lime	*	Yes	Yes	No	*	Yes
Lime - pozzolan	Yes	*	No	Yes	Yes	*
Number of samples	17	14	11	8	7	6

Notes: 1 * indicates that that stabiliser will have marginal effectiveness

2 PP = Plasticity Product (PI x the percentage passing the 0.075mm sieve)

4.3 Field Trials of Cement and Lime Stabilisation Techniques in Banteay Meanchy

A field trial of lime and cement stabilisation techniques was conducted on the roads around Tean Kam village in preparation for the construction of the Chob-Tean Kam Ponley road in Banteay Meanchey Province (NZAID - ADAF (2007)). Each trial section was about 50 m long. Stabilisation was carried out over the full road width of 3.5m, and the stabilised layer was approximately 200 mm thick after compaction. Both local and imported lime was used.

Initial laboratory tests had showed that the strength of the material measured in CBR testing increased after stabilisation from a CBR of approximately 55% for the control gravel to over 250% CBR (maximum) with the addition of stabiliser. Different quantities of lime, or cement or both stabilisers were used as shown in Table 4.3.

Table 4.3 Laboratory test results (Source NZAID - ADAF (2007))

Stabiliser	CBR at 90% of specified dry weight density	CBR at 90% of specified dry weight density	Maximum dry density	Optimum moisture content (%)	Plasticity Index
2% hydrated lime	63	87	2.110	9.1	8.4
3% hydrated lime	55	95	2.120	9.1	10.3
4% hydrated lime	75	125	2.102	9.0	9.0
5% hydrated lime	65	145	2.094	9.9	8.8
2% hydrated lime + 1% cement	64	108	2.138	9.1	8.5
2% hydrated lime + 2% cement	75	125	2.152	8.0	10.7
2% hydrated lime + 3% cement	89	140	2.148	8.3	10.0
3% hydrated lime + 1% cement	86	115	2.128	9.0	8.9
3% hydrated lime + 2% cement	95	160	2.138	9.0	9.0
3% hydrated lime + 3% cement	98	185	2.150	9.0	11.5
4% hydrated lime + 1% cement	105	153	2.110	9.4	9.5
4% hydrated lime + 2% cement	107	165	2.116	9.2	10.0
4% hydrated lime + 3% cement	115	190	2.134	9.4	9.7
5% hydrated lime + 1% cement	112	180	2.104	10.0	9.7
5% hydrated lime + 2% cement	115	205	2.112	10.2	9.6
5% hydrated lime + 3% cement	175	250	2.124	10.4	9.4
Laterite control sample	22	50	2.200	8.0	11.6

Core samples from the pavement were taken about six weeks after construction and unconfined compressive strength tests (UCS) were carried out at a local laboratory. The results are shown in Table 4.4. Strengths were remarkably uniform (between 4.3 MPa and 4.6 MPa), values that indicate the material would be suitable for a roadbase (see for example, ORN31 (TRL, 1993)). During the trials some cores could not be extracted whole. This was said to be because the density was low in the bottom of the core caused by difficulties in compacting the layer. Difficulties such as this are sometimes encountered, especially with cement, if the processing time is too long (i.e. the recommended time limits are exceeded). If the contractor is more experienced, with improved practices and better quality control, such problems should easily be eliminated.

The trial roads were not sealed with a bituminous surfacing, which is very unusual. However, the main project roads were sealed with a double bituminous surface treatment (DBST).

4.3.1 Performance of the trial sections

After one year (in March 2008) the unsealed trial sections were in good condition. The surface was hard and no erosion was evident even on sections that were super-elevated (i.e. where rain water flows from one side of the road to the other under an increased hydraulic gradient). Furthermore, no edge damage was evident, even where vehicles were entering or leaving the road. Finally there was little visible dust and passing traffic did not appear to raise any.

No testing has been done to monitor the performance of the trial sections and so it is not known whether or not the exposed stabilised layer is carbonating and whether this will lead to accelerated deterioration. If it is durable, the use of an un-surfaced stabilised layer is significantly cheaper because the high cost of the bituminous surfacing is saved. This may be a viable option for LVRRs. These road trials should be monitored periodically. If successful they will provide an important new way of providing durable local roads that are not susceptible to erosion or gravel loss.

It was reported that the laboratory testing was not reliable and that the site work was being carried out using techniques best described as following 'method' specifications rather than 'end-product' specifications.

