FIBRE REINFORCEMENT OF STABILISED PAVEMENT BASECOURSE LAYERS

LITERATURE REVIEW

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EXECUTIVE SUMMARY

This report presents the results of the first stage of a three stage research project investigating the viability of using fibres to reinforce cemented base materials of a pavement. This stage comprised a review of the international technical literature on the topic. The literature databases held by ARRB[1] Transport Research were used to identify relevant references. These were subsequently collected and supplemented by additional references obtained from the engineering libraries of the University of Auckland and the Massachusetts Institute of Technology.

The review showed that very little literature is available specifically on the topic of fibre-reinforced cemented base materials, although there is a significant amount of literature describing research carried out on fibre-reinforced concrete. Communications with experts in the fibre-reinforcing field indicated that issues regarding fibre-reinforced concrete could be reasonably extended to fibre-reinforced cemented base materials, at least in a qualitative fashion. Using this connection, the potential for using fibres to improve the mechanical properties of cemented base materials was examined.

It is well established that cemented materials are susceptible to tensile cracking from drying shrinkage, plastic shrinkage, and fatigue-induced stresses. Before the first-crack point occurs, the properties of a cemented material with fibres are dictated by the properties of the cemented matrix and they are virtually independent of the presence of fibres. The technical literature shows that the presence of fibres in a cemented material can significantly improve the material's post-cracking performance however. Fibres can have several beneficial influences and, in particular, the ultimate tensile strength and the toughness are both increased.

The performance of a fibre-reinforced cemented material is largely influenced by three factors, i.e. the nature of the cemented matrix, the nature of the fibres, and the bond between the fibres and the cemented matrix. The fibres intercept cracks in the cemented matrix and re-distribute stresses so that crack propagation is minimised. Fibres also hold the cemented matrix together so that crack apertures are minimised. Therefore, cracks do not represent significant structural defects as they do in conventional unreinforced cemented materials. While a good bond between the fibres and the cemented matrix is important for achieving high ultimate strengths, toughness is maximised when fibres stretch and fail by pulling out rather than rupturing. This represents the maximum strain capacity that the material can tolerate.

The literature indicates that several materials have been used to produce reinforcing fibres. Of the common materials, steel, polypropylene, cellulose and glass have all been used to good effect. Recycled waste products, such as plastic bottles, have also been transformed into reinforcing fibres. This provides extra economies as well as being environmentally beneficial.

Construction of fibre-reinforced cemented base materials can be achieved using either mix-in-place or batch mixing techniques. Although both techniques have their own sets of strengths and weaknesses, the important objectives are to achieve a uniform distribution of the correct proportions of cementing agent, fibres and water, and to subsequently apply sufficient compaction to achieve an appropriate layer density.

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[1] Australian Road Research Board

An indicative economic appraisal of using fibres in cemented base materials has been carried out. The appraisal is totally hypothetical and includes a number of simplifying assumptions. However it shows that fibre reinforcement could be economically attractive. The process could become even more attractive if it facilitates the use of higher than normal cementing agent contents and/or the use of recycled waste materials for fibre production.

The report recommends that sufficient evidence of the potential viability of fibre reinforcing in cemented base material has been established and that the second stage of the project should be carried out.

For this, further research should be undertaken to study the effects of variables such as fibre type and content, and cementing agent type and content on the physical properties of cemented base materials.

This will involve the performance of a suite of laboratory tests to further investigate the influence of selected cementing agent and fibre configurations using typical New Zealand materials and conditions and, in particular, their influence on physical properties such as strength, toughness and cracking resistance.

ABSTRACT

This report presents the results of a literature review on the topic of fibre reinforcement in cemented pavement base materials. While this specific topic has not been widely researched an abundance of literature exists on the topic of fibre-reinforced concrete. The researchers have used the qualitative similarity between fibre-reinforced cemented base materials and fibre-reinforced concrete to investigate the potential viability of using fibres to improve the mechanical performance of cemented base materials.

Using fibres has great potential in cemented pavement base materials. Reinforcing fibres generally increase the ultimate tensile and flexural strengths, toughness and residual strength of cemented materials. In the realm of pavement base performance, reinforcing fibres may limit the extent of both drying shrinkage and fatigue cracking so that any cracks forming in the cemented matrix do not represent significant structural defects.

Reinforcing fibres have been produced using a large number of synthetic and natural materials. The most commonly used fibre materials include steel, polypropylene, cellulose, and glass. Recycled waste products have also been used as they offer benefits in terms of both cost and environmental issues.

1. INTRODUCTION

1.1 General

Most of the pavements constructed in New Zealand comprise compacted, unbound aggregate layers with a thin asphalt or sprayed bituminous surface course. This pavement configuration is popular for a number of reasons, i.e:

- plentiful supplies of good quality aggregate mean that the materials and construction techniques have been relatively inexpensive;
- the environmental and traffic configurations in New Zealand are such that flexible pavement structures have performed well; and
- unbound aggregate pavements are relatively easy to maintain and are amenable to staged construction.

These reasons all support the continued use of unbound aggregate pavements. However, the availability of high quality aggregates is diminishing in some areas of high demand and there will be increasing pressure in the near future to accommodate axle loads that are increasing in both magnitude and volume.

One method of improving the performance of unbound aggregate materials is to treat them with a chemical stabiliser. This generally involves mixing the aggregate with an hydraulic binding agent such as Portland cement, lime, KOBM[2] or some combination of these materials. However, the use of hydraulic binding agents can be complex and the potential is for cracking to occur in reaction to various loading mechanisms. One way of mitigating these negative effects is to provide reinforcement within the material.

This report presents the results of the first stage of a three stage project that investigates the viability of using fibre reinforcing in cemented pavement base layers. The first stage of the project involves a literature review on the topic, while the upcoming two stages will involve laboratory investigations and in-situ trials respectively.

Clarifying the term *stabilisation* is important as it may have different connotations for different readers. In general, stabilisation of pavement layers can be performed at two levels, i.e. *modification* and *cementation*.

Modification typically involves the provision of a suitable additive that improves the mechanical or working properties of a material without necessarily achieving significant cohesion of the soil or gravel particles.

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[2] KOBM is a byproduct of the steel-making process from BHP New Zealand Steel Ltd's operation at Glenbrook, approximately 50 km south of Auckland city.

Conversely, *cementation* involves the provision of an additive with the primary objective of achieving cohesion of the soil or gravel particles. Therefore, a cemented material generally has significant tensile strength which is mobilised in the resistance of applied loads.

In the context of this study, a *stabilised base layer* represents a *cemented material* where the cementing agent is Portland cement or a similar hydraulic binding agent.

1.2 Objectives

The overall purpose of this project is to investigate the viability of using fibre reinforcing in cemented pavement base layers. The objective of this first stage of the project is to review the topic in recent international technical literature. This was achieved by performing a search of the literature databases held by the library services of ARRB Transportation Research in Melbourne (Australia). Literature has also been gathered from engineering libraries at the University of Auckland and the Massachusetts Institute of Technology (USA). Additional information was obtained by making contact with leading researchers in the field of fibre reinforcing as well as with manufacturers of fibres and fibre-reinforced products.

1.3 Cemented Pavement Base Materials

When a basecourse aggregate is stabilised with an hydraulic binder the material may gain considerable strength and stiffness to a point where it is considered to be in a *cemented* state. This is achieved because the aggregate is held within a matrix of hardened cementitious paste.

The magnitude of the strength increase is dependent upon factors such as:

- binder type;
- binder content;
- binder mixing efficiency;
- water content;
- aggregate type and grading;
- curing time and conditions; and
- layer density.

Cemented materials generally have very high strength under compressive loading, however their strength in tension is relatively low. They also have very limited strain capacity making them brittle and very sensitive to defects and discontinuities. The combination of limited tensile strength and low strain capacity makes cemented materials very susceptible to cracking. In other words, cemented materials generally have a low *toughness*.

Cracking of cemented materials is induced through a number of mechanisms, but the ones that are generally of interest to pavement engineers are *drying shrinkage* cracking and *fatigue* cracking.

Cracking caused by *plastic shrinkage* or *thermal gradients* are not considered to be significant to this discussion and are not pursued in further detail.

It is postulated that fibre reinforcement of cemented base materials may provide improved and more reliable post-cracking performance.

1.3.1 Drying Shrinkage Cracking

Drying shrinkage cracking occurs when the cemented material loses water while in a hardened state (Soroushian 1997). The loss of water causes the material to decrease in volume, resulting in the formation of tensile stresses. When the tensile stress locally exceeds the tensile strength of the cemented matrix a crack is formed. The crack propagates until the stresses at the head of the crack have been distributed sufficiently that they no longer exceed the available tensile strength.

In pavement engineering design, little can be done to prevent shrinkage cracking in cemented layers. This excludes concrete pavements which have sawn joints, designed to relieve stresses associated with shrinkage. Cracks can be minimised by using favourable curing conditions, but it is common to specify a certain minimum cover of unbound aggregate on top of the cemented layer to act as a barrier, that will lessen the likelihood of cracks being reflected at the pavement surface.

1.3.2 Fatigue Cracking

Fatigue cracking is caused by repeated stressing of a material at a level below its strength under static loading. Each stress excursion has a minuscule detrimental influence on the structure of the material, until the combined effect of a large number of stress excursions will result in the sudden, brittle failure of the material.

Fatigue cracking is exacerbated by the conditions that are found in a pavement structure. One important factor is that the relatively high elastic modulus of a cemented layer means that the layer attracts a large proportion of the applied stresses. This is beneficial for the underlying layers as they are well protected by the high modulus layer, but the cemented layer itself may not possess sufficient strength to resist the applied stresses from repeated axle loads.

Another important factor regarding the performance of cemented base materials is the abundance of stress concentrations available to initiate cracks. As a cemented layer is loaded it experiences tensile stresses at the underside of the layer. This lower portion of the layer receives the lowest compactive effort during construction, thus making it conducive to the formation of cracks.

Pavements incorporating cemented base layers are generally designed to ensure that the applied stresses are below the level required to achieve fatigue failure. This is done by providing a sufficient thickness of material above the cemented layer and/or providing a competent supporting layer that restricts the level of stress or strain confronting the cemented base.

1.4 Reinforcement

Cracking in a cemented material can be minimised by transforming the material into a *composite* with satisfactory mechanical properties in both compression and tension. This can be achieved by incorporating inclusions that either obstruct cracks within the cemented matrix or provide a tensile strength component in the portion of the cross-section that attracts tensile stresses. These inclusions can take the form of steel bars or meshes, or various types of fibres.

These forms of inclusions in the composite are generally termed *reinforcement*. In particular, *primary reinforcement* is provided to resist the tensile stresses imposed by dead and live loads. *Secondary reinforcement* is provided to resist tensile stresses imposed by internal actions such as drying shrinkage, plastic shrinkage and thermal effects.

1.5 Fibre-reinforced Cemented Materials

Fibres are used to reinforce numerous cemented materials. These include:

- concrete used for pavements, structures, water protection works, etc.;
- sprayed concrete used for tunnel linings and slope stabilisation;
- cemented mortars used for pipes, tanks, etc.;
- cemented boards used for building linings and cladding;
- lightweight concrete used where dead loads need to be minimised;
- epoxy composites used in the manufacturing of cars, boats, aircraft, etc.

Fibres are also used as *fillers* in several applications. In the realm of pavement engineering, fibres are sometimes used as fillers in asphalt mixes. However they are also used in such diverse applications as the food and pharmaceutical industries.

The review of the technical literature carried out for this project showed that there has been a vast amount of research carried out on the topic of fibre-reinforced concrete but that very little research has been carried out on fibre-reinforced cemented pavement base materials. In fact, only three references were identified that were specifically applicable to fibre-reinforced cemented pavement base materials, i.e. Cavey et al. (1995), Sobhan et al. (1996) and Shahid & Thom (1998). However, Thom (University of Nottingham, UK, pers.comm. 1998) suggested that, *in general terms fibre-reinforced cement bound base materials perform, at least qualitatively, in a similar fashion to other fibre-reinforced cemented materials such as fibre-reinforced concrete.* Naaman (University of Michigan, Ann Arbor, USA, pers.comm. 1998) also stated that a fibre-reinforced cement bound base would act as a low strength fibre-reinforced concrete.

