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DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

SEACAP 19 Technical Paper No 1

Bamboo Reinforced Concrete Pavements

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ABBREVIATIONS AND TERMINOLOGY

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic (sum of both directions)
AIT	Asian Institute of Technology
BRC	Bamboo Reinforced Concrete
BRCP	Bamboo Reinforced Concrete Pavement
CBR	California Bearing Ratio
CRCP	Continuously Reinforced Concrete Pavement
DfID	Department for International Development (United Kingdom)
E	Elastic modulus
esa	equivalent standard axles
h	thickness of a pavement layer in mm.
ILO	International Labour Organisation
INBAR	International Network for Bamboo and Rattan
JRCP	Jointed Reinforced Concrete Pavement
km	kilometre
KN	Kilo Newtons
LCS	Low Cost Surfacing
LVRR	Low Volume Rural Roads
m	metres
mesa	million equivalent standard axles
mm	millimetres
MN	Mega Newtons
MPa	Mega Pascals
psi	pounds per square inch
SEA	South East Asia
SEACAP	South East Asia Community Access Programme
ToR	Terms of Reference
US	United States
UNDP	United Nations Development Programme
vpd	vehicles per day

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EXECUTIVE SUMMARY

Bamboo has high tensile strength and is relatively light in weight. It is therefore an attractive material for engineering purposes and has had many applications in construction works for hundreds of years. Its properties are such that it also has the potential for reinforcing weaker materials and it was inevitable that its use for reinforcing cemented materials, including concrete, should be considered. However, it is not an easy material to use for this purpose. This is because (a) it has poor bonding characteristics with cement and concrete, (b) it undergoes considerable volume changes due to absorption of water (or as it dries out), (c) it is prone to deterioration as a result of the action of chemicals, insects, and fungi, (d) its properties are extremely variable depending on its species, harvesting, age, treatment, and other uncontrollable factors. Furthermore, and most importantly, its elastic modulus is relatively low compared to steel, the principal alternative reinforcing material. Considerable research has therefore been necessary to determine whether these problems can be solved. This report reviews this research and confirms that there are numerous successful uses of bamboo for reinforcing cemented materials in *specific circumstances*. However, the review also shows that bamboo is frequently not suitable.

Very few examples of its use in reinforcing cement concrete road pavements could be found and the review shows that this particular use has given rise to a certain amount of confusion and controversy. The report clarifies the issues and, based on both the review and the performance of trial pavements built to study the effectiveness of bamboo reinforcement, concludes that bamboo provides no identifiable benefit as reinforcement in concrete pavements..

There are essentially three main reasons that are cited for using bamboo reinforcement in concrete pavements. These are,

1. *To prevent cracking under traffic load by providing all the tensile strength required in the concrete slab.*

2. *To minimise the width of any cracks that do form in the concrete (for whatever reason) and to hold the slab together as an entity for as long as possible*

3. *To prevent the cracking that normally occurs when a large slab of concrete cures and shrinks*

Load induced cracking. The argument is that, since concrete has almost no tensile strength, tensile stresses applied to the slab will cause it to crack. Reinforcement can only comprise a small fraction of the cross section of the slab, hence high tensile strength in the reinforcement is essential if it is to carry the total load. Bamboo has this high strength.

For the reinforcement to work in this way and to carry a large proportion of the stress generated by the traffic load, its elastic modulus must be much greater than that of the concrete. If this is not so, then as the strain increases, the concrete will crack long before the stress in the reinforcement is high enough. *The elastic modulus of bamboo is much lower than that of cured concrete and so bamboo can never fulfil this function*.

It should be noted that for cement-based materials which have a low elastic modulus e.g. sand-cement mortar, or soil-cement, bamboo does provide reinforcement and fulfils a useful function.

Although the tensile strength of concrete is low, concrete roads are normally designed to utilise this strength. The stresses are highly dependent on the support provided to the concrete slab by the underlying layer and provided that this layer is constructed adequately, the concrete should not crack. Thus reinforcement is rarely used for roads carrying relatively low volumes of traffic. In the UK, for example, reinforcement (steel) is not recommended unless cumulative traffic exceeds 8.0 million equivalent standard axles.

Minimising crack width. If cracks form for any reason (e.g. poor concrete, heavily overloaded vehicles) it is clearly advantageous to minimise their width to maintain as much interlock across the crack and to minimise the amount of water that could enter and cause weakening of the underlying layers. Reinforcement with a high elastic modulus (and good bonding characteristics with the concrete) means that the full load can be borne by the reinforcement with only a small amount of associated strain, hence the cracks will only open a small amount. Bamboo has a relatively low elastic modulus and poor bonding characteristics. It has proven very difficult to provide enough bamboo reinforcement in a concrete slab, and to treat it to improve the bond, so that the crack widths are acceptable according to current structural engineering practice.

It is not expected that a properly designed concrete road will crack during its early life. If, eventually, it does so, it is highly likely that the quality of the bamboo will have deteriorated to such an extent that it provides no reinforcement at all. The bamboo reinforcement in samples taken in mid 2007 from a trial pavement constructed in 2002 at Puok market were found to have disintegrated.

