Some Aspects of Low-Content Mono- and Hybrid-Fibre Reinforced Cementitious Composites

Z.H. Shui
STELLINGEN

Behorende bij het proefschrift

Some Aspects of Low Content Mono- and Hybrid-Fibre
Reinforced Cementitious Composites

van
Z. H. Shui
9 January 2001

1. Mechanische karkteristieken van vezelgewapende cementgebonden composieten kunnen in het algemeen worden uitgedrukt in samenstellingscomponenten, waarbij die van de vezelwapening de zogenoemde 'vezelfactor' omvat [1]. Experimenteel is aangetoond dat relatief kleine vezels de voorplanting van scheurtjes, ge nudgeerd in de cementmatrix door het uittrekken van grotere staalvezels, kan beperken [2]. Dit zou de basis kunnen vormen voor incorporatie van synergie – waargenomen bij de in deze studie beschreven proeven op hibriede koolstof-staalvezelgewapende betonmengsels - in de eerderbedoelde uitdrukkingen voor mechanische karakteristieken.

2. De toevoeging van vezels aan cementgebonden composieten kan de toepassing daarvan, ondanks de daaraanverbonden kostenverhoging, in sterke mate bevorderen.

3. De verbetering van de eigenschappen van vezelgewapende betoncomposieten is niet simpelweg proportioneel te stellen aan de wapeningshoeveelheid, immers (te) hoge wapeningspercentages kunnen tot negatieve effecten aanleiding geven.
4. Een minimum aan technische bijdragen en menselijke inspanningen kunnen als noodzakelijke maar onvoldoende voorwaarden gezien worden voor het welslagen van een internationaal samenwerkingsprogramma; cruciaal daarvoor zijn het verlangen, of tenminste de bereidheid, culturele grenzen te overschreiden teneinde elkaar te leren begrijpen en te waarderen.

5. Om tafeltenniswedstrijden te winnen, dient te worden geoefend met sterkere tegenstanders.

6. Anders dan bij een boom zal verplaatsing bij een mens tot een grotere groeipotentie leiden.

7. Meer scherpzinnigheid is nodig bij het formuleren van een profeem dan bij het oplossen ervan.

8. Veel opwindende en opzienbarende nieuwtjes die door een *avant garde* van software- en computerontwikkelaars op de markt worden gebracht, moeten door de teleurstellende ervaringen bij de gemiddelde gebruiker wat betreft de mensvriendelijkheid en de toepassingsmogelijkheden tot de schone schijn worden gerekend.

9. Hoewel het vertrek naar een andere bestemming gepaard zou kunnen gaan met verdriet om het verlies van enkele vrienden, zullen zich daarbij ruime kansen aandiennen tot het aangaan van nieuwe vriendschappen.

10. Chinese ouders wensen dat hun kinderen meer kennis zullen kunnen vergaren om zich een vooraanstaande positie te verwerven. Dit zal onderwijs tot een van de grootste markten in China maken.

11. Vanwege het vakkundig combineren van verschillende componenten en procedures vertoont het maken van beton veel gelijkenis met de voedselbereiding in de Chinese keuken.
1. Mechanical characteristics of fibre reinforced cementitious elements are generally described by law-of-mixtures type of equations in which the fibre component is composed, among other things, of the so-called fibre factor [1]. It has been demonstrated experimentally [2] that relatively small fibres inhibit side cracking due to pull-out of larger steel fibres, thereby effectively improving the interfacial friction resistance. This could be a way of incorporating in law of mixtures concept the synergy as observed in this thesis with carbon-steel hybrid reinforcement [3].


2. The addition of fibres in cementitious composites, although increasing material cost, can largely extend the application areas of such composites.

3. Improvement of composite properties is not simply in proportion to fibre content. Too high fibre contents in cementitious materials may lead to negative effects.

4. Minimum levels of technical input and human efforts are necessary but insufficient conditions to guarantee the success of an international co-operation program; of prime importance are the human eagerness, or at least willingness, to cross cultural borders, to learn understanding and appreciating each other.

5. To win more ping-pong matches, you have to play with stronger players than yourself during exercises.

6. For a man, trying different positions will make him better, whereas for a tree, being moved from a place to another, the reversed is true.
7. To present a problem is far more difficult than to solve it, because the former needs more discernment.

8. Exiting and astonishing innovations are brought to the market in an ever increasing rate by the avant garde of software and hardware developers. The average user is however frequently confronted with disappointments as to usefulness and handiness of all these glamor and glitter.

9. Leaving for a new place might make you sad for losing some friends, but new horizons will open for developing new friendships.

10. Chinese parents want their kids to get more knowledgeable and to be outstanding, hence education will become one of the biggest markets in China.

11. Matching of different components and combining different procedures make concrete production quite similar to cooking the Chinese way.
Some aspects of low content mono- and hybrid-fibre reinforced cementitious composites
SOME ASPECTS OF LOW CONTENT MONO- AND HYBRID-FIBRE REINFORCED CEMENTITIOUS COMPOSITES

PROEFSCHRIFT

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Chapter 1

Introduction

1.1 Development of FRCC

Fibre reinforced cementitious composites (FRCC) display combined behaviour, such as strength, stiffness, crack control, toughness and energy absorption capability [Swamy 2000], that derives from the different ingredients, such as the cement matrix and the fibres. Therefore, FRCC are to an increasing degree applied in civil and structural engineering.

Cement matrices (paste, mortar and concrete) are brittle materials, which easily fail when subjected to flexural or tensile stresses. When fibres are incorporated in the cement matrix, the composite can withstand increased tensile load due to the fibres sharing in the stress transfer, or behave more ductile and show a higher energy absorption than the cement matrix due to the fibre pull-out. The inherent shortcomings of the matrix, in terms of strengthening and toughening, can be eliminated, so that a novel composite with new characteristics emerges.

Hannant [1978] stated that fibre additions to cementitious materials can:

- improve the tensile or flexural strength;
- improve the impact strength;
- control cracking and the mode of failure by means of post-cracking ductility;
- adjust the rheology or flow characteristics of the material in the fresh state.

Fibrous materials have been used for many thousands of years to stabilize structural materials. Straw in mud bricks and horsehair in plaster are two examples from the past. Asbestos fibres in cement is an example of more recent date. Modern developments of fibre-reinforced cement composites date back only to the 1960s [Balaguru 1992]. Since then, a wide variety of other fibre types have been used in hydraulic cements, from conventional fibres, of steel or glass, to new types such as carbon and Kevlar fibres.
Chapter 1

[Bentur 1990]. In covering the now available range it would have been relevant to refer to newer developments, such as in France. The diversification in this field is continuing promoting application of more established fibre composites to more novel materials.

FRCC has been used in many areas of building technology and civil engineering for new constructions [Brandt 1996], as well as for repair works [Barr 1992]. China is one of the fastest developing countries in this sector. For example, the year-production capacity of alkali-resistant-glass (AR-glass) fibres was about 2000 tons in 1997, whereas it exceeded 6000 tons in 1999 [Bian 1998]. In recent years, various advanced technologies related to new types of fibres and FRCC composites have been developed or imported. This study was undertaken in the framework of a Dutch-Chinese co-operation project on "Modern Concrete Composites". It is expected that the results, like those presented in this study, will further promote development in this field of fibre reinforced cementitious composites.

1.2 Main constituents of FRCC

1.2.1 Cement matrix

The cementitious component (paste, mortar or concrete) in FRCC that does not contain fibres is called the matrix (paste, mortar or concrete). The cement matrix used in fibre composites is not significantly different from that in other cementitious materials. Portland cement is the main type of cement used in fibre reinforced composites. Typical properties of the cementitious matrix are shown in Table 1-1.

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Density (kg/m³)</th>
<th>Young's modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Strain at failure (×10⁻⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC paste</td>
<td>2000-2100</td>
<td>10-25</td>
<td>3-6</td>
<td>100-500</td>
</tr>
<tr>
<td>OPC mortar</td>
<td>2200-2300</td>
<td>25-35</td>
<td>2-4</td>
<td>50-150</td>
</tr>
<tr>
<td>OPC concrete</td>
<td>2300-2450</td>
<td>30-40</td>
<td>1-4</td>
<td>50-150</td>
</tr>
</tbody>
</table>

- 2 -
Special demands sometimes require to select a special type of cement, or to adjust matrix compositions. For example, when steel fibres are used in conventionally reinforced concrete, a higher ratio of fine to coarse aggregates is required [Balaguru 1992]. In glass fibre reinforced composites, a low-alkalinity cement or a modified Portland cement is often demanded.

The type of cement will govern the hydration progress and strength development of the cement matrix. Portland cement blended with silica fume, slag, fly ash or meta-kaolin will reveal significantly different hydration characteristics [Young 1985, Canham 1987 and Wang 1997]. The hydration and strength development processes strongly affect the initial properties of fibre reinforced composites.

Accompanying the cement hydration, the alkalinity of the pore solution in the cement matrix varies [Taylor 1997]. Longuet et al [Majumdar 1991] found that the hydroxyl, sodium and potassium ion concentrations, which govern the pH values of the pore solution, to increase to a maximum level between 7 and 28 days and then to remain constant or to decrease slightly.

1.2.2 Fibres

A wide range of fibres of different mechanical, physical and chemical properties have been studied and thereupon used for reinforcement in cementitious matrices. The fibres can be classified by type in the following way.

- Natural Fibres
  - Organic fibres: wood, coconut, sisal, vegetable
  - Inorganic fibres: asbestos
- Synthetic Fibres
  - Metallic fibres: steel, brass
  - Polymer fibres: polypropylene, nylon, polyester
  - Inorganic fibres: carbon, glass, ceramic

Fig.1-1 A brief classification of fibres for reinforcement in cementitious composites
Chapter 1

According to fibre geometry and size, fibres can be divided into continuous fibre, short chopped fibre; macro fibre, micro fibre, plain (straight) fibre, deformed fibre, and so on. According to some special properties, fibres can be divided into multiplicate, such as conductive fibre, alkali-resistant fibre, high ductile fibre. Typical properties of fibres are presented in Table 1-2.

Table 1-2 Typical properties of some fibres

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Diameter (μm)</th>
<th>Density (kg/m³)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Tensile strength (GPa)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>5-500</td>
<td>7840</td>
<td>200</td>
<td>0.5-2.0</td>
<td>0.5-3.5</td>
</tr>
<tr>
<td>Glass</td>
<td>9-15</td>
<td>1700-2600</td>
<td>70-80</td>
<td>2.4</td>
<td>2-3.5</td>
</tr>
<tr>
<td>Asbestos</td>
<td>0.02-0.4</td>
<td>3400</td>
<td>196</td>
<td>3.5</td>
<td>2-3.5</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>20-200</td>
<td>900</td>
<td>5-77</td>
<td>0.5-0.75</td>
<td>8.0</td>
</tr>
<tr>
<td>PAN carbon</td>
<td>9</td>
<td>1900</td>
<td>230</td>
<td>2.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Basically, fibre reinforcement transforms the cementitious matrix into a composite with inherent possibilities for stress transfer between fibre and matrix. So, the components of the composite share tasks according to their abilities. Hence, depending on load intensity, fibres contribute in the following ways:

1) Fibres carry part of the load to which the composite is subjected.

2) Fibres bridge cracks which are introduced at higher loadings, thereby partly restoring the integrity and the load-bearing capacity of the composite.

These stress transfer effects in the pre-cracking and in the post-cracking ranges of brittle matrix composites can be quite different. Before any cracking has taken place, elastic stress transfer is the dominant mechanism, so that the longitudinal displacements of the fibre and matrix at the interface are geometrically compatible. This is the relevant situation in the early stages of loading.

In the post-cracking range the fibres in FRCC composites exert their main influences on mechanical behaviour [Bentur 1990]. The fibres bridge across the cracks that have propagated in the brittle matrix, thereby preventing catastrophic failure. An important effect of fibre reinforcement is multiple cracking [Hannant 1978]. When the fibres bridging a crack can transmit sufficient load across the crack, more cracks will form along
the length of the specimen. As a result, a pattern of parallel and roughly equi-distant cracks arises under direct tensile stresses. The so-called critical fibre volume fraction is associated with this condition of the “multiple cracking” in the composite. The critical fibre volume fraction is defined as the volume of fibres which, after matrix cracking, will carry the load which the composite sustained before cracking [Hannant 1978]. For the situation in direct tension, taking into consideration the strengthening efficiency of the fibres, the critical fibre volume fraction, \( V_{f(crit)} \), can be given by [Bentur 1990]:

\[
\begin{align*}
V_{f(crit)} & \approx \frac{\sigma_{mu}'}{\tau_{fu}} \frac{d}{l} \quad (1.1) \\
V_{f(crit)} & \approx \frac{\pi}{2} \frac{\sigma_{mu}'}{\tau_{fu}} \frac{d}{l} \quad (1.2) \\
V_{f(crit)} & \approx 2 \frac{\sigma_{mu}'}{\tau_{fu}} \frac{d}{l} \quad (1.3)
\end{align*}
\]

where, \( \sigma_{mu}' \) is the tensile strength of the matrix, \( \tau_{fu} \) is the shear strength, \( d \) and \( l \) are the diameter and length of the fibres, respectively.

Eqns (1.1) to (1.3) indicate that for short fibres, the critical fibre volume fraction is a function of both the aspect ratio \((l/d)\) of the fibre and the fibre-matrix bond [Bentur 1990]. For a specific application, \( \sigma_{mu}' \) is given. It is necessary to decrease the critical fibre volume fraction by improving the interfacial bond and by properly increasing the aspect ratio.

1.2.3 Additions
Apart from the basic matrix constituents and fibres, additional materials like fly ash, slag, zeolite, meta-kaolin and polymers are often incorporated in the composites. They generally serve to:

- improve interfacial bond between fibre and matrix, thereby updating the
mechanical properties of the composite;
  - improve the durability of the composites;
  - cut down the cost of the composites.

More specially, silica fume and meta-kaolin have been demonstrated highly effective in reducing the OH\(^-\) ion concentration in the cement matrix [Hewlett 1998, Purnell 1999 and Basheer 1999]. Further, fly ash additions can reduce the material costs and improve the durability of the material.

In the case of GRC, the addition of polymer can improve not only the interfacial bond between fibres and matrix, but also the durability of the composite [Bijen 1980, Jacobs 1986 and Su 1995].

However, these additions may exert negative side effects. For example, silica fume increases the risk of composite embrittlement as a result of the hydration products filling up filament space [Litherland 1985 and Katz 1995]. And, the addition of the mineral additives (such as fly ash) leads to a decrease in the initial mechanical properties of the composites, although the strength retention is high.

1.3 Cementitious composites reinforced by low volume fraction of fibres

In practice, high and low volume fractions of fibres are employed. A typical example of a high content of fibres is SIFCON (slurry infiltrated fibre reinforced concrete), which can achieve far higher strength and fracture energy than ordinary steel fibre reinforced concrete. However, in many applications, high fibre content is not necessary. ACI 544.1R-82 suggested a volume fraction in normal weight steel fibre concrete of 0.3–1.0%.

In a GRC lightweight internal wall panel, the volume fraction of the glass fibres is about 0.2–0.5% [Zhu 1994]. Carbon fibres are used in a low dosage for controlling micro cracks in concrete and improving the interfacial bond between new and old concrete. Hence, the use of fibres in the low volume content range is relatively popular. Still, the study of the properties of the fibre composites in this range of reinforcements is quite limited.

1.3.1 Significance of using low volume content of fibres

In general, mechanical properties of the composites will be benefit from higher fibre
contents. However, fibre dosage will be limited in practical applications, due to technological but also to economic reasons. Technologically, with an increase of fibres, fibre dispersion in cementitious matrix becomes more and more difficult. Also, weight, electrical conductivity and thermal conductivity of the composites will change. Sometimes the changes may be dramatic, with serious implementations for saving energy, safety and durability of the relevant structures.

Electrical properties are of concern in some specific applications, such as in the case of railway structures. Electrical resistance of concrete also influences the corrosion rate of the embedded steel [Neville 1995]. Indeed, experimentally it was confirmed that the addition of steel and carbon fibres to concrete significantly decreased the electrical resistance of the concrete [Banthia 1992]. This may lead to some problems. The use of low content of these conductive fibres can reduce the risks.

Fibres are normally the most expensive ingredient in cementitious composites. With an increased fibre content, the composite’s cost will dramatically increase. For example, the addition of 1% (by volume) of pitch type of carbon fibres may lead to a doubling in costs of the fibre cement composite. Economic considerations therefore require controlling the fibre content to a level as low as possible.

1.3.2 Hybrid fibre reinforcements in cementitious composites

Hybrid fibre systems consist of two or more types of different fibres, or the same type of fibres but encompassing different fibre sizes. Hybrid fibre systems have been used for reinforcing cementitious materials for many years [Walton 1975, Kobayashi 1982 and Rudzinski 1994]. It is found that this is an effective approach to improve strength and toughness. In such reinforcement systems, different fibres play different roles. Bentur et al [1990] stated that hybrid fibre systems can be used to achieve two main purposes:

(1) provide reinforcement, in which one type of fibre (the primary fibre) provides for additional strength or toughness and the second type of fibre gives the fresh mix properties suitable for processing (the processing fibre);

(2) provide reinforcement, in which one type of fibre, which is stronger and stiffer, improves the first crack stress and ultimate strength, while the second type of fibre, which is more flexible and ductile, leads to improved toughness and strain capacity in the post-cracking zone.
Betterman et al [1995] suggested that the larger fibres could arrest propagation of macro-cracks and substantially improve the toughness of the composite. Whereas micro-fibres can bridge micro-cracks, hence, significantly enhance the tensile strength of the composite.

Walton et al [1975] highlighted the combination of organic and inorganic fibres. They concluded that the higher impact strength derived from the organic fibres, such as nylon and polypropylene, would remain stable over a very long period of time under normal use. Further, more behaviour in bending can be obtained with inorganic fibres by improving the stress transfer to the fibres and by using higher volume fractions. However, the volume fraction of the hybrid fibre systems considered in this research were relatively high (1~6% in volume), leaving the field of low contents of hybrid fibres to be relatively unexplored. It is necessary therefore to extend the research efforts from high fibre content to the low fibre content ranges.

It can be expected, that different types of hybrid fibre systems will be developed for different purposes. For example, to improve durability, to control the electrical properties, to adjust the thermal properties of the fibre composites, an appropriate fibre combination should be designed.

1.4 Aim and outline of this research work

The objective of this research is to study the behaviour of cementitious composites reinforced by low volume fraction of hybrid fibre systems. The study focuses in the first place on the mechanical properties of the composites reinforced by such systems. Since steel and carbon fibres are conductive fibres, the influences of these fibres on the electrical properties of the composites are taken into account prior to performing a study into the mechanical capabilities of this fibre combination. A problem of paramount importance is also the durability of the fibre reinforced cementitious composite. Therefore, this study additionally pursues a study of some microstructural details of glass fibre reinforced cementitious composite. Thereupon, their effects on GFRC durability are discussed.

Chapter 2 deals with a detailed study of the mechanical properties of fibre composites reinforced by low volume content of single or hybrid fibres. In particular, the mechanical behaviour and energy-absorption capacity is considered of the composites in flexure. It is
experimentally shown that significant improvements in mechanical properties can be achieved with the addition of low volume fraction of fibres.