These observations provided the justification to use several references on fibre-reinforced concrete (and other cemented materials) in this literature review.

Having established that there are at least qualitative similarities between fibre-reinforced cemented base materials and other fibre-reinforced cemented materials, describing some of the fundamental differences between them is also appropriate:

- Cemented base layers do not contain steel rod or mesh reinforcing whereas concrete elements generally include some level of primary and/or secondary reinforcement.
- Cemented base materials generally have a relatively low binder content. In New Zealand, typical Portland cement contents range from 2% to about 6% (by dry weight) although in some instances both higher and lower cement contents have been used. This is somewhat less than the cement content used in typical concrete mixes.
- Cemented base materials can incorporate some proportion of hydraulic binders other than Portland cement. KOBM is an example of an alternative binding agent.

1.6 Terminology

Section 1.5 of this report provides a justification for linking the performance of fibre-reinforced cemented base materials with other fibre-reinforced cemented materials that have received additional attention in the technical literature. Table 1.1 defines the terminology used in the body of this report to describe the various materials described in the technical literature.

Table 1.1 Definition of terminology used in this report.

Terminology	Description
Fibre-reinforced cemented base	A pavement base aggregate stabilised with sufficient quantities of hydraulic binder(s) and reinforcing fibres to produce a strong, cohesive layer.
Fibre-reinforced concrete	Concrete that has been dosed with fibres to achieve improved mechanical properties.
Fibre-reinforced cemented material or fibre-reinforced cemented composite	General terms for a cemented material reinforced with fibres.

2. PERFORMANCE OF FIBRE-REINFORCED CEMENTED MATERIALS

2.1 General

Numerous researchers have found that adding fibres to a cemented material can have a significant influence on the mechanical properties of the material. In particular the toughness, tensile strength and deformation characteristics can be dramatically improved by fibre reinforcement (Ramakrishnan & Yalamanchi 1994, Banthia & Trottier 1995a,b, Marikunte & Shah 1994, Maher & Ho 1993).

Reinforcing fibres can also control the frequency and aperture of cracks in a cemented material (PCA 1991). The source of cracking could be the result of drying shrinkage, plastic shrinkage, thermal effects, static loading, impact loading or cyclic loading. Micro-mechanical analyses that show that crack apertures in fibre-reinforced concrete specimens can be limited to 0.05 mm or less. This results in superior material durability and performance when compared with conventionally reinforced concrete specimens, which typically may have crack apertures of approximately 0.25 mm or more (Li 1992).

The benefits of providing tensile reinforcement for brittle materials have been understood for a very long time. Since ancient times sun-baked bricks have been reinforced with materials such as straw and horse hair. Reinforcing rods have been used in the tensile zone of concrete since approximately the middle of the nineteenth century, and steel wire segments were first incorporated in concrete mixes at the start of the twentieth century. However rigorous research into the performance of fibre-reinforced cemented materials did not occur until the 1950s (ACI 1974). At this time alternative fibre materials such as plastic and glass started to emerge in the United States (USA), the United Kingdom (UK) and Russia.

In recent times (1990s), a number of types of fibres have been used to reinforce cemented materials. These include both natural and synthetic organic fibres, and natural and synthetic inorganic fibres. Further discussion is detailed in Section 3 of this report.

2.2 Performance Mechanism

PCA (1991) reports that there are three factors that control the performance of a fibre reinforced cemented material. These are:

- the properties of the reinforcing fibres;
- the properties of the cemented matrix; and
- the strength of the bond between the fibres and the matrix.

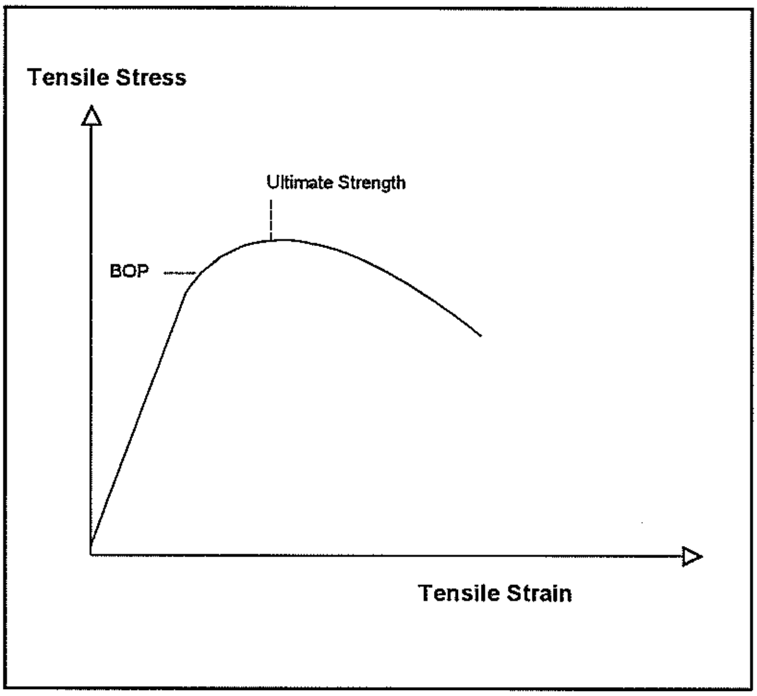
When a fibre-reinforced cemented material is subjected to an external load the resulting stresses are distributed throughout the cross-section of the specimen. The stresses are initially resisted by the cemented matrix of the composite. The zones of material experiencing tensile stresses are critical as the cemented matrix has a lower strength in tension than it does in compression.

As the applied load increases, the stresses in the tensile zone increase correspondingly. Eventually the tensile stresses reach a point where the tensile strength of the cemented matrix is exceeded and a crack is initiated in the cemented matrix. The crack propagates until the stresses are redistributed sufficiently that they no longer exceed the tensile strength of the matrix and/or the tensile stresses are transferred from the cemented matrix to one or more reinforcing fibres which span the crack. As the stresses increase further, the fibres tend to stretch and ultimately may pull out or rupture completely. The extent of fibre stretching and the resistance to pull-out or rupture are all functions of the mechanical properties of the fibre and the nature of the fibre–matrix bond.

When a fibre-reinforced cemented specimen is subjected to a bending, or modulus of rupture test, the typical stress–strain response is as shown in Figure 2.1. Figure 2.1 shows that the stress versus strain response can be divided into two parts (Marikunte & Shah 1994):

- an initial part that is relatively steep and linear, and
- a residual part that is substantially flatter.

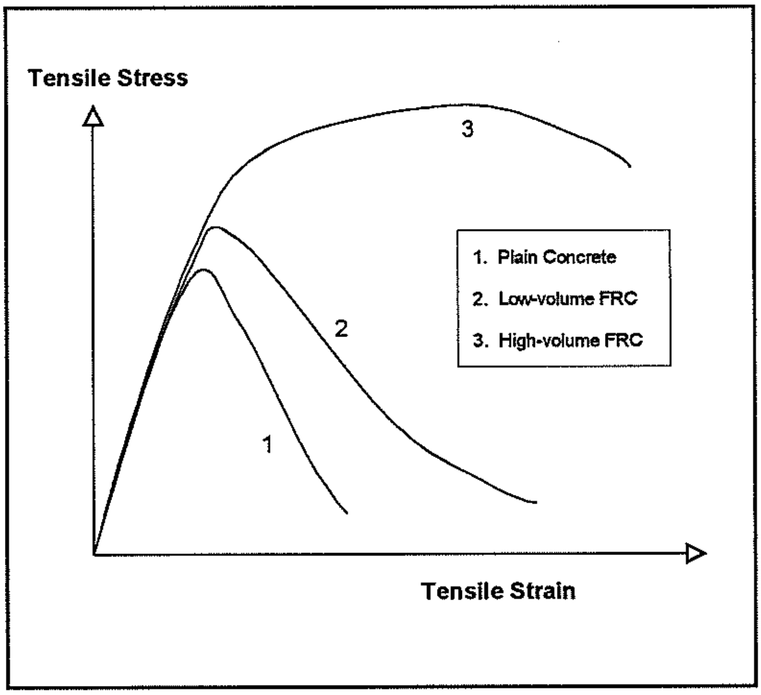
Figure 2.1 Typical form of stress versus strain curve for a fibre-reinforced cemented composite.



The initial stress–strain response is essentially the same for both plain and fibre-reinforced specimens. This confirms that the initial performance is controlled by the strength and stiffness of the cemented matrix only. The point where the stress versus strain response departs from linearity is termed the *bend-over point* (BOP), and this signifies the occurrence of the first crack in the cemented matrix. This point is also referred to as the *first cracking strength, elastic limit*, or *proportional limit* (ACI 1974).

Figure 2.2 shows that progressing the modulus of rupture test past the BOP produces a material response that is dependent on the quantity of fibres in the composite. While it is not shown in Figure 2.2, the response will also be dependent upon several other factors relating to the fibres and their bonding with the cemented matrix. As the volume of fibres increases there is an increased obstruction to the progression of micro-cracks in the cemented matrix. This results in the specimens showing an increased strain capacity and sometimes an increased ultimate strength (Marikunte & Shah 1994).

Figure 2.2 Typical stress versus strain curves for plain, low-volume and high-volume fibre-reinforced concrete (FRC).



In the case of a beam specimen, increasing the applied load past the first crack strength causes the neutral axis to move towards the upper part of the specimen. This changes the bending moment and causes the tensile strains below the neutral axis to increase. As the tensile strain increase the fibres start to pull out and/or rupture. At this point the beam specimen offers a decreasing resistance to further loading and the stress versus strain plot declines correspondingly (Banthia 1990).

The elongated stress versus strain plot associated with fibre-reinforced composites compared with unreinforced cemented materials represents the energy that the material absorbs under loading (Gopalaratnam et al. 1991). This also represents the *toughness* that the fibres provide for the composite material. A group of material parameters known as the *toughness indices* are used as a measure of the performance of a fibre-reinforced composite. This concept is discussed in further detail in Section 4.7 of this report.

Toughness is promoted by high fibre strength and a strong bond between the fibres and the cemented matrix. The result of these two mechanisms is generally referred to as *pull-out resistance*. Banthia & Trottier (1995a) state that the pull-out resistance of individual fibres is the most important factor influencing composite material toughness. However, under extreme loading conditions it is preferable for the fibres to pull-out rather than rupture. This gives the material maximum tensile strain tolerance.

Johnson & Gray (1986) conclude that the toughness of a fibre-reinforced concrete specimen is strongly dependent on fibre properties and manifestly independent of the matrix parameters over a wide range of matrix strengths.

2.3 Fibre-Cemented Matrix Bond

Bartos (1981) investigated the characteristics of fibre–cement matrix bonding using various fibre materials and reported that strong fibre bonds can result in brittle composite behaviour, and therefore it is desirable to have some slippage along the fibre-cemented matrix interface. Bartos (1981) describes the fibre–cement matrix bond in terms of two components, both of which are generally present in fibre-reinforced composite materials. These are the *shear bond* and the *tensile bond*.

The *shear bond* influences the transfer of stress along the axis of the fibre. This is divided into two components, the elastic shear bond and the frictional shear bond. The *elastic shear bond* ensures compatibility at the interface of the fibre and the cemented matrix, i.e. there is no relative displacement between the fibre and the matrix. The *frictional shear bond* restricts the relative displacement between the fibre and the matrix once slippage has been initiated.

The *tensile bond* resists the stresses working to pull the fibre away from the cemented matrix in a direction perpendicular to the fibre-cemented matrix interface. This type of bond is dependent on, among other factors, the cross-sectional shape of the fibre.