It was reported that the processing time for the pavement layers was proving too long for cement stabilisation to be effective. Two hours is normally considered the maximum allowable time from the moment that water is added to the cement in the mix. It was concluded that only lime should be used and this produced a reduction in costs.

Table 4.4 Unconfined compressive strengths after construction (method AASHTO T-106)

Sample ID	Stabiliser	Compressive strength
Trial Section 1	3% lime	4.50
Trial Section 2	2% lime + 1% cement	4.29
Trial Section 3	4% lime	4.55
Trial Section 4	3% lime + 1% cement	4.44

Source: NZAID - ADAF (2007)

4.4 National Road NR1

Cement stabilisation has been used for the construction of the roadbase on the southern section of NR1 towards Bavet on the border with Vietnam. The surfacing is a double bituminous surface treatment. A visual inspection indicated that the stabilisation process was successful and that the resulting pavement structure is strong with little sign of deformation after several years in service (estimated to be 5 years). However, the surfacing shows extensive transverse cracking at a regular spacing of several metres (4 m to 12 m). Such cracking is caused by shrinkage and is a natural characteristic of stabilised roadbase layers. However, such roadbases usually continue to perform well structurally. The reflection of these cracks though the surfacing may lead to the infiltration of water down into the lower pavement layers and the subgrade and therefore the cracks should be sealed. Simple crack sealing alone may be sufficient for a considerable period although, in the longer term, a resealing of the pavement may also be necessary.

If aggregate roadbase materials are available at reasonable cost, an alternative pavement structure may be provided by stabilising the sub-base instead of the roadbase. For similar traffic loading and using a strongly bound sub-base, a stiff and impermeable sub-base layer will be formed which will tend to inhibit the movement of water through the pavement. Any cracking in the sub-base is much less likely to be reflected through the unbound aggregate base to the surfacing and the stiffer sub-base will permit a thinner roadbase to be used which will, in turn, offset costs of the stabilised layer.

4.5 Local Lime Production

Lime is manufactured in two provinces in Cambodia namely in Kampot and in Battambang at Phnom Sampour Commune, Banom district.

There are two kilns at Banom which are located side by side at the base of a limestone outcrop. One has a capacity of 15 m^3 and the other 10 m^3. Both are the same construction and similar to those used in local lime burning elsewhere. One is shown in Plate 6 and was built about 20 years ago.

Plate 6 View of lime kiln at Banom, Battambang Province

Originally the limestone outcrop was used as the source of the limestone for burning but this is now prohibited because the hill is both a local landmark, with a spiritual house, and is of interest to tourists. The operator now imports limestone from some distance away. The operator supplied lime to the Chob-Tean Kam Ponley road in Banteay Meanchey Province (see Section 4.3), although the supply rate was insufficient and lime also had to be imported from Thailand for the project.

Wood fuel is loaded at the base and the limestone stacked around and above it, partly though an opening at the top of the kiln. The fire is started and maintained throughout a 72-hour burning cycle. The fire is then extinguished, the kiln allowed to cool, and the lime (as lump lime) is raked out through the fire hole.

The maximum output from the two kilns is 35 tonnes of lime (calcium oxide) per month. To produce 18 m^3 of lime requires 50 m^3 of wood. Wood for firing is purchased at USD12 per m^3. Dried wood must be used rather than freshly cut (wet) wood in order to achieve the temperature required. Apparently rice husks cannot be used because they do not generate a sufficiently high temperature to burn the limestone.

Lime is supplied to order rather than being continuously produced and stored. Often the customer will request fresh burned lime rather than slaked lime to ensure the quality of the lime is retained. It is then slaked as required. The lime is bagged but the bags are not sealed and therefore unslaked lime slowly becomes slaked naturally from exposure to the air. In time, it would also naturally take-up sufficient carbon dioxide and revert to limestone (calcium carbonate) albeit now as a powder). The slaked lime is pure white and likely to be of high quality.

The process of slaking emits considerable heat and is otherwise dangerous. It should not be undertaken without knowledge, experience and with sufficient safety precautions being taken. For road construction, lime is usually provided slaked as it is less dangerous to work with, unless it is being used to dry-out a construction site. In the UK, lime slurry is preferred for road construction because this eliminates problems from dust, but equipment for spraying is required.

4.5.1 Long term prospects for the lime industry

There is little doubt that local production of lime would provide long term opportunities for livelihoods and produce a resource for Cambodia both for road construction and for other uses, agriculture for example. However the consumption of wood for lime production is an issue that must be addressed to ensure that the business is sustainable and that Cambodia's problems with forestry degradation are not exacerbated. On balance it is concluded that Cambodia would probably benefit from a domestic lime production industry but a more rigorous investigation is required.