Chapter 3 discusses the interactions between fibres and matrix. The resulting "additional porosity" of the composite is defined and its influence on the fibre reinforcement's efficiency is discussed. The mechanisms that lead to the dramatic changes in material properties due to hybrid fibre additions are analysed. Synergy effects of the hybrid fibres on the mechanical properties of the composites are discussed. A classification is proposed on the basis of the degree of influence of the hybrid fibre systems on the mechanical properties of FRCC.

The electrical properties of the cementitious composites with conductive fibres are experimentally investigated in Chapter 4. This study involves carbon fibre-cement paste systems as well as hybrid carbon-steel fibre-concrete composites. Resistivity measurements were executed at various measuring frequencies on cementitious composites containing various amounts of conductive fibres. The data outline the tendencies in conductive behaviour of concrete reinforced with low volume fraction of hybrid steel-carbon fibres.

Chapter 5 discusses some new approaches to study particular aspects of the behaviour of fibre reinforced cementitious composites as an implementation of Chapter 4. In this framework, the assessment of the dispersion degree of carbon fibres in cement paste by impedance measurements is outlined. As a potential application in smart cementitious materials and structures, the resistance response of carbon fibre-cement to compressive stress is studied. The relative contribution coming from the hydrate phases on the outcomes is also experimentally investigated and the impact on the earlier data is discussed. Finally, the influence of carbon fibres on the corrosion risks of steel rebars in concrete is experimentally established.
Chapter 2

Mechanical Properties of FRCC with Low Content of Fibres

Structure as well as mechanical properties of fibre reinforced cementitious composites have been investigated. Especially, composites containing low volume content (0.1~1.0%) of hybrid fibres were considered. Compressive, splitting and bending tests were executed on these composites for a range of compositions. The results reveal the composites with low volume content of fibres to behave attractive potential. The following more detailed observations pertain to the outcomes of the present experimental programme.

- Low volume fibre contents can exert significant improvements of the mechanical properties of these composites, when properly produced. However, negative effects may be induced by the addition of micro fibres when they are improperly dispersed in the matrix.
- Synergy effects can be achieved by the use of hybrid fibre systems. In these studies, carbon (micro) fibre and steel (macro) fibre were combined as reinforcing systems, causing the compressive strength, flexural strength and fracture energy to increase by 5~15%, 45~80% and 10~20 times, respectively.

It is shown that these cementitious composites with low fibre content are attractive due to their economic and technological advantages.

2.1 Basic mechanical properties of fibre-cement composites

The primary reason for using strong fibres in a relative weak brittle matrix (such as the cement paste) is to improve the ductility of the matrix. It is well-recognized that the cement matrix is a brittle material, which has a low tensile strength. The addition of fibres can overcome this shortcoming by providing a stress transfer capacity. Because the
tensile strength of the fibre is considerably higher than that of the matrix, the fibres can enhance the load-bearing capacity of the composites, when properly designed.

2.1.1 Tensile behaviour of FRCC
A more general objective of introducing fibres into the cement matrix is to improve the mechanical properties, and in particular to enable it to withstand tensile loading without catastrophic failure [Majumdar 1991]. In other words, the addition of fibres can convert the process of forming a single macro-crack into multiple cracking during failure of the composite [Naaman 1995].

2.1.1.1 The rule of mixture
Because of the different elastic moduli of the cement matrix and the fibres, the fibre reinforced composite will have an elastic modulus somewhat between that of matrix and fibres provided the composite is uncracked. For a fibre reinforced composite system, the stress supported by the composite at a strain $\varepsilon$ is

$$\sigma_c = E_c \varepsilon = E_f V_f \varepsilon + E_m V_m \varepsilon$$  \hspace{1cm} (2.1)$$

where, $E_f, E_m$ are the elastic modulus of the fibre and the matrix, respectively, and $V_f$ and $V_m$ are the respective volume contents of fibres and matrix of the composites.
Hence, the elastic modulus of the composite according to rule of mixture, based on a parallel arrangement of matrix and fibres is:

$$E_c = E_f V_f + E_m V_m = E_f V_f + E_m (1 - V_f)$$  \hspace{1cm} (2.2)$$

For the series arrangement of matrix and fibre, the elastic modulus of the composite can be expressed as:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_f}{E_f} = \frac{1 - V_f}{E_m} + \frac{V_f}{E_c}$$  \hspace{1cm} (2.3)$$
Equation (2.2) and (2.3) are valid only if the fibres are continuous and aligned in the loading direction and if there is perfect bond between the matrix and the fibres. They contribute under such conditions upper and lower bound solutions. So, reality will be in between the outcomes of eqs. (2.2) and (2.3)

2.1.1.2 Fibre reinforcement efficiency
In dealing with the mechanical effect of randomly dispersed fibres, a discount value, or the so-called efficiency factor of dispersed fibres, should be taken into account.

Fibre length and orientation efficiency factor, $\eta_l$ and $\eta_\theta$ are very important parameters, which are frequently used in expressions correlating composite properties by the rule of mixtures.

For example, in the elastic, pre-cracked stage of a fibre reinforced cement composite, the modulus of elasticity can be expressed as:

$$E_c = \eta_l \eta_\theta E_f V_f + E_m V_m$$  \hspace{1cm} (2.4)

Substituting values typical for fibre reinforced cements into the above equation readily demonstrates that the change in the modulus of elasticity is very limited.

However, the tensile strength of a cracked fibre composite reinforced by 3-D randomly distributed fibres can be given by following relationship [Bentur 1990]:

for $V < V_{(crit)}$: $\sigma_{cu} = \sigma_{mu} = \sigma_{mu} V_m + \eta_\theta V_f (l / d)$ \hspace{1cm} (2.5)

for $V > V_{(crit)}$: $\sigma_{cu} = \eta_\theta V_f \sigma_{fu} (l / d)$ \hspace{1cm} (2.6)

These equations show vital importance of fibre efficiency to the mechanical properties of the fibre composites.

The length efficiency factor is defined as the average stress along the fibre, $\bar{\sigma}_f$, relative to its strength, $\sigma_{fu}$, i.e., $\eta_l = \bar{\sigma}_f / \sigma_{fu}$. The typical expressions were given by Kelly [1973]:

for $l > l_c$ \hspace{1cm} $\eta_l = 1 - \frac{l_c}{2l}$ \hspace{1cm} (2.7)
for \( l < l_c \)

\[
\eta_t = \frac{l}{2l_c}
\]  

(2.8)

where, \( l_c \) is the critical fibre length, and it relates to fibre ultimate strength, \( \sigma_{fu} \), maximum fibre-matrix frictional bond strength, \( \tau_{hu} \). Based on a stereological analysis, Stroeven [1994] proposed an approach for fibre orientation efficiency factor:

\[
\eta_\theta = \frac{1}{3} (1 + f)(1 + \frac{2 - f}{1 - f} \omega)
\]  

(2.9)

where, \( f \) is the coefficient of friction at crack edge, and \( \omega \) is the degree of fibre orientation, and it is expressed by a ratio of fibre length in a direction to the total fibre length in a unit volume.

For aligned short fibres, \( f << 1 \), hence, (2.9) can be written in the simple form:

\[
\eta_\theta = \frac{1}{3} (1 + f)[1 + (2 + f)\omega]
\]  

(2.10)

Further, when \( f = 0, \omega = 0, \eta_\theta = 1/3 \).

2.1.1.3 Stress-strain relationship in tension

A typical stress-strain curve of FRCC subjected to tensile stresses is shown in Fig.2-1. For a composite with a sufficiently large amount of fibres, the curve of stress-strain behaviour can be divided into three regions identified as initial elastic range, inelastic range, and post-peak range [Balaguru 1992].

The linear range may be characterized by means of Young's modulus of the composite. At the end of this range, the first crack appears. Over the inelastic range, cracking takes place, whereby fibre debonding and slip occurs. In this region, the stress variations are small, whereas the strain varies dramatically. Away from the crack face, load is transferred back from fibre to matrix by shear forces at the fibre/matrix interface. As a consequence, the stress in the matrix will finally rise to failure level, whereupon another crack is formed. On further loading, the fibres will gradually slip so that the existing
cracks widen. This process of multiple cracking provides the composite with a high deformability and energy absorption capacity [Cem-FIL 1999].

In the post-peak range, the deformations concentrate in the major crack that opens up by fibre pulling out of their sockets.

2.1.2 Flexural behaviour of FRCC

In many applications, FRCC elements are subjected to flexure. Hence, numerous bending tests have been carried out on various fibres reinforced composites in the past decades. The basic mechanism of fibre contributions to bending resistance and to ductility can be understood by observing the load-deflection behaviour of the composite [Balaguru 1992]. Flexural behaviour of FRCC is often investigated by the four-point bending test [Brandt 1992]. The load-deflection curves of FRCC in flexure are similar to the load-deflection curves in tension, consisting of a common initial linear portion, but sometimes dissimilar as to the post-cracking branches.

In the case of bending, the area under the load-deflection curve is used to estimate the energy-absorbing capacity or toughness of the material. Increased toughness also means improved performance under fatigue, impact, and impulse loading. Based on these load-
deflection curves, a series of parameters, such as first crack strength, flexural strength, flexural toughness and fracture energy, can be calculated.
The recent study mainly concentrated on the flexural behaviour. The above mentioned mechanical parameters have been measured and discussed.

2.1.3 Mechanical contributions of low volume content of fibres to cementitious composites
A high content of fibres is an important way to obtain excellent material behaviour. However, high fibre contents inevitably lead to economic problems, but can also give rise to technical problems. These problems are:

- With an increase in fibre content, the material costs will markedly increase, because fibres constitute the most expensive component in fibre cement composites.
- Properly dispersing the fibres will be more difficult at higher fibre contents. On the contrary, a uniform dispersion of fibres is easy to achieve when fibre content is low.
- Fabrication process of FRCC is more complicated when fibre content is high.
- For conductive fibres of carbon and steel, high fibre content will dramatically enhance electrical conductivity of the composites [Banthia 1992]. Such situations should be avoided in cases where electrical insulation is required.
- Metallic fibres of steel and brass are thermal conductors that can increase heat dissipation. At higher contents of such fibres, the composite may loose its energy-saving and thermal insulation capacity.

In many cases, fibre cement composites with a low content of fibres therefore offer optimum solution. Unfortunately, such fibre systems were not extensively and systematically studied. Hence, supplying in these deficiencies is of paramount economic and technical importance.

Based on the concept of multiple cracking, the critical volume fraction of fibre has to be determined. This means that multiple cracking will occur when the fibre additions exceed the critical volume percentage [Majumdar 1975]. The critical volume percentages for some fibre types are given in Table 2-1. These data are based on a continuous and one-dimensional array of fibres. For discontinuous fibres that are randomly arranged in 2-D or 3-D, the efficiency factors for fibre orientation and length have to be taken into account.
Table 2-1 Critical fibre volume fraction for some fibres

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter ($\mu$m)</th>
<th>Density (kg/m$^3$)</th>
<th>$V_{f(crit)}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass fibre</td>
<td>9–15</td>
<td>~2600</td>
<td>0.2–0.1</td>
</tr>
<tr>
<td>Carbon fibre-I</td>
<td>8</td>
<td>1900</td>
<td>0.3</td>
</tr>
<tr>
<td>Carbon fibre-II</td>
<td>9</td>
<td>1900</td>
<td>0.2</td>
</tr>
<tr>
<td>Steel fibre</td>
<td>5–500</td>
<td>7800</td>
<td>0.5–0.2</td>
</tr>
<tr>
<td>Polypropylene fibre</td>
<td>20–200</td>
<td>900</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 2-2 presents different $V_{f(crit)}$ for steel fibre concrete derived by different authors.

Table 2-2 Numerical comparison of the critical volume fraction of steel fibres by different approaches ($V_{f(crit)}$) [Naaman 1995]

<table>
<thead>
<tr>
<th>Author, Date</th>
<th>Naaman, 1987</th>
<th>Naaman, 1987</th>
<th>Li and Wu, 1992</th>
<th>Tjiptobroto and Hansen, 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Aspect Ratio, L/d</td>
<td>$\tau/\sigma_{mu} = 1$</td>
<td>$\tau/\sigma_{mu} = 2$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>28.6</td>
<td>16.7</td>
<td>-</td>
<td>10.3</td>
</tr>
<tr>
<td>20</td>
<td>16.7</td>
<td>9.1</td>
<td>-</td>
<td>5.28</td>
</tr>
<tr>
<td>50</td>
<td>7.41</td>
<td>3.85</td>
<td>2.73</td>
<td>2.14</td>
</tr>
<tr>
<td>100</td>
<td>3.85</td>
<td>1.96</td>
<td>0.55</td>
<td>1.07</td>
</tr>
<tr>
<td>200</td>
<td>1.96</td>
<td>1</td>
<td>0.13</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Balaguru et al [1992] reported that markedly improved bending behaviour was achieved by using relatively low contents of steel fibres. The load-deflection curves are shown in Fig.2-2.

Chen et al [1993] obtained more than 50% increased flexural strength by incorporating up to 0.2 vol.% of carbon fibres into mortar or concrete. Shui et al [1997a] developed low volume fraction hybrid steel and carbon fibre systems and effectively improved the properties of the composite.

On the other hand, even when the fibre content exceeds the critical volume fraction, the positive effect of fibres on mechanical properties is not always guaranteed. In materials containing 2–3% of chopped 3-D randomly dispersed steel fibres, Edgington et al, did not obtain any significant improvement due to the fibres [Majumdar 1975]. At least, the
production technology that influences fibre dispersion and the degree of compaction of the material body should be among the variables controlling the critical fibre content. These previous research studies can serve as reference for mix design. However, the marked differences of the research results imply that some interactions between fibres and matrix are still obscure.

Fig.2-2 Load-deflection curve of cement composites with relatively low content of steel fibres (in bending) [Balaguru 1992]

Hence, the effect of adding fibres on material performance is due to many factors, such as fibre properties, matrix properties and the interaction between fibre and matrix, not just to fibre content. By proper design, significant improvements of composite performance can be expected therefore by adding low volume content of fibres. This study aims to improve the interfacial bond, and to enhance fibre reinforcement efficiency, therefore decrease the critical fibre content, $V_{f(crit)}$.

To exploit the potential applications of low fibre content composites, further research is required, particularly in the field of high-performance fibre reinforced composites. This study aims at least partly supplying in these deficiencies with respect to an experimental framework for practical design.
2.2 Test Arrangements

To study mechanical properties of cement composites reinforced with low content of hybrid fibres, a test program was made. This program involves fibre reinforced cement mortar and concrete. The studied properties include compressive, flexural and splitting strength, flexural toughness and fracture energy.

The experimental study consists of three parts: Series I, Series II and Series III. Series I and Series III are fibre reinforced concretes prepared by different processes. Series II is fibre reinforced mortar.

2.2.1 Raw Materials

- **Cement**: Portland cement with a characteristic strength of 52.5 MPa was used. The cement was produced by ENCI, The Netherlands.

- **Steel fibre-1**: Hooked type, length 30mm, diameter 0.5mm, stainless steel, produced by Bekaert, Belgium.

- **Steel fibre-2**: Plain and straight type, diameter 0.4mm, length 25mm (for concrete); length 12mm (for mortar), produced by Bekaert, Belgium.

- **Carbon fibre-1**: Pitch-based, mean diameter 10μm, nominal length 12mm, tensile strength 485MPa, made in Anshan, China.

![Graduation of the coarse and fine aggregates](image)
• **Carbon fibre-2**: PAN-based, length 5mm, diameter 7μm, produced by Shanghai Carbon Work, China.

• **Sand**: Dutch river sand, fineness modulus 3.23, gradation is shown in Fig.2-3.

• **Aggregate**: Dutch gravel, maximum size is 8mm for Series-I, and 16mm for Series-III, gradation is shown in Fig.2-4.

• **Water reducer**: FDN-440 water reducer, efficiency 10%, dosage 0.5% by weight of cement, made in China, used in Series-I and Series-II.

• **Superplasticizer**: Type Tillman OFT 4, pH=7, solid content 40%, produced by Tillman B.V., The Netherlands.

• **Fly ash**: Low alkali fly ash produced in The Netherlands, specific surface area about 2600 cm$^2$/g.

2.2.2 Considerations for mix design

• Concrete strength grade: 60MPa; amount of cement in concrete: <500kg/m$^3$;

• The Absolute Volume Method was employed in the mix design. Chinese Standard JGJ55-85 and ACI Standard Practice ACI 211.1-91 served as references.

• Fluidity of fresh concrete: The slump of the concrete mixture should be controlled around 100mm, so as to properly disperse carbon fibres into matrix and to easily densify the concrete.

• Water reducer and superplasticizer were used to decrease water to cement ratios in the concrete mixtures, and to partly compensate for slump loss due to the addition of fibres.

• Higher ratio of fine to coarse aggregate was accepted than for ordinary plain mixes.

• The maximum volume fraction of steel fibres was 1.0%, of carbon fibres was 0.2%, in the Series I. In Series II (fibre reinforced mortar), maximum fibre volume fraction was 1% for hybrid fibre systems. In Series III, maximum fibre volume fraction was 0.8%.

2.2.3 Mix proportions

Mix proportions for this study are presented in Table 2-3 to Table 2-8.
### Table 2-3 Mix proportions for concrete of Series I (in weight)

<table>
<thead>
<tr>
<th>Material</th>
<th>Cement</th>
<th>Sand</th>
<th>Gravel</th>
<th>Water</th>
<th>Fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion</td>
<td>1.0</td>
<td>2.0</td>
<td>2.40</td>
<td>0.38</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### Table 2-4 Fibre contents in Series I (in volume fraction)

<table>
<thead>
<tr>
<th>Code</th>
<th>CS-00</th>
<th>CS-20</th>
<th>CS-02</th>
<th>CS-11</th>
<th>CS-12</th>
<th>CS-21</th>
<th>CS-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon fibre</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Steel fibre</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Table 2-5 Mix proportions for cement mortar of Series II (in weight)

<table>
<thead>
<tr>
<th>Material</th>
<th>Cement</th>
<th>Sand</th>
<th>Water</th>
<th>Superplasticizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion</td>
<td>1</td>
<td>4</td>
<td>0.46</td>
<td>0.015</td>
</tr>
</tbody>
</table>

### Table 2-6 Fibre contents in various mortar mixtures (in volume fraction)

<table>
<thead>
<tr>
<th>Code</th>
<th>Steel Fibre</th>
<th>Pitch Fibre</th>
<th>PAN Fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M02</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M03</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M04</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>M05</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>M06</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>M07</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>M08</td>
<td>0.8</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>M09</td>
<td>0.5</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>M10</td>
<td>0.7</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>M11</td>
<td>0.6</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>M12</td>
<td>0.5</td>
<td>0.3</td>
<td>0</td>
</tr>
</tbody>
</table>
Fig. 2-4 Mixing procedure for the hybrid fibre concrete mixtures (Series I)

Table 2-7 Matrix concrete formula of Series III (in weight)

<table>
<thead>
<tr>
<th>Material</th>
<th>Cement</th>
<th>Sand</th>
<th>Gravel</th>
<th>Water</th>
<th>Superplasticizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion</td>
<td>1</td>
<td>1.92</td>
<td>2.35</td>
<td>0.40</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 2-8 Fibre volume fraction in various mixtures of Series III

<table>
<thead>
<tr>
<th>Code</th>
<th>PAN fibre</th>
<th>Pitch fibre</th>
<th>Hooked fibre</th>
<th>Plain fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>N01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N02</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>N03</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>N04</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N05</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N06</td>
<td>0.25</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>N07</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>N08</td>
<td>0</td>
<td>0.3</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>N09</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>N10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.8</td>
</tr>
</tbody>
</table>
2.2.4 Preparation of specimens
Proper dispersion of carbon micro-fibres requires special preparation procedure of the specimens. The effects of the dispersion characteristics of the carbon fibres on the properties of the composites will be discussed later.
2.2.4.1 Specimen preparation for Series I
a) Mixing procedures
The water reducer was dissolved in the water in advance.
The sequences of feeding the materials into the mixer are schematically shown in Fig.2-4.

b) Specimen making
100×100×100mm cubic specimens were prepared from the mixes of Series I. Further, the mixtures were cast into 500×400×100mm wooden molds for concrete slabs. The concrete slabs were sawn into 100×100×500mm beams for the bending tests after one-week normal curing. Next, the concrete beams were notched by a saw-cut at the middle of the bottom surface. The notch depth was about one third of the beam depth.
The specimen surfaces were covered with plastic sheets during the first day after casting, whereupon they were demoulded. All specimens were thereupon stored under climatized conditions (23 ± 3°C, 95~100%RH) until the day of testing.
2.2.4.2 Specimen preparation for Series II

The preparation procedure of the specimens of Series II mixtures is schematically presented in Fig.2-5. To properly disperse the carbon fibres into the cement matrix, a "two-step" mixing procedure was employed.