Marikunte & Shar (1994) reported that there is a weak transition zone at the *fibre–cement matrix* interface. The *weak transition zone* comprises calcium hydroxide and calcium silicate hydrates, and Marikunte & Shar suggest that this zone primarily dictates the nature of the pull-out resistance rather than the strength of the cemented matrix itself. The addition of silica fume to the composite is beneficial as it increases the density of the materials present in the weak transition zone (Marikunte & Shah 1994, Banthia & Trottier 1995a).

Bartos (1981) reported that nodules on the fibres can be employed to promote mechanical anchorage. This results in the localised transfer of stresses between the fibre and the cemented matrix. A number of possible fibre configurations are possible, including fibres that are deformed at one or both ends or fibres that are crimped to achieve deformations along their entire length. The deformations in the fibres not only promote local stress transfer, but they also absorb energy as the fibres tend to straighten out under tensile loading. Banthia & Trottier (1995a) report that the most effective steel fibres were found to be those configured with deformations at the ends of the fibre only.

Trottier & Banthia (1994) performed a suite of tests on concrete specimens reinforced with four configurations of steel fibres:

- hooked ends;
- curved crimping;
- sawtooth crimping; and
- coned ends.

Three different cemented matrix specifications were used, i.e. normal strength, mid strength, and high strength, and the fibre dosage was 40 kg/m^3 for each specimen.

The test results showed that the presence of fibres had little or no effect on the compressive strength, modulus of rupture strength, or the elastic modulus of the specimens. As expected, these parameters were influenced by the strength of the cemented matrix. It was found that the fibres increased the toughness of the material significantly. In particular, the two fibre configurations with deformed ends (hooked ends and coned ends) performed better than the fibres that were continuously deformed (curved crimping and sawtooth crimping). This result was also achieved in studies on the fracture toughness of fibre-reinforced concrete reported by Gopalaratnam et al. (1991) and Ramakrishnan & Yalamanchi (1994).

2.4 Fibre Content and Aspect Ratio

In the literature, the influence of the fibre content and aspect ratio parameters are often combined. *Fibre content* is generally expressed as a percentage volume of fibre in the composite, while the *aspect ratio* is defined as the ratio of the fibre's length to diameter. Aspect ratios are typically in the range 30 to 150 (ACI 1974).

As described in Section 2.3, the presence of fibres significantly influences the ultimate tensile (and flexural) strength and toughness of cemented composite materials. The fibres arrest the progression of cracks and help hold the composite together in the post-cracking phase. Therefore it is intuitive that the higher the fibre content, the more opportunity there is for a fibre to be in the appropriate location and orientation to perform these tasks.

ACI (1974) reported that the two most important factors that influence the performance of a fibre-reinforced cemented composite are the volume percentage of fibres and the aspect ratio of the fibres. Figure 2.3 shows a plot of relative toughness versus % volume of fibres for concrete specimens reinforced with fibres with an aspect ratio of 37.5. The relative toughness parameter is the ratio of the toughness of fibre-reinforced to plain concrete specimens. The plot shows that the benefit of increasing fibre volume is significant and that twenty-fold (or more) increases in toughness can be achieved by the introduction of fibres in concrete specimens.

Figure 2.3 Relative toughness versus % fibre volume (after ACI 1974).

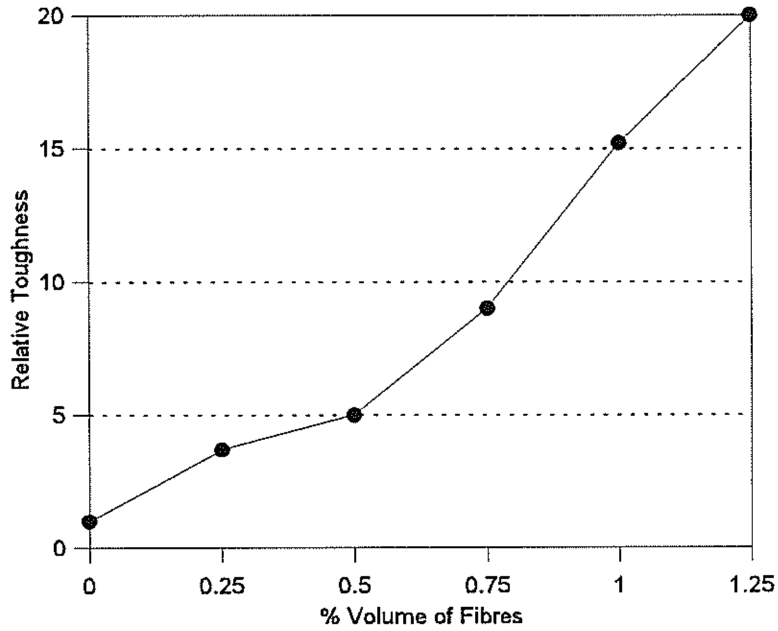
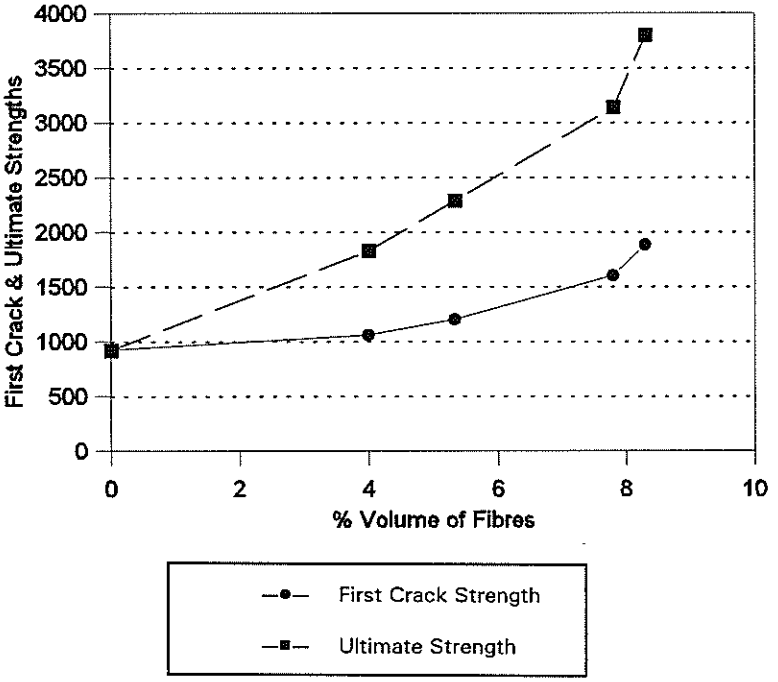


Figure 2.4 First crack and ultimate strength versus % fibre volume (after ACI 1974).



ACI (1974) reported that the ultimate strength of a fibre-reinforced cemented material is also significantly influenced by the fibre content. However, the first crack strength is only moderately influenced by fibre content. To illustrate this, Figure 2.4 shows a plot of ultimate strength and first crack strength versus fibre content for concrete beam specimens containing fibres with an aspect ratio of 88.

Johnston & Gray (1986) combined the fibre percent volume and aspect ratio in the parameter VL/d, where V is the % volume, L is the fibre length, and d is the fibre diameter. They state that VL/d values of 50 to 100 are common in practice. Their research showed that, at high VL/d values, the ultimate flexural strength of fibre-reinforced cemented specimens was primarily influenced by the properties of the fibres. Conversely, at low VL/d values the ultimate flexural strength was primarily influenced by the properties of the cemented matrix.

Benson & Khire (1994) investigated the reinforcement of (uncemented) sand specimens using strips of high density polyethylene. Their study showed that the California bearing ratio (CBR) of a sand specimen increased as the % fibre volume increased over the range 0 to 4%. The study also showed that the CBR initially increased with increasing fibre aspect ratio but that the CBR tended to reach a peak and then decrease at elevated values of aspect ratio. Benson & Khire explained this observation by stating that, at low aspect ratios, the fibres are too short to develop sufficient friction to achieve high CBR values. Conversely, at high aspect ratios (and constant % fibre volume), fewer fibres are available to provide tensile reinforcement, even though the fibres that are there have extra length to develop high tensile stresses. The secant modulus of the fibre-reinforced sand specimens was found to mirror the performance of the CBR parameter with respect to fibre aspect ratio.

Ramakrishnan & Yalamanchi (1994) investigated the toughness characteristics of steel fibre-reinforced concrete and concluded that the fracture toughness of the specimens increased with increasing fibre content. Associated with this conclusion was the observation that specimens with high fibre contents suffered less post-crack strength reduction than specimens with relatively low fibre contents. This shows that to maximise specimen toughness it is desirable to have additional fibres available to take up the stresses that are shed by the fibres that pull-out or rupture.

Marikunte & Shah (1994) reported that it is practical to use relatively short (steel) fibres, i.e. about 25 mm long, with a fibre volume content of less than 1% and still achieve mechanical benefits. Larger quantities of fibres increase the viscosity of the mix and can make it difficult to place and work.

Bartos (1992) concluded that, while a high fibre content can provide toughness benefits, an excessive fibre content can have deleterious effects. For example, a high fibre content can cause high porosity and poor fibre distribution in the composite.

2.5 Fibre Distribution

In most fibre-reinforced cemented composites the fibres are introduced at the time of initial mix preparation. Therefore they are incorporated in the composite without significant effort. Conversely, the fabrication and placement of conventional reinforcement can be a very time-consuming and labour-intensive procedure.

However, when conventional reinforcement is incorporated in a concrete member, the rods and/or meshes are placed so as to maximise their efficiency. Primary tensile reinforcement is placed in the tensile zone of the member, and secondary reinforcement is placed adjacent to exposed surfaces to resist shrinkage and thermal cracking.

The same degree of efficiency cannot be achieved using fibres for reinforcement. Because fibres are distributed uniformly through a member's cross-section, a reasonably high proportion of fibres can end up in areas where they have little or no influence. In addition, the reinforcement ratio, i.e. the area of reinforcement relative to the area of concrete, is generally much higher for conventionally reinforced members (Panarese 1992).

Panarese reported that, while the uniform distribution of fibres can be somewhat inefficient, it can also be a significant advantage, especially in the construction of members with intricate detail. Fibres generally have easy access to all parts of a member's cross-section whereas conventional reinforcement may be difficult to fabricate in finely detailed sections.

In general, reinforcing fibres are randomly distributed, i.e. the location and the orientation of the fibres are uncontrolled. However, in some instances the fibre distribution can be regulated so that the most favourable fibre orientations are achieved. This is important for applications that are essentially two-dimensional, such as cemented board products and sprayed concrete.

3. FIBRE TYPES

3.1 General

A large number of materials have been used to produce fibres for fibre-reinforced cemented composites. They include natural organic, natural inorganic, synthetic organic, and synthetic inorganic materials. The various fibre materials possess a wide range of physical and mechanical properties and each has an array of strengths and weaknesses. Table 3.1 (PCA 1991) lists a number of fibre types and their associated properties.

Table 3.1 Fibre types and properties (from PCA 1991).