4.5.2 Use of wood as fuel

A desk study of the consumption of wood in Cambodia was carried out by Sok Bun Heng in 2002 (Heng, 2002). Based on studies in 1996, it was found that 90% of the wood energy used in Cambodia was consumed by households, less than 1% was consumed by industry, usually in brick-making kilns, and less than 1% was consumed by Services, the latter using mainly charcoal. Of the total wood fuel used, only 6% was converted to charcoal. Given the costs of alternative fuels, LPG mainly, the consumption of fuel wood is likely to continue to increase for a considerable time although it will be overtaken gradually as a proportion of the total fuel demand.

Although the consumption of wood for industry is very small, it is expected to double by the year 2010. This will increase the pressure on the forests and the need for other wood sources, or alternative fuels must be addressed. However, Heng shows that the major cause for deforestation is clearing the forests for agriculture, not for fuel, but that fuel use exacerbates the problem. Part of the problem is that direct combustion for fuel is generally very inefficient; only about 10% is actually used productively because most is lost to the atmosphere. Although the efficiency can be doubled by using better methods and better equipment, the efficiency remains low at only 20% hence the scope for large reductions is small.

Environmental concerns and increased lime production costs caused by using wood burning kilns should be addressed. As an alternative to buying dried wood, an established lime producing enterprise can produce its own wood for burning as an associated part of the business. Better use may come from firing the kilns using LPG which is becoming more widely available and is used in Cambodia for motor vehicles, even in remote areas. At present LPG is considered to be more expensive than wood burning but this is likely to change as consumption increases. Waste materials may produce another source of fuel.

4.5.3 Clay brick making – can the kilns be used to produce lime

The manufacture of clay bricks is a well established local industry in many areas of Cambodia where suitable soils are found. While this report concentrates on stabilisation for road making, there are similarities to lime burning and therefore similarities in the skills required. The processes for burning bricks are shown in Table 4.5. Bricks are made from wet clay materials and the process starts by a gradually drying out the brick, and thereafter gradually increasing the temperature. The process takes from 10 to 40 hours, and the cooling down a further 5 to 24 hours. The wide temperature ranges are indications of the differing raw materials. It should be noted that the temperature range for vitrification is similar to that required for calcification of limestone. Clearly the brick kilns can reach temperatures suitable for burning lime. However, it is not known if the kiln design, especially for the emission of gases, is sufficiently similar to that of lime burning kilns. For the latter it is essential to remove the carbon dioxide that is released and so ensure effective calcination.

Table 4.5 Clay brick making processes

Process	Temperature ranges ^{O}C	
Drying	38	204
Dehydration	149	982
Oxidation	538	982
Vitrification	871	1316

Vertical Shaft Brick Kilns (TERI, 2004) which are in use in China are far more efficient in reaching the required temperatures (900 ^{O}C) and therefore much less fuel is used. It is reported that 110 grams of coal are needed per kilogramme of brick whereas normal kilns use 700 grams of coal per kilogram. Brick losses are also lower. The use of such kilns is being promoted in South East Asia. Whether they can be used to produce lime is not known at this time but a study of this is recommended.

4.5.4 Cement production in Cambodia

Since 2004 two industrial scale cement plants have been established in Cambodia. One, in Kampot Province has an annual capacity of 850,000 tonnes.

5 Summary

Use of stabilisation

In many Cambodia provinces, there is a lack of locally available materials of suitable quality to construct unbound pavement layers for either unsealed or bitumen sealed roads. Quality materials are hauled considerable distances. This not only increases construction costs but also increases structural wear on the existing road network by heavily loaded construction traffic. At the same time a wide range of local materials from sandy gravels to fine plastic soils are available and are likely to be suitable for stabilisation as indicated by an examination of the soils found in the ENS studies. Stabilised roads maybe readily designed using standards and specifications modified from existing documents.

Hydraulic stabilisers (cement or lime) are likely to be the most suitable technically and economically. For some soils, stabilisation using bituminous binders may be appropriate, but experience from regional trials has indicated some difficulties in using equipment readily available to small contractors

All hydraulically or bituminous bound stabilised materials will have high resistance to infiltration of water, adding protection to other parts of the road, and will retain high strength when wet.

Bituminous stabilisation may find application where only clean sands are available for construction, but this is likely to be very limited. Based on cost and difficulties in mixing bitumen with soils without specialist equipment, it is unlikely to become an economic or technically better alternative to using hydraulic stabilisers.