Cement, carbon fibres and 50% of the mixing water were supplied to a Hobart mixer and manually mixed for a while. Then, the mixer ran with a low speed of 100 r/min, and another 30% of the mixing water was poured into the mixture during the 1-minute mixing period. Finally, the mixture was mixed with a medium speed of 200 r/min for 2 minutes. This is the first step.

During the second step, the superplasticizer, the rest of the water and the sand were added and mixed for another 2 minutes.

For the hybrid steel-carbon fibre system, the carbon fibres were added during the first step, and the steel fibres during the second one.

The various mortar mixtures were poured into 40×40×160mm moulds. The specimens were stored under 23 ± 3°C and 95~100% RH for a curing period of 14 days.

2.2.4.3 Specimen preparation for Series III
Mixing procedure was proven an important factor to the properties [Chen 1993a]. The conventional mixing procedure, such as the one employed for Series I, proved unsuitable for the uniform dispersion of carbon fibres in concrete. Hence, the "two-step" mixing procedure developed in Series II was extended to fibre-concrete systems (Series III).

a) Mixing procedure
The mixing procedure for the hybrid fibre cement mixtures is shown in Fig.2-6.

b) Specimen making and curing
The processes of specimen making and curing for Series III were the same as that of Series I.

2.2.5 Test methods and test set-up
2.2.5.1 Test methods
- Compression and splitting tests of concrete followed the Chinese Standard “GBJ 81-85 Tests for Physical and Mechanical Properties of Concrete”;
- Compressive and flexural strength of fibre mortar were determined according to relevant Chinese and Dutch Standards, which are the same for this test purpose;
- Slump and consistency of the fibre reinforced mortar were determined according to ASTM C230-80;
- Flexural and fracture properties of the fibre concrete were determined by the four-point bending tests. "RILEM Draft Recommendation, 50-FMC Committee Fracture Mechanics of Concrete" [RILEM 1986], "ASTM C1018-92 Standard Test Method for Flexural Toughness and First-crack Strength of Fibre-reinforced concrete" [ASTM 1992] were used as references.

2.2.5.2 Test set-up
The basic configuration of the four-point bending test is shown in Fig.2-7.

![Diagram of four-point bending test](image)

**Fig.2-7 The basic configuration of four-point bending test**

The test set-up consists of three parts, i.e. the loading system, the sensor system and the data-acquisition system.
- A Schenck servo-hydraulic loading system was employed, allowing to perform the test at constant crack opening rate.
• Eight sensors (LVDTs) were used in the test. They were installed at different positions to monitor the local displacements, or deflections of the concrete beam during loading. The arrangement of the sensors is shown in Fig.2-8.

• The Data-acquisition system consists of hardware and software. The hardware was Pentium I personal computer and the software developed by Delft University of Technology. This system is capable of simultaneously collecting 16 series of data.

2.2.6 Basic test procedures for bending tests

![Diagram of sensor arrangement](image)

(Bottom view)

![Diagram of sensor arrangement](image)

(Side view)

Fig.2-8 Sensor arrangement on the specimen
Chapter 2

• **Loading and unloading cycling:** The peak value of the load was recorded during loading, and the 95% peak value was set as the first unloading point. From this point, the unloading-reloading cycle procedure was performed. The unloading process was carried out down to a zero load value. For each fibre reinforced composite specimen, three loading-unloading cycles were conducted. The second and third unloading points were at 80% and 65% of the maximum load value, respectively.

• **Adjustment of loading rate:** The loading rate (also crack opening rate) depends on the type of specimen. For plain concrete and carbon fibre concrete specimens the rate was 0.05mm per minute. For steel fibre and the hybrid steel-carbon fibre concrete, the rate was 0.1mm per minute during the initial period. After the first unloading-reloading cycle, the rate was controlled at about 0.2~0.3mm per minute.

• **Data collection:** Suitable intervals between data scans were set for various composites. For steel fibre reinforced concrete, data were scanned once per second, while for plain concrete, 5 scans per second were conducted. The loading process was continued until the beam broke into two parts or the CMOD was exceeding 3.5mm.

2.3 Test results

Test results of various physical and mechanical properties are presented as follows.

2.3.1 Basic physical and mechanical properties

2.3.1.1 Workability and compressive strength of fibre-reinforced composites
Table 2-9 Compressive strength of fibre cement mortars (Series II)

<table>
<thead>
<tr>
<th>Code</th>
<th>Slump (mm)</th>
<th>Consistency (mm)</th>
<th>Compressive strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>11</td>
<td>124</td>
<td>45.2</td>
</tr>
<tr>
<td>M02</td>
<td>8</td>
<td>118</td>
<td>59.1</td>
</tr>
<tr>
<td>M03</td>
<td>9</td>
<td>122</td>
<td>52.3</td>
</tr>
<tr>
<td>M04</td>
<td>7</td>
<td>114</td>
<td>42.4</td>
</tr>
<tr>
<td>M05</td>
<td>6</td>
<td>110</td>
<td>43.8</td>
</tr>
<tr>
<td>M06</td>
<td>7</td>
<td>118</td>
<td>46.4</td>
</tr>
<tr>
<td>M07</td>
<td>5</td>
<td>113</td>
<td>45.5</td>
</tr>
<tr>
<td>M08</td>
<td>4</td>
<td>106</td>
<td>58.6</td>
</tr>
<tr>
<td>M09</td>
<td>5</td>
<td>110</td>
<td>57.0</td>
</tr>
<tr>
<td>M10</td>
<td>5</td>
<td>108</td>
<td>55.1</td>
</tr>
<tr>
<td>M11</td>
<td>6</td>
<td>111</td>
<td>54.5</td>
</tr>
<tr>
<td>M12</td>
<td>5</td>
<td>107</td>
<td>54.9</td>
</tr>
</tbody>
</table>

- (Three data are averaged for each value, the same below.)
- (The age: 14 days)

Table 2-10 Compressive strength of fibre reinforced concrete (N/mm²)

<table>
<thead>
<tr>
<th>Series I</th>
<th>Series III</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-00</td>
<td>N01</td>
</tr>
<tr>
<td>CS-20</td>
<td>N02</td>
</tr>
<tr>
<td>CS-02</td>
<td>N03</td>
</tr>
<tr>
<td>CS-11</td>
<td>N04</td>
</tr>
<tr>
<td>CS-12</td>
<td>N05</td>
</tr>
<tr>
<td>CS-21</td>
<td>N06</td>
</tr>
<tr>
<td>CS-22</td>
<td>N07</td>
</tr>
<tr>
<td></td>
<td>N08</td>
</tr>
<tr>
<td></td>
<td>N09</td>
</tr>
<tr>
<td></td>
<td>N10</td>
</tr>
</tbody>
</table>
Table 2-9 reveals the effects of the fibres on the workability and on compressive strength of the fibre reinforced mortar. Both slump and consistency of the fibre cement mortars decreased with the addition of the fibres. The influence of the fibres on the slump of the fibre cement composites is significant, but it is minor on the consistency of the mortars. Steel fibres increased the compressive strength and density, whereas carbon fibres worked in an opposite way.

100mm concrete cubes were used to determine the compressive and splitting strength of fibre-reinforced concrete. The compressive strength results were converted to the strength of standard specimen size (150mm cube) by multiplying with a coefficient 0.95. Results are average values of three specimens.

For Series I and Series II, the compressive strength of the composite improved with an increase in steel fibre content, and decreased by the addition of carbon fibres, whereas the composites reinforced by the hybrid fibre systems have an intermediate compressive strength.

In Series III, the addition of fibres increased the compressive strength of the cementitious composite. Comparing the mono fibre composites, the effect of the steel fibres is more pronounced than that of the carbon fibres. The best results were obtained by the hybrid fibre systems, though the compressive strength of the four series of hybrid fibre composites (mix N06 to N09) is very close to each other.

2.3.2 The relationship between load and deformation of fibre concrete

Fig.2-9 Load-deflection curve of plain concrete

Fig.2-10 Load-deflection curve of concrete reinforced by 0.5% hooked steel fibres
Two types of curves, Load-deflection and Load-CMOD curves were simultaneously obtained during testing. Some typical load-deflection curves are shown in Fig.2-9 to Fig.2-12.

![Fig.2-11 Load-CMOD curve of concrete reinforced by 0.25% PAN carbon fibres](image1)

![Fig.2-12 Load-CMOD curve of concrete reinforced by 0.25% PAN carbon and 0.5% hooked steel fibres](image2)

The load-CMOD curves of Series I specimens are presented in Fig.2-13, Fig.2-14 and Fig.2-15 for plain concrete and for various composites reinforced by different hybrid fibre systems, respectively.

![Fig.2-13 Load-deflection curve of plain and carbon fibre reinforced concrete](image3)

![Fig.2-14 Load-deflection curve of hybrid fibre reinforced concrete (steel fibre 0.5%)](image4)
These pictures allow to draw the following conclusions. Steel fibres positively improved the bending behaviour in all the cases, whereas carbon fibres did not show a systematic effect. In the composite only containing carbon fibre reinforcement, the flexural strength and flexural toughness were enhanced. However, in the hybrid fibre systems, carbon fibres seemed to have no effect or even to play a negative role. This is a phenomenon that needs to be explained. The reason causing this negative effect is mainly the additional porosity due to the micro fibres. This will be discussed in Chapter 3.

The strengthening and toughening effects dramatically improved in Series III, as compared to Series I.

Fig.2-15 Load-deflection curves of the hybrid fibre reinforced concrete (1.0% steel fibres)

Experimental load-displacement curves of the various composites are plotted in Fig.2-16 and in Fig.2-17. It is seen in the figures that the maximum deflection values for plain and carbon fibre concrete were arrived at rather shortly before failure. The displacements of the steel fibre reinforced concrete are considerably larger. The toughening effect of the fibres on the composites can be estimated according to the areas under the load-deflection
curves. Some primary conclusions can be drawn on the basis of the load-deflection relationships.

**Fig.2-16** Load-deflection curves for plain concrete and for carbon fibre concrete composites

**Fig.2-17** Load-CMOD curves for steel fibre and hybrid fibre concrete composites
Chapter 2

- The composites with either steel or carbon fibres had a higher ultimate strength and strain capacity than plain concrete, whereby the effect of steel fibres on the mechanical properties was more pronounced.
- Under conventional mixing and preparation conditions, the addition of carbon fibres to steel fibre concrete decreased the ultimate flexural strength of concrete. This means that a negative effect emerged from the addition of carbon fibres.
- The degree of strength loss depended on the volume fraction of carbon fibres and on the relative proportion of steel and carbon fibres. When the volume fraction of steel fibres amounted 0.5%, the carbon fibres had a significant negative effect resulting in an increasing strength reduction at higher carbon fibre content. At 1.0% steel fibre content, this negative effect was considerably diminished.
- With the improved technical procedure (Series III), the load-displacement relationship considerably improved. In particular, when steel and carbon fibres were in an optimum combination, further strengthening and toughening effects arose.

2.3.3 Flexural and splitting strength

2.3.3.1 Flexural strength of the hardened fibre mortars

<table>
<thead>
<tr>
<th>Code</th>
<th>Flexural strength (N/mm²)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>6.43</td>
<td>±5.91</td>
</tr>
<tr>
<td>M02</td>
<td>6.68</td>
<td>±2.53</td>
</tr>
<tr>
<td>M03</td>
<td>6.49</td>
<td>±8.21</td>
</tr>
<tr>
<td>M04</td>
<td>6.85</td>
<td>±8.13</td>
</tr>
<tr>
<td>M05</td>
<td>6.41</td>
<td>±3.32</td>
</tr>
<tr>
<td>M06</td>
<td>6.48</td>
<td>±1.39</td>
</tr>
<tr>
<td>M07</td>
<td>6.60</td>
<td>±3.23</td>
</tr>
<tr>
<td>M08</td>
<td>7.12</td>
<td>±2.63</td>
</tr>
<tr>
<td>M09</td>
<td>7.37</td>
<td>±5.67</td>
</tr>
<tr>
<td>M10</td>
<td>7.24</td>
<td>±3.58</td>
</tr>
<tr>
<td>M11</td>
<td>7.68</td>
<td>±3.68</td>
</tr>
<tr>
<td>M12</td>
<td>7.15</td>
<td>±1.72</td>
</tr>
</tbody>
</table>
The results show that the addition of steel fibres as mono-fibre reinforcement had only a minor effect on flexural strength of fibre-reinforced mortar, while an obvious enhancement in compressive strength occurred. The addition of carbon fibres had only marginal effects on flexural strength. However, in hybrid fibre mortar systems encompassing steel and carbon fibres, flexural strength of the composites improved dramatically. A double positive effect on mechanical properties was achieved by incorporating these two different kinds of fibres in the cementitious matrix.

2.3.3.2 Splitting and flexural strength of Series III

<table>
<thead>
<tr>
<th>Code</th>
<th>Splitting Strength (N/mm²)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N01</td>
<td>4.2</td>
<td>±6.42</td>
</tr>
<tr>
<td>N02</td>
<td>5.1</td>
<td>±14.62</td>
</tr>
<tr>
<td>N03</td>
<td>5.5</td>
<td>±12.89</td>
</tr>
<tr>
<td>N04</td>
<td>4.3</td>
<td>±7.16</td>
</tr>
<tr>
<td>N05</td>
<td>4.3</td>
<td>±3.78</td>
</tr>
<tr>
<td>N06</td>
<td>5.9</td>
<td>±10.40</td>
</tr>
<tr>
<td>N07</td>
<td>6.2</td>
<td>±12.17</td>
</tr>
<tr>
<td>N08</td>
<td>5.7</td>
<td>±0.95</td>
</tr>
<tr>
<td>N09</td>
<td>5.2</td>
<td>±5.21</td>
</tr>
<tr>
<td>N10</td>
<td>6.1</td>
<td>±3.57</td>
</tr>
</tbody>
</table>

The net flexural strength of the composites was determined by a four-point bending test by assuming zero notch-sensitivity [Zhou 1995]. The flexural strength of the composite is expressed as:

\[
\sigma_{b(net)} = \frac{3P_{\text{max}} \cdot S}{2b \cdot (h - a_0)^2}
\] (2.11)
where, $\sigma_{b(\text{net})}$, net flexural strength of the composite (N/mm²);

$P_{\text{max}}$, the ultimate load (N);

$S$, span (mm);

$b$, width of specimen (mm);

$h$, height of specimen (mm);

$a_0$, notch depth (mm).

The flexural strength results are presented in Table 2-13.

Splitting strength and flexural strength are collected in Fig.2-18. This reveals the mechanical effects of the fibres to be similar for both strength characteristics.

Table 2-13 Net flexural strength of the concrete composites

<table>
<thead>
<tr>
<th>Code</th>
<th>Net flexural strength (N/mm²)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N01</td>
<td>4.9</td>
<td>±8.88</td>
</tr>
<tr>
<td>N02</td>
<td>7.0</td>
<td>±12.98</td>
</tr>
<tr>
<td>N03</td>
<td>7.3</td>
<td>±14.90</td>
</tr>
<tr>
<td>N04</td>
<td>7.0</td>
<td>±2.30</td>
</tr>
<tr>
<td>N05</td>
<td>6.8</td>
<td>±8.00</td>
</tr>
<tr>
<td>N06</td>
<td>8.9</td>
<td>±7.31</td>
</tr>
<tr>
<td>N07</td>
<td>8.5</td>
<td>±5.74</td>
</tr>
<tr>
<td>N08</td>
<td>7.9</td>
<td>±7.29</td>
</tr>
<tr>
<td>N09</td>
<td>7.1</td>
<td>±8.20</td>
</tr>
<tr>
<td>N10</td>
<td>7.8</td>
<td>±1.72</td>
</tr>
</tbody>
</table>

In the case of the optimum fibre combinations (N6 and N7), the flexural strength and splitting strength increased by 82% and 47%, respectively, with respect to the plain concrete. In these cases, the flexural strength attained even higher values than that of the composite reinforced with the same volume fraction of steel fibres only.
2.3.4 Flexural toughness
The measurements of the composite toughness index were performed on Series III, N01 to N09. According to ASTM 1018 [1992], the first-crack deflection is the deflection corresponding to the length OB in Fig.2-19. The first crack is assumed to occur at the point where the load-deflection curve deviates from the initial linear portion (i.e., A). Now, $I_5$ is obtained in the following way.

Fig.2-19 Calculation of the flexural toughness index
Divide the area under the load-deflection curve up to a deflection of 3 times the first-crack deflection by the area up to first crack. This ratio is defined as the toughness indices $I_5$. Hence,

\[ I_5 = \frac{(AREA)_{OACD}}{(AREA)_{OAB}} \quad (2.12) \]

Accordingly, $I_{10}$ and $I_{20}$ can be expressed as:

\[ I_{10} = \frac{(AREA)_{OAEF}}{(AREA)_{OAB}} \quad (2.13) \]

\[ I_{20} = \frac{(AREA)_{OAGH}}{(AREA)_{OAB}} \quad (2.14) \]

The calculated results of the toughness indices are shown in Table 2-14.