Fibre Type	Diameter (mm)	Specific Gravity	Young's Modulus (GPa)	Tensile Strength (MPa)	Strain at Failure (%)
Steel					
High tensile	0.10 - 1.00	7.8	200	0.3 - 1.7	3.5
Stainless	0.01 - 0.33	7.8	160	2.1	3
Glass					
E	0.01	2.5	72	3.4	4.8
Alkali resistant (AR)	0.01	2.7	80	2.5	3.6
Polymeric					
Polypropylene - monofilament	0.10 - 0.20	0.9	5	0.5	18
Polypropylene - fibrillated	0.50 - 4.05	0.9	3.4	0.6 - 0.8	8
Polyethylene	0.03 - 1.00	0.96	5.0 - 172	0.2 - 3.0	3 - 80
Polyester	0.01 - 0.10	1.38	10 - 17	0.6 - 1.2	10 - 50
Acrylic	0.01 - 0.02	1.18	18	0.2 - 1.0	28 - 50
Aramid - Kevlar 29	0.01	1.44	62	3.6	3.6
Aramid - Kevlar 49	0.01	1.44	117	3.6	2.5
Asbestos					
Crocidolite	< 0.02	3.4	196	0.2 - 1.8	2 - 3
Chrysotile	< 0.03	2.6	164	3.4	2 - 3
Carbon					
I (high modulus)	0.01	1.9	380	1.8	0.5 - 0.7
II (high strength)	0.01	1.9	230	2.6	1.0 - 1.5
Natural					
Wood cellulose	0.02 - 0.10	1.5	10 - 40	0.3 - 0.9	-
Sisal	< 0.20	-	13 - 26	0.3 - 0.6	3 - 5
Coir (coconut)	0.10 - 0.40	1.12 - 1.15	19 - 26	0.1 - 0.2	10 - 25
Bamboo	0.05 - 0.40	1.5	33 - 40	0.4 - 0.5	1.5 - 1.9
Jute	0.10 - 0.20	1.02 - 1.04	26 - 32	0.2 - 0.4	-
Akwara	1.00 - 4.05	0.96	0.5 - 3.2	-	-
Elephant grass	0.45	-	4.9	0.2	3.6

3.2 Steel Fibres

Steel fibres have been used to reinforce concrete since approximately the late 1950s. The many applications of steel fibre-reinforced concrete include spillways, bridge decks, industrial floors and tunnel linings. In the pavement engineering sphere, steel fibre-reinforced concrete is mainly used in heavy duty applications such as airport and freight yard pavements. Typically fibre contents of 0.5% to 2.0% are used, although Panarese (1992) reports that fibre contents as low as 0.25% have been successful in the reduction of shrinkage crack widths. Note that a steel fibre volume of 1% represents a dosage of approximately 78 kg of fibres per cubic metre of concrete.

PCA (1991) reported that steel fibre-reinforced concrete is often used as an overlay to strengthen existing pavements. In most cases the overlay material does crack, but the fibres generally hold the cracks closed so that there is no decrease in pavement serviceability or ride quality. The best results have been obtained where the fibre-reinforced layer has not been bonded to the underlying layer.

PCA suggests that, for steel fibre-reinforced concrete, the cement content should be in the range of 325 to 565 kg/m^3 to achieve an adequate cement paste coating on the aggregate. They also state that the optimum aggregate grading has a particle top-size of 9.5 mm and a sand percentage of 45% to 60%.

Shahid & Thom (1998) undertook one of the few experimental investigations focusing specifically on fibre-reinforced cemented pavement base materials that has been reported in the literature. They prepared cube, cylinder and direct tensile test specimens using a materials design specifying an average (unreinforced) specimen cube strength of 20 MPa and a minimum individual cube strength of 13.5 MPa. This corresponds to the CBM 5 (cement-bound material) described in the Highways Agency's Specification for Highway Works (which they refer to). The aggregate used in the mix had a particle top-size of 20 mm and it was all retained on the 200 micron sieve. The steel fibres were 30 mm long with hooked ends. The fibre content was 1.0% and it was constant for each specimen.

Shahid & Thom reported the following conclusions from their testing programme:

- The addition of 1% by volume of steel fibres produced a 33% increase in the direct tensile strength of the cement-bound material.
- The cylinder compressive strength was increased by 12% by the addition of steel fibres.
- The first crack strength was increased by 38% by the addition of steel fibres.
- The cube compressive strength and the elastic moduli (in tension and compression) were not influenced by the steel fibres.
- Cracks in the fibre-reinforced cemented material were observed to be of negligible width.

The main conclusion presented by Shahid & Thom (1998) is that steel fibre reinforcement has the potential to provide an economic pavement design by reducing the thickness of the base layer and/or the bituminous surfacing.

Sobhan et al. (1996) also investigated the use of reinforcing fibres in cement-treated pavement base materials. The research involved testing a recycled aggregate with various proportions of both cement and fly-ash ranging from 0% to 16%.

Sobhan et al. reported that recycled aggregates with as little as 4% cement, 4% fly-ash and 1% (by volume) of steel fibres developed sufficiently high flexural, compressive and tensile strengths to be classified as a high quality base material. Using the results of a laboratory testing programme they rated hooked-end steel fibres as providing better performance than crimped steel and polypropylene fibres.

Other points of interest reported by Sobhan et al. (1996) include the following:

- Replacing half of the cement content with fly-ash produced specimens that performed just as well or better than specimens with no fly-ash;
- Addition of 4% steel fibres or 0.5% polypropylene fibres had little influence on specimen tensile strength but it had a significant influence on toughness and residual strength; and
- The fibre content must exceed some threshold value before significant improvement in mechanical performance is achieved, i.e. approximately 1% for steel fibres or 0.25% for polypropylene fibres.

FAA (1998) reported that steel fibre-reinforced concrete pavements have been used with some success at a number of airports. The report stated that while the cost of the material is approximately twice that of conventional concrete, the slabs are typically only half as thick. However, designers should be aware that relatively thin slabs are prone to curling caused by temperature gradients. When in a curled state, the edges of the slabs are susceptible to damage by the trafficking of heavy wheel loads.

FAA (1998) also reported that some sawn joints in fibre-reinforced concrete have failed to open completely. This makes for excessive movement in the joints that do open. Other difficulties include segregation at the edges of the paving machine and concerns over fibres exposed at the pavement surface.

Knapton & Meletiou (1996) reported that steel or polypropylene fibres are commonly used to reinforce concrete floors in the United Kingdom. They concluded that steel fibres are beneficial in that they limit the extension of micro-cracks that are present in all concrete materials. Steel fibres function by bridging cracks and thus transferring stresses from one side of a crack to the other. Steel fibres also resist crack growth because the elastic modulus of the fibre is higher than the elastic modulus of the cemented matrix.

In the British Ports Association (BPA) procedure for designing industrial pavements, Knapton & Meletiou (1996) state that steel fibres can be used in place of mesh reinforcement in concrete slabs. The resulting composite material achieves a considerable increase in flexural strength and enhanced resistance to shock loading and fatigue. The fibre content is recommended to be between 20 and 40 kg/m^3 (0.25% to 0.5% by volume) and the typical fibre aspect ratio is 60 to 75.

Knapton & Meletiou (1996) report that steel fibre-reinforced concrete pavement layers can provide economies over conventional concrete pavement layers. The savings stem from the following factors:

- Elimination of labour costs for preparing and placing conventional reinforcement;
- Reduced slab thickness; and
- Savings from using mechanical laying techniques.

The slab thickness reduction referenced above is quantified using equivalence factors for layer thicknesses. Table 3.2 is an excerpt from that reference showing that the use of steel fibre-reinforced concrete can result in layer thickness reductions in the range of 30% to 55% when compared with the reference material, where the reference material is described as a *wet lean concrete* with a flexural strength of 2 MPa. The wet lean concrete is formally specified as C10 concrete in the *Manual of Contract Documents for Highway Works*, Specification for Highway Works (UK Department of Transport 1991).

Table 3.2 Layer equivalence factors (after Knapton & Meletiou 1996).

Pavement Layer Material	Flexural Strength (MPa)	Layer Equivalence Factor
Wet lean concrete (C10)	2.0	1
Plain C30 concrete	4.0	0.70
C30 concrete + 20 kg/m^3 steel fibre	4.8	0.65
C30 concrete + 30 kg/m^3 steel fibre	6.4	0.55
C30 concrete + 40 kg/m^3 steel fibre	7.6	0.50
Plain C40 concrete	4.8	0.65
C40 concrete + 20 kg/m^3 steel fibre	5.6	0.60
C40 concrete + 30 kg/m^3 steel fibre	7.6	0.50
C40 concrete + 40 kg/m^3 steel fibre	9.0	0.45
Crushed rock (CBR > 80%)	-	3

Balaguru et al. (1992) performed a comprehensive study of the performance of steel fibre-reinforced concrete specimens. The specimens comprised aggregate with a particle top-size of 20 mm and hooked-end fibres with lengths of 30 mm, 50 mm and 60 mm. Fibre dosages ranged from 0 to 120 kg/m^3.

The results of the study showed that the toughness of the specimens was significantly improved at fibre contents of 30 kg/m^3. Further increases in toughness were achieved at high fibre contents, however the rate at which the toughness increased diminished at high fibre contents. It was also found that the length of the fibres did not significantly influence the specimen toughness.

Trottier & Banthia (1994) stated that at a low fibre content, i.e. 40 kg/m^3 (0.5% by volume), no improvement in strength or elastic modulus was achieved. This contradicts the data from Knapton & Meletiou (1996) shown in Table 3.2, which indicates that flexural strength benefits are achieved at steel fibre contents significantly lower than 40 kg/m^3

Ozyildirim et al. (1997) investigated the mechanical properties of steel fibre and various polymer fibre-reinforced concrete specimens. They found that specimens containing steel fibres had a tensile strength up to 70% higher than unreinforced specimens. The steel fibres also had a beneficial influence on the first crack strength, toughness and residual strength. The steel fibres outperformed the polymer fibres in all aspects of the mechanical testing.

Panarese (1992) reported increases in concrete tensile strength and first crack strength of about 40% and up to 150% respectively with the inclusion of 1.5% by volume of steel fibres.

While steel fibres are available in stainless steel or with a galvanised coating, PCA (1991) stated that corrosion is not a significant problem for uncracked composite materials. If the material suffers cracking, as could be expected in cemented pavement base materials, some drop-off of load capacity could be expected. The severity of the decreased load capacity will be dependent on the extent of cracking, fibre diameter, and the environmental conditions.

3.3 Polypropylene Fibres

Polypropylene fibre-reinforced concrete was developed in 1965 by the US Army Corps of Engineers (USACE). It was used for the construction of blast-resistant structures (PCA 1991). The USACE found that a small proportion of polypropylene fibres had a significant influence on the toughness and blast resistance of concrete materials.

Polypropylene fibres are manufactured by drawing the polymer material through a die. This results in a favourable orientation of the molecular structure. If a circular die is used, the resulting fibre is a single strand which is subsequently chopped into appropriate lengths. This fibre is termed *monofilament*.

Alternatively the polymer can be drawn through a rectangular die to produce a tape form of the material. It is subsequently chopped to the appropriate lengths and slit into numerous fibrils. This fibre is termed *fibrillated* and it forms an open network of fibres (PCA 1991).

Polypropylene makes a suitable fibre material because it is lightweight and chemically inert. It is also hydrophobic, and therefore it does not influence the hydration reaction of the cement binder. In preparing the composite, the fibres can be added to the mix at any time as they do not interact with the hydration water. However, the mixing time should be as short as possible for fibrillated film or tape fibres to avoid unnecessary shredding (PCA 1991).

Panarese (1992) reported that polypropylene fibres are the most commonly used of the synthetic fibre category. They have the benefits listed above, as well as being relatively inexpensive. Panarese stated that dosages of polypropylene fibres of 2% or more can provide significant benefits with respect to drying shrinkage crack control, ultimate strength, and other mechanical properties. Note that a polypropylene fibre volume of 1% represents a dosage of approximately 9 kg of fibres per cubic metre of concrete.

A weakness of polypropylene as a fibre material is that it does not bond well with cement. This property is affirmed by the use of polypropylene in constructing concrete forms to ensure easy release from the hardened concrete. Therefore, the fibres must rely on friction and mechanical interlock to achieve bond strength. The use of fibrillated fibres is beneficial as the cement and aggregate can penetrate into the spaces between individual fibrils (PCA 1991). A consequence of the dependence on mechanical interlock and friction is that polypropylene fibre-reinforced concrete can be less workable, and quite often significant reductions in slump are achieved compared with other concrete materials. This is especially evident at fibre volume contents in excess of 0.3%.

Knapton & Meletiou (1996) reported that polypropylene fibres are not a substitute for conventional structural reinforcement but they can be used as an alternative to non-structural mesh for the control of shrinkage and temperature gradient cracks. In the British Ports Association pavement design manual, Knapton & Meletiou (1996) recommend a fibre volume dosage of 0.1%.

Soroushian et al. (1992) tested cemented composite specimens containing a 0.1% volume of polypropylene fibres. They concluded that the fibres had negligible effect on the specimen flexural strength at such a low dosage. However, the impact resistance of the material was superior to that of unreinforced specimens.