The stabilisation of the local roads without placing a surfacing is unusual, but appears effective in the short term. It is not known if the pavement will be durable; technical concerns are that the stabilised layer will carbonate, lose its strength and revert to the original material. If it proves durable then it saves the very large cost of providing a bituminous surfacing.

Maintenance of stabilised roads

Potentially, the maintenance of stabilised roads is relatively easy and readily achieved by local communities. Defective areas, potholes for example, can be cut back with hand tools and repaired using local materials mixed with a little cement or lime as appropriate, avoiding the need for quality materials (aggregates) which are unlikely to be at hand. Cement or lime will be locally available.

Cement

The availability of cement in Cambodia is good. Local supply has improved recently with the establishment of two new cement factories. Alternatively, cement is readily available from imports from neighbouring countries.

Lime

Local supplies of lime are severely restricted. Only two local industry suppliers are available in the country. In the short term the use of lime stabilisation will require the use of imported lime from neighbouring countries. The cost of locally available lime is similar to the cost of imported lime. In the longer term it would be beneficial to increase the availability of locally produced lime, not only for the road construction industry but also as a manufactured resource for the benefit of many sectors including agriculture. However, expansion of the lime production industry would need to be established on a sustainable basis with regard to fuels used. There is an opportunity through research to create a local industry with better designed and more efficient lime burning facilities as are now used internationally. It should not be necessary for Cambodia to endure the long learning process experienced by other countries that now have an efficient capability to produce lime.

In the medium term the use of the local experience and kilns adapted or used in brick making should be investigated for lime production. Studies such as the small kiln design in USA should be considered for Cambodia to develop a rational approach to efficient kiln design.

Constraints for the production of lime on the large scale should be investigated to see if there is likely to be opportunity and scope for production on this scale in the medium to long term.

Contractor capability

The processes are not difficult and can be readily learned by local contractors although they may need guidance and training. Agricultural equipment is available for mixing the stabiliser. Larger scale projects are likely to be undertaken by local contractors in association with international contractors who may be expected to have experience in the processes involved. Quality control and adherence to good methodology and procedures will need to be exercised, as always.

Testing of materials

Generally the laboratory and site testing methods for testing stabilised materials make use of existing equipment found in materials laboratories. These laboratories will be able to form, cure and test specimens. However, using standard equipment for forming samples can be laborious and time consuming and is more suitable for final testing for design and for quality control on site.

Minor equipment such as a pH meter to test the initial consumption of lime or cement will need to be provided. The standards define the equipment required.

Cost of stabilisation

An accurate calculation of total costs over the life of a road constructed using stabilisation techniques and a comparison with alternatives has not been possible at this stage. Stabilisation provides a number of engineering benefits that should enhance the life of a road and reduce maintenance costs. When the lack of locally available quality materials is taken into account and long hauls are required, damaging the existing network and adding to pollution, the whole life costs of stabilisation of local materials will usually favour the stabilisation approach over alternatives but definitive data for Cambodia is not available at present and needs to be the subject of research studies.

6 Recommendations

The recommendation on further research arising out of this study are contained in a Concept Note showing the recommended way forward to implementing a sustainable national use of stabilisation techniques for low volume rural roads. This Concept Note is a stand-alone document but is reproduced below as Appendix A for completeness.

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DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

Stabilisation Techniques to Improve Local Materials for Rural Road Pavements in Cambodia