<table>
<thead>
<tr>
<th>Mix code</th>
<th>First crack load (kN)</th>
<th>Peak load (kN)</th>
<th>$I_5$</th>
<th>$I_{10}$</th>
<th>$I_{20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N01</td>
<td>3.6</td>
<td>3.7</td>
<td>2.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N02</td>
<td>4.6</td>
<td>4.9</td>
<td>3.6</td>
<td>6.5</td>
<td>10.2</td>
</tr>
<tr>
<td>N03</td>
<td>4.7</td>
<td>5.1</td>
<td>4.3</td>
<td>7.6</td>
<td>12.3</td>
</tr>
<tr>
<td>N04</td>
<td>4.6</td>
<td>4.7</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N05</td>
<td>4.5</td>
<td>4.6</td>
<td>2.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N06</td>
<td>5.6</td>
<td>6.1</td>
<td>5.2</td>
<td>9.6</td>
<td>13.6</td>
</tr>
<tr>
<td>N07</td>
<td>5.4</td>
<td>5.8</td>
<td>4.7</td>
<td>8.5</td>
<td>12.1</td>
</tr>
<tr>
<td>N08</td>
<td>5.2</td>
<td>5.5</td>
<td>4.8</td>
<td>8.1</td>
<td>12.5</td>
</tr>
<tr>
<td>N09</td>
<td>4.3</td>
<td>4.9</td>
<td>3.7</td>
<td>6.8</td>
<td>10.5</td>
</tr>
</tbody>
</table>
The capacity of fibre concrete to undergo larger deformations before failure is often measured by toughness indices. In other words, the toughness index reflects the capacity of energy-absorption and deformation-resistance in different stages of material flexure. The test results show flexural toughness to be quite sensitive to the addition of fibres. In particular, the hybrid fibre systems N06 and N07 provided double positive toughening effects to concrete. In these cases, the extra toughening effect on concrete appears with respect to the mono fibre concrete. To demonstrate the effects of the hybrid fibre systems, the ratios of relevant toughness indices were calculated, i.e.,

\[
R(6/3)_{i} = \frac{I_{i}(N06)}{I_{i}(N03)} \quad (i = 5, 10, 20) \quad (2.15)
\]

\[
R(8/3)_{i} = \frac{I_{i}(N08)}{I_{i}(N03)} \quad (i = 5, 10, 20) \quad (2.16)
\]

Similarly, \(R(7/2)_{i}\) and \(R(9/2)_{i}\) were calculated. The calculated results are presented in Table 2-15.

<table>
<thead>
<tr>
<th></th>
<th>(I_{5})</th>
<th>(I_{10})</th>
<th>(I_{20})</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(6/3)</td>
<td>1.31</td>
<td>1.31</td>
<td>1.19</td>
</tr>
<tr>
<td>R(8/3)</td>
<td>1.03</td>
<td>1.05</td>
<td>1.03</td>
</tr>
<tr>
<td>R(7/2)</td>
<td>1.21</td>
<td>1.26</td>
<td>1.11</td>
</tr>
<tr>
<td>R(9/2)</td>
<td>1.12</td>
<td>1.07</td>
<td>1.02</td>
</tr>
</tbody>
</table>

N03, N06 and N08 contain hooked steel fibres while N02, N07 and N09 contain plain steel fibres. Table 2-15 shows that the fibre combinations of steel fibre and PAN carbon fibre significantly increase composite toughness. The results show a double positive effect particularly on the toughness of the composite manifested over the initial part of the post-peak region. However, the combination of steel fibres and pitch carbon fibres only has minor extra toughening effect, in comparison to the steel fibre concrete. Obviously, the hooked steel fibre is more effective than the plain fibre in enhancing toughness. The
strong anchorage effect of the hooked fibre is the main reason of superior strengthening and toughening capacities.

PAN and pitch carbon fibres have originally a slenderness \((l/d)\) of 810 and 860, respectively. After mixing, the ratios will dramatically decrease. The pitch carbon fibres are more easily broken than PAN carbon fibres according to experimental observations. Hence, the strengthening and toughening effects of the pitch carbon fibre is less than that of PAN carbon fibre.

2.3.5 Fracture Energy \((G_F)\)

(1) Calculation method for the fracture energy

RILEM Draft Recommendations of the 50-FMC Committee on Fracture Mechanics of Concrete entitled “Determination of fracture energy of mortar and concrete by means of three-point bend tests on notched beams” [RILEM 1986] served as reference for the calculation of the fracture energy.

In the load-displacement curve, the area under the curve represents the work performed by the external force to which the specimen is subjected during the loading process. The area can be measured by means of splitting the curve into many small lattices.

The fracture energy \(G_F\) is calculated by the following formula:

\[
G_F = \frac{W_0 + m \cdot g \cdot \delta_0}{A_{lig}} \quad \text{(N·m/m²)}
\]  

(2.17)

where:

\(W_0\) = area under the curve as indicated in Fig.2-20;
\(g\) = acceleration due to gravity, 9.81 \((\text{m/s}^2)\)
\(\delta_0\) = displacement \((\text{m})\): for plain and carbon fibre concrete, at final failure of the beam, while for steel and hybrid fibre concrete, at the mean deflection = 0.0025m.
\(A_{lig}\) = area of the ligament \((\text{m}^2)\)

The load \(m\) of the specimen is coming from two components, i.e.

\[
m = m_1 + 2m_2 \quad \text{(kg)}
\]  

(2.17a)
Fig. 2-20 Fracture energy measurement

Fig. 2-21 Testing configuration and geometry of specimen. P = load = $m_1$, L = specimen length, h = beam height, b = beam width, HO = distance of holder axis to beam surface.

Here, $m_1$ is the mass of the beam between the supports and $m_2$ is the mass of those parts of the loading frame that are not attached to the machine, but permanently rest on the beam.
For the present research, \( m_2 = 0.5 \text{kg} \). \( m_1 \) can be derived from the mass of the specimen \( M \) by:

\[
m_1 = M \cdot \frac{S}{L} = \frac{450}{500} \cdot M \quad \text{(kg)}
\]  

(2.18)

In equation (2.1): 
- \( M \) = mass of the specimen (kg)
- \( S \) = span of the beam (m)
- \( L \) = the total length of the beam (m)

The area of the ligament equals the projection of the fracture zone on a plane perpendicular to the beam axis. Hence,

\[
A_{lig} = b \cdot (h - a_0)
\]  

(2.19)

where:
- \( b \) = width of the beam (m);
- \( h \) = height of the beam (m);
- \( a_0 \) = the initial depth of the notch (m).

(2) Results on fracture energy \( G_F \)

For plain and carbon fibre reinforced concrete, the actual maximum deflections were taken. Since the deflection at fracture of the steel fibre concrete specimen will be out of the measuring range of the test, for the other situations (including steel fibre and hybrid fibre reinforced concrete) 2.5mm was taken as calculation range.

The data on fracture energy are presented in Fig.2-22.

The results show that in the measuring range, the addition of PAN or pitch carbon fibres increases the fracture energy of the composite by 87% and 72%, respectively. The addition of hooked or plain steel fibres increases the fracture energy 13.5 and 11.6 times, respectively. Fracture energy data up to 20 times these of plain concrete were achieved in the case of hybrid fibre systems.
However, as an exception, the fracture energy of N09 specimens (reinforced with 0.3% pitch carbon fibres and 0.5% plain steel fibres) is lower than that of N02, which was reinforced with 0.5% plain steel fibres alone. In the pre-cracking range, this hybrid fibre system provides positive effects on the mechanical properties (reflected by the improved compressive, splitting and flexural strength), but in the post-cracking range, the energy-absorbing capacity drops quickly. This may be related to fibre type and fibre combination in the composite, but this should be confirmed by additional investigations.

The results can be briefly described as follows:

- Fracture energy ($G_F$) of mono-steel fibre concrete exceeded that of plain concrete by a factor 11.6~13.5.
- In the case of carbon fibre reinforced composites, $G_F$ was raised by a factor of 1.8.
- The mechanical properties were further improved by applying hybrid fibre systems (N06, N07 and N08). In comparison to the plain concrete, $G_F$ was 16~19 times increased.
- The mechanical properties of the hybrid fibre reinforced specimens N06 and N07 were similar to or even better than those reinforced by 0.8% plain steel fibres (N10).
Chapter 2

- A negative effect on fracture energy in No9 was observed. The result shows that the hybrid fibre system of plain steel fibres and pitch carbon fibres is a combination that should be avoided.

2.4 Summary

The results of Series I and III are comparable since both deal with concrete reinforced by steel and carbon fibres and have a similar matrix composition. Series II encompasses the fibre mortars serving as reference for the analysis of the mechanisms of fibre reinforcement and of fibre interactions.

The strength levels of the plain concrete of Series I and Series III were quite similar, but the reinforcing effects of the hybrid fibre systems on the two kinds of composites were very much different. Series III with lower steel fibre content achieved a marked improvement in bending behaviour of the composites. On the contrary, the hybrid fibre systems in Series I only played a minor role or even had a negative effect. Serious consideration should be given to the reasons for this distinct behaviour.

Seeing the results obtained in Series I, Series II and Series III, the procedures for producing the mixtures were modified, and the fibre types and fibre combinations adjusted. The modified procedure aimed to improve the uniformity of fibre dispersion in concrete. The benefit of the procedure to fibre dispersion will be discussed in 5.2. The improvements of the fibre reinforced concretes in structure and mechanical properties due to the modified procedure and fibre combination will be analysed in next chapter.
Chapter 3

Synergy Effects of Hybrid Fibre Reinforcement

According to the experimental results presented in the previous chapter, some dramatic strengthening and toughening effects were achieved by adding low volume fraction of hybrid steel-carbon fibres to the cementitious matrix. A further analysis with respect to the strengthening mechanism is performed in this chapter. As a result of fibre-matrix interactions, the additional porosity of the composite due to fibre addition is defined and its influence on the properties of material behaviour is analysed. The results show that the steel (macro) fibres and carbon (micro) fibres impose different effects on the porosity of the composites. The addition of the fibres leads to an additional porosity. The additional porosity of the composite affects the efficiency of fibre reinforcement. Synergy effects of the hybrid fibre systems on the mechanical properties of the fibre composites are revealed. The combinations of different interfacial bonds between fibre and matrix and fibre-fibre interactions lead to the synergy effects. A classification is proposed on the basis of the degree of influence of the hybrid systems on the mechanical properties of FRCC.

3.1 Introduction

It is well-known that dramatically improved mechanical properties of cementitious materials can be achieved by the additions of fibres. The improvement of the properties depends on the interactions between matrix and fibres [Betterman 1995]. The matrix-fibre interaction is very complicated. Up to now, the interaction mechanisms are not fully understood.

On meso-structural level, the fibres can change to a certain degree the structure of the cementitious matrix. Pierre et al [1999] found that micro-steel fibres can lead to as high as 40% air content in the mixture. In another case, the addition of up to 0.2 v.% of carbon fibres led to an increased air content in the fresh concrete [Chen 1993a]. On the other
hand, Shui et al [1998] observed that low volume fraction of steel (macro) fibres can decrease the porosity of the cementitious composites. An increase or decrease of the porosity will lead to relevant changes in material properties. On microstructural level, the interactions between fibres and matrix influence the structural features of the fibre-matrix inter-phase layer. For example, in steel fibre cement composite, a duplex film is formed on the fibre surface with a thickness of 1 to 2 μm, followed by a relatively porous layer [Bentur 1995]. In carbon fibre cement composites, the interface layer between the fibre and the matrix was found homogeneous and dense with a thickness varying from 10 to 40μm with moderate amount of portlandite crystals.

A similar structure was found at the fibrillated polypropylene fibre-cement interface [Bentur 1995]. The effects of some vegetable fibres on the structure were studied [Savastano 1992]. In sisal and coir fibre cement composites, much wider ITZ (up to 200μm) and high cracking rate close to the fibres were observed.

To pursue optimum reinforcement results, growing attention is given to hybrid fibre reinforcement systems that consist of two or more types of fibres [Walton 1975, Kobayashi 1982, Xu 1992 and 1998]. As mentioned before, different fibre types impose different effects on the cement matrix. The stronger and stiffer fibres are used to improve the first crack stress and the ultimate strength, while the flexible and ductile fibres are used to enhance toughness and strain capacity [Bentur 1990]. With the low modulus fibres, such as polypropylene fibres, it is therefore hard to obtain a higher first crack strength [Bentur 1995]. Hence, some specific performance of fibre reinforced cementitious composites can be obtained by changing fibre combination.

With respect to crack control, even a low volume content of micro-fibres can effectively bridge micro-cracks, due to large number of fibres. As a result, they can inhibit the propagation of the micro-cracks. Once the micro-cracks have coalesced into macro-cracks, the large fibres can further restrict the evolution of these macro-cracks, thereby substantially improving the toughness of the composite [Betterman 1995].

The improvements achieved in the mechanical properties of the composites due to hybrid fibre reinforcement largely depend, of course, on the relative proportions of the types of fibres. In research carried out by Betterman et al [1995], the first peak stress and the fracture energy of a cement composite reinforced with 2 vol.% of 4mm and 2 vol.% of 12mm long PVA fibres were significantly higher than the corresponding properties of
composite containing a mono fibre reinforcement of 4 vol.% 12mm long of PVA fibres. Hence, hybrid fibre reinforcement is an attractive way to obtain high performance FRCC. However, the information on the mechanisms of hybrid fibre reinforcements is as yet insufficient for proper design. In particular, the influence of hybrid fibre systems on the meso-structure of the composites has not been quantitatively described. This would require insight into the structural changes due to hybrid fibre reinforcement, ultimately allowing for the establishment of a quantitative framework in which technological input parameters are related to mechanical output data. Hence, this makes it possible to estimate the synergetic effect as to mechanical properties, achieved with cementitious composites reinforced by certain fibre combinations, given the mixture proportions and the production technology of the composite. This study will contribute to the establishment of such a framework.

In the previous chapter, this author presented experimental data on mechanical properties of cementitious composites reinforced by low contents of hybrid fibre systems. The results show the properties of the composites to be quite different for different reinforcement systems and for different processing procedures. Some negative effects on the mechanical properties of hybrid steel-carbon fibre concrete were observed. Contrary, in Series III, double strengthening effects were recorded in such low volume content of hybrid fibre systems. The apparent discrepancies should be explained by means of the mentioned structural information. This will be accomplished in this chapter.
3.2 The influences of fibres on the structure of the composites

The synergy effect of fibre reinforced cementitious composites is the consequence of the interactions of fibre-matrix and fibre-fibre. Hence, the influences of fibres on the material structure are firstly taken into account.

Pore structure can affect the mechanical properties of FRCC [Katz et al 1994]. The addition of fibres can cause structural changes of the cementitious matrix. Increased air contents in the fresh mixture were reported [Pierre 1999]. Bentur [1991] pointed out that the addition of micro-carbon fibres in cementitious composite may cause a porous multiple-filament structure. Hence, the addition of fibres can change the density of the cementitious matrix. The porosity changes caused by fibres can reflect the structural changes on macro- and meso-structural level. Herein, a density analysis approach is proposed.

3.2.1 Density analysis approach

When fibres are introduced in cement matrix, the composite’s density may change, because some clusters of fibre filaments remain grouped together in the cement matrix. These so-called multi-filament structures increase the porosity due to entrapped air. To study this phenomenon, density measurements were performed on the composites. Next, the porosity changes in the composites were determined by a simple method.

A fibre reinforced cementitious composite consists of at least four volumetric parts, i.e., cement paste, fibres, aggregates and pores (cracks).

For a dense fibre composite, the ideal bulk density, \(d_0\), can be expressed as:

\[
d_0 = \frac{W_1 + W_2 + W_3 + \ldots}{V_1 + V_2 + V_3 + \ldots} = \frac{\sum W_i}{\sum V_i} = \frac{\sum W_i}{\sum (W_i / \gamma_i)} \tag{3.1}
\]

where, \(W_i\) stands for the weight of a material component (cement, aggregates, fibres, water, and so on), and \(V_i\) and \(\gamma_i\) are the relevant volume and density of the same component, respectively.

Cementitious materials always contain some voids or pores, of course. All these pores are assumed being filled with water since the specimens were water saturated. When this air
volume is denoted by $V'_w$, and the weight of the water filling this space by $W'_w$, then:

$$W'_w = V'_w \cdot \gamma_w$$  \hspace{1cm} (3.2)

where, $\gamma_w$ is the volumetric density of water.

The actual material density, $d_c$ is given by:

$$d_c = \frac{\sum W_i + W'_w}{\sum V_i + V'_w}$$  \hspace{1cm} (3.3)

From (3.2) and (3.3), $W'_w$ can be derived as:

$$W'_w = \frac{\sum W_i - d_c \cdot \sum V_i}{(d_c / \gamma_w) - 1} = \frac{\sum W_i - d_c \cdot \sum (W_i / \gamma_i)}{(d_c / \gamma_w) - 1}$$  \hspace{1cm} (3.4)

Further, the porosity of the composite can be obtained from (3.4).

$$p = \frac{100V'_w}{\sum V_i + V'_w} \%^{\text{[\%]}} = \frac{100(W'_w / \gamma_w)}{\sum (W_i / \gamma_i) + (W'_w / \gamma_w)} \%^{\text{[\%]}}$$  \hspace{1cm} (3.5)

The porosity as defined here is dependent of the absorption-dehydration behaviour of the specimen; hence, the results can be slight different from measurements obtained by other approaches.

When the mix proportion and the volumetric densities of the material components are given, and the bulk density ($d_c$) of the composite is measured, the porosity of the composite can be obtained.

Finally, the effect of the fibres on the material's porosity can be derived by comparing the porosity of the fibre composite with that of the plain composite, or
\[ \Delta p = p_{\text{fibre}} - p_{\text{plain}} \]  

(3.6)

\( \Delta p \) is here defined as the Additional Porosity of the fibre composite. Under strictly controlled conditions, \( \Delta p \) will indeed be a reflection of the influence of fibres on the composite's porosity.

3.2.2 The influence of hybrid steel-carbon fibre systems on the porosity of the composites

Three series of fibre reinforced cement composites were prepared and subjected to the additional porosity analysis. The fibre contents of the three series of fibre cement composites, and the measurement results of the bulk density and the calculated results of the additional porosity according to equation (3.5) and (3.6), are shown in Table 3-1, Table 3-2 and Table 3-3. The measured densities are average values of at least three specimens. The details regarding the materials, the procedures and the mix proportions have been described in Chapter 2.

<table>
<thead>
<tr>
<th>Code</th>
<th>Pitch carbon fibre (v.%%)</th>
<th>Hooked steel fibre (v.%%)</th>
<th>( \rho_c ) (kg/m(^3))</th>
<th>Porosity, ( p ) (%)</th>
<th>( \Delta p ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-00</td>
<td>0.0</td>
<td>0.0</td>
<td>2359</td>
<td>6.38</td>
<td>0.00</td>
</tr>
<tr>
<td>CS-20</td>
<td>0.2</td>
<td>0.0</td>
<td>2353</td>
<td>6.70</td>
<td>0.32</td>
</tr>
<tr>
<td>CS-02</td>
<td>0.0</td>
<td>1.0</td>
<td>2419</td>
<td>5.80</td>
<td>-0.58</td>
</tr>
<tr>
<td>CS-11</td>
<td>0.1</td>
<td>0.5</td>
<td>2368</td>
<td>7.55</td>
<td>1.17</td>
</tr>
<tr>
<td>CS-12</td>
<td>0.1</td>
<td>1.0</td>
<td>2381</td>
<td>8.27</td>
<td>1.89</td>
</tr>
<tr>
<td>CS-21</td>
<td>0.2</td>
<td>0.5</td>
<td>2375</td>
<td>6.93</td>
<td>0.55</td>
</tr>
<tr>
<td>CS-22</td>
<td>0.2</td>
<td>1.0</td>
<td>2377</td>
<td>8.48</td>
<td>2.10</td>
</tr>
</tbody>
</table>
## Chapter 3

### Table 3-2 Additional porosity of the composites of the Series II

<table>
<thead>
<tr>
<th>Code</th>
<th>PAN fibre (v.%)</th>
<th>Pitch fibre (v.%)</th>
<th>Plain fibre (v.%)</th>
<th>$d_e$ (kg/m$^3$)</th>
<th>Porosity (%)</th>
<th>$\Delta p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2289</td>
<td>6.47</td>
<td>0.0</td>
</tr>
<tr>
<td>M02</td>
<td>0.0</td>
<td>0.0</td>
<td>0.8</td>
<td>2353</td>
<td>4.84</td>
<td>-1.63</td>
</tr>
<tr>
<td>M03</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
<td>2319</td>
<td>5.79</td>
<td>-0.68</td>
</tr>
<tr>
<td>M04</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>2266</td>
<td>8.05</td>
<td>1.58</td>
</tr>
<tr>
<td>M05</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>2270</td>
<td>7.72</td>
<td>1.25</td>
</tr>
<tr>
<td>M06</td>
<td>0.0</td>
<td>0.2</td>
<td>0.0</td>
<td>2270</td>
<td>7.74</td>
<td>1.27</td>
</tr>
<tr>
<td>M07</td>
<td>0.0</td>
<td>0.3</td>
<td>0.0</td>
<td>2261</td>
<td>8.35</td>
<td>1.88</td>
</tr>
<tr>
<td>M08</td>
<td>0.2</td>
<td>0.0</td>
<td>0.8</td>
<td>2337</td>
<td>5.88</td>
<td>-0.59</td>
</tr>
<tr>
<td>M09</td>
<td>0.3</td>
<td>0.0</td>
<td>0.5</td>
<td>2323</td>
<td>5.74</td>
<td>-0.63</td>
</tr>
<tr>
<td>M10</td>
<td>0.1</td>
<td>0.0</td>
<td>0.7</td>
<td>2349</td>
<td>4.72</td>
<td>-1.75</td>
</tr>
<tr>
<td>M11</td>
<td>0.0</td>
<td>0.2</td>
<td>0.6</td>
<td>2333</td>
<td>5.42</td>
<td>-1.05</td>
</tr>
<tr>
<td>M12</td>
<td>0.0</td>
<td>0.3</td>
<td>0.5</td>
<td>2309</td>
<td>6.71</td>
<td>0.24</td>
</tr>
</tbody>
</table>

* Both Pitch and PAN fibres are carbon fibres, and Plain fibres are steel fibres.