Preventing shrinkage cracking. It has been suggested that the introduction of bamboo reinforcement may prevent or control shrinkage cracking as the concrete cures. Initially the elastic modulus of concrete and its strength will be very low (i.e. much less than that of the bamboo). As the concrete cures, both its elastic modulus and its tensile strength increase, but not necessarily at the same rate. At the same time, the concrete begins to bond with the bamboo and shrinkage stresses also begin to develop in the concrete matrix. At the point when the concrete would normally crack, the modulus and strength of the concrete compared with bamboo might be such that true reinforcement occurs and cracking is prevented.

However, with no reinforcing, worldwide experience tells us that a concrete slab is only likely to suffer shrinkage cracks if it is longer than about 4.5m. The curing process is too complicated to calculate this accurately but it can be tested by experiment. Indeed, this was one of the main purposes of the experiments that were carried out at Chiang Mai University in Thailand in the mid-1980s. The results showed that slabs as long as 6.0m could be made without shrinkage cracking occurring and therefore indicated that some reinforcing effect may have been taking place during curing of the concrete, but the effect was small. The research was not sufficiently comprehensive to confirm that 6.0m slabs could always be used. Furthermore, the benefit of using 6.0m slabs rather than 4.5m slabs is doubtful given the effort required to add the bamboo reinforcing.

Experimental trials

As part of the SEACAP programme in South East Asia, trials of bamboo and steel reinforced concrete pavements have been built in Vietnam. The results to date show that out of 236 bamboo reinforced slabs, 27 have cracked (11%), but out of 201 unreinforced slabs, only 12 have cracked (6%). These slabs need to be studied in more detail before final conclusions can be drawn (e.g the width of the cracks needs to be assessed) but the evidence indicates that bamboo reinforcement is having no significant effect. This is as expected from the analysis contained in the full report.

Conclusions

It is therefore concluded that bamboo reinforcement is of no benefit in the construction of LVRRs made with concrete.

SEACAP 19: Technical Paper No. 1

Bamboo Reinforced Concrete Pavements

1 Introduction

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

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

Despite the fact that the report by Azam et al. (2002) refers to research on bamboo reinforced concrete pavements (BRCP) carried out at Chiang Mai University in Thailand, the report does not reference any documents from that source, nor does it describe how the design of the reinforcement was carried out. It appears that a report was submitted to ILO by the University but was never published (see Appendix A). A review by Gleeson (2002) identifies a key reference by Brink and Rush (1966) which was placed on the worldwide web in 2000 by the originating organisation because of its historical interest. However, the definitive paper on the topic is probably that by B V Subrahmanyam in 'New Reinforced Concretes' published by the University of Surrey in the UK. Typical properties of bamboo quoted in this paper are shown in Table 1.1

Table 1.1 Mechanical properties of bamboo reinforcement

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

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

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

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

2 Structural reinforcement

2.1 Steel reinforcement

Steel is ideal for reinforcing concrete because it has a high tensile strength and a high modulus of elasticity. These two attributes are essential if the reinforcement is to function effectively in the two principal roles that it normally has to play. These are,

1. *Providing all the tensile strength required in the structural member*. Since the concrete has almost no tensile strength, tensile stresses applied to the member will cause it to crack. Since the reinforcement can only comprise a small fraction of the cross section of the member, high tensile strength in the reinforcement is essential if it is to carry the total load.

2. *Minimising the width of the cracks that exist in the concrete*. Since cracks are usually inevitable in a structural member in tension, it is important to minimise their width, both for structural and aesthetic reasons. A high elastic modulus means that the full load can be borne by the reinforcement with only a small amount of associated strain, hence the cracks will only open a small amount. Limits are usually set for crack width for different purposes.

In order to determine the amount of reinforcement required it is necessary to know the safe level of stress that the reinforcement can tolerate. For steel, this is relatively easy because its properties are consistent, they do not change significantly with time, and they have been very well documented. Thus the requirements for coping with long-term loads, short-term loads and repeated loads (i.e. creep properties, strength properties, fatigue properties and so on) are well known and reliable solutions to the design problems are available. The situation is somewhat different when bamboo reinforcement is considered.

2.2 Bamboo reinforcement

Bamboo reinforcement has been well documented by Subrahmanyam (1984). To begin with, unlike steel, the properties of bamboo are not consistent but cover a wide range as shown in Table 1.1. This is because they depend on a considerable number of variables including such obvious ones as,

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

But also on less obvious factors such as…

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

As a result, the properties of bamboo vary a great deal. Much academic research has been devoted to measuring the properties of bamboos under a very wide range of conditions (see, for example, Appendix A and papers published in the INBAR[1] series of conferences and workshops) but, despite this, the detailed situation is not very clear because test methods have not been standardised and insufficient research has been done. Nevertheless, the broad range of likely values for the key variables of elastic modulus and tensile strength are well documented and therefore, for design purposes, realistic and safe values can probably be assumed, subject to checks made on samples of bamboo that it is proposed to use.

Interaction with water

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

[1] International Network for Bamboo and Rattan

Bonding with concrete

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

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

Response of bamboo to the load regime

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

Consequences

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

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

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

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

3 Principles of Rigid Pavement Design.

Gleeson's review includes design charts for concrete beams and slabs taken from the Brink and Rush paper. This paper emphasises that….