Ozyildirim et al. (1997) performed a number of mechanical tests on polypropylene-reinforced concrete specimens. The fibres were both monofilament and fibrillated, and they were used in volume dosages of up to 0.7%. The study showed that polypropylene fibres caused a reduction in the compressive strength and only a modest increase in tensile strength of the specimens. Specimen toughness was increased by the presence of fibres but the magnitude of the increase was the lowest of the three fibre types used, i.e. polypropylene, polyolefin and steel.

Gopalaratnam et al. (1991) investigated the properties of polypropylene fibre-reinforced concrete specimens. The fibres were fibrillated and had a length of 50 mm. Fibre volume contents of 0.1% and 0.5% were used. Gopalaratnam et al. (1991) concluded that the first crack strength and the elastic modulus of the specimens were relatively independent of the fibre content. However the energy absorbed by the specimens during post-crack loading (i.e. toughness) increased appreciably with increasing fibre content.

Majumdar & Laws (1979) reported that the ultimate strength of polypropylene-reinforced cement boards is significantly lower than for boards reinforced with asbestos, glass or polyamide (Kevlar) fibres. However, the strain tolerance of the polypropylene-reinforced boards was approximately three times, five times and twenty times higher that for than the boards reinforced with Kevlar, glass and asbestos fibres respectively. This is attributable to the relatively low level bond achieved between the polypropylene fibres and the cemented matrix.

Mobasher & Li (1996) used 4% and 8% volume dosages of polypropylene fibres in cemented specimens and achieved significant increases in toughness. The fibres used in this investigation were 12 mm long with a rectangular cross-section of 0.25 mm by 0.035 mm.

PCA (1991) described the results of a number of investigations into polypropylene fibre-reinforced concrete specimens conducted at both high and low fibre volumes. The discussion suggests that the beneficial effect of polypropylene fibres at the low dosages that are generally used in industry can be questionable. Although increased benefits were achieved at higher fibre contents, the workability of the composite however can be significantly affected.

3.4 Cellulose Fibres

Cellulose fibres are produced when wood is pulped in the paper-making industry. Pulping involves removing the lignin that holds the cellulose fibres together. This can be done, using either a chemical or a mechanical process. The chemical process is often referred to as the *kraft* process. In the kraft process, wood chips are cooked in a mixture of caustic soda and sodium sulphide until the lignin is dissolved. Mechanical pulping involves grinding wood blocks to release the cellulose fibres.

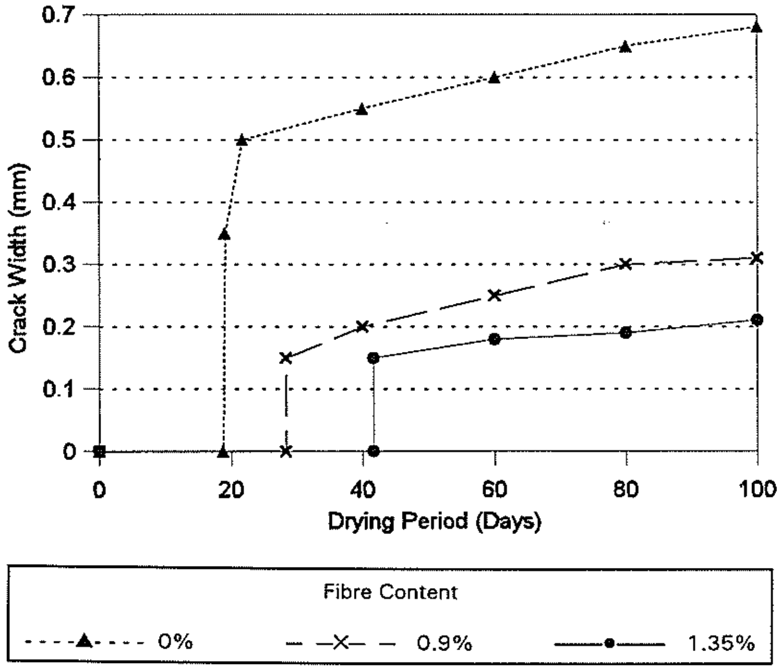
Fletcher Challenge Limited's Tasman Mill, at Kawerau, New Zealand, produces cellulose fibres using both the chemical and mechanical pulping techniques. The fibres obtained from the radiata pine plantations comprise 92% cellulose. The fibre dimensions are typically 31.6 microns by 10.5 microns by 2.7 mm long. Note that a cellulose fibre volume of 1% represents a dosage of approximately 15 kg of fibres per cubic metre of composite.

While cellulose fibres are reported to have a relatively high strength and modulus, they are also criticised for having a number of weaknesses. Andonian et al. (1979) reported that cellulose fibres absorb water which can cause the fibres to swell and may result in a degradation in strength and toughness. They may also be vulnerable to attack by insects and fungi.

Cellulose fibres are commonly used to reinforce cemented boards used in the building industry. In this application, the fibres are generally subjected to a refining process before use. The refinement typically involves coating the fibres with a melamine and phenolformaldehyde compound (Andonian et al. 1979). This coating, sometimes referred to as a coupling agent, increases the fibre's bonding ability and minimises the effects of moisture variations.

Soroushian (1997) investigated the influence of *speciality cellulose* fibres with regard to secondary reinforcement of concrete specimens. The results showed that cellulose fibres had a significant beneficial effect on the extent of drying shrinkage cracking observed in the specimens. Figure 3.1 shows a plot of crack width versus drying time for specimens with three fibre contents. The plot shows that the presence of fibres both delays the onset of drying shrinkage cracking and reduces the crack aperture. The higher the fibre content, the smaller the crack aperture.

Figure 3.1 Shrinkage crack width versus drying time (days) for 3 fibre contents (from Soroushian 1997).



Soroushian (1997) also found that moderate dosages of cellulose fibres (0.08 to 0.12% by volume) increased specimen strength, toughness and the bond strength to deformed primary reinforcing bars. Higher fibre dosages (0.24% by volume) increased specimen flexural strength and ductility. The improved properties obtained using fibre reinforcement were maintained under severe environmental and biological conditions.

Sarigaphuti et al. (1993) studied the influence of a variety of types of cellulose fibre on the performance of cemented specimens. The results showed that a 0.5% dosage (by volume) of cellulose fibres produced a significant reduction in the width of shrinkage cracks, and the effect was comparable to that of the same dosage of polypropylene fibres. The crack widths in the fibre-reinforced specimens were found to be approximately one-third of those found in unreinforced specimens.

Sarigaphuti et al. also used accelerated aging techniques to show that cellulose fibres are unlikely to be attacked by the alkali environment of the cement matrix. However, a degradation of specimen toughness was observed when the specimen was subjected to cyclic wetting and drying. This was most likely caused by embrittlement of the fibre-matrix bond and/or a loss of strength of the fibres.

3.5 Glass Fibres

Glass fibres have been used to reinforce a wide variety of materials for many years. Research into glass fibre composites has been undertaken mainly in the United Kingdom and Japan. One of the most important uses for glass fibre has been in the replacement of asbestos fibres in cemented board and insulation products.

Majumdar & Laws (1979) reported that fibres composed of *A-glass* and *E-glass* were found to be detrimentally affected by the alkalinity of the cement matrix. This led to the development of so-called *alkali resistant* or *AR glass*.

Mayer & Ho (1993) studied the behaviour of glass fibre-reinforced cemented sand specimens under both static and cyclic loading. The fibres used in the research ranged from 5.0 mm to 25.4 mm in length, and the fibre volume percentages ranged from 0.5% to 5.0%. Note that a glass fibre volume of 1% represents a dosage of approximately 25 kg of fibres per cubic metre of concrete.

Mayer & Ho found that the presence of glass fibres increased the peak strength of composite specimens, and the higher the fibre dosage, the higher the peak strength. This behaviour is shown in the plot of principal stress difference versus axial strain in Figure 3.2. They also found that the tensile strength of the specimens increased with both fibre content and fibre length.

The presence of fibres was also found to be beneficial under cyclic loading conditions. Figure 3.3 shows that increasing the fibre content increases the number of cycles to failure under cyclic triaxial testing conditions.

Figure 3.2 Stress versus strain plots for fibre-reinforced sand specimens (from Mahar & Ho 1993).

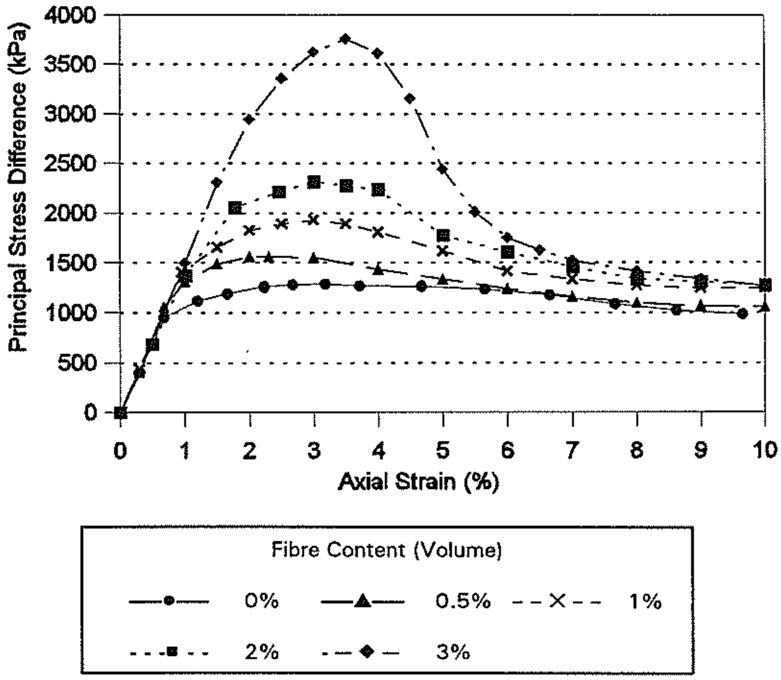
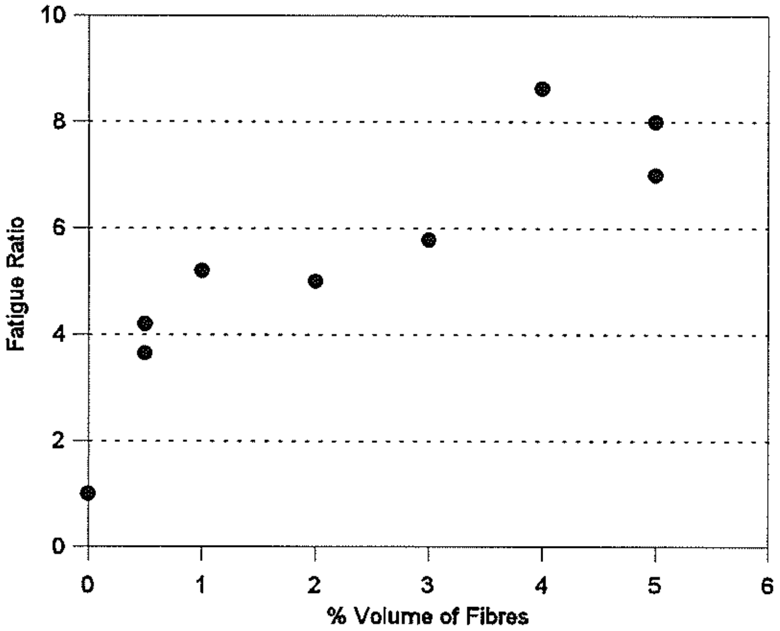


Figure 3.3 Fatigue ratio (ratio of cycles to failure (reinforced) to cycles to failure (unreinforced)) versus fibre content for sand specimens (from Mahar & Ho 1993).



PCA (1991) presents the results of long-term and accelerated aging mechanical tests using glass fibre composites. Even though AR-glass fibres were used in the tests, the results showed that the modulus of rupture strength of specimens decrease with time. Two explanations for this behaviour have been advanced.