### Table 3-3 Additional porosity of the composites of the Series III

<table>
<thead>
<tr>
<th>Code</th>
<th>PAN fibre (v.%)</th>
<th>Pitch fibre (v.%)</th>
<th>Hooked fibre (v.%)</th>
<th>Plain fibre (v.%)</th>
<th>$d_e$ (kg/m$^3$)</th>
<th>Porosity (%)</th>
<th>$\Delta p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2406</td>
<td>2.82</td>
<td>0</td>
</tr>
<tr>
<td>N02</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.50</td>
<td>2440</td>
<td>2.31</td>
<td>-0.51</td>
</tr>
<tr>
<td>N03</td>
<td>0</td>
<td>0</td>
<td>0.50</td>
<td>0</td>
<td>2442</td>
<td>2.12</td>
<td>-0.70</td>
</tr>
<tr>
<td>N04</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2397</td>
<td>3.28</td>
<td>0.46</td>
</tr>
<tr>
<td>N05</td>
<td>0</td>
<td>0.30</td>
<td>0</td>
<td>0</td>
<td>2403</td>
<td>2.85</td>
<td>0.03</td>
</tr>
<tr>
<td>N06</td>
<td>0.25</td>
<td>0</td>
<td>0.50</td>
<td>0</td>
<td>2437</td>
<td>2.36</td>
<td>-0.46</td>
</tr>
<tr>
<td>N07</td>
<td>0.25</td>
<td>0</td>
<td>0.50</td>
<td>0.50</td>
<td>2429</td>
<td>2.88</td>
<td>0.06</td>
</tr>
<tr>
<td>N08</td>
<td>0</td>
<td>0.30</td>
<td>0.50</td>
<td>0</td>
<td>2441</td>
<td>2.02</td>
<td>-0.80</td>
</tr>
<tr>
<td>N09</td>
<td>0</td>
<td>0.30</td>
<td>0</td>
<td>0.50</td>
<td>2431</td>
<td>2.68</td>
<td>-0.14</td>
</tr>
<tr>
<td>N10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.80</td>
<td>2464</td>
<td>1.73</td>
<td>-1.09</td>
</tr>
</tbody>
</table>

* Both Pitch and PAN fibres are carbon fibres, and Plain and Hooked fibres are steel fibres.
The results clearly indicate that the influence of the fibres on the matrices is significant. In the three series of tests, the addition of a mono steel fibre reinforcement decreases the porosity of the composites ($\Delta p<0$), whereas the addition of a mono carbon fibre reinforcement increases the porosity of the composites ($\Delta p>0$). The mechanism underlying the porosity decline of the steel fibre composites may be piercing. The steel fibres pierce through air voids in the matrix, allowing them to merge more easily during vibration. These larger air voids are easy to escape from the matrix.

It can be concluded from a comparison of Series I and Series III, that the additional porosity is directly depending on the mixing procedures. In the Series I, the carbon fibres were mixed simultaneously with other components in the concrete mixer, resulting in poorly dispersed fibres, although the total mixing time was longer than in Series III. It should be noted that the additional porosity of the hybrid fibre systems in Series I was much higher than the composites containing mono carbon or steel fibre reinforcement. This demonstrates that the additional porosity is very sensitive to mixing procedures. Of course, the higher additional porosity will affect the mechanical properties of the composites.

With the improved mixing procedures (described in Chapter 2), the additional porosity of the composites reinforced with the hybrid fibre systems dramatically decreased. The total porosity of the composites with the hybrid fibre systems is even lower than that of the plain composite.

The influence of fibre combinations on the additional porosity is similar for mortars (Series II) and concrete systems (Series III).
3.3 Strengthening and toughening mechanisms of low hybrid fibre contents

The mechanical properties of the cementitious composites reinforced by low content of hybrid fibres were studied. The test results were presented in Chapter 2. The density analysis shows that the additional porosity is an important factor governing the strengthening results of the fibres. Herein, the contributions of various fibre combinations to the improved mechanical properties of concrete composites are discussed on the basis of the test results of Series III.

3.3.1 The rule of mixtures for hybrid fibre systems

The rule of mixture for the mono fibre-matrix system has been discussed in 2.1. For a hybrid fibre-cement system, the rule of mixture can be similar with the mono fibre system. Fig.3-1 shows two ideal models for hybrid fibre composites, the parallel model and the series model. The composite is assumed in elastic and pre-cracked zone, and the fibre-matrix bond is perfect. In model A, two types of fibres are parallel to the stress direction, and the matrix and the fibres undergo a similar same strain, \( \varepsilon \). Hence, the elastic modulus of the composite will be:

\[
E_c = V_{f1} \cdot E_{f1} + V_{f2} \cdot E_{f2} + (1 - V_{f1} - V_{f2}) \cdot E_m
\]  

(3.7)

---

Fig.3-1 Ideal mechanical models for hybrid fibre composites.
\[ \sigma_c = V_{f1} \cdot \sigma_{f1} + V_{f2} \cdot \sigma_{f2} + (1-V_{f1}-V_{f2}) \cdot \sigma_m \] (3.8)

This is the upper limit in the elastic, pre-crack zone of the fibre reinforced cement. When the matrix exceeds its elastic limit, equation (3.8) still holds but with

\[ \sigma_c \neq E_m \varepsilon \] (3.9)

For the model B, the relationship of the elastic moduli is given by:

\[ \frac{1}{E_c} = \frac{V_{f1}}{E_{f1}} + \frac{V_{f2}}{E_{f2}} + \frac{1-V_{f1}-V_{f2}}{E_m} \] (3.10)

or:

\[ \frac{\varepsilon_c}{\sigma_c} = \frac{\varepsilon_{f1} \cdot V_{f1}}{\sigma_{f1}} + \frac{\varepsilon_{f2} \cdot V_{f2}}{\sigma_{f2}} + \frac{\varepsilon_m (1-V_{f1}-V_{f2})}{\sigma_m} \] (3.11)

This is the lower limit of the composite system.

Approximately, in a low fibre volume fraction composite,

\[ \therefore V_{f1}, V_{f2} \ll 1, \text{ and } \varepsilon_{f1}, \varepsilon_{f2} \ll \varepsilon_m \]

\[ \left( \frac{\varepsilon_{f1} \cdot V_{f1}}{\sigma_{f1}} + \frac{\varepsilon_{f2} \cdot V_{f2}}{\sigma_{f2}} \right) \ll \frac{(1-V_{f1}-V_{f2}) \cdot \varepsilon_m}{\sigma_m} \] (3.12)

\[ \therefore \sigma_c = \sigma_m \] (3.13)

When a composite is reinforced by a 3-D randomly dispersed hybrid fibre system, the mechanical properties of this fibre composite should be between model A and model B.
In a practical case, the fibres distribute in various directions, and the bond will not be perfect. Hence, the effects of fibre orientation and of length have to be taken into account when using the rule of mixture.

Theoretically, Young’s modulus, $E_c$, first crack strength, $\sigma_{mi}$, of a composite reinforced with two kinds of fibres (continuous fibres and perfect bond) can be expressed as:

$$E_c = E_m \cdot V_m + \eta_{f1} \cdot \eta_{\theta1} \cdot E_{f1} \cdot V_{f1} + \eta_{f2} \cdot \eta_{\theta2} \cdot E_{f2} \cdot V_{f2}$$  

(3.14)

$$\sigma_{mi} = \sigma_{mu} \cdot V_m + \eta_{f1} \cdot \eta_{\theta1} \cdot \sigma_{f1} \cdot V_{f1} + \eta_{f2} \cdot \eta_{\theta2} \cdot \sigma_{f2} \cdot V_{f2}$$  

(3.15)

And, in a cracked medium, splitting strength, $\sigma_{ST}$, of a fibre composite is given by

$$\sigma_{ST} = \frac{1}{3} (a_1 \cdot \tau_1 \cdot V_{f1} + a_2 \cdot \tau_2 \cdot V_{f2}) + \sigma_{mu} \cdot V_m$$  

(3.16)

where,

$\sigma_c$ – tensile strength of composite;

$\epsilon_c$ – strain of the fibre composite;

$\epsilon_m$ – strain of the cement matrix;

$\epsilon_{fj}$ – strain of the fibres ($j=1, 2$);

$a_j$ – aspect ratio of the fibres, ($j=1, 2$);

$\tau$ – interfacial shear strength, ($j=1, 2$);

$\sigma_{mu}$ – matrix tensile strength;

$\sigma_{fj}$ – fibre tensile strength, ($j=1, 2$);

$V_m$ – fraction of the cross-sectional area transmitting tensile stresses;

$V_{fj}$ – nominal fibre volume content, ($j=1, 2$);

$\eta_{fj}$ – length efficiency factor of the fibres;

$\eta_{\theta}$ – orientation efficiency factor of the fibres.

3.3.2 Analysis of the synergy effects

The relationships between the mechanical properties and the material parameters have
been discussed above. These relations were developed based on a rule of mixtures. In practice, many factors affect the mechanical properties of the composites reinforced by hybrid fibre systems. The sole effect of the fibre additions can be assessed by means of the rule of mixtures. Although the rule of mixtures is valid only if all the components are linearly elastic, and the bond between fibre and matrix is perfect, the calculated results still can serve as a reference. And, the analysis demonstrated that the synergy effects of hybrid fibre systems mainly depend on the improvement of fibre efficiency.

To reveal the strengthening and toughening effects of fibre reinforcement, the increments of the mechanical properties of the fibre composites comparing to the plain concrete were taken into account. The splitting strength of the matrix (plain mortar or plain concrete) is \( \sigma_{ST}(1) \). Hence, the splitting strength of N02, N03... can be indicated by \( \sigma_{ST}(2), \sigma_{ST}(3), \) and so on. The increment of the splitting strength is as a consequence:

\[
\Delta \sigma_{ST}(i) = \sigma_{ST}(i) - \sigma_{ST}(1) \quad (i = 2-10)
\]  

(3.17)

Accordingly, increments for the first-crack strength, the flexural strength and the fracture energy can be expressed by, respectively

\[
\Delta \sigma_{mi}(i) = \sigma_{mi}(i) - \sigma_{mi}(1)
\]  

(3.18)

\[
\Delta \sigma_{b}(i) = \sigma_{b}(i) - \sigma_{b}(1)
\]  

(3.19)

\[
\Delta G_F(i) = G_F(i) - G_F(1)
\]  

(3.20)

The calculated results are presented in Table 3-4.
Table 3-4 The effects of various fibre systems on the mechanical properties

<table>
<thead>
<tr>
<th>Code</th>
<th>$\Delta \sigma_{mi}(i)$ (N/mm$^2$)</th>
<th>$\Delta \sigma_{ST}(i)$ (N/mm$^2$)</th>
<th>$\Delta \sigma_{i}(i)$ (N/mm$^2$)</th>
<th>$\Delta G_F(i)$ (Nm/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N01 (i=1)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N02 (i=2)</td>
<td>1.0</td>
<td>0.9</td>
<td>2.1</td>
<td>952</td>
</tr>
<tr>
<td>N03 (i=3)</td>
<td>1.1</td>
<td>1.3</td>
<td>2.4</td>
<td>1114</td>
</tr>
<tr>
<td>N04 (i=4)</td>
<td>1.0</td>
<td>0.1</td>
<td>2.1</td>
<td>72</td>
</tr>
<tr>
<td>N05 (i=5)</td>
<td>0.9</td>
<td>0.1</td>
<td>1.9</td>
<td>60</td>
</tr>
<tr>
<td>N06 (i=6)</td>
<td>2.0</td>
<td>1.7</td>
<td>4.0</td>
<td>1470</td>
</tr>
<tr>
<td>N07 (i=7)</td>
<td>1.8</td>
<td>2.0</td>
<td>3.6</td>
<td>1240</td>
</tr>
<tr>
<td>N08 (i=8)</td>
<td>1.6</td>
<td>1.5</td>
<td>3.0</td>
<td>1266</td>
</tr>
<tr>
<td>N09 (i=9)</td>
<td>1.7</td>
<td>1.0</td>
<td>2.2</td>
<td>640</td>
</tr>
<tr>
<td>N10 (i=10)</td>
<td>-</td>
<td>1.9</td>
<td>2.9</td>
<td>1448</td>
</tr>
</tbody>
</table>

The results reveal fibre contributions to mechanical properties in the various systems, although occasionally of marginal importance. By comparing in the same way hybrid fibre systems with those of the relevant mono fibre systems, the possible occurrence of synergy can be assessed. For example, a considerable strengthening effects was found for the splitting tensile strength of hybrid fibre composites compared to that of mono fibre composites. For example, the synergy in mix N06 due to the hybrid reinforcement, $\Delta \Delta \sigma_{ST}$ (6), is:

$$\Delta \Delta \sigma_{ST}(6) = \Delta \sigma_{ST}(3, 4) - [\Delta \sigma_{ST}(3) + \Delta \sigma_{ST}(4)] = 1.7 - 1.4 = 0.3 \quad (3.21)$$

A similar analysis was performed for the other mixes and the various properties. The results are shown in Table 3-5.
Table 3-5 Synergy effects of the hybrid fibre systems

<table>
<thead>
<tr>
<th>Items</th>
<th>Hybrid System</th>
<th>Sum of mono systems</th>
<th>Synergy</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-crack Strength</td>
<td>$\Delta\sigma_{mi} (6)=2.0$</td>
<td>$\Delta\sigma_{mi} (3)+\Delta\sigma_{mi} (4)=2.1$</td>
<td>-0.1</td>
<td>-5.0</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_{mi} (7)=1.8$</td>
<td>$\Delta\sigma_{mi} (2)+\Delta\sigma_{mi} (4)=2.0$</td>
<td>-0.2</td>
<td>-11.1</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_{mi} (8)=1.6$</td>
<td>$\Delta\sigma_{mi} (3)+\Delta\sigma_{mi} (5)=2.0$</td>
<td>-0.4</td>
<td>-25.0</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_{mi} (9)=0.7$</td>
<td>$\Delta\sigma_{mi} (2)+\Delta\sigma_{mi} (5)=1.9$</td>
<td>-1.2</td>
<td>-171.4</td>
</tr>
<tr>
<td>Splitting Strength</td>
<td>$\Delta\sigma_{ST} (6)=1.7$</td>
<td>$\Delta\sigma_{ST} (3)+\Delta\sigma_{ST} (4)=1.4$</td>
<td>0.3</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_{ST} (7)=2.0$</td>
<td>$\Delta\sigma_{ST} (2)+\Delta\sigma_{ST} (4)=1.0$</td>
<td>1.0</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_{ST} (8)=1.5$</td>
<td>$\Delta\sigma_{ST} (3)+\Delta\sigma_{ST} (5)=1.4$</td>
<td>0.1</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_{ST} (9)=1.0$</td>
<td>$\Delta\sigma_{ST} (2)+\Delta\sigma_{ST} (5)=1.0$</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>$\Delta\sigma_b (6)=4.0$</td>
<td>$\Delta\sigma_b (3)+\Delta\sigma_b (4)=2.4+2.1=4.5$</td>
<td>-0.5</td>
<td>-12.5</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_b (7)=3.6$</td>
<td>$\Delta\sigma_b (2)+\Delta\sigma_b (4)=2.1+2.1=4.2$</td>
<td>-0.6</td>
<td>-16.7</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_b (8)=3.0$</td>
<td>$\Delta\sigma_b (3)+\Delta\sigma_b (5)=2.4+1.9=4.3$</td>
<td>-1.3</td>
<td>-43.3</td>
</tr>
<tr>
<td></td>
<td>$\Delta\sigma_b (9)=2.2$</td>
<td>$\Delta\sigma_b (2)+\Delta\sigma_b (5)=2.1+1.9=4.0$</td>
<td>-1.8</td>
<td>-81.8</td>
</tr>
<tr>
<td>Fracture Energy</td>
<td>$\Delta G_F (6)=1470$</td>
<td>$\Delta G_F (3)+\Delta G_F (4)=1186$</td>
<td>284</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>$\Delta G_F (7)=1240$</td>
<td>$\Delta G_F (2)+\Delta G_F (4)=1024$</td>
<td>216</td>
<td>17.4</td>
</tr>
<tr>
<td></td>
<td>$\Delta G_F (8)=1266$</td>
<td>$\Delta G_F (3)+\Delta G_F (5)=1174$</td>
<td>92</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>$\Delta G_F (9)=640$</td>
<td>$\Delta G_F (2)+\Delta G_F (5)=1012$</td>
<td>-372</td>
<td>-58.1</td>
</tr>
</tbody>
</table>

The following conclusions can be drawn from the results:

- Splitting strength and fracture energy reveal synergy due to hybrid fibre reinforcement. Hence, hybrid fibre reinforcement can disproportionately increase splitting strength and fracture energy of the composites.

- Hybrid fibre systems can further improve flexural strength and first crack strength compared to the single fibre systems, but the effect is not significant. There is a negative effect of the hybrid fibre system on the first crack strength of N09.

- The results show that the hybrid fibre systems N06 and N07 are highly effective combinations for improving the mechanical properties of the composites, whereas N09 is a negative hybrid fibre system.

Using equation (3.8) and (3.9) to analyze and compare the single fibre systems and the
hybrid fibre systems, one can find that the improvements of the mechanical properties of the composites depend on the fibre reinforcement efficiency. In hybrid fibre reinforced composites, the reinforcement efficiency of fibres can be enhanced in various ways; this will be discussed next.