'Due to the low modulus of elasticity of bamboo, flexural members will nearly always develop some cracking under normal service loads. If cracking cannot be tolerated, steel reinforced designs or designs based on unreinforced sections are required'.

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

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

3.1 The role of steel reinforcement in road pavements

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

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

The exception to these principles occurs in the case of Continuously Reinforced Concrete Pavements (CRCP). In such pavements there are no contraction joints and therefore cracks might occur just as in normal structural concrete. The reinforcement therefore performs exactly the same role as in other structures (Section 2.1) and, for the reasons described in Section 2.2, bamboo is not suitable for such reinforcement; it will simply allow wide cracks to develop and will, itself, deteriorate quickly.

[Note. For historical reasons (see Appendix A) much of the literature describing the recent trials in Cambodia and in Vietnam erroneously refer to 'continuous reinforcement'. This is not the normal nomenclature for the trial pavements. Proper contraction joints have been included in the trials and therefore the correct description is Jointed Reinforced Concrete Pavements (JRCP), not CRCP. CRCP is the most expensive form of pavement construction and used only for the most heavily trafficked roads].

4 The use of bamboo as reinforcement for pavements.

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

4.1 Anomalous design principles

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

4.2 Reinforcing action of bamboo

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

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

The assumptions are shown in Table 4.1 and the stresses at the two critical points at the underside of the concrete, calculated using multilayer elastic theory, are shown in Table 4.2. For those familiar with pavement deflections, Table 4.3 has also been included.

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

Table 4.1 Assumptions

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

Table 4.2 Tensile stress at base of concrete

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

Table 4.3 Calculated deflections

Subgrade modulus (MPa)	Deflection at surface (microns)	
	Model A	**Model B**
10	1092	1085
20	683	679
50	365	363
100	226	225
200	139	138
300	104	104
500	72	71

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

The effect of increasing the elastic modulus of the reinforcement is shown in Figure 4.1. Only when the modulus of the reinforcement is greater than that of the concrete (very unlikely for bamboo) is there any reduction in the critical stress. To achieve a worthwhile level of stress reduction requires both a much greater quantity of reinforcement and a much higher modulus.

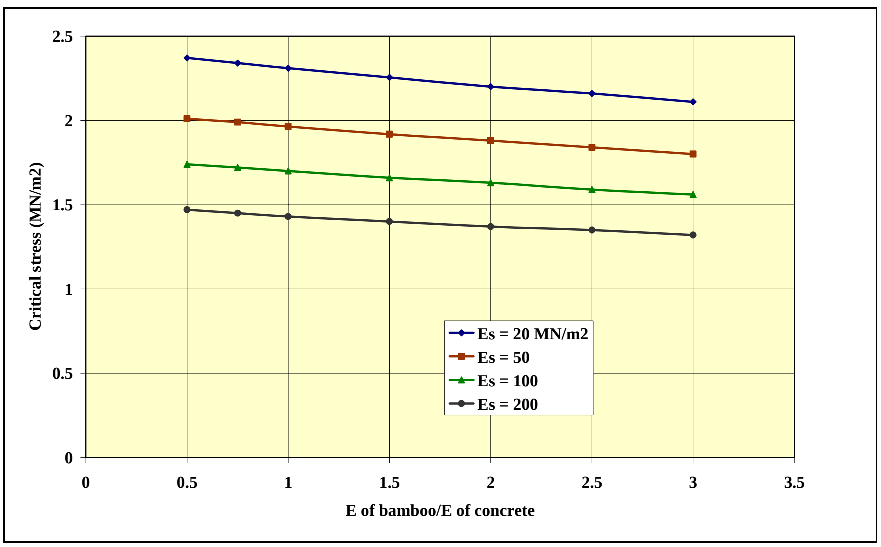

Figure 4.1 Relationship between critical stress in the concrete and bamboo modulus

However, to keep the stresses in the concrete to acceptable levels, the supporting layer beneath the concrete is of vital importance. Table 4.2 and Figure 4.1 show that the tensile stress in the concrete depends very strongly on the modulus of the supporting layer; this is why a good sub-base is required. The rule of thumb for calculating the tensile strength of concrete is that it is between 0.4 and 0.7 times √(compressive strength). This gives a very wide range (1.7 – 4.2 MPa, typically) and is really not much use for calculation purposes. However, it does indicate that a sub-base of elastic modulus greater than 100MPa is normally required. The tensile strength of the concrete from the Puok trials has been measured and found to be an average of about 3.7 MN/m^2 (Table 5.1) but this is after five or more years. A reasonable estimate of its value at 28 days is difficult to obtain accurately but is likely to be at least 3.0 MN/m^2.

4.3 Shrinkage cracking

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

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

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

4.4 Belts and braces

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

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

5 The condition of samples extracted from the Puok market road

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

Figure 5.1 Beams cut from the road at Puok showing bamboo

Figure 5.2 The condition of the bamboo after six years within a cut block (No 3)

Figure 5.3 The condition of the bamboo after extracation from crushed block (No 3)

The flexural strength of the concrete was tested using 3-point bending (now called the centre-point loading method) (BS EN 12390-5:2000).and the results summarised in Table 5.1. The compressive strength was also measured on 100mm cubes. The results are also shown in Table 5.1.