Appendix A

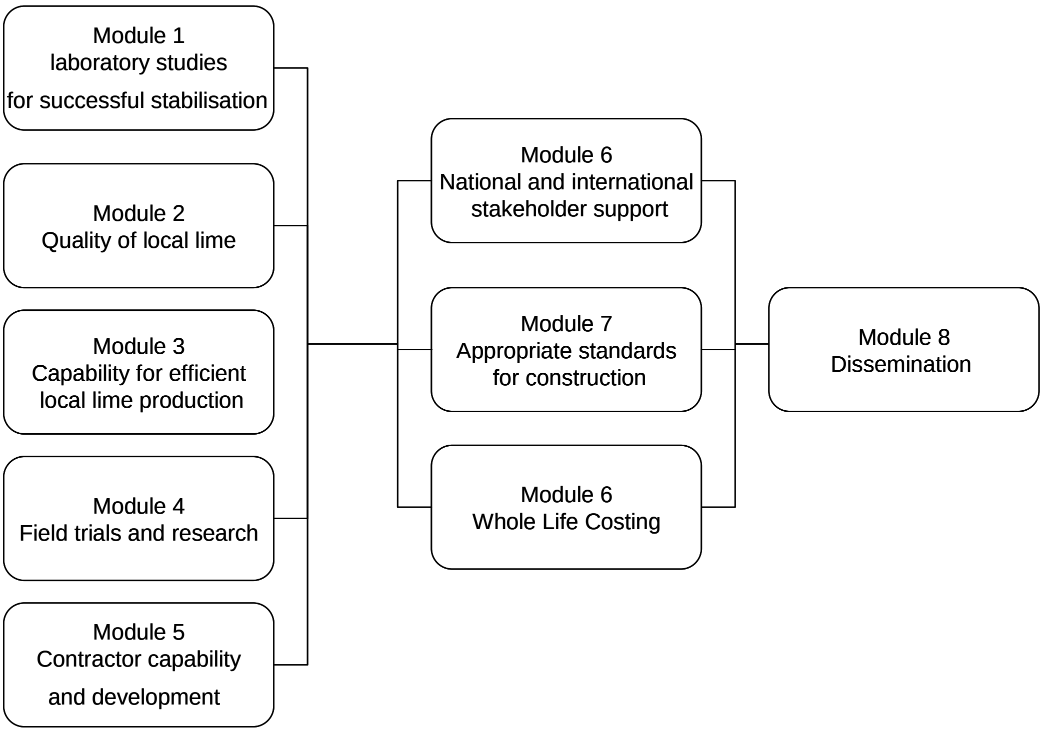
Developing the use of stabilisation techniques in Cambodia

A.1 Introduction

In many of the provinces in Cambodia, there is a lack of locally available materials of suitable quality to construct unbound pavement layers for either unsealed or bitumen sealed roads. Quality materials are hauled considerable distances. This not only increases construction costs but also increases structural wear on the existing road network by heavily loaded construction traffic. At the same time a wide range of local materials from sandy gravels to fine plastic soils are available and are likely to be suitable for stabilisation. Hydraulic stabilisers (cement or lime) are likely to be the most suitable technically and economically. Stabilised roads may be readily designed using standards and specifications modified from existing documents.

However at present there are few examples of the use of stabilisation and little practical experience in the local road building community. Cement is readily available but lime is predominantly imported. A local lime production industry would be advantageous, but there are also concerns about developing such an industry that relies on inefficient kilns and using wood as fuel. This concept note presents a research based programme to address these issues and others and develop standards for an alternative and cost effective means for the construction of durable roads in the rural areas. The concepts are set out in modules as shown in Figure A1 and the ideas are developed in the following paragraphs.

Figure A1 Stabilisation Techniques to Improve Local Materials for Rural Road Development



A.2 Module 1- Laboratory studies for successful stabilisation

Module 1 addresses the difficulty of introducing the concepts and benefits of stabilisation through research based studies of the local materials and their technical response to stabilisation. A laboratory based study will be carried out to show the extent that stabilisation may be used. Representative sample of soils and other road building materials of different types will be collected from different regions and provinces and commonly available cement and lime will be used to determine the changes in properties that can be achieved through stabilisation.

At the same time the qualities of the commonly and currently available limes and cements will be established.

The module will also include bituminous and mechanical stabilisation of materials for those circumstances where it is appropriate, and to complete the knowledge base on the use of conventional stabilisers and stabilisation techniques.

A.3 Module 2- Quality of available limestone

Module 2 addresses the potential of the locally available limestone to produce hydraulic lime. In association with other stakeholders including NGOs operating in this field, the location of sizeable rock outcrops and their potential to be exploited, or not, as sources for the production of lime. Outcrops that are deemed potentially available for lime production will be sampled and the specimens will be "burned" in the laboratory and the quality of the lime so produced will be quantified according to standard test methods.

A.4 Module 3 - Capability for efficient local lime production

Module 3 will address the processes and kiln design required for the efficient burning of lime. In the first instance a connection will be arranged to determine the feasibility of using the existing kilns that are used for brick making. Pilot burning will be undertaken to clearly establish the potential. Modification to those types of kilns will be considered, as necessary. At the same time, the two existing small scale lime burning industries will be visited to gain an understanding of the kiln efficiencies and the quality of lime they produce, and the efficiency of the business.