3.3.3 Improvement of fibre reinforcement efficiency
For a system short of chopped fibres, the first condition of improving reinforcement efficiency is to homogeneously disperse the fibres in the cement matrix. In this study, an innovative “two-step” mixing procedure was employed in the preparation process. As a result, the reinforcement efficiency significantly improved. To further improve the efficiency, the following mechanisms can be taken into account.

3.3.3.1 Interlock effect of the hooked steel fibres
The hybrid fibre systems containing hooked steel fibres show higher reinforcing efficiency, according to the test results.

![Hooked steel fibre in cement matrix](image)

Fig.3-2 Hooked steel fibre in cement matrix (after Bentur [1991])
The two sides of the fibre are embedded and anchored inside the matrix. This kind of fibre is particularly good for improving flexural strength and fracture energy. As a result, the pull-out force versus displacement curve can be significantly different from the one obtained with a straight fibre, especially in the post-peak zone [Bentur 1991]. The
special shape of the hooked fibres can lead to a strengthening efficiency of more than 100%. Hence, even though the fibres are used in low volume content, a marked improvement in the mechanical properties can be achieved. A direct pull-out test of a hooked fibre by Bentur et al [1991] showed that damage occurs in the matrix which extends well beyond the interfacial zone.

3.3.3.2 Bonding effect of the micro carbon fibres
In Series III, two types of carbon fibres, PAN and pitch carbon fibres, were employed. The two kinds of carbon fibres have different surface textures. The SEM analysis (Fig.3-3 and Fig.3-4) showed the pitch type of carbon fibre to have very smooth surfaces, whereas the PAN type of carbon fibre had a coarse-textured surface containing large numbers of twisty veins. The microstructure of the interfacial transition zone between PAN fibre-cement and pitch fibre-cement will be different. The SEM images also revealed the pitch type of carbon fibre to detach readily from the matrix, implying a poor bond between the pitch fibre-matrix interfaces. On the contrary, the frictional bond between PAN fibres and the matrix will be relatively strong due to the rough surface. Hence, the PAN carbon fibres are more effective in controlling the propagation of micro-cracks. This is one of the reasons why the PAN type of carbon fibres is more effective than the pitch type of carbon fibres in strengthening and toughening the cementitious composites.
3.4 Classification of the Combined Effects

The Combined Effect can be summarized as follows. Assuming $f_X$ is one of the mechanical properties ($\sigma_{ST}$, $G_F$, and so on), $\Delta f^*_X (i, j)$ is the mechanical increment due to the hybrid fibre system, and $\Delta f^*_X (i)$, $\Delta f^*_X (j)$ are the mechanical increments in the relevant single fibre systems, then the Combined Effects can be defined as:

1) Super-double effect:

$$\Delta f^*_X (i, j) \geq [\Delta f^*_X (i) + \Delta f^*_X (j)]; \quad (3.22)$$

2) Normal effect:

$$\Delta f^*_X (i, j) > \max\{\Delta f^*_X (i), \Delta f^*_X (j)\}; \quad (3.23)$$

3) Negative effect:

$$\Delta f^*_X (i, j) < \max\{\Delta f^*_X (i), \Delta f^*_X (j)\}. \quad (3.24)$$

These equations can serve to assess the reinforcement efficiency of a hybrid fibre system. For hybrid fibre reinforcement, equation (3.22) is an ideal target. However, the test results presented in this research show that the synergy effects depend on different mechanical properties. For splitting strength and fracture energy, the super-double effect can be achieved due to the hybrid fibre systems, whereas for first-crack strength and flexural strength, the synergy effects of hybrid fibre systems were limited to the range of (3.23). Hybrid fibre systems have larger capabilities, however that should be exploited by further improvement of the fibre reinforcement efficiency.
Chapter 4

Electrical Properties of Fibre Reinforced Cement Composites

Electrical properties were investigated of cement composites reinforced with conductive fibres. A series of experimental studies were performed on carbon fibre-cement paste and on hybrid steel-carbon fibre concrete. Direct current (D.C.) and alternative current (A.C.) were applied in the study. The test results revealed the influences of fibre type, fibre content, mix proportion, measuring frequency and curing age on the electrical behaviour of the composites.

The D.C. resistivity measurements at increasing carbon fibre contents on oven-dry specimens showed this to be a percolation phenomenon, whereby a dramatic drop is found around 0.8 volume % of fibres. When A.C. measurements were employed on moist carbon fibre-cement specimens, the variation of impedance vs. fibre content became relatively moderate, namely, impedance gradually declined with increasing carbon fibre content. The applied frequency had a significant effect on the impedance measurements on the fibre-cement paste and concrete composites. The most dramatic impedance drop took place in the frequency range of 0-1000Hz. Conductive model of carbon fibre-cement is discussed in this study.

Electrical properties of concrete with low volume content of hybrid steel-carbon fibres were also studied. Impedance of the concrete was found to quickly decline with the total fibre content. When the fibre content was more than 0.6 volume %, the decline became slow. The hybrid fibre systems did not cause dramatic impedance wave.
4.1 Introduction

Fibres are normally used to improve mechanical properties of brittle cement-based materials. However, some additional effects arise when fibres are added to such materials. For example, density, electrical or thermal conductivity of the fibre-cement composite will increase upon the addition of heavy, electrical conductive or thermal conductive fibres, respectively.

Steel and carbon fibres are electrical conductors. They are presently used as secondary reinforcement in cementitious composites. Electrical properties of these fibre composites have been found to dramatically change with the addition of even low volume fraction of steel or carbon fibres once exceeding the critical limit [Banthia 1992 and Neville 1995].

As Neville [1995] pointed out, electrical properties are of concern in some special applications, such as railway ties (where inadequate resistivity affects some signalling systems) or in structures in which concrete is used for protection from stray currents. Resistivity changes of cement materials also affects corrosion process of rebars or steel fibres embedded in the cement matrix.

A large number of studies on the electrical properties mainly deal with plain cement paste and concrete. There are only few studies conducted on cementitious composites reinforced by conductive fibres [Banthia 1992, Reza 1999]. Regarding the experimental assessment of the electrical properties of plain cement paste and plain concrete, the following achievements can be mentioned [McCarter 1990, Xie 1993, Gu 1992, 1993a and 1993b]:

1) The established relationships between electrical resistivity and mix proportions (W/C, cement content, etc.);
2) The establishment of relationships between the constituents, microstructure and frequency response by A.C. Impedance spectroscopy;
3) The development of some equivalent R-C circuits models for cement paste.
4) The development of a method for monitoring the strength development of young concrete using the dielectric properties of concrete [Beek 2000].

With respect to cementitious composites reinforced by conductive fibres, the following achievements can be added:
1) The assessment of the effects of conductive fibre on electrical properties of cementitious composites [Shen 1992], i.e., conductive fibres in the cement matrix were found very sensitive to A.C. signals.

2) The assessment of electrical properties of cementitious composites reinforced by hybrid steel-carbon fibre system, in which the fibre volume fraction was exceeding 1% [Banthia 1992];

3) The establishment of the relationship between contact resistance and interfacial bond strength [Fu 1995a and 1995b];

4) The assessment of electrical properties of fibre composites under compressive and bending conditions. Hereby, the electrical output signal was related to the external loading to which the composite was subjected. This relationship between the load and the electrical response was found approximately linear in a loading range [Li et al 1995].

5) The assessment of electro-magnetic shielding behaviour of conductive fibres reinforced cementitious composites [Johan 1999].

Yet, although the interest of studying electrical properties of FRC is increasing, the picture derived from the research results is still incomplete. Such research efforts have been mainly focusing on plain cement paste and concrete and do not sufficiently cover fibre-cement systems.

As a consequence, the insight into the various aspects of the electrical properties of low content of hybrid fibre reinforced composites is insufficient. Moreover, the studies on the electrical properties mainly focus on the positive effects while neglecting the negative ones, such as the effects of conductive fibres on durability of cementitious materials.

In this study, carbon fibre-cement paste and steel-carbon fibre-concrete are investigated. The electrical response of fibre cement composites under direct current (D.C.) and alternative current (A.C.) were measured. Especially, concrete composites reinforced with a low volume content of hybrid steel and carbon fibres are considered. The results will be beneficial to the practical use of the conductive fibre cement composites.
4.2 Electrical conductive behaviour of carbon fibre-cement paste

To study the electrical conductive properties of carbon fibre-cement paste, specimens of fibre-cement paste were subjected to direct current (D.C.) and alternative current (A.C.) conditions. Such different conditions can lead to distinct differences in material performance.

The pore water solution of cement paste generally contains various positive and negative ions, such as Ca$^{2+}$, Na$^+$, K$^+$, OH$^-$, SO$_4^{2-}$, and so on. Hence, it will behave essentially as an electrolyte. As a result, the true resistivity of a moist cement specimen can not be determined by means of the Ohm’s law using a single D.C. measurement of $V$ (voltage) and $I$ (current). This is due to the chemical reactions that take place in the vicinity of the electrodes and the hydrogen and oxygen gases that are liberated as a result. Deposits are thus formed around the electrodes in the form of a thin film, that will create a polarization potential [Banthia 1992]. In this study, D.C. measurements were performed on oven-dry cement-paste specimens to eliminate the polarization potential. A.C. measurements were carried out on moist and even water-saturated specimens. The first series of tests is tended to reveal the influence of carbon fibres on the resistivity of the composites. The other tests will represent practical cases whereby resistivity is affected by the water content.

4.2.1 Experiments on fibre-cement paste systems
4.2.1.1 Resistivity vs. carbon fibre content under D.C. conditions
The effect of carbon fibre content on the resistivity of the composites was experimentally studied.

A Portland cement #525 was used, produced by Huaxin Cement Plant, Hubei, China. Further, a PAN-type carbon fibre was applied, produced by Shanghai Corbon Work, China. The main properties of the fibre are shown in Table 4-1. The physical properties of the carbon fibre mesh are presented in Table 4-2.

<table>
<thead>
<tr>
<th>Filament diameter (µm)</th>
<th>Density (g/cm$^3$)</th>
<th>Elongation (%)</th>
<th>Tensile strength (GPa)</th>
<th>Tensile modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7±0.2</td>
<td>≥ 1.75</td>
<td>≥ 1.2</td>
<td>1.95</td>
<td>175</td>
</tr>
</tbody>
</table>

- 66 -
Table 4-2 Physical properties of the PAN carbon fibre mesh

<table>
<thead>
<tr>
<th>Tensile strength (MPa)</th>
<th>Thickness (mm)</th>
<th>Area density (g/m²)</th>
<th>Carbon content (wt. %)</th>
<th>Resistivity (Ω/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 400</td>
<td>0.5–0.8</td>
<td>150–380</td>
<td>≥ 95</td>
<td>0.12–0.3</td>
</tr>
</tbody>
</table>

The water to cement ratio was 0.30. Mixtures were prepared with an Hobart paste mixer; mixing time around 3 minutes. The fibre-cement paste was cast into 40×40×40mm molds. Two pieces of carbon fibre mesh were embedded as electrode material near two opposite surfaces of the specimen. The specimens were cured for 28 days at 23°C and at 95% RH or higher, and thereupon dried for 48 hrs in oven at 50°C.

Resistance measurements were performed with the set-up shown in Fig.4-1. A constant voltage power source supplied the energy to the specimen. The applied current was kept below 200μA to avoid heating of the specimen. The resistance, R, was obtained by means of Ohm’s law:

\[ R = \frac{V}{I} \] (4.1)

Fig.4-1 Set-up for resistance measurement on carbon fibre-cement composites
where, $V$ and $I$ represent voltage and current, respectively. The resistivity, $\rho$, was calculated by following formula:

$$\rho = \frac{RA}{L}$$  \hspace{1cm} (4.2)

where, $A$ is the area of the specimen perpendicular to the electrical field direction, and $L$ is the distance between the two electrodes. For the D.C. measurements, the specimens were in dry state.

4.2.1.2 Electrical properties of carbon fibre-cement paste under A.C. conditions

Electrical conductive behaviour of the carbon fibre-cement paste was studied by applying successively A.C. signals with various frequencies. The influences of fibre content, frequency and curing ages on electrical properties were taken into account. Carbon fibres and cement quality in this study were the same as in 4.2.1.1. Water to cement ratio of the carbon fibre cement paste was 0.28. Volume fraction of the carbon fibre cement paste ranged from 0 to 1% of the composite. 6 cylindrical specimens (ϕ30×30mm) were prepared for each mix. Average values were determined of the results. Impedance measurements were performed with HP-4275A and HP-4284A Electron Property Meter (EPM), produced by Hewlett Packard Corporation, USA. The applied frequency of the equipment varied from 20Hz to 10MHz, the measuring ranges for the resistance amounted 0.01Ω to 100MΩ, and for the capacitance 0.01pF to 100mF. After one day curing in air, the specimens were immersed until the measuring date in water of 20°C. Stainless steel electrodes were applied for the measurements. A contact surface between specimen and electrode was created with an electrical conductive gel. The applied measuring frequencies were 20, 100, 500, 1000, 5000, 10000 and 1000000Hz. It should be noted that the specimens for A.C. measurements were close to water-saturated.

4.2.2 Electrical properties of carbon fibre-cement paste systems

4.2.2.1 Relationships between fibre content and resistivity under D.C conditions.
Results are presented in Fig.4-2. Because the specimens were dried, the resistivity

directly reflects the influence of carbon fibres on the electrical conductivity of the
composites. The curve of Fig.4-2 demonstrates that when fibre content is less than 0.2%,
resistivity is fairly constant. The resistivity quickly drops when the carbon fibre content is between 0.2 and 0.8%. A fairly constant resistivity but on a much lower level than before is regained when carbon fibre content exceeds 0.8%.

Based on the results, the curve can be divided into three parts: the first part (0–0.2% of fibres) represents a situation of independently dispersed carbon fibres in the cement matrix (I). In the second part (0.2–0.8% of fibres), fibre network elements are locally formed in the cement matrix (II). The fibre network in the matrix is continuous in the third part (> 0.8% of fibres) (III). These fibre dispersion situations are sketched in Fig.4-3. The electrical conductive behaviour of the composite is closely associated with the distribution of the fibres. The results show that the resistivity drop in the second stage can be associated with the formation of the local fibre network in the cement matrix.

4.2.2.2 Impedance of CFRC under different frequency conditions

Fig.4-4 shows the impedance variations with fibre content under various applied frequencies. The influence of fibre content on the impedance of the composites is minor at the lowest measuring frequency. This result may be associated with an electrode-cement interface effect.

Fig.4-4 Impedance variations versus fibre content and for different frequencies in Hz under A.C. conditions (28days).
The impedance vs. fibre content relationship becomes more regular at higher frequencies. An approximately linear trend is found between fibre content and the impedance when the applied frequency exceeds 500Hz.

Fig.4-5 presents the impedance variations as a function of the applied frequency for different volume fractions of fibres. For all cases (including the plain cement paste), impedance declines with increasing frequency, but the rate is highest for the fibre-cements. The most significant impedance drop takes place between 0 and 1000Hz. At higher frequencies, the decline rate is slower.

Fig.4-5 Impedance variations versus applied frequency and for different volume fractions of fibres.

More specifically, the results showed that at the lowest frequency, the impedance fluctuated with fibre content. The relevant contribution of the electrode-cement contact to the impedance measurements is according to McCarter et al [1990] particularly important at lower frequencies and will diminishes rapidly as the modulating frequency is increased. Hence, they suggested the applied frequency should exceed 100Hz to eliminate the electrode effects. This is supported by the present experiments.
4.2.2.3 Effect of curing time on the impedance

The effect of curing time on impedance of the carbon fibre cement composites is shown in Fig.4-6. The results show that for each frequency, the impedance increases with time.

![Impedance vs Frequency Graph]

**Fig.4-6 Impedance of CFRC at different ages and frequencies**
(Carbon fibre content is 0.2%).

For different fibre contents, the trends of impedance variations with time are similar, confirming data published in the literature [Banthia 1992]. The change of impedance with time reflects the evolution of the cement matrix density due to hydration. Together with an increasing density as a result of the hydration reactions, also part of capillaries in the matrix will get (partly) filled by hydrates, inhibiting the current to pass. At the same time, the microstructure at the inter-phase of the system will develop with cement hydration, resulting in variation in the interfacial capacitance.

4.2.2.4 Discussions

The obtained results evidence the carbon fibre composites to display different behaviour under D.C. current and A.C. signals. In the case of D.C. measurements, only the resistor element was taken into account, hence, direct contacts of inter-filaments would directly influence the recorded conductive performance of the composite. In the case of A.C. measurements, another electronic element, the capacitor, has been introduced.
Capacitance effects are due to the existence of various interfaces, such as those of electrode-cement, hydrate-solution, fibre-solution and fibre-fibre.

The solid-liquid interfacial zone consists of two parts, a “stern layer” and a “diffuse layer”. The stern layer is a layer of counter-ions strongly absorbed to the solid surface. The diffuse layer exists on top of the stern layer. The schematic structure of the double-layer is shown in Fig.4-7.

![Schematic structure of the double-layer of solid-liquid interfacial zone](image)

**Fig.4-7 Schematic structure of the double-layer of solid-liquid interfacial zone**

Based on a physical model of ordered elements shown at the left of Fig.4-8, Xie et al [1993] derived a model for the electrical conductivity of a hydrated cement system. For an element with thickness \( \Delta x \), the model circuit is shown in Fig.4-8 at the right.

where, \( R_s \) and \( R_l \) are the solid and liquid resistance respectively, and \( R_{int} \) and \( C_{int} \) are the interfacial resistance and capacitance, respectively. This model consists of \( N \) elements with thickness \( \Delta x \).

Finally, these elements are merged into a simple equivalent circuit shown in Fig.4-9.

When conductive fibres, such as carbon fibres are 3-D randomly dispersed in the cement paste, the contribution of the fibres to the electrical conductivity is similar to the capillary water in cement paste. In cement paste, some of capillary pores are blocked, whereas
some of them are connected to each other. The fibres in cement matrix hold the same. Some of fibres are independent, while others are in mutual connect. Of course, there is difference between the fibres and the capillary water. The capillary water is transmitting electrolytic ions, whereas the fibres only allow electrons to pass by. Hence, a resistor ($R_{\text{fibre}}$) can be parallel to the liquid resistor, $R_l$. The addition of the fibres increases the solid-liquid interfaces, hence, the interfacial resistance and capacitance will change.