First, when subjected to prolonged alkali attack the glass fibres may be weakened. Second, the composite may be subject to an *embrittlement* mechanism where further hydration of the cement in the matrix of the composite results in an increasingly stronger bond between the fibres and the matrix. At elevated levels of stress the fibres tend to rupture rather than pull out and therefore the toughness of the composite is reduced.

Recent research has focussed on improving the long-term durability of glass fibre-reinforced composites. This has involved the development of coatings for the fibres and the use of low-alkaline cement (PCA 1991).

3.6 Waste Materials

Using waste materials to produce reinforcing fibres provides three potential benefits:

- Fibre reinforcing provides crack control and improved mechanical properties;
- Recycled materials reduce the demand on waste disposal facilities; and
- Fibres comprising waste materials are likely to be economical to produce.

Cavey et al. (1995) investigated the use of recycled materials to construct fibre-reinforced cemented base layers. They used recycled materials to produce both the aggregate and the reinforcing fibres. The aggregate comprised crushed concrete and other building materials, while the reinforcing comprised strips from shredded plastic bottles and three forms of waste material derived from scrap tyres. The scrap tyre products included *tyre wire*, *tyre straps* and *tyre chips*. Details of the reinforcing elements are presented in Table 3.3.

Table 3.3 Reinforcing elements used in the investigation of Cavey et al. (1995).

Reinforcing Element	Dimensions (mm)	Comments
Plastic strips	50 to 100 mm long by 6 mm wide by 2.5 mm thick	Produced by shredding plastic bottles
Tyre wire	50 to 75 mm long	Wire strands connected by chunks of rubber
Tyre straps	250 mm to 600 mm long	Cross-sections of scrap tyres
Tyre chips	50 to 100 mm long and wide by 13 mm thick	Chips include wire strands

Pavement test sections were constructed using 8% and 12% Portland cement. The fibres and cement were spread on the surface of the aggregate layer and an in-situ mixer was used to combine the materials.

The results showed that the use of waste products as reinforcement was detrimental to the performance of the base layer. The detrimental effect was caused by the reinforcement acting as defects in the composite system, instead of as beneficial additives. This was most likely related to the forms and dimensions of the reinforcing elements, which in general were relatively large. In addition, uniform distribution of both cement and reinforcement was difficult to achieve using the in-situ mixing plant.

3.7 Other Fibre Materials

A number of other fibre materials have been investigated and they all have various benefits and weaknesses. These materials include the following:

- aramid (e.g. Kevlar) - Majumdar & Laws (1979), Panarese (1992);
- alumina - Mobasher & Li (1996);
- acrylic - PCA (1991);
- polyester - PCA (1991);
- polyethylene - Soroushian et al. (1992), Panarese (1992), PCA (1991);
- polyolefin - Ozyildirim et al. (1997);
- carbon - Majumdar & Laws (1979), Mobasher & Li (1996);
- palm tree frond - Abdel-Azim (1995); and
- bamboo - Balaguru & Shah (1985).

Also discussed in the literature is the use of asbestos fibres (PCA 1991). However, the size of these fibres is such that they can be ingested into the human respiratory system and therefore they represent a significant health hazard.

The fibre materials mentioned in this Section 3 are not pursued in further detail in this report because they either have little support in the literature or they suffer from obvious drawbacks (generally economic) that make them unsuitable for use in cemented pavement base layers.

4. TESTING PROCEDURES

4.1 General

The recent technical literature shows that most of the testing performed on fibre-reinforced cemented materials are laboratory based rather than in-situ programmes. Laboratory based tests give the benefit of superior control over test variables, e.g. state of stress, drainage and environmental factors, specimen monitoring and materials quality control. However, laboratory tests do suffer from having an environment which can be somewhat artificial. Also, relatively small laboratory specimens can be influenced by both scale and edge effects.

The mechanical properties of fibre-reinforced cemented materials that are generally subjected to testing are as follows:

- unconfined compressive strength;
- tensile strength;
- flexural strength;
- elastic modulus;
- fibre pull-out resistance;
- toughness; and
- shrinkage cracking.

Test procedures for the specimen properties listed above are discussed in this Section 4 of the report. Many of the test procedures described utilise specimens that are either cast in precision moulds or sawn/cored from test sections. Both methods of specimen preparation have different strengths and weaknesses. However, it is vital that all laboratory prepared specimens are representative of the material that is constructed in the field, particularly with respect to variables such as cementing agent content, aggregate grading, water content, and density. The main concern with sawn specimens is their geometrical accuracy. Poor geometrical control of specimens is a common cause of inter-laboratory test variation (Johnston 1992).

4.2 Unconfined Compressive Strength

The unconfined compressive strength is a basic parameter for cemented specimens. The specimens are generally cylindrical with a length of 300 mm and a diameter of 150 mm. The cemented material is compacted in layers into steel moulds. The specimens are generally stored for 48 hours before being removed from the mould and allowed to cure under controlled atmospheric conditions.

Testing is usually carried out after a 28-day curing period. The specimen is placed between the platens of a compression testing apparatus and the load versus deflection response is monitored. The compressive strength is taken as the maximum compressive load divided by the cross-sectional area of the specimen.

4.3 Tensile Strength

The tensile strength of a pavement material is generally determined using either the direct or indirect methods.

Direct methods involve simply pulling on either end of a specimen and determining the force required to achieve failure. The direct test is the only procedure in which pure tension is responsible for the failure of the specimen. A difficulty associated with direct tensile tests is achieving an effective connection between the specimen and the test apparatus. Some procedures use platens that are glued to the ends of the specimens, but this can result in detrimental shear stresses being imposed in the specimen caused by Poisson's effects. Other test procedures grip the ends of the specimen using a mechanical linkage, although these linkages can produce detrimental stress concentrations.

Indirect tensile tests rely on tensile stresses being imposed by an alternative configuration of applied stresses. The most common form of the indirect tensile test is the *Brazilian* or *split tensile* test. The Brazilian test involves loading a cylindrical specimen across its diameter as described in the document, *Methods of Tests for Concrete* (SANZ 1986). The diametrical loading produces compressive stresses beneath the loading platens and a very uniform distribution of tensile stresses perpendicular to the axis of loading. The magnitude of the compressive stress is three times that of the tensile stress. Therefore, the Brazilian test is only applicable to materials that have a compressive strength at least three times that of their tensile strength, such as concrete. If this condition does not prevail, the specimen will fail in a compressive mode instead of the desired tensile mode.

4.4 Flexural Strength

Flexural strength is established using a procedure called the *modulus of rupture* test (SANZ 1986). The test has the benefit of being a reasonable simulation of the loading imposed on a cemented pavement layer. The modulus of rupture test involves subjecting a moulded or sawn beam-shaped specimen to central or third point loading. The specimen size may vary, although 350 mm x 100 mm x 100 mm specimens are commonly used. Loading is applied to the centre of the specimen at a rate of approximately 0.05 to 0.1 mm per minute. The applied load and deflection are monitored throughout the test until the specimen ultimately fails. The strength of the specimen is calculated using the fundamental beam bending formula.

The modulus of rupture test is sensitive to irregularities in the tensile zone of the specimen. A variation of the standard modulus of rupture test is to provide an exaggerated irregularity in the tension face of the specimen in the form of a notch. This focuses the tensile stresses at the location of the notch. As the test is performed the aperture of the notch is monitored. This is referred to as the *crack mouth opening displacement* (CMOD). One advantage of the CMOD approach is that the crack width observed in the test specimen can be related easily to serviceability in the field (Sarigaphuti et al. 1993). It is also argued that the CMOD procedure has a lower potential for measurement errors compared with the test procedure incorporating plain beam specimens (Gopalaratnam et al. 1991).

4.5 Elastic Modulus

The elastic modulus of a specimen is simply the slope of the straight line portion of the stress versus strain plot. The elastic modulus may be obtained from direct tension, compression, or modulus of rupture test data.

4.6 Fibre Pull-out Resistance

Banthia (1990) devised a test procedure to determine fibre pull-out resistance that resembles a direct tensile test. The specimen is cast with a single fibre running longitudinally along the major axis. A thin separation sheet is placed transversely across the specimen mould so that the specimen is effectively cast as two halves connected by the fibre. The ends of the specimen are then pulled apart until the fibre either pulls out or ruptures.

4.7 Toughness

The toughness of a test specimen is loosely defined as the energy absorbed during the application of a load. The magnitude of the energy is represented by the area beneath the load versus deflection plot. Two standard toughness tests are described in the literature, i.e. the American (ASTM C1018) and the Japanese (JSCE-SF4) test procedures. These two test procedures involve the use of similar techniques, but the results are analysed slightly differently and they define separate toughness parameters.

4.7.1 American Toughness Test Procedure

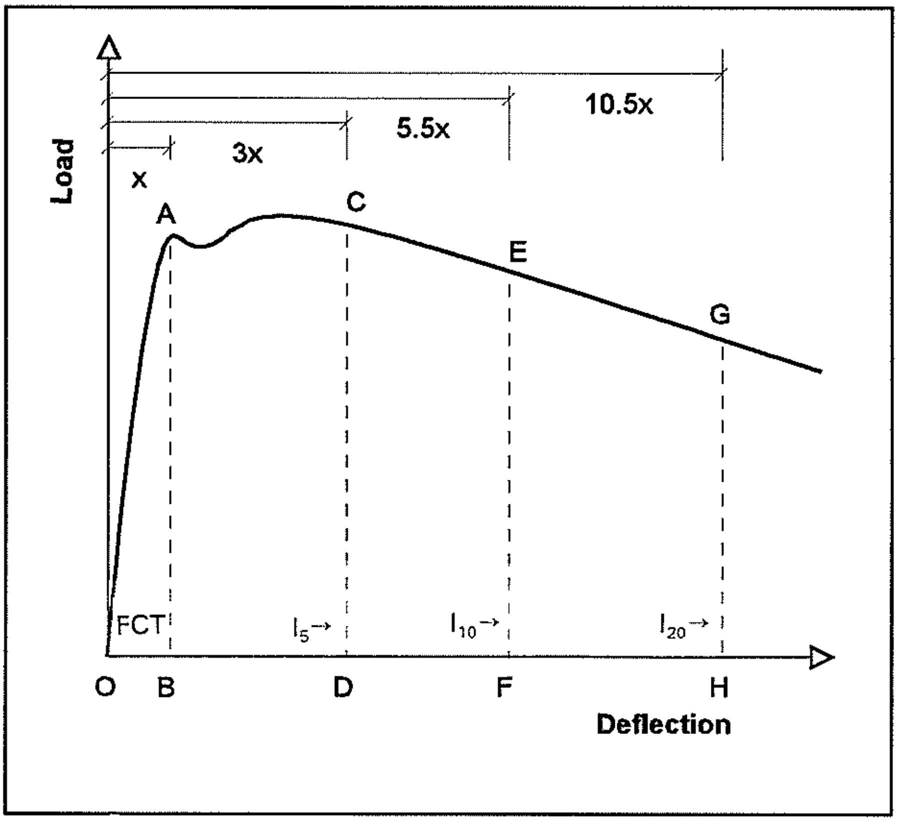
The American toughness test (ASTM C1018, 1995) is based on the flexural test with the specimen loaded at its one-third points. The beam specimen is loaded at a constant rate and a load versus deflection plot is generated. A typical load versus deflection plot is shown in Figure 4.1.

Up to eight parameters can be determined from the load versus displacement plot, i.e:

- first-crack strength;
- first-crack toughness;

- toughness indices I_5, I_{10} and I_{20};
- flexural strength; and
- residual strength factors $R_{5,10}$ and $R_{10,20}$.

Figure 4.1 Typical load versus deflection plot for calculation of toughness indices.



- The first-crack strength is obtained using the beam bending formula. The first-crack toughness is defined as the area beneath the load versus deflection plot up to the first-crack (or bend over) point, i.e. area OAB on Figure 4.1.

- The toughness index I_5 is defined as the area beneath the load versus deflection plot up to a point corresponding to three times the first-crack deflection divided by the first-crack toughness, i.e. area OACD / area OAB in Figure 4.1.