If necessary, pilot size efficient kilns will be designed and constructed as a model for the development of the industry. A successful design will address the problem of efficient fuel for burning and the potential for sustainable wood growing areas attached to the business for a sustainable supply. Other fuel sources, such as LPG will be investigated to understand any constraints to its use and to seek solutions to overcome these, leading to the adoption of LPG as a fuel. Use of waste products as fuel will also be addressed.

From a successful model a full-scale kiln could be constructed at a suitable site. This may be in association with the brick making industry, the existing local lime kilns of on a green field site with support from the stakeholders.

A.5 Module 4 - Field trials and research

Module 4 will develop confidence in the use of stabilisation from an understanding of the performance of those roads where stabilisation has been used. It will be important to include the innovative work carried out under the NZaid project where the trial local roads were left unsealed, since large savings may be made in the provision of roads at that level of the road network. It will also be informative to investigate the main road constructed in association with the trial roads and also the other existing roads such as National Road NR1 where the road pavement was stabilised. The study of existing roads and the prediction of their service life under existing traffic and environment presents opportunities for the rapid consolidation of knowledge into practice. Investigations followed by analysis will enable the benefits and durability to be established and reported.

Opportunities for new pilot and full-scale trials should be sought. These are likely to be in association with ongoing or planned civil works. Their importance is to address the variables for which a solution cannot be found from the existing road trials and in-service roads. As demonstration trials, they do not contain the range of parameters required for the full and effective implementation of stabilisation for local roads.

When the lack of locally available quality materials is taken into account and long hauls are required, including as assessment of damage to the existing network and adding to pollution, the whole life costs of stabilisation of local materials will usually favour the stabilisation approach over alternatives but definitive data for Cambodia is not available at present and this needs to be established through research studies.

A.6 Module 5 Contractor capability and development

Module 5 moves the technical understanding into the local construction industry. Larger scale projects are likely to be undertaken by local contractors in association with international contractors who may be expected to have experience in the processes involved, but this capability does not exist within the government construction units or the local contracting industry that are more likely to undertake civil works on local roads. However the processes of stabilisation are not difficult and can be readily learned but there is a need to provide guidance and training.

A training capacity will be established where government entities and private contractors may be taught and may practice the techniques required. As well as imparting training, an evaluation will be made to establish whether method based or end product based compliance standards are the most suitable for the industry. It may be that a composition of both will be required. Quality control and adherence to good methodology and procedures will need to be exercised, as always.

At the same time, laboratory capabilities will be established and the need for the expansion of equipment, along with training. Much of the test equipment will already be present in a standard laboratory for road building, but it is likely that there will be some specific equipment that needs to be procured.

Contractor training will be very much a practical exercise and lengths of road or trial areas will need to be made available for this purpose.

An assessment of the availability of construction equipment will be made. Agricultural equipment for mixing stabiliser with the host material is available, but its efficiency and importantly the depth of material it can process will be important factors in the development of suitable standards. Availability of other equipment that forms a road construction unit with also be evaluated so an efficient capable unit may be formed and minimum requirements advised.

Potentially, the maintenance of stabilised roads is relatively easy and readily achieved by local communities. Defective areas, potholes for example, can be cut back with hand tools and repaired using local materials mixed with a little cement or lime as appropriate, avoiding the need for quality materials (aggregates) which are unlikely to be at hand. Cement or lime will be locally available. This capability will be explained and taught to contractors, and other entities responsible for the maintenance of low volume local roads.

A.7 Module 6 Whole Life Costing

An accurate calculation of total costs over the life of a road constructed using stabilisation techniques and a comparison with alternatives is required. In concert with the technical evaluations it will be essential to demonstrate the economic benefits, or otherwise, of using stabilisation as an alternative to using unbound materials in road building. This will be achieved by taking into account the whole life costing approach for infrastructure development.

Important aspects of this will be to establish the variables and true costs of building road pavements using unbound materials and the alternative of using stabilised materials. The well understood basis for estimating financial unit costs of materials equipment and labour costs together with overhead and profit and construction unit daily outputs will be examined to produce realistic estimates that can be used to compare construction costs. Data will need to be sourced from current knowledge and research studies, as will information on maintenance costs.

A.8 Module 7 - National and international stakeholder support

There is considerable will and activity amongst bilateral and multilateral donors and the Cambodian Ministries to develop the rural road network in Cambodia for the alleviation of poverty amongst the rural poor. These entities and other stakeholders will be advised and approached for opportunities for research and demonstration trials to assist in the implementation of stabilisation for full scale civil works projects.

For the development of a local lime industry support will also be sought from international and civil authorities to consider the potential for investment in the lime industry. For example micro finance or business grant opportunities may be available to support the start-up of such ventures.