With this information, an electrical model for conductive fibre-cement paste can be designed. It is shown in Fig.4-10. The model is almost the same as the one for cement.
paste, but the elements have a different physical interpretation, as indicated. The impedance of the circuit shown in Fig.4-10 is given by the complex relationship:

$$Z = Z_1 + Z_2$$  \hspace{1cm} (4.3)

where, $Z_f$ is the total impedance (actually, resistance) of the left part in Fig.4-10

$$Z_1 = \frac{R_1 \cdot R_{\text{fibre}}}{R_1 + R_{\text{fibre}}}$$  \hspace{1cm} (4.4)

$R_{\text{fibre}}$ is apparent fibre resistance, and it depends on fibre content and fibre connectivity, and $Z_2$ is the total impedance of the right part in Fig.4-10

$$Z_2 = \frac{R_2'}{1 + (\omega \cdot C_d' \cdot R_2')^2} - j \frac{\omega \cdot C_d' \cdot R_2'^2}{1 + (\omega \cdot C_d' \cdot R_2')^2}$$  \hspace{1cm} (4.5)

Further,

$$R_1 = \frac{L}{S_e} \cdot \frac{1}{S_l} \cdot \frac{1}{\sigma_1} = \frac{L}{S_e} \cdot \frac{1}{(1 - S_s - S_f)} \cdot \frac{1}{\sigma_1}$$  \hspace{1cm} (4.6)

It can be proven that the area fraction of the fibres, $S_f$, equals its volume fraction, $V_f$, in a 3-D randomly dispersed fibre system. Hence,

$$R_1 = \frac{L}{S_e} \cdot \frac{1}{S_l} \cdot \frac{1}{G_l} = \frac{L}{S_e} \cdot \frac{1}{(1 - S_s - V_f)} \cdot \frac{1}{G_l}$$  \hspace{1cm} (4.7)

where, $G_l$ and $G_{\text{fibre}}$ are liquid conductance and fibre conductance, respectively. $S_e$ is the specimen cross-sectional area normal to electrical field. $S_l$ and $S_s$ are liquid and solid area fractions, respectively. And,
\[ R_{\text{fibre}} = \frac{L}{S_e} \cdot \frac{1}{V_f} \cdot \frac{1}{G_{\text{fibre}}} \]  \hspace{1cm} (4.8)

Let:

\[ R'_1 = \frac{R_1 \cdot R_{\text{fibre}}}{R_1 + R_{\text{fibre}}} \]  \hspace{1cm} (4.9)

\[ X = R'_1 + \frac{R'_2}{1 + (\omega \cdot C'_d \cdot R'_2)^2} \]  \hspace{1cm} (4.10)

\[ Y = \frac{\omega \cdot C'_d \cdot R'_2}{1 + (\omega \cdot C'_d \cdot R'_2)^2} \]  \hspace{1cm} (4.11)

Substitution of eqs. (4.9)- (4.11) in eq. (4.3) yields \( Z = X - jY \)

It can be proven that the following equation holds:

\[ [X - (R'_1 + \frac{R'_2}{2})]^2 + Y^2 = \left(\frac{R'_2}{2}\right)^2 \]  \hspace{1cm} (4.12)

This equation represents a circle with radius \( R'_2/2 \), and center \([(R'_1 + R'_2)/2, 0]\) in the X-Y plane (real-imaginary plane of Z), as shown in Fig.4-11.

\( R'_1, \omega_b \) and \( R'_2 \) can be determined by experiment. Hence, \( C'_d \) can easily be calculated. Fibre contributions on interfacial resistance and capacitance can be obtained by comparing the test results of fibre-cement paste and plain cement paste.
Fig. 4-11 A visualization of Equation (4.12) in the X-Y plane (real-imaginary plane), after Xie et al [1993].
4.3 Electrical conductive behaviour of concrete with low content of hybrid steel-carbon fibres

4.3.1 General remarks
Electrical properties of cementitious composites have been widely studied. Measurements of the electrical responses of such composites can be an effective way to study material properties, particularly microstructural ones. The addition of electrical conductive fibres dramatically changes the electrical properties of the composite and this can cause some engineering problems. Steel fibres are used in concrete elements, like concrete sleepers, to improve mechanical properties and to prolong service life. However, potential corrosion risks and cost requirements limit the content of the conductive fibres to a low level.

Hybrid steel-carbon fibre systems were shown effective in improving mechanical properties of the concrete. Results pertaining to this subject are presented in Chapter 2. The influences of hybrid steel-carbon fibre systems on the electrical conductive properties were also taken into account.

Although a few studies cover the electrical properties of hybrid fibre-cement systems, the fibre contents were in all cases relatively high (> 1% by volume fraction). Studies extending in the low fibre volume range are unfortunately missing. Hence, the recent study is significant.

Mechanism of electrical conduction in low volume content of fibre composites will be different from the ones in high volume content of fibre composites. In low content case, the fibres are basically isolated elements (assuming adequately dispersed fibres) in the cement matrix. On the contrary, in high-density fibre systems, basically a continuous fibre network is formed. Hence, the conductive properties of low content of fibre composites will depend to a certain degree on the pore solution (ion conducting mechanism), whereas in the high content case the conduction process is controlled predominantly by the fibre network (electron conducting mechanism).

In the present study, the effect of measuring frequencies on the impedance is also taken into account. The results show that the effect of frequency is pronounced in the present case
4.3.2 Experiments

4.3.2.1 Raw materials

Cement: Portland cement with a characteristic strength of 52.5MPa, produced by ENCI, The Netherlands.

Steel fibres: Hooked, length 30mm, diameter 0.5mm, stainless steel, produced by Bekaert, Belgium.

Carbon fibres: Pitch-based, mean diameter 10μm, nominal length 12mm, tensile strength 485MPa, Young’s Modulus 45GPa, made by Anshan, China.

Sand: River sand from The Netherland, graded as follows: 1-2mm 35%; 0.5-1mm 18%; 0.25-0.5mm 25%; < 0.25mm 22%.

Gravel: Crushed limestone, composed of 51.5% 2-4mm and 48.5% 4-8mm grains.

Water reducer: FDN-440 type of water reducer, efficiency about 10%, dosage 0.5% by weight of the cement, produced by Xhanjiang, China.

4.3.2.2 Mix proportion

The mix proportions of the concrete and the fibre contents are presented in Table 4-3 and Table 4-4.

Table 4-3 Concrete mix proportions (by weight)

<table>
<thead>
<tr>
<th>Cement</th>
<th>Sand</th>
<th>Gravel</th>
<th>Water</th>
<th>Additive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
<td>2.8</td>
<td>0.38</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Table 4-4 Fibre contents in concrete (in % by volume)

<table>
<thead>
<tr>
<th>Mix code</th>
<th>CS-00</th>
<th>CS-20</th>
<th>CS-02</th>
<th>CS-11</th>
<th>CS-12</th>
<th>CS-21</th>
<th>CS-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Steel</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

4.3.2.3 Test procedures

Fresh concrete mixtures were prepared by Hobart paste mixer and by ZL-190 concrete mixer. The carbon fibres were dispersed in the cement paste, next, the fibre-cement mixture was mixed with the aggregates.

The fibre concrete mixtures were cast into 100×100×100mm steel molds. The specimens were de-molded at the next day. Then, the specimens were cured under climatized conditions (23°C, > 95%RH) until the day of testing.
Chapter 4

The impedance analyzer used for the experiments has a frequency capacity of 0–1000Hz. The data-acquisition system was developed by Delft University of Technology. To eliminate the contact resistance between electrodes and specimen surfaces, the stainless steel plate electrodes were closely attached to opposite surfaces of the specimens with carbon powder cement paste.

4.3.3 Results and discussions
4.3.3.1 The effect of measuring frequency
The impedance values of the various concrete samples were recorded in the frequency range 0.98-1000Hz. Fig.4-10 presents the measured results for 28 days old fibre concrete.

![Graph showing impedance vs frequency](image)

**Fig.4-10 The influence of the applied frequency on the impedance**

When the frequency is 0.98Hz, the impedance difference between plain concrete and fibre reinforced concrete is small. This difference gradually enhances by raising the frequency up to its maximum value of 1000Hz (Fig.4-11).

The results further indicate that at lower frequencies, the electrical conductivity is primarily governed by the capillary water in the concrete. In the higher frequency range, the effect of fibre content on the impedance becomes more important. For plain concrete,
the impedance decreased 21.5% when the frequency was raised from 0.98Hz to 1000Hz. On the contrary, the impedance of hybrid fibre reinforced concrete decreased 82.9% in the same frequency range. The major part of the impedance reduction is realized in the low frequency range up to 31Hz. The reduction of impedance with frequency is only moderate over the rest of the frequency range up to 1000Hz, as can also be seen in Fig.4-10.

![Graph showing impedance differences](image)

**Fig.4-11 Impedance differences of the composites at 0.98Hz and 1000Hz.**

4.3.3.2 The effects of fibre content on impedance

Fig.4-12 shows the relationship between fibre content and impedance at 1000Hz. It is seen that the impedance decreases with an increase of fibre content. 0.6% fibre content seems to be a turning point, after which the reduction rate of impedance with increasing fibre content is reduced.

The results demonstrate that in the low volume content range of hybrid fibre composite systems under specific measuring conditions (1000Hz), the impedance of the composite mainly depends on the total conductive fibre content, fibre type and fibre geometry being of secondary importance.
Fig.4-12 Relationship between the hybrid fibre content and the impedance of concrete at 1000Hz

This situation (low fibre volume fraction) is obviously different from that at higher fibre contents. Banthia et al (1992) found that the impedance of cement paste with 1~5% carbon fibres was much lower than that of a composite containing the same content of steel fibres, indicating the important influence of fibre geometry on the electrical properties of fibre composites.

4.3.3.3 The influence of age on impedance
The effect of age on impedance has been discussed in previous sections. For concrete reinforced with hybrid fibre systems, the trend in impedance changes with time is similar to data published by other authors [Neville 1995 and Banthia 1992]. Fig.4-13 presents the impedance data of various concrete systems at 14 days, 28 days and 80 days, at 1000Hz measuring frequency. The results show that the largest increase in impedance with age occurs in the low fibre volume range (CS-00, CS-20). For the other systems, the impedance increase with age becomes minor.

The variation of impedance with age is in line with cement hydration. With the progress of hydration, the pore solution is gradually consumed and the matrix become denser, hence, the impedance of the composite accordingly increased.
Fig. 4-13 Impedance of different fibre concretes at different ages

Under A.C. conditions, interfacial capacitance of fibre-concrete is the major contribution of the conductivity. When concrete contains lower volume content of conductive fibres, the direct conduction of the fibres is very limited. Hence, impedance is sensitive to the age. When the fibre content is higher, the direct conduction through the concrete relatively enhances, hence, the impedance increase is less.

4.3.4 Conclusions

1) The addition of carbon and steel fibres alone or in combination will significantly influence the impedance of concrete, even in the low volume content range;

2) The impedance of fibre concrete decreases with increasing measuring frequency. A dramatic drop takes place over the low frequency range, i.e. 0.98-31Hz.

3) Under higher frequency conditions (>1000Hz), the impedance of the fibre concrete mainly depends on the conductive fibre content, while the effects of fibre type and fibre geometry are only minor.

4) At early age and at lower fibre contents (lower than 0.6%) the impedance changes with fibre content and with age are dramatic, whereas at higher fibre contents the trend of impedance increase becomes moderate.
Chapter 5

Further Measurements on the Electrical Properties

The electrical properties of fibre-reinforced composites were studied in the previous chapter for both fibre-cement paste and fibre-concrete systems. The test results are important for application purposes. In this chapter, three types of applications are discussed. In the first example, the dispersion degree of carbon fibres in cement paste is assessed on the basis of the relationship between fibre content and material resistivity. The resistivity of the composite is approximately linearly related to the carbon fibre content under optimized measuring conditions. The coefficient of variation of the material resistivity of various small paste samples can serve as criterion for evaluating the uniformity of the fibres in the cement paste. Secondly, the electrical response of carbon fibre-cement paste to compressive stresses is investigated. The relationship between compressive stress and resistivity is presented. The study revealed that the ratio of crystal to gel phase significantly affects the compressive sensitivity. Finally, the effect of carbon fibres on the corrosion risks of steel rebars in concrete is taken into consideration. The tests show that a very low content of carbon fibres can reduce steel corrosion, but when a critical fibre content (0.6 v.% in this study) is exceeded, the corrosion risks will increase instead.
5.1 General remarks

The aim of applying fibre reinforcement is not only to improve mechanical properties. The improvement of the electrical properties is also an important aspect of practical significance.

Carbon and micro-steel fibres have been used for many years in electrical-magnetic waves shielding materials [Johan 1999]. Further, it was reported that carbon fibre cementitious composites are intrinsically smart materials that can sense compressive or tensile stresses both in elastic or inelastic regimes [Chen 1996]. Recently, the thermo-electric phenomenon of carbon fibre-cement was revealed [Sun 1998b and 1999]. These related phenomena in the electrical domain indicate potential possibility to use carbon and other conductive fibres in smart structures for nondestructive health monitoring in real time. Hence, the relevant studies become more and more popular.

However, the mentioned studies concentrate on the mutual influences of physical parameters, such fibre contents, stresses and temperature. Attention has not been paid to a sufficient degree to the influences exerted by the cement paste microstructure and hydrate composition on the electrical responses.

Uniformity in the carbon fibre dispersion in the cement matrix is a very important factor in governing the properties of the composite. However, to check the dispersion degree of such small fibres is complicated. The relationship between carbon fibre content and impedance gives the possibility to reveal the deviations from uniformity of the fibre distribution in the cement matrix.

The use of the conductive fibres changes the resistivity of the cementitious composite. Hence, the possible influence on durability of the composite should be taken into consideration. When conductive fibres (such as steel and carbon fibres) are used for reinforcement in concrete, the fibres may change the corrosion process of the steel rebars in the concrete. An example presented in this chapter will deal with this issue.
5.2 Case study I: Uniformity assessment of carbon fibres dispersion in cement paste by impedance measurements

An alternative current (A.C.) was applied to measure the impedance of a harded cement paste in which the carbon fibre content was varied. When the free water content in the cement paste is about 95% of saturated conditions, and the measuring frequency 500Hz, an approximate linear relationship was found between fibre content and impedance of the composite. Based on this relationship, a new method was assessed to evaluate the dispersion uniformity of carbon fibres in cement paste by impedance measurements. To that end, the standard deviation $S$ and the coefficient of variation $S / \bar{X}$ were determined of impedance measurements on a random set of small fibre cement samples. They were taken from a larger specimen in which the fibre uniformity should be determined. In this example, four different mixing procedures were designed for dispersing carbon fibres in the cement paste. The results demonstrate that a longer mixing time increases the dispersion uniformity of carbon fibres in cement paste. Further, the addition of a water reducing agent dramatically improves the uniformity due to a change of the fluidity of the paste. Ground fly ash can also increase the uniformity in fibre dispersion degree to a certain degree.

5.2.1 Introduction

The reinforcing capabilities of short carbon fibres in cementitious composites are extensively studied. Uniform dispersion of short carbon fibres in cementitious composites is an important but difficult issue that limits the application of carbon fibre reinforcement. It was found that improperly dispersed short carbon fibres in concrete led to negative effects on the mechanical properties of the composite materials. Many attempts have been made to properly disperse short carbon fibres in paste or in concrete, but the results were not always satisfactory.

Stroeven [1978] elaborated a stereological approach to assess the distribution of macrosteel fibres in concrete. However, for micro fibres (such as carbon ones), this does not seem an effective approach. Based on previous experience, the possibility to evaluate the degree of fibre dispersion by resistivity measurements is elaborated.

A variety of studies on the electrical properties of cement paste were performed during the
past years. It is well known that the addition of carbon fibres decreases the resistivity of fibre composites, even several orders of magnitude, when a critical fibre content is attained. The conductivity of the carbon fibre composite will depend on the fibre content when the other conditions are defined. Based on this point of view, it could be demonstrated that the resistivity of the cementitious composite is related to the volume percentage of carbon fibres. However, when direct current is applied, a polarization potential will occur in the vicinity of the electrodes, resulting in incorrect measuring results. Hence, A.C. is often used in assessing electrical properties of cement and concrete materials. Also in this case, a good correlation exists between carbon fibre content and impedance of fibre composites.

5.2.2 Principle and procedure

Based on previous experimental results, the mutual relationships between fibre content, free water content, measurement frequency and impedance have been discussed [Shui 1997b]. This author found that under specific conditions, the relationship between fibre content and the impedance of the composite is approximately linear. This presents the opportunity to quantitatively determine fibre content at different locations in the

![Impedance graph](image)

Fig.5-1 Relationship between fibre content, frequency and impedance
composite specimen by impedance measurements. In this study, the total amount of free water in the cement paste was 7.34% of the paste weight, and 4.83% of the mortar weight.
Repeated tests have shown that in the fibre-cement paste systems, optimum test conditions involve a free water content of about 7.0% and a measuring frequency of 500Hz. The relationship between fibre content, measuring frequency and impedance is shown in Fig.5-1. With an increase in the measuring frequency from 0.98 to 100Hz, the impedance of the composites gradually decrease. Impedance changes with an increase of the amount of carbon fibres. In particular, a linear correlation is found when the measuring frequency is 500Hz and the free water is about 95% of that in the saturated state. This constructs the basis for the assessment of the dispersion degree of carbon fibres.

After mixing, carbon fibres are dispersed in the bulk cement paste but of course with a fluctuating density. This is due to stochastic reasons. To describe this scattering phenomenon of measured density values, standard deviations are calculated. Theoretically, the smaller the standard deviation, the more uniform the fibre dispersion. The Standard Deviation is given by:

\[
S_i = \sqrt{\frac{\sum_{i,j=1}^{n} (x - x_{ij})^2}{n-1}} = \sqrt{\frac{\sum_{i,j=1}^{n} x_{ij}^2 - nx^2}{n-1}}
\]

(5.1)

\[
\bar{x} = \frac{1}{n} \sum_{i,j=1}^{n} x_{ij}
\]

(5.2)

in which,

where, \(x_{ij}\) is the impedance of sample \(ij\), and \(\bar{x}\) is the average impedance of a mix. \(S_i\) is the standard deviation of the impedance values of a mix.

Further, the coefficient of variation \((K_i)\) should be calculated to compare the scattered degree of the fibres at the same level. Hence,

\[
K_i = \frac{S_i}{\bar{x}}
\]

(5.3)

To evaluate the uniformity of carbon fibres in cement paste, the following procedures
were carried out.

(1) Specimen preparation: a standard procedure was followed for making cubic specimens with a size of 100×100×100mm.

(2) Surface polishing: to eliminate the "surface effects", an 1-2mm layer of the specimen surface was removed by polishing.

(3) Specimen sawing: along three orthogonal directions, specimen was sawn into small cubic samples.

(4) Numbering: each small sample was attributed a code (shown in Fig.5-2).

(5) Density measurement: Volume density of all of the small specimens was determined. The specimens of which the density deviated more than 1% from the mean density were removed.

(6) Impedance measurement: impedance measurements were performed with the set-up introduced in the previous chapter.

(7) Calculation: the standard deviation and the coefficient of variation were calculated based on eq. (5.1) and eq. (5.3).

Fig.5-2 Sawing and numbering of the specimen for impedance measurement

5.2.3 Uniformity assessment of carbon fibres in cement paste
As an application of the assessment method, a case is presented here. The effects of different mixing procedures on the dispersion degree of carbon fibres were taken into
account.

The system consists of cement, water, water reducing agent and carbon fibres. The ratio of water to cement was 0.3, and the dosage of the water reducer was 0.4%. Four mixes were prepared, and their fibre contents were 0%, 0.32%, 0.56% and 0.80% in volume, respectively.

Four different mixing procedures were designed for each mix. The four mixing procedures are described as follows.

A—mixing for 1 minute;
B—mixing for 2 minutes;
C—mixing for 3 minutes;
D—mixing for 3 minutes, moreover, 3% cement was replaced by a ground fly ash.

Four mixes and four procedures form 16 combinations. For each combination, 12-14 small specimens were selected. The average impedance and standard deviations of these specimens were determined and calculated. Results are shown in Table 5-1.