Table 5.1 Strength of the concrete samples from Puok market trial road

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

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

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

6 Results from Vietnam

The conditions of the trial sections in Vietnam after the latest survey in April 2007 are shown in Appendix B. The results are summarised below.

6.1 Rural Road Surfacing Trials Phase 1

There are 22 concrete slabs that have cracked up to April 2007 out of a total of 266 slabs. These represent five sections of road in four provinces. The results are summarised in Table 6.1

Table 6.1 Performance of the concrete sections in RRST I

Type of reinforcement	Number of cracked slabs	Total number of slabs	Percentage
Steel	2	110	2
Bamboo	20	156	13

The primary problems are on sections TG 2 and TG 9 in Tien Giang province. Note that TG 3 is uncracked (this is reinforced with steel) and is situated next to TG 2. The cracked slabs in TG 2 are all adjacent to each other (slabs 3-14). The probable reason is that the underlying sub-base has eroded during flooding leaving no support for the concrete at these chainages. This needs to be confirmed; also whether TG 3 has similar undermining but has been resistant to cracking because of the steel reinforcement.

6.2 Rural Road Surfacing Trials Phase II

There are 24 concrete slabs that have cracked out of a total of 320. This represents 19 test sections in six provinces. The results are summarised in Table 6.2.

Table 6.2 Performance of the concrete sections in RRST II

Type of reinforcement	Number of cracked slabs	Total number of slabs	Percentage cracked	Notes
Bamboo	7	80	9	On 2 sites only
Unreinforced	12	201	6	
Steel	5	20	25	One trial section only

At Ha Tinh, 7 out of 40 bamboo-reinforced slabs have cracked whereas only 3 out of 61 unreinforced slabs have cracked (at the same sites).

6.3 Interim conclusions from the trials in Vietnam

The results of trial monitoring up to April 2007 indicate that overall the bamboo reinforced sections are cracking more often than unreinforced sections. Site specific effects have not been examined in detail, but the evidence supports the hypothesis that the bamboo reinforcement is not providing any positive benefit in the early performance of the trial sections. Where site specific effects are minimised, for example, at road Hong Loc in Ha Tinh province, the bamboo reinforced section has 5 cracked slabs whereas the unreinforced section has only one. However, the overall sample size is relatively small and therefore the statistical reliability is not sufficiently high to be *certain* that the bamboo reinforced sections are performing significantly less well than the unreinforced sections; it is also likely that the bamboo is actually making no difference whatsoever but, at this stage, it is not improving performance.

Previously it has been shown that bamboo reinforcement cannot improve the long-term performance of concrete sections in terms of preventing cracking because of its low elastic modulus compared with concrete. Furthermore, once the concrete becomes cracked (or even earlier) the bamboo deteriorates quickly; it can therefore provide no subsequent benefit.

7 Conclusions

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

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

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

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

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

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

8 References and Bibliography

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Appendix A.

The Historical Context of Bamboo Reinforced Concrete Pavements.

A literature search using internet search engines reveals 1140 items on bamboo reinforced concrete but only 67 on bamboo reinforced concrete *pavements*. Most of the latter refer to publications emanating from the recent ILO and DfID/SEACAP projects and so are of little or no help in examining the history of the subject. An international library search resulted in only about 20 papers, only 10 of which were relevant.

There are several key documents emanating from the 1960s that seem to have been the inspiration for much of the more recent work on bamboo reinforced concrete. These are the papers by Glenn (1950), McClure (1963) and Brink and Rush (1966). None of these papers deal specifically with road pavements but it is worth quoting from these with reference to the history of the subject. The Glenn paper is probably not available but McClure draws heavily on Glenn. The following is from McClure.

> *Published references to the use of bamboo in reinforcing cement concrete structures or parts thereof indicate that the practice has been followed for some decades at least, in the Far East (China, Japan, and the Philippine Islands). During the 1930's several experiments were carried out in Europe, particularly in Germany and Italy, to test the performance of cement concrete beams reinforced with bamboo. The most recent, comprehensive, and readily available information on the subject is to be found in the report of a series of experiments carried out by and under the direction of Professor H. E. Glenn.*

Below is a partial summary of the conclusions of Glenn from results of tests on various beams.

1. *The load capacity of bamboo reinforced concrete beams increased with increasing percentages of the bamboo reinforcement up to an optimum value.*
2. *The load required to cause the <u>ultimate</u> failure of concrete beams reinforced with bamboo was from four to five times greater than that required for concrete members having equal dimensions and with no reinforcement.*
3. *This optimum value occurs when the cross-sectional area of the longitudinal bamboo reinforcement was from three to four percent of the cross-sectional area of the concrete in the member.*
4. *Bamboo reinforcement in concrete beams does not prevent the failure of the concrete by cracking at loads materially in excess of those to be expected from an unreinforced member having the same dimensions*
5. *When unseasoned untreated bamboo was used as the longitudinal reinforcement in concrete members, the dry bamboo swelled due to the*

absorption of moisture from the wet concrete, and this swelling action often caused longitudinal cracks in the concrete, thereby lowering the load capacity of the members.