- The toughness index I_{10} is defined as the area beneath the load versus deflection plot up to a point corresponding to 5.5 times the first-crack deflection divided by the first-crack toughness, i.e. area OAEF / area OAB in Figure 4.1.

- The toughness index I_{20} is defined as the area beneath the load versus deflection plot up to a point corresponding to 10.5 times the first-crack deflection divided by the first-crack toughness, i.e. area OAGH / area OAB in Figure 4.1.

The residual strength factors $R_{5,10}$ and $R_{10,20}$ are defined as follows:

$$R_{5,10} = 20\,(I_{10} - I_5)$$

$$R_{10,20} = 10\,(I_{20} - I_{10})$$

It is important that all toughness results are reported as both first-crack strength and toughness indices. This is because it is possible for two vastly different materials to produce identical toughness indices. Also it is the combination of parameters that best characterises the energy absorption properties of the material (Johnston 1992).

Banthia & Trottier (1995a) criticised the ASTM C1018 test procedure stating that, although the indices are dependent on the first-crack toughness, locating the first-crack point on the load versus deflection curve is however often very difficult. They also point out that when the first crack occurs a large amount of energy can be released because the testing machine tends to recoil. This can distort the post-first-crack load applied to the specimen and therefore influence the values of the toughness indices. This effect is accentuated for composites with low fibre volumes and/or high cemented matrix strength.

Banthia & Trottier (1995b) proposed a method of toughness characterisation that is independent of the first-crack strength. Instead, the load versus deflection plot is divided into areas with respect to the *peak load*. A parameter termed the *post-crack strength* is then determined over a range of deflections as a function of the pre-peak energy, the post-peak energy, and the specimen geometry. The definition of the post-crack strength (PCS) is as follows:

$$PCS_m = \frac{E_{post(m)}\,L}{\left(\frac{L}{m} - d_{peak}\right) b h^2}$$

where PCS_m = post-crack strength index m;
L = specimen span;
L/m = specimen deflection as a fraction of specimen span where m ranges from approximately 150 to 3000;
$E_{post\,(m)}$ = post-peak energy, i.e. area under stress versus strain curve from the peak deflection to the L/m deflection;
d_{peak} = deflection at peak load;
b = specimen width; and
h = specimen height.

Banthia & Trottier (1995b) stated that the *post-crack strength* parameters are sensitive to the characteristics and volume fraction of the fibres as well as to the strength and composition of the cemented matrix.

4.7.2 Japanese Toughness Test Procedure

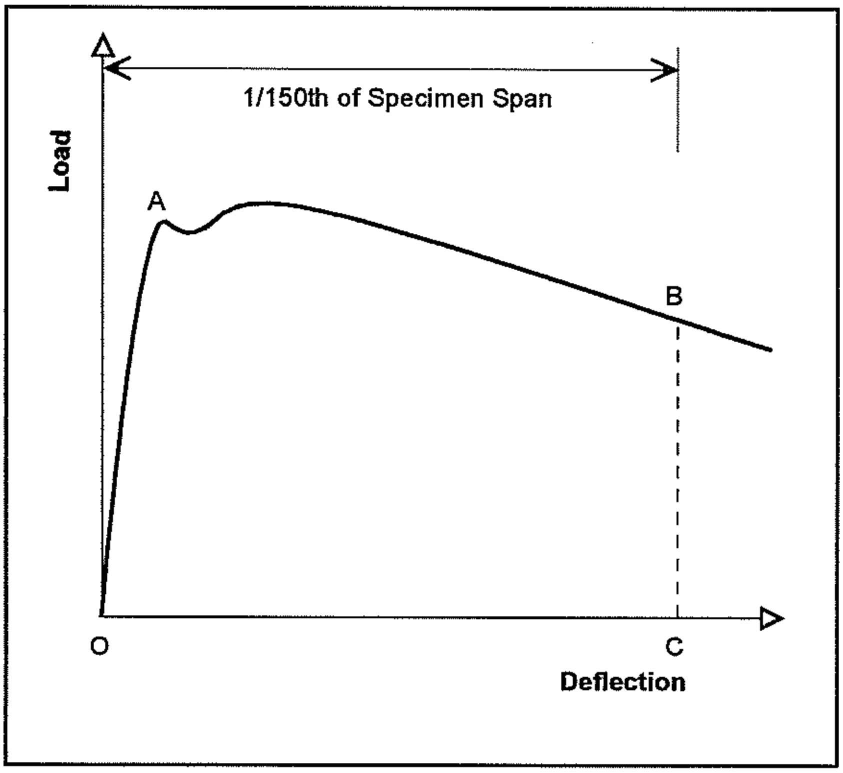
The JSCE (1984) procedure for determining toughness involves subjecting a beam specimen to third point loading until a vertical deflection equal to 1/150th of the specimen span is achieved. The toughness of the specimen (T) is taken as the area under the load versus deflection plot. This corresponds to the area OABC in Figure 4.2.

In addition to the toughness parameter, the JSCE test includes a *flexural toughness factor*, σ_b, where σ_b is defined as follows:

$$\sigma_b = \frac{TS}{d_{150}\, wd^2}$$

where T = toughness;
S = specimen span;
d_{150} = 1/150th of span;
w = specimen width; and
d = specimen depth.

Figure 4.2 Typical JSCE load versus deflection plot for calculation of toughness and flexural toughness factor.



Reporting the toughness, flexural strength and flexural toughness factor for a specimen provides an indication of the shape of the load versus deflection curve (Gopalaratnam et al. 1991).

The specimen size used in the test is dependent on the length of the reinforcing fibres. When the fibre length is greater than 40 mm the recommended specimen dimensions are 150 mm x 150 mm x 450 mm. When the fibres are shorter than 40 mm the recommended specimen dimensions are 100 mm x 100 mm x 350 mm.

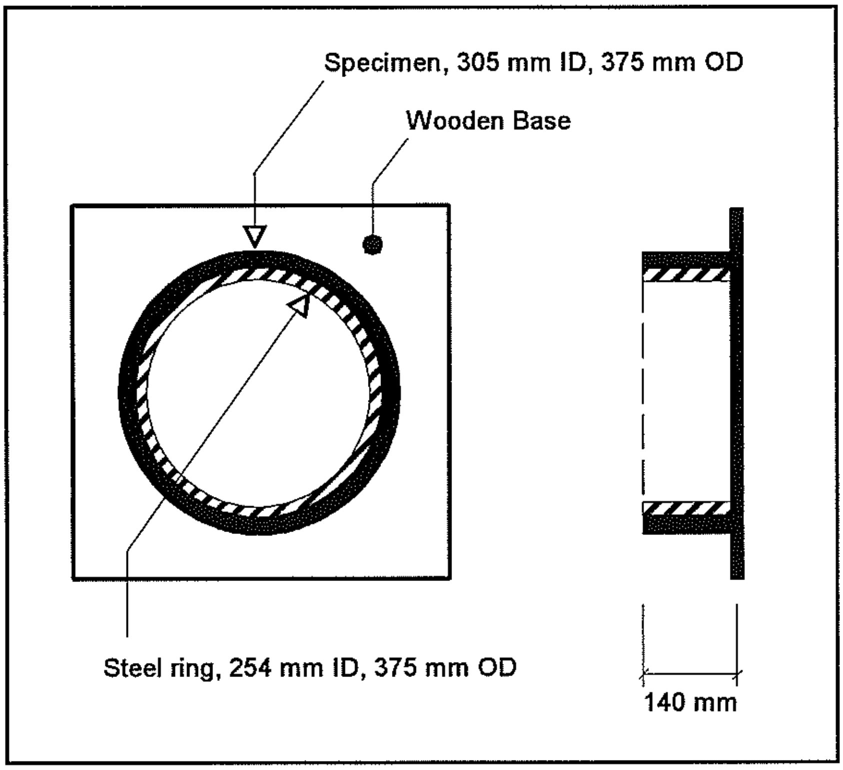
Ramakrishnan & Yalamanchi (1994) stated that the toughness parameters determined in the JSCE test procedure are relatively more sensitive to fibre types and contents than the corresponding indices determined in the ASTM test procedure.

Banthia & Trottier (1995a) criticised the JSCE test procedure, stating that the specified end of the test (i.e. 1/150th of the specimen span) is arbitrarily set and it is excessive for most serviceability considerations.

4.8 Shrinkage Cracking

A test procedure designed to evaluate the drying shrinkage cracking performance of fibre-reinforced cemented materials has been described by Soroushian (1997) and Sarigaphuti et al. (1993).

Figure 4.3 Restrained drying shrinkage cracking test apparatus (from Sarigaphuti et al. 1993).



The test involves casting an annular specimen using two concentric rings placed on a wooden board. The inner ring is made from steel and remains in place during the test. The outer ring is made from PVC and is removed after a short curing period. Finally, the exposed upper edge of the annular specimen is sealed with silicone rubber. This ensures that drying occurs only at the outer circumferential surface of the specimen. A diagram of the specimen configuration is presented in Figure 4.3.

As the specimen dries its tendency is to shrink, however it is restrained by the inner steel ring. This results in the formation of radial compressive stresses and tangential tensile stresses. The tensile stresses cause cracking in the outer unrestrained edge. Test results are reported in terms of crack width versus drying period.

Balaguru (1994) used high velocity fans to push air across the surface of slab specimens measuring 600 mm by 900 mm in plan and 19 mm, 50 mm and 100 mm in thickness. In most cases the drying shrinkage cracking was complete in 8 hours. The effectiveness of various fibre types and dosages was established by measuring the crack widths and lengths after 24 hours of drying.

5. CONSTRUCTION CONSIDERATIONS

5.1 General

Fibre-reinforced composite structures are constructed using either an in-situ mixing process or a batch production process. In the in-situ process, the fibres are combined with the cement matrix materials in-place. At present, most of the cement stabilisation treatment that is carried out in New Zealand is in the rehabilitation of existing pavements. In-situ mixing is the only technique that is suitable for this task.

In the batch production process, the fibres and cement matrix materials are combined in advance of being placed. Placing the composite may involve pouring or pumping the fresh mix into forms. Alternatively the material is placed using slip-form plant or simply sprayed onto an existing surface.

The main factors that need consideration in the construction of a fibre-reinforced cemented base layer are as follows:

- uniform distribution of the correct proportion of fibres;
- uniform distribution of the correct proportion of cementing agent;
- uniform distribution of the correct moisture content;
- accurate construction thickness; and
- provision of adequate compaction throughout the layer thickness.

Clearly, achieving a uniform distribution of the correct proportion of fibres is an essential construction requisite. The contractor must guard against any situation that may cause *segregation* or *balling* of the fibres. ACI (1974) reports that segregation or balling of fibres during mixing is related to a number of factors:

- fibre aspect ratio;
- fibre volume percentage;
- size and quantity of coarse aggregate particles;
- water to cement ratio; and
- mixing method.

Increases in fibre aspect ratio, volume percentage and quantity of coarse aggregate particles are all reported to increase the potential for fibre segregation.

5.2 In Situ Mixing

In New Zealand, cement-bound base layers are generally constructed by spreading the required amount of cementing agent (and water) on top of the aggregate component, and then the material is mixed with water in situ using a purpose-built pavement rotary hoe (stabilising machine). This is followed by compaction using vibratory and/or static rolling plant. The stabilising agent(s) are generally spread using accurately calibrated mechanised spreaders. An alternative approach is to introduce the stabilising agent(s) in a slurry form directly into the mixing chamber of the stabilising machine. The layer is then mixed, trimmed and compacted.

Boocock (Hiway Stabilizers Ltd, New Zealand, pers.comm. 1998) suggests that using a pavement stabilising machine would be possible, providing the fibre length is not excessive (initially estimated at 50 mm). Fibres longer than this length may tend to ball which would not promote uniform fibre mixing. Boocock also made the observation that synthetic fibres may be easier to mix than steel fibres because steel fibres could be deformed severely by the blades of the hoe.

Boocock stated that although introduction of fibres using a slurry may be possible in theory, it may not be easily achieved in practice. It is likely that the fibres would clog the injection system and a uniform distribution of fibres in the slurry itself may also be difficult to achieve.