Table 5-1 Average impedance and standard deviations of impedance (x: Ohms)

<table>
<thead>
<tr>
<th>Fibres (vol.%)</th>
<th>$\bar{x}_A$</th>
<th>$S_A$</th>
<th>$\bar{x}_B$</th>
<th>$S_B$</th>
<th>$\bar{x}_C$</th>
<th>$S_C$</th>
<th>$\bar{x}_D$</th>
<th>$S_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1761.2</td>
<td>64.9</td>
<td>1705.5</td>
<td>47.1</td>
<td>1713.8</td>
<td>49.1</td>
<td>1850.6</td>
<td>23.0</td>
</tr>
<tr>
<td>0.32</td>
<td>929.9</td>
<td>245.7</td>
<td>975.6</td>
<td>204.5</td>
<td>995.1</td>
<td>161.3</td>
<td>1439.2</td>
<td>164.0</td>
</tr>
<tr>
<td>0.56</td>
<td>778.3</td>
<td>226.7</td>
<td>786.7</td>
<td>209.8</td>
<td>770.5</td>
<td>182.9</td>
<td>1089.2</td>
<td>137.4</td>
</tr>
<tr>
<td>0.80</td>
<td>358.2</td>
<td>96.0</td>
<td>418.1</td>
<td>78.5</td>
<td>442.2</td>
<td>80.5</td>
<td>476.0</td>
<td>80.7</td>
</tr>
</tbody>
</table>

Furthermore, the coefficients of variation, $S_j / \bar{x}$, were calculated according to formula (5.2). The results are shown in Fig.5-3.

The results reflect the following tendencies.
- Plain cement paste yields uniform impedance measurements.
- With an increase in mixing time, the dispersion uniformity of carbon fibres increases.
Fig. 5-3 Fibre dispersion uniformity expressed by the coefficient of variation

- With an increase in fibre content, it becomes increasingly difficult to achieve fibre uniformity.
- The ground fly ash can enhance the uniformity of the fibre dispersion to a certain degree.

5.2.4 Conclusions

(1) An approximately linear relationship between fibre content and impedance of fibre-cement can be achieved under specific conditions. It provides the possibility to assess the dispersion degree of carbon fibres in cement paste by impedance measurements.

(2) In a mathematical statistical concepts, the standard deviation ($S_v$) and the coefficient of variation ($S_v / \bar{x}$) serve as main parameters reflecting the dispersion degree of carbon fibres in cement paste.

(3) As a test case, the influence of mixing time on the dispersion degree of carbon fibres was investigated. The result confirm the conclusions drawn in other studies.
5.3 Case study II: The electrical response of carbon fibre cement composites to compressive stress

By adding a dispersed conductive phase (such as carbon fibres), cementitious materials can develop conductive behaviour, the degree of which may also depend on compressive stresses to which the material is subjected—this is referred to as compression sensitivity [Chen 1993b]. The electrical response characteristics under pressure can be estimated from the slope and from the linear coefficient of correlation of the $G_r$-$\sigma_i$ curve. Herein, $G_r$ is the conductance and $\sigma_i$ the compressive stress.

The influence of mineral phases of the cement paste on the electrical compressive sensitivity was investigated. The ratios of crystal to CSH gel phases ($C/G$) were determined for two kinds of cement, Dam Portland cement (DPC) and Slag Portland cement (SPC). There is a marked difference in $C/G$ in the two cements. The results revealed that the higher gel phase improved the sensitivity of the conductance to compressive stresses. A further improvement in the sensitivity was obtained by adding synthetic calcium silicate gel to a carbon fibre-cement paste system.

Furthermore, the influence of the pore structure of the cement paste on the compressive sensitivity was studied. The pores within 100-300$\mu$m range were found to be of particular significance for the compression-sensitivity. Hence, the response characteristics can be improved to a certain extent by adjusting the pore size distributions.

5.3.1 Introduction

Extensive studies have been carried out on the smart behaviour of carbon fibre reinforced cementitious composites (CFRC). Chan et al [1993b and 1995] studied the response behaviour of this material to compressive and tensile stresses and the possibility in monitoring elastic and inelastic deformations. Sun et al [1998a, 1998b and 1999] revealed the thermoelectrical phenomenon and the potential application of the thermal self-monitoring of CFRC. These studies are supporting to the development of smart materials and structures.

The mechanisms of the stress-electrical and temperature-electrical responses are attributed to the interactions of fibre-fibre, and fibre-cement interfaces, whereas the cement matrix itself is hardly dealt with. In fact, the re-distribution of stresses in the composite due to
external loading will lead to material deformation, and will result in the movement of moisture in the material. Gu [1992, 1993a, 1993b, 1993c] and Xie et al [1993] revealed the hydration process and microstructural development of cement paste to significantly influence the electrical responses. Hence, this author believes that the type, microstructure and mineral composition of the cement matrix can to a certain degree govern the smart behaviour of CFRC.

On this basis, the influences of cement paste composition and structure on the compression-electrical response behaviour were investigated.

Electrical resistance of plain cement paste will change with varying stress fields and structural features. For example, the electrical resistivity of the cement paste was gradually reduced when a growing micro-crack was filled with liquid phase during compressive loading [Gu 1993c]. In this case, the electrical current is conducted through moist cement paste essentially by electrolytic means, that is by ions in the evaporable water. However, in a homogenous fibre-reinforced cement system, when the evaporable water is removed, the current is to be conducted mainly by the fibrous network. Experimental as well as theoretical results have demonstrated the electrical conduction to be a percolation phenomenon [Shui 1995], but this aspect will not be discussed in the present study.

In previous research [Li et al, 1995], the compressive stress-electrical conductance relationship was found approximately linear in a specific stress range. Hence, the slope of the relationship curve can serve as a parameter to assess the compression sensitivity of the CFRC. And, an attempt was made to improve the compressive sensitivity by changing the ratio of crystal to CSH gel phase (C/G) of the cement paste.

5.3.2 Experiments on the compression sensitivity

5.3.2.1 Raw materials

* Cement: #525 Dam Portland cement (DPC), with characteristic strength of 52.5MPa, produced by Jingmen Cement Plant, China; #425 Slag Portland cement (SPC) with characteristic strength 42.5MPa, produced by Hongqi Cement Plant, Huangshi, China. The main mineralogical composition of the cements are shown in Table 5-2 [45], [46].
Table 5-2 Mineralogical composition of the cements (wt. %)

<table>
<thead>
<tr>
<th>Type of cement</th>
<th>$\text{C}_3\text{S}$</th>
<th>$\text{C}_2\text{S}$</th>
<th>$\text{C}_3\text{A}$</th>
<th>$\text{C}_4\text{AF}$</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>#525 DPC</td>
<td>48–51</td>
<td>24–29</td>
<td>5</td>
<td>14–18</td>
<td>3–5</td>
</tr>
<tr>
<td>#425 SPC</td>
<td>36–41</td>
<td>14–21</td>
<td>4.5–8</td>
<td>8–13</td>
<td>25–30</td>
</tr>
</tbody>
</table>

* Carbon fibre: PAN carbon fibres, described in Chapter 2.
* Fibre mesh: PAN-based carbon fibre mesh.
* Water reducer: Melamine-type of water reducing agent was employed to improve the fluidity of the cement paste and to promote a proper dispersion of the micro-fibres. The efficiency of the chemical additive is about 15-20%.
* Synthetic dehydrated CSH gel: The gel was prepared by lime and silica fume in a Ca/Si ratio of 1.5. The suspension reaction continued for one week at 95°C in a thermal steam. The main hydrates were verified as CSH (I) and CSH gel. Then, the hydrates were burnt in an oven at 120 °C for 4 hours.

5.3.2.2 Specimen preparation and resistance measurements
Water to cement ratio is 0.4 for all the specimens. Carbon fibre content is 0.8% in weight of the cement. The specimen size and preparation processes are the same as described in 5.2.1.1. The set-up for the resistance measurements was described in Chapter 4. The specimens were subjected to compressive stresses in a mechanical testing machine. The electrodes were embedded at surfaces that were subjected to the compressive loading.

5.3.2.3 Image analysis
VDP-1750 Image Analyzer was used to determine the ratio of crystal to gel phase (C/G) of the hardened cement paste. The selected specimen was sawn into 2mm plates, whereupon the hydration reactions were stopped by adding acetone. Then, the plates were polished down to about 0.03mm thin sections. Ten photos per sample were taken through a polarizing microscope. Finally, the photos were quantitatively analyzed to determine C/G.

5.3.2.4 Pore size distribution determination
Pore size distributions were determined for four cement paste samples with the Mercury Intrusion Porosimetry (MIP).
5.3.3 Results and discussions
The electrical response behaviour or compression sensitivity of the fibre composites can be estimated from the slope and from the linear correlation coefficient of the stress-conductance ($\sigma_i-G_i$) curve. The linear coefficient of correlation is defined as:

$$r = \frac{L_{XY}}{\sqrt{L_{XX} \cdot L_{YY}}}$$  \hspace{1cm} (5.4)

$$L_{XX} = \sum_{i=1}^{n} (\sigma_i - \bar{\sigma})^2$$  \hspace{1cm} (5.5)

$$L_{XY} = \sum_{i=1}^{n} (\sigma_i - \bar{\sigma}) \cdot (G_i - \bar{G})$$  \hspace{1cm} (5.6)

$$L_{YY} = \sum_{i=1}^{n} (G_i - \bar{G})^2$$  \hspace{1cm} (5.7)

where, $\sigma_i$ is compressive stress, $\bar{\sigma}$ is the mean stress, $G_i$ is the electrical conductance corresponding to $\sigma_i$, and $\bar{G}$ is the mean electrical conductance.

5.3.3.1 The influence of crystal to gel phase ratio ($C/G$)
For two cement-fibre systems, the relationship between applied stress and conductance is shown in Fig.5-4.
Fig. 5-4 The relationship between stress and electrical conductance

The main electrical response parameters of the two systems are presented in Table 5-3.

<table>
<thead>
<tr>
<th>System</th>
<th>Slope (kΩ⁻¹·MPa⁻¹)</th>
<th>Intercept (G₀) (kΩ⁻¹)</th>
<th>Correlation coefficient r</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPC-fibre</td>
<td>0.0071</td>
<td>0.1518</td>
<td>0.9881</td>
</tr>
<tr>
<td>SPC-fibre</td>
<td>0.0010</td>
<td>0.1338</td>
<td>0.9595</td>
</tr>
</tbody>
</table>

The results reveal a marked difference between the two kinds of cement composites. The DPC cement has higher electrical conductivity and much higher electrical sensitivity to compressive stresses than the SPC cement.

For the two hardened fibre cement paste systems, the ratios of crystal phase to gel phase were determined by means of image analysis, and for each sample 10 regions were taken. The obtained results are shown in Table 5-4.
Chapter 5

Table 5-4 Volume fraction of crystal phase and the ratio of crystal to gel phase

<table>
<thead>
<tr>
<th>Cement</th>
<th>Volume percentage of crystal phase</th>
<th>C/G</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPC</td>
<td>16.0 12.9 12.3 13.6 13.6 13.4 12.5 12.5 14.2 14.9</td>
<td>0.16</td>
</tr>
<tr>
<td>SPC</td>
<td>23.3 22.0 21.8 21.0 25.3 24.1 25.8 27.7 24.9 25.1</td>
<td>0.32</td>
</tr>
</tbody>
</table>

The ratio of crystal to gel phases of the slag cement is about twice as large as for the Dam cement. This result demonstrates that higher crystal fractions do not favour a more sensitive response of electrical conductance to compressive stresses.

To verify the effect of gel phase on the electrical compression sensitivity, 5% synthetic CSH gel by weight of the cement was added to the fibre cement paste, thereupon the electrical response was determined under the same test conditions. The addition of the gel changed the C/G ratio and the parameters of the electrical compression response of the fibre-cement systems. The changes of C/G and the electrical response parameters are shown in Table 5-5 and Table 5-6.

Table 5-5 C/G ratio for DPC and SPC before and after adding the synthetic gel

<table>
<thead>
<tr>
<th>System</th>
<th>DPC</th>
<th>DPC + gel</th>
<th>SPC</th>
<th>SPC + gel</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/G ratio</td>
<td>0.157</td>
<td>0.137</td>
<td>0.318</td>
<td>0.233</td>
</tr>
</tbody>
</table>

Table 5-6 Main parameters for the two cement systems with additional gel

<table>
<thead>
<tr>
<th>System</th>
<th>Slope (kΩ⁻¹·MPa⁻¹)</th>
<th>Intercept (G₀) (kΩ⁻¹)</th>
<th>Correlation coefficient (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPC + gel</td>
<td>0.00787</td>
<td>0.1642</td>
<td>0.9892</td>
</tr>
<tr>
<td>SPC + gel</td>
<td>0.00156</td>
<td>0.1441</td>
<td>0.9890</td>
</tr>
</tbody>
</table>

The addition of the gel decreased the C/G ratios for both DPC and SPC systems, and as a consequence improved the compression sensitivity. For the slag cement system, the change was particularly marked.

The gel was regarded [Taylor 1997] as a three-dimensional assemblage of C-S-H layers, which tend to form subparallel groups of a few layers thick and which enclosed pores of dimensions ranging from interlayer spaces upwards. Most of the gel water is interlayer water, which can be reversibly removed and absorbed [Wang 1997]. Various properties of hardened cement paste are influenced by the exchange of the interlayer water.
Under the experimental conditions, the capillary water was removed but most of the gel water and the interlayer water were retained. When the capillary water in a plain cement paste is segmented, passage of the electrical current through gel water takes place [Shui 1997b]. Of course, the electrical conductivity of cement paste will be reduced with the removal of the evaporable water. However, for the carbon fibre cement paste under compressive stress, the movement of interlayer water may cause a bridging of the disconnected fibres in the cement paste, hence, augmenting the conductive effect. On the other hand, the interlayer spacing will diminish under the compressive stresses, and the spacing of neighbouring carbon fibres will be accordingly reduced. As a result, the joint points of the fibre to fibre will firmly contact, resulting in the decrease of the contact resistance. The high compression modulus of crystalline materials reduces the deformability of cement paste with large amounts of crystal phase. This may be the main reason that the gel phase has a more sensitive response to the compressive stresses than the crystal phase.

5.3.3.2 The influence of the pore size distribution

The influence of the pore-size distribution on the compressive on sensitivity was studied. The pore size distributions of four cement paste samples with different phase compositions were determined with MIP. The results are shown in Fig.5-5, Fig.5-6 and Table 5-7.

Fig.5-5 Pore size distribution for the Dam cement

Fig.5-6 Pore size distribution for the slag cement
Table 5-7 Pore size distribution of cement samples with different phases (v. %)

<table>
<thead>
<tr>
<th>Pore size (nm)</th>
<th>&lt; 7.5</th>
<th>7.5~10</th>
<th>10~30</th>
<th>30~100</th>
<th>100~300</th>
<th>&gt;300</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPC</td>
<td>9.14</td>
<td>7.75</td>
<td>31.15</td>
<td>7.41</td>
<td>5.42</td>
<td>39.11</td>
</tr>
<tr>
<td>DPC + gel</td>
<td>5.06</td>
<td>4.05</td>
<td>65.97</td>
<td>13.18</td>
<td>4.87</td>
<td>6.87</td>
</tr>
<tr>
<td>SPC</td>
<td>5.79</td>
<td>6.22</td>
<td>44.81</td>
<td>15.22</td>
<td>11.34</td>
<td>16.61</td>
</tr>
<tr>
<td>SPC + gel</td>
<td>12.25</td>
<td>10.60</td>
<td>47.58</td>
<td>11.60</td>
<td>6.03</td>
<td>9.38</td>
</tr>
</tbody>
</table>

Adding the calcium silicate gel changed the pore size distribution. For DPC, the location of the peak value of the pore-size distribution fraction moved from >300nm to 10-30nm. For SPC the pores smaller than 30nm increased by more than 10%. The results show that the pore size distribution is significant for the electrical response behaviour of the composites. With the increase of the amount of 10-30nm pores and the decrease of the larger than 100nm pores, the compression-sensitivity of the composites improved accordingly. As mentioned in 5.3.3.1, gel water plays an important role in the electrical response of the composites to compressive stresses, hence, the increase of gel pore and interlayer pores enhances the interaction between the gel water and the fibrous network. This indicates that the gel pores and interlayer pores are particularly important to the electrical response of the composites to compressive stresses.

The experimental results denote that to obtain carbon fibre cement composite with outstanding compressive-sensitivity, it is necessary to control the pore size distribution in a proper range.

5.3.4 Conclusions

1) A carbon fibre-reinforced cement composite displays an electrical response to compressive stresses. This is the so-called compression-sensitivity, which is caused mainly by the conductive fibrous network. The relationship between compressive stress and electrical conductance is approximately linear, hence, the compression-sensitivity of the fibre cement composites can be estimated by the slope and by the linear coefficient of correlation of stress-conductance curve.

2) The ratio of crystal to gel phase (C/G) in cement paste dramatically affects the compression-sensitivity. DPC that contains higher CSH gel phase amount,
Chapter 5

responded in a more sensitive way than SPC that contains lower gel amount.

3) Adding the synthetic CSH gel to the fibre-reinforced cement composites, enhances the proportion of gel phase in the cement systems, resulting in the improvement of the compression-sensitivity.

4) The addition of the synthetic gel improves the pore structure of the two kinds of cement paste; particularly, the amount of pores smaller than 30nm increase while the larger pores decrease. The proper pore structure favours the compression-sensitivity of the composites. Hence, it is an effective method to improve the compression-sensitivity by adjusting the pore size distribution of the fibre composites.
5.4 Case study III: Influence of carbon fibres on corrosion risks of steel reinforcements in concrete

5.4.1 Introduction
Because of excellent behaviour and declining price, carbon fibres are applied to an increasing degree in civil engineering. It is widely recognized nowadays that carbon fibres can significantly improve mechanical properties of cementitious materials. On the other hand, the conductivity and stress-electrical response behaviour of carbon fibre-cement has been investigated and applied in electromagnetic waves sheltering and construction self-diagnosis [Sun 1998a, 1998b and 1999, Johan 1999]. Hence, carbon fibre-cement materials have a prospective future.

Generally, chopped carbon fibres are used. At low fibre contents and an adequate dispersion, only few fibres will make contact with each other in the cement paste. The number of fibre contacts will increase rapidly above a specific volume content, resulting in the formation of a local or complete fibre network in the cement matrix [Shui 1995]. The connectivity of this fibre network will depend on the content and dispersion degree of the fibres. The mechanical and electrical properties of carbon fibre cement composites are closely associated with the spatial features of this fibre network.

Localized corrosion of reinforcement in concrete is favoured by the presence of chloride ions [Wilkins 1990]. It was noted that with increased electrical conductivity of concrete, the corrosion process would speed up. One of the reasons is that the corrosion-current will increase at larger conductivity.

As mentioned above, the addition of carbon fibres can increase the conductivity of the cement materials. In many cases, carbon fibres are used in rebar elements, or used in combination with steel fibres. Hence, the question arises how carbon fibres will influence the corrosion processes of rebars or steel fibres? Only a limited number of contributions are available. A marked improvement has been reported of a mortar cover layer by applying carbon fibres for cathodic protection [Hou 1997]. The effects of the conductive fibres on durability of cementitious composites have not been paid enough attention.

Since carbon fibres are frequently used for improving the strength of concrete and for repair work, it is necessary to more thoroughly evaluate the effect of carbon fibre on steel corrosion.
5.4.2 Experimental details

5.4.2.1 Raw materials

- Cement: #525 Portland cement, produced by Huaxin Cement Plant, Hubei, China;
- Carbon fibre: PAN type carbon fibre, produced by Shanghai Carbon Work, Shanghai, China