6. *Members having optimum percentage of bamboo reinforcement (between three and four percent) are capable of producing tensile stresses in the bamboo of from 8,000 to 10,000 pounds per square inch.*
7. *In designing concrete members reinforced with bamboo, a safe tensile stress for the bamboo of from 5,000 to 6,000 pounds per square inch may be used.*
8. *Concrete members reinforced with seasoned bamboo treated with a brush coat of asphalt emulsion developed greater load capacities than did equal sections in which the bamboo reinforcement was seasoned untreated or unseasoned bamboo.*
9. *Concrete members reinforced with unseasoned sections of bamboo culms, which had been split along their horizontal axes, appeared to develop greater load capacities than did equal sections in which the reinforcement consisted of unseasoned whole culms.*
10. *When split sections of seasoned untreated large diameter culms were used as the reinforcement in a concrete beam, longitudinal cracks appeared in the concrete due to the swelling action of the bamboo. This cracking of the concrete was of sufficient intensity as to virtually destroy the load capacities of the members*
11. *Ultimate failure of bamboo reinforced concrete members usually was caused by diagonal tension failures even though diagonal tension reinforcement was provided*
12. *A study on the deflection data for all the beam specimens tested indicated:*

    (a) That the deflections of the beams when tested followed a fairly accurate straight line variation until the appearance of the first crack in the concrete

    (b) Immediately following the first crack, there was a pronounced flattening of the deflection curve (probably due to local bond slippage) followed by another period of fairly accurate straight line variation, but at a lesser slope, until ultimate failure of the member occurred. This flattening of the deflection curve was more pronounced in the members where the amount of longitudinal bamboo reinforcement was small

    (c) In all cases noted, the deflection curve had a lesser slope after the appearance of the first crack in the concrete, even though high percentages of bamboo reinforcement were used.

To summarise, result number 4 above shows that the load at which the initial cracking of the concrete occurs is not dependant on whether bamboo is present or not. The study showed that the ultimate load of a bamboo reinforced concrete beam can be very much higher than that of an unreinforced beam, but the ultimate load occurs in the bending tests long after the concrete has cracked. The tensile strength of bamboo is high and so this is not surprising.

A very recent study carried out at the University of Texas in Arlington came to similar conclusions (Khare L, 2005) although the maximum load capacity in these studies (measured) was found to be 2.5 times that of an unreinforced beam (calculated) compared with a maximum of 4 to 5 times found by Glenn. (Even so, the capacity was, on average, about 35% of that expected if steel reinforcement were to be used instead). Different bamboos and different arrangements for the reinforcing could easily explain the differences between the two studies. The report includes numerous photographs showing the progress of cracking until ultimate failure.

The second key document is that by Brink and Rush (1966). Fortunately this has recently been made available on the world-wide-web. Once again the report does not mention reinforcement in road pavements but mentions that bamboo reinforcement of concrete received very little attention until the experiments carried out by Glenn. It is, of course, impossible to determine how thoroughly the authors carried out their literature review but it is likely that access to relatively little known publications in SE Asia was not readily available.

The report was prepared specifically to assist field personnel in the design and construction of bamboo reinforced concrete. The information in the report was compiled from reports of test programmes by various researchers and represents 'current' (i.e. 1966) opinion. It clearly also leans heavily on the work of Glenn. Comments on the selection and preparation of bamboo for reinforcing are given and construction principles for bamboo reinforced concrete are discussed. The report deals with the ultimate load design of bamboo reinforced beams, columns, ground-supported slabs and walls. Thus the concrete cracks long before the reinforcement itself fails. Design procedures and charts are described and conversion methods from steel-reinforced concrete design are shown. Six design examples are presented. No mention is made of BRC in road pavements.

A study of the feasibility of using bamboo as the reinforcing material in pre-cast concrete elements was conducted at the U. S. Army Engineer Waterways Experiment Station (Smith and Saucier, 1964). Once again, ultimate strength design procedures, modified to take into account the characteristics of the bamboo reinforcement, were used to estimate the ultimate load carrying capacity of the pre-cast concrete elements with bamboo reinforcing.

The abstract of the paper by Geymayer and Cox (1970) reports essentially the same conclusions as those quoted above.

> *Tentative design and construction recommendations for the use of bamboo as an expedient reinforcement are formulated. Bamboo has a tensile strength as high as 54,000 psi (3800 kg/cm2), but its modulus in tension is less than one-tenth of that of steel. Thus, bamboo-reinforced members tend to have large deflections and wide cracks when loaded to capacity. Bamboo-reinforced members, designed and built as suggested herein, should develop two to four times the ultimate flexural load-carrying capacity of unreinforced members of equal dimensions.*

Subrahmanyam (1984) provides a more up to date review (though 23 years old now). His review mentions a pioneering investigation of the use of bamboo in reinforced concrete carried out at the Massachusetts Institute of Technology in 1914 by Chu. This research was the basis of a student thesis and does not seem to have led to any further publications although it was reported that applications were made in China in 1919 (of what? – bamboo in structures one assumes, not in road pavements). Interest waned in BRC until 1936 when some unspecified research was carried out in Germany.