Cement-bound base materials generally contain only a very small proportion of cement which makes uniform mixing a somewhat demanding task. It may be advantageous to incorporate a second additive (such as lime or KOBM) to maximise the opportunity to achieve uniform mixing.

5.3 Batch Production

The second method of production is best suited to new pavement construction. It involves the use of a central batching plant to mix the cementing agent and aggregate. The mixture is then transported to a paving machine to place the material in the pavement layer. The critical factor in this operation again is to achieve a uniform distribution of each component of the composite. This is achieved by ensuring adequate mixing time. Using a paving machine has its benefits, e.g. tighter tolerances and reduced compaction requirements, but the somewhat unforgiving nature of cement-bound materials means that the contractor must be experienced in handling these materials.

The mixing may be carried out in a purpose-built device such as a pug mill. Alternatively it may simply be achieved by adding the correct proportion of fibres to the fresh concrete in the ready-mix delivery truck. In the case of a cement-bound pavement base layer, a pug mill apparatus would be appropriate.

In small scale operations, such as the preparation of laboratory test specimens, mixing may effectively be achieved by using a small industrial mixer or simply by hand mixing.

When using hydrophilic fibres it is sometimes desirable to mix the dry components first. The water is only added once the aggregate, cementing agent and fibres have been thoroughly mixed. This is to ensure that the fibres do not scavenge water that is required for the hydration of the cementing agent.

6. ECONOMIC CONSIDERATIONS

6.1 General

In New Zealand, fibre reinforcement, at least of Portland cement-bound materials, is typically only associated with specialist applications that require premium materials. Therefore, fibre reinforcement generally has the connotation of high cost. However, an increasing availability of a wide range of fibre types, generally with decreasing cost, is making fibre reinforcement more viable for common applications (Li 1992).

When designing a pavement base layer comprising fibre-reinforced cemented material, the objectives are to provide a level of crack control, toughness and reliable post-cracking serviceability. There is not necessarily a requirement to increase the ultimate strength of the material. Therefore, minimal fibre contents are expected to be appropriate. In addition, fibres which have only moderate mechanical properties should be satisfactory.

The best scenario would involve utilising recycled waste materials as reinforcing fibres. Fibres manufactured from waste materials would clearly attract some nominal processing and handling costs, although this would be largely offset by the many benefits that recycling offers. This is especially relevant as the types of waste materials that are suitable for use as reinforcing fibres, i.e. durable plastics and the like, are inherently difficult to dispose of because of their enduring, non-biodegradable nature.

A further economic and environment benefit that could be realised by the use of fibre-reinforced cemented base materials is a reduced requirement for premium aggregates. This is significant as premium aggregate resources are severely diminished in many parts of New Zealand. The reduced aggregate demand is likely to result from the following factors:

- fibre-reinforced cemented bases will most likely be thinner than conventional cemented (or uncemented) bases;
- the premium aggregates that are generally used may be substituted with lower quality aggregates; and
- as reflection cracking would no longer be a concern, an unbound covering layer over the cemented base would not be required.

6.2 Indicative Economic Appraisal

An indicative economic appraisal of the use of fibre reinforcing in a cemented base is presented in this Section 6. Note that the appraisal is totally hypothetical and somewhat simplified as it is based on many assumptions. These assumptions are necessary as much of the data is yet to be confirmed. Further information will be available following the research tasks planned for future stages of the current project. In this appraisal it is assumed that construction of the fibre-reinforced cemented base is carried out using the in-situ mixing technique.

Consider two hypothetical pavements: Pavement A includes a 300 mm-thick cemented base layer while Pavement B includes a fibre-reinforced cemented base layer. To protect against reflective cracking at the surface of Pavement A, the cemented base must be overlain with (say) 150 mm of compacted, high quality aggregate. The cost of constructing the aggregate layer would be approximately \$11/m^2 at 1998 construction rates.

Assume that the beneficial effect of the fibres in Pavement B allows the thickness of the cemented base layer to be reduced by (say) 25% and the requirement for an unbound cover layer is removed completely. This reduced thickness of the cemented base realises savings in aggregate, cementing agent cost and mixing time which amount to a monetary figure estimated to be \$2/m^2. Assume that the extra cost of spreading and mixing the fibres into the base material is more than offset by the \$2/m^2 savings. Therefore, the only differential cost between the two pavements is the difference in cost between the unbound cover layer in the unreinforced pavement (\$11/m^2) and the cost of the fibres in the reinforced pavement.

Current (NZ\$ 1998) costs for steel and polypropylene fibres are approximately \$2.20/kg and \$18.00/kg respectively. These are typical unit costs that could be reduced for bulk quantities. Assuming appropriate fibre dosages to be 20 kg/m^3 and 0.9 kg/m^3 for the steel and polypropylene fibre respectively, relates to their square metre costs of \$9.90 and \$3.65.

Table 6.1 shows a schedule of costs summarising the economic appraisal described above. This shows that the fibre-reinforced option could be at least competitive with the unreinforced option, and possibly significantly cheaper. The economic and environmental benefits would be further improved with the use of fibres produced from recycled waste materials.

Table 6.1 Summary of estimated costs for hypothetical unreinforced and fibre-reinforced cemented base layers.

Item	Estimated Cost NZ\$(1998) / m^2		
	Unreinforced	Fibre Reinforced	
		Steel Fibres	Polypropylene Fibres
Unbound cover layer	11.00	-	-
Cemented layer material savings	-	(-2.00)	(-2.00)
Mix aggregate & cementing agent	8.00	8.00	8.00
Supply fibres	-	9.90	3.65
Laying & extra mixing of fibres	-	2.00	2.00
Total cost	**\$19.00**	**\$17.90**	**\$11.65**

While the indicative economic appraisal presented here is based on an in-situ mixing technique, it is considered that further cost savings could be realised when using the batch mixing technique. This is because very little additional effort is required to incorporate reinforcing fibres in a batch-mixed process. The fibres are simply added along with the cementing agent. Once mixed, the material is laid just as if it were a conventional unreinforced cemented layer.

7. SUMMARY & RECOMMENDATIONS

7.1 Summary

This study has shown that very little information is in the international technical literature on the topic of fibre-reinforced cemented base materials. However, there is a vast amount of information on fibre-reinforced concrete and other cemented composite materials. It has also been established from the literature that fibre-reinforced cemented base materials behave at least qualitatively like fibre-reinforced concrete. Therefore to take the fundamental aspects of the behaviour of fibre-reinforced cemented materials in general and relate them to the behaviour of fibre-reinforced cemented base materials is appropriate.

Beneficial Effects

It is virtually unanimously reported in the literature that fibre reinforcing has beneficial effects on the mechanical properties of cemented composite materials. In particular, fibres can add considerable toughness and maintain high levels of post-cracking strength. These attributes would be beneficial with respect to the performance of cemented pavement base layers.

Superior toughness and post-cracking strength are achieved by the fibres obstructing the progression of cracks and transferring stresses from one side of a crack to the other. The aperture of any cracks that do form as a result of shrinkage and/or in-service stresses is minimised by the mechanism of fibre reinforcement. Therefore the serviceability of fibre-reinforced composites can greatly exceed that of corresponding unreinforced materials. Fibre reinforcement may also facilitate the use of higher contents of cementing agent than those that are currently (1998) used in New Zealand.

The benefits of the fibres in a fibre-reinforced composite are generally not realised until the composite material experiences its first crack. Up to that point the mechanical properties of the composite are dictated by the properties of the cemented matrix. Therefore, material parameters such as elastic modulus and compressive strength are not significantly influenced by the fibres. After the first-crack point the properties of the composite are influenced by the properties of the fibres, the proportion of fibres, and the bond between the fibres and the cemented matrix. The properties in question are primarily the ultimate flexural and tensile strength, toughness and residual strength.

Most of the literature shows that increasing the proportion of fibres and the fibre aspect ratio in a cemented composite increases the post-crack performance benefits. However, there is an upper limit as excessive fibre volumes can cause workability difficulties. While high fibre strength is clearly beneficial, it is desirable that fibres should pull-out from the cemented matrix rather than rupture. This gives the composite maximum strain capacity and correspondingly maximum toughness.

Fibre Types

Comparative tests indicate that steel fibres provide the best performance, and in particular hooked end steel fibres are preferred over crimped or straight fibres. Polypropylene fibres are also commonly used, as are glass and cellulose fibres except that these materials can have durability problems. Many other fibre types, e.g. aramid, alumina, acrylic, etc., are available but economic considerations do not make them attractive. Natural fibres such as bamboo and palm tree frond are inexpensive but they also suffer from durability problems. Fibres produced from recycled waste products are attractive although little information is in the literature regarding successful applications.

Test Procedures

A number of test procedures are used to define the performance of fibre-reinforced cemented composites. These include fundamental tests that are used for conventional concrete, e.g. cube or cylinder compressive strength, modulus of rupture strength and direct or indirect tensile strength.

The tests that best show the influence of fibre reinforcement are those designed to measure specimen toughness and resistance to shrinkage cracking. The two generally recognised toughness tests are the ASTM and the JSCE procedures. Both tests use the area beneath the load versus deflection plot as a measure of energy absorbed by the test specimen, to be representative of specimen toughness. The literature also describes an innovative test for determining a specimen's resistance to drying shrinkage cracking, using an annular specimen which is restrained around its inner circumference.

Construction Issues

The key construction issues in the production of a fibre-reinforced cemented base are the uniform distribution of the correct proportions of cementing agent, water and fibres. This must be followed by the provision of adequate compaction and curing conditions. Mixing of the cementing agent and fibres with the aggregate can be carried out using a batch processing plant or an in-situ pavement stabilising machine. Both methods have their strengths and weaknesses, although the use of a pavement stabilising machine is very attractive.

Rehabilitating poorly performing aggregate courses by using a hoe to add various stabilising agents is a relatively common procedure, and fibres could be included in this mixing process. While fibres could theoretically be introduced to the aggregate in a slurry form, this method is likely to be difficult to achieve in practice.

Economic Appraisal

A hypothetical economic appraisal indicates that fibre-reinforced cemented base layers are potentially economically viable compared with conventional unreinforced cemented layers. This is mainly because an unreinforced cemented layer generally requires an unbound cover layer to arrest the propagation of cracks. This would not be required for fibre-reinforced cemented layers.

The analysis shows that polypropylene fibres are likely to be (economically) more attractive than steel fibres, although fibres produced from recycled waste materials would be even more attractive.

7.2 Recommendations

The review of the technical literature described in this report indicates that the use of fibre reinforcing in cemented pavement base materials has considerable potential. Fibre reinforcing provides the toughness and post-cracking attributes that currently detract from the use of conventional cemented base materials.

The recommendation is that the second stage of this project be initiated to gain further information on the practical viability of fibre-reinforced cemented base materials. The second stage of this project involves the performance of a suite of laboratory tests to investigate the performance of various types and quantities of fibres and cementing agents.

A detailed project specification will be developed at the initiation of the laboratory investigation, and in the interim the following general strategy is recommended:

- Select four fibre types for detailed investigation. These would most likely comprise steel, polypropylene, cellulose and a recycled waste plastic. The exact configuration of the fibres will be established just before testing, but fibre lengths should be kept reasonably short which should facilitate uniform fibre mixing.
- For each fibre type, adopt two fibre volume percentages representing a low and a moderate fibre content.
- Select cementing agents and dosages, most likely confined to Portland cement and KOBM.
- Prepare fibre-reinforced test specimens (as well as unreinforced control specimens). The specimen preparation procedure will be established at the time, but the objective will be to produce test specimens that closely represent the material that would be produced in the field.
- Perform the following test procedures for each specimen configuration:
  - cylinder compression;
  - indirect tension;
  - toughness; and
  - restrained cracking.
- Analyse the test data and report the results. Determine if the test data support the performance of the third stage of the project, i.e. construction and monitoring of pavement test sections. If so, develop a construction and monitoring strategy to best achieve in-situ material performance data.

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