A.9 Module 8 provision of appropriate standards for construction

The knowledge gained from the modules outlined above will enable practical and focused specifications and standards to be prepared that will permit technical requirements to be achieved but reduce the complexity of those currently available. This will enhance the application of stabilisation techniques by providing a better balance between the essential need to retain technical quality with compliance requirements. A structured and systematic approach is required that sets out the procedures to be followed to lead the supervisor and contractor though the processes to the common goal of efficiently undertaken quality construction. These will complement the existing Cambodia Road Standards and be applicable for local road construction.

A.10 Module 9 Dissemination

The activities, analysis and information gained from the modules above will be reported and so will provide the basis for disseminating knowledge and experience required for the use of stabilisation for road building in Cambodia. Together with dissemination of whole life costing approach and application, this will assist road planners and designers. The capacity building for the government and contracting civil works entities will provide the expertise to carryout the works to the required standard. Dissemination of the information to the international donors and the highest levels of government will engender their support leading to take-up of stabilisation as a viable alternative for the development of the Cambodia road network.

Appropriate Dissemination will also need to be provided to international and local business entities to gain support for a local lime industry.

Much of the early dissemination routes will be workshops and technical reports, but as the certainty of output, technique and application and quality assurance develops and standards and specifications ole of are achieved the deliverables should be disseminated on local regional and internationally accessible websites. As an example the whole of the UK road design and contract documents for works including standard drawings are freely available for download. Achieving this level of dissemination truly ensures all designers and practitioners have the concerted view on best practice at hand and can be applied.

DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

Stabilisation Techniques to Improve Local Materials for Rural Road Pavements in Cambodia

Appendix B
ASTMS Test Methods for Lime

ASTMS Test Methods for Lime

Subject	Code	Title
Soil Stabilisation:	C977	Specification for Quicklime and Hydrated Lime for Soil Stabilisation
	C593	Specification for Fly Ash & Other Pozzolans for use with Lime for Soil Stabilisation
Test Methods:	D6276	Using pH to Estimate the Lime Requirement for Soil Stabilisation
	D5102	Unconfined Compressive Strength of Compacted Soil-Lime Mixtures
Asphalt:	C1097	Specification for Hydrated Lime for Use in Asphalt
	D4867	Test Method for the Effect of Moisture on Asphalt Paving Mixtures:
Environmental Uses	C1529	Specification for Quicklime and Hydrated Lime for Environmental Uses
	D6249	Guide for Alkaline Stabilisation of Wastewater Treatment Plant Residuals
Test Methods:	C400	Quicklime and Hydrated Lime for Neutralization of Waste Acid
	C1318	Determination of Total Neutralizing Capability and Dissolved Calcium and Magnesium Oxide in Lime for Flue Gas Desulfurization (FGD)
Building Lime	C207	Hydrated Lime for Masonry Purposes
	C206	Finishing Hydrated Lime
	C821	Lime for Use with Pozzolans
	C5	Quicklime for Structural Purposes
	C270	Mortar for Unit Masonry
Other Applications:	C911	Quicklime and Hydrated Lime for Selected Chemical and Industrial Uses
	D5050	Guide for Commercial Use of Lime Kiln Dusts
	E1266	Practice for Processing Mixtures of Lime, Fly Ash, and Heavy Metal Wastes in Structural Fills and Other Construction
Applications	C602	Specification for Agricultural Liming Materials General Testing
General testing	C25	Chemical Analysis of Quicklime and Hydrated Lime
	C110	Physical Testing of Quicklime and Hydrated Lime
	C1271	X-Ray Spectrometric Analysis of Lime
	C1301	Major & Trace Elements in Lime by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP) & Atomic Absorption (AA)
Other:	C51	Terminology Relating to Lime
	C50	Sampling, Sample Preparation, Packaging, & Marking of Lime Products
Note 1: List obtained from The National Lime Association. USA. www.lime.org		

DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

Stabilisation Techniques to Improve Local Materials for Rural Road Pavements in Cambodia