During the Second World War both American and Japanese armed forces were known to have used bamboo for reinforcement, but only in temporary or emergency situations. The specific uses were not mentioned. Subrahmanyam states that investigations were then carried out in America, India, Thailand and the Philippines but gives no references at this point in his narrative. The American work he had in mind was probably that of Glenn and possibly also of Brink and Rush. Indian and other research is referenced later in his review. He makes an interesting point that none of the research had so far dealt with the effects of repetitive loading on BRC or of sustained loading. It has been reported that the sustained strength could be as low as 50% of the short-term strength, leading to specific rules on long-term design criteria.

Subrahmanyam's paper is 53 pages long and is very comprehensive, covering the properties of bamboo, the problems of its integration into concrete matrices, traditional structural engineering, including beams, walls, roofs, floor slabs and columns, and innovative uses such as bamboo-cement composites. It is notable that he does not discuss bamboo reinforcement in concrete *road pavements* but does provide the following references.

> **Purushotham, A (1963).** *A preliminary note on some experiments using bamboo as reinforcement in cement concrete*. J. Timb. Dry. Preserv. Ass. India, **9.** pp 3-14
>
> **Anon (1978).** *Bamboo used to reinforce concrete pavements in Asia.* Transportation Research News, No 79. TRB, Washington, DC.

Purushotham reviews the history of bamboo in concrete reinforcement and all the problems of its use. He then describes the construction of six structures including a pavement slab three metres square, but there are few details and no information on subsequent performance.

The anonymous note in Transportation Research News refers to a paper by R P Pama (and others not named) published in the First Conference of the Road Engineering Association of Asia and Australasia held in Bangkok in 1976 (we have not been able to find this paper to date). The note states that a prototype bamboo reinforced concrete pavement had been built at the Asian Institute of Technology and was performing satisfactorily. Several studies associated with bamboo reinforcement were carried out at AIT at that time, usually as part of Master's degrees (private communications). The thesis of A J Durrani (1975) '*A study of bamboo as reinforcement for slabs on grade'* describes the design and the construction of the trial pavement itself and also provides a summary of the behaviour of concrete pavements and the role of reinforcement. To quote from the thesis:

> *'In the case of pavements, the reinforcement is intended to maintain each slab as an integral unit, regardless of cracking of the concrete, by tying the portions on each side together without appreciable separation at the crack'*
>
> *'The cracks themselves are not detrimental as long as they are held tightly together so that load can be transferred across the crack by mechanical interlock.'*

This second statement needs qualification; it would not be fully supported by many pavement specialists today unless the cracks were very fine indeed. Any crack will allow the entry of water and every precaution is usually taken to minimise this potential problem. Nevertheless, fine cracks are much less serious than wide cracks and reinforcement that holds together a cracked pavement can extend the life of a pavement very considerably (see Section 4.4 above).

Durrani describes the thermal stresses that develop as a result of temperature changes and considers these to be the primary cause of the movements at a crack that need to be minimised. (The original cause of the crack could arise from various causes as described in Sections 4.3 and 4.4 above). The design of the reinforced slab was then based on attempting to restrict the opening of the crack to less than 0.25mm. Such calculations depend, amongst other things, upon the strength of the bond between the bamboo and the concrete. Such calculations are difficult to do accurately because of the many uncertainties about the bond strength and how it changes over time (for example, the bamboo itself expands and contracts as its moisture content changes and this affects the bamboo/concrete bond). The relatively low value of the elastic modulus of bamboo is also a major problem if the widening of cracks is to be kept very small.

The original calculations were the best estimates that could be made with the data available at that time but the longer-term purpose of the trial pavement was to examine this problem experimentally. The trial consisted of two 3 x 3 metre slabs, one reinforced with bamboo and the other with steel. The subsequent paper reporting that the pavements were behaving in a satisfactory manner does not say anything about any cracking or the control of the crack widths by the reinforcement. In such a small slab, it is very probable that no cracks developed at all and therefore the effectiveness of the bamboo in holding the cracks together could not be determined at that time. It is notable, however, that the literature search has failed to find any follow-up paper describing the outcome of this research study.

Subrahmanyam also mentions bamboo-reinforced soil-cement. However, the design of soil-cement is based on different principles to those that apply to concrete pavements. Soil-cement is not considered to behave elastically because it has an extremely low tensile strength. Also, and most importantly, its elastic modulus is also very low (~ 350 MN/m^2 - depending on properties of the soil, cement content etc.) and because of this it can be reinforced in the normal way using bamboo (elastic modulus ~ 18,000 MN/m^2) (see, for example, the paper by Nainan and Kalam (1977) for a comprehensive study). To all intents and purposes soil cement can be treated as a cracked layer similar to any other structural member that is designed to carry tension in its reinforcement, hence the references are not helpful in understanding the evolution of BRC in pavements.

Soil-cement.

Mehra, S R, R K Ghosh and L R Chadda (1957). *Bamboo reinforced soil cement as a construction material.* Central Road Research Institute, New Delhi, India.

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Nainan, P K and A K A Kalam (1977). *Bamboo reinforced soil cement for rural use.* Indian Concrete J. **51.** pp 382-389.

Subrahmanyam also mentions the design of concrete slabs and provides references. Papers on the design of concrete slabs *could* possibly include road pavements but they usually deal solely with floor slabs and these are treated in a similar way to structural members, not as pavements that should not be allowed to crack.

Concrete slabs

Ali, Z and R P Pama (1978). *Mechanical properties of bamboo reinforced slabs.* Proc Int. Conf. Materials of Construction for Developing Countries. Bangkok. pp 49-66.