Appendix C

Comments and application of the reviewed literature

Comments and application of the reviewed literature

Literature on conventional stabilisers

Author	Date	Title	Comment	Subject				Specifications	
				Mechanical	Cement	Lime	Bituminous	Material	Construction
		Stabilisation Of Natural Materials For Road Building	Bitumen and other stabilisers are also mentioned, as is carbonation.	√	√	√		√	
Austroads	1998	Guide to Stabilisation in Roadworks Sydney							
Auststab	2002	Model Specification for Insitu Stabilisation of Local Government Roads using Bituminous Binders. Model Specification 2 for Local Government Roads	Design and specification of bitumen stabilisation using emulsion or foamed bitumens				√		
AustStab	2004	Lime stabilisation practice Technical Note No.lB.	Practical design with information on using available lime concept and indicative costs			√			√
Bagonza, S.	2002	Experience With Lime Stabilisation In Uganda:	Successful use of soil stabilisation						
CIRIA	1988	CIRIA Special Publication 47: Laterite in road pavements	Of particular use to understand the properties of lateritic materials in Cambodia and around the world	√	√	√		√	√
Dept Army and Air Force	1994	Soil Stabilisation For Pavements TM 5-822-14	Comprehensive manual including lime treatment of expansive clays		√	√	√		
Hicks Gary R.	2002	Alaska Soil Stabilisation Design Guide	Broad based review. Providing a brief on a wide range of stabilisation methods including other types.	√	√	√	√		
Ingles & Metcalf	1972	Soil Stabilization	Comprehensive review of the theory and practice of stabilization for civil engineering projects	√	√	√	√	√	√

IRC	1992	Guidelines For The Use Of Soil-Lime Mixes In Road Construction.				√			
IRC	2000	State of the Art: Lime-Soil Stabilisation	Comprehensive review. Specifications are for subgrade and sub-base			√			√
Makaeff, T	2007	Stabilising Cambodia's Roads	Supportive brief of the concept			√			
MOT	2007	RRST Guidelines:Rural Road Pavement And Surface Condition Monitoring.	Includes the stabilisation of local soils by lime, cement and bitumen emulsion		√	√	√		
MRD	Undated	Study of Laterite Road Sustainability. Ministry of Rural Development, Seila Programme.	About the deterioration of lateritic and other gravel roads; not stabilised						
NZAID – ADAF	2007	Local Resources For Local Roads In North western Cambodia.	Construction practical experience with some design considerations. Includes valuable trial sections with unsealed surface. Mentions local lime production in Cambodia. Battambang and Kampot. small scale family businesses		√	√			
OB9	1969	Lime stabilisation of soils for use as road foundations in Northern Rhodesia (Zambia).							
Perera, ASR, A. Al-abbaa, J.M. Reidb, J.A. Stegemann'	Undated	State Of Practice Report UK Stabilisation/Solidification Treatment And Remediation Part Iv: Testing & Performance Criteria	Considers original material as contaminant and stabilisation as the treatment. Provides a review of the wide range of test methods used including the control of leaching, (by using the stabiliser). Wide scope than roads.		√	√			
Transit	2000	Draft Guidelines for the Sampling and Testing of Stabilised Materials during Construction.							
Sherwood, P. T.		Soil stabilisation with cement and lime. State of the art review.	Comprehensive in depth review of current understanding.	√	√	√			
O'Reilly, M P	1980, Pre	The compaction of soils and stabilised bases on roads in East Africa.							
Bofinger, H E, H O Hassan and R I T	Pre 1980	The shrinkage of fine-grained soil-cement. SR398. Transport Research Laboratory, UK	Cracking is a feature of cement stabilised materials often caused by shrinkage. Offers an in depth understanding of the factors and causes of cracking.		√				

Williams			In stabilised road layers based on a comprehensive laboratory study.						
Hitch, L S and R B C Russell	Pre-1980	Bituminous bases and surfacings for low-cost roads in the tropics. SR284.	Describes full scale road trials supported by laboratory studies giving acceptance criteria for sand bitumen bases. Construction issues are discussed				√	√	√
O G AND J B METCALF	1972	Soil stabilisation – Principles and practice							
ORN31	1993	A Guide To The Structural Design Of Bitumen – Surfaced Roads In Tropical And Sub-Tropical Countries.	Comprehensive guideline		√	√		√	√
Hitch, L S and R B C Russell	1980, pre	Sand-bitumen for road bases: an examination of five methods of measuring stability LR717					√		
Jones, C R and H R Smith	1980	Tensile and compressive strength of some stabilised road bases in Kenya. SR623.	Measurement of the direct tensile and unconfined compressive strength stabilised road bases in Kenya. Comparison with road performance.						
Smith, H R, T E Jonesand C R Jones	1980	Performance of sections of the Nairobi to Mombasa road in Kenya. LR886 Transport Research Laboratory							
		R6898 : Guidelines on the selection and use of road construction materials							