Singh, M P J and S K Jain (????). *Use of bamboo as reinforcement in concrete slabs.* Technical Note, Central Building Research Institute, Roorkee, India.

The first paper was based on the Master's thesis of Zahid Ali under the supervision of Ricardo Pama at AIT in 1974. This research was based purely on the reinforcement of a cement-sand mortar and was carried out the year before the research that led to the construction of the trial pavement described above. Ali carried out a considerable number of tests to determine the properties of the bamboo itself. However, a cement-sand mortar has rather different properties to those of concrete. In particular, its elastic modulus and its tensile strength are much lower. In this respect it is much more akin to soil-cement. Ali tested the reinforced material in both the uncracked and the cracked phases and obtained results that agreed reasonably well with theoretical calculations based on the laws governing mixed composite materials. Some tests were unsatisfactory owing to failure of the bamboo/mortar bond. The thesis is most notable for the detailed results of testing the bamboo alone.

The research at Chiang Mai University

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

The control of shrinkage cracks in continuously-laid unreinforced concrete slabs by inducing the cracks at preset intervals is a very well known and relatively easy technique (introducing dowels for load transfer is, however, more difficult). For local resource-based construction, concrete slabs are automatically made with the correct dimensions without the need to induce cracks. Therefore the slight benefit that arises by reducing the number of joints by increasing the slab length from, say, 4.0m to 6.0m seems to be outweighed by the complexity of adding bamboo reinforcement to achieve this. Furthermore the experiments at Chiang Mai University were not sufficiently comprehensive to be certain that a 6.0m slab would be possible in all likely situations; indeed, this was one reason why the results were not published more widely at that time.

The way that reinforcement *will* affect behaviour is if the concrete slab does crack for any reason (e.g. severe overloading, partial loss of underlying support caused by erosion, pumping, subgrade volume changes, etc). Without a connection between the two parts of the cracked slab, differential vertical movement of the two parts of the slab occurs, especially if there is poor support from the sub-base layer and interlock across the crack is lost. Thus, under these conditions, reinforcement will hold a cracked slab together and allow it to carry traffic for considerably longer. This is a belt and braces approach. Bamboo, however, will not fulfil this function for very long because it is then exposed to water and attack by insects and will surely decay quickly. If steel is used, the eventual disadvantage is the added difficulty in the future of reconstructing a pavement which contains strong reinforcement. The public works authority in Thailand initially adopted bamboo reinforcement for use in LVRRs but did not adopt the 6.0m slab, reverting to the traditional 4.5m slab in their designs. Eventually the use of bamboo was discontinued and steel was used instead. The primary reason for using reinforcement at all was to eliminate the need for reconstructing the existing road; in other words, the concrete was laid on a relatively unprepared sub-base and therefore the quality and uniformity of the support was not guaranteed and some cracking was therefore likely.

If BRC pavements have been constructed and used, even in a small way, outside Thailand, it would be expected that rather more references could be found to describe them and their design. As has been shown, almost no references have been found and, unfortunately, those that have been found are rather old and published in relatively unknown sources; they are therefore difficult or impossible to obtain.

The only relatively modern 'reference' is that contained in the report by Azam et al (2002). Azam does not actually provide details of his reference but does attempt to summarise the research and the results. It is thought that he is describing the same research (at Chiang Mai University) as discussed above concerning the control of shrinkage and other cracks but, if so, he has concentrated on rather different aspects of it. The following is a direct quote from Azam summarising the research...

> *The bamboo reinforced concrete pavement was designed on the basis of research carried out at Chiang Mai University, Thailand but with due regard to current practice in the design of Portland cement concrete rigid pavements. Load tests using a 10-wheeled truck were carried out on pavements of varying thickness with varying bamboo mesh positions within the depth of the pavement slabs. The overall findings of the research are:*
>
> 1. *For a relatively rigid existing soil, the position of the bamboo mesh within the depth of the pavement had little significance with regard to resistance against the imposed load of the 10-wheeled truck used for the tests.*
>
> 2. *The non-reinforced sections showed a significant increase in deflections during the test when compared to sections reinforced with bamboo mesh.*
>
> 3. *The suitable thickness for BRCP, in view of the limited tests carried out, indicate no significant difference. Hence the present practice of specifying a slab thickness of 150mmm may be reduced to 125mm or even 100mm provided proper care is taken in preparing a good supporting subsoil (recommended CBR > 25%)*

This has been quoted verbatim because, in the absence of any research report on the work, it is necessary to interpret what is being said.

First of all the phrase *resistance against the imposed load* in the first 'result' is not recognised engineering terminology. It is assumed that this phrase means that the deflections under load were not dependant on the depth of the reinforcement. Since the reinforcement is not expected to have any effect on the response to applied loads of an uncracked cemented layer, this is as expected. Unfortunately it is not known whether the imposed loads did or did not crack the slabs.

The second result is also a puzzle unless the slabs actually did crack under the loads. In these conditions the reinforced slabs are expected to support the load because the reinforcement will come into play, but the deflection will also be strongly influenced by the supporting layer. However, the supporting layer underneath the concrete slabs was quite strong hence not only would this prevent cracking of the slabs, it should also have ensured that the deflections were very small. Furthermore, even if the slabs were cracked as a result of some other cause (e.g. shrinkage), high deflections are necessary before the effect of the reinforcement is likely to be measureable because the elastic modulus of the bamboo is so low. Thus some other explanation of this result seems to be required.

It is not known how the deflections were measured but a Benkelman beam is the most likely method and this is not particularly accurate. With the small deflections expected from measurements on concrete slabs, it is postulated that this result may not be statistically valid.

The third result is also unclear. It would appear to say that the thickness of the slab (reinforced and unreinforced) did not affect the deflections. The conclusion from this is that the lowest thickness used in the trials is acceptable provided that the supporting layer is as strong as that used in the trials. In fact the supporting layer at the site of the proposed construction was much weaker than this hence a thicker slab of 150mm was chosen instead. No design details were included in the versions of the paper available to the SEACAP 19 team (the appropriate Appendix was not present).

Conclusions

The conclusion from this review is that the behaviour of bamboo reinforced concrete is reasonably well understood. Bamboo has a high tensile strength but a low modulus. If cracks can be tolerated, a bamboo reinforced member will carry loads up to about 4 (even 5) times the load that causes the first crack to appear in the concrete. This load could also be up to 35% of that which could be carried by the same volume of steel reinforcement. The magnitude of these tolerable loads depends on the type of bamboo, its harvesting and subsequent treatment. Little is known of the effects of repetitive loads or sustained loads although it is believed that, under such loading, the tolerable loads are about halved. Thus in situations where cracking can be tolerated, where deterioration of the bamboo as a result of fungal, bacterial or chemical attack can be prevented, and a service life much less than can be achieved with steel is acceptable, then bamboo can be used to reinforce concrete. However, since:

(a) cracks cannot be tolerated in our pavements,

(b) a long service life is required, and

(c) bamboo will deteriorate relatively rapidly in an exposed road pavement,

bamboo reinforcement is of no benefit to the pavement engineer.

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Appendix B.

Condition of the Concrete Slabs on the Trials in Vietnam

Province	Road	From	To	Monitoring length	Monitoring reference	Type	Age @ April 2007 (Months)	Current condition April 2007	Cracked slabs
Dong Thap	Tan Thuan Tay	0.133	0.308	175	DT02	Bamboo	23	1 transverse	1/36
Hue	Thong Nhat	0.200	0.400	200	H02	Bamboo	30		0/40
Tien Giang	My Phuoc Tay	1.100	1.300	200	TG02	Bamboo	23	Slabs 3-14 badly cracked (block)	12/40
Tien Giang	My Phuoc Tay	2.200	2.400	200	TG09	Bamboo	23	3 short transv'e, 4 long'l	7/40
Dong Thap	Tan Thuan Tay	0.308	0.483	175	DT03	Steel	23		0/35
Da Nang	Binh Ky	0.190	0.365	175	DaN02	Steel	15	2 transverse	2/35
Tien Giang	My Phuoc Tay	1.300	1.500	200	TG03	Steel	23		0/40
Ha Tinh	Hong Loc	2.700	2.800	100	HT(2)-3	Bamboo	12	5 longitudinal	5/20
Ha Tinh	Thac Minh	0.100	0.200	100	HT(1)-1	Bamboo	12	2 transverse	2/20
Hung Yen	Tan Hung	1.250	1.350	100	HY(1)-1	Bamboo	12		0/20
Quang Binh	Ngu Hoa	3.910	4.010	100	QB(1)-3	Bamboo	12		0/20
Tuyen Quang	Lang Quan	1.000	1.100	100	TQ(1)-2	Bamboo	12		0/20
Gia Lai	Ia Pnol	1.900	2.000	100	GL(1)-2	Steel	12	3 transverse, 2 ???	5/20
Dak Lak	Ea Soup	0.220	0.320	100	DL(1)-3	Un-reinforced	12		0/20
Dak Nong	Kien Duc	6.900	7.000	100	DN(1)-5	Un-reinforced	12	2 longitudinal, 2 ??	4/20
Gia Lai	Xa Trang	2.060	2.160	100	GL(2)-3	Un-reinforced	12	1 transverse	1/20
Ha Tinh	Chu Le	2.600	2.700	100	HT(3)-2	Un-reinforced	12		0/20
Ha Tinh	Hong Loc	1.710	1.810	100	HT(2)-2	Un-reinforced	12	1 transverse	1/21
Ha Tinh	Thac Minh	1.300	1.400	100	HT(1)-2	Un-reinforced	12	1 transverse, 1 long'l	2/20
Hung Yen	Tan Hung	1.350	1.450	100	HY(1)-2	Un-reinforced	12		0/20
Ninh Binh	Dong Huong	1.500	1.600	100	NB(1)-2	Un-reinforced	12	1 longitudinal	1/20
Quang Binh	Cam Lien	1.005	1.105	100	QB(2)-2	Un-reinforced	12	1 crack after construction	
Tuyen Quang	Lang Quan	3.000	3.100	100	TQ(1)-4	Un-reinforced	12		0/20
Tuyen Quang	Lang Quan	3.775	3.875	100	TQ(1)-5	Un-reinforced	12	3 transverse	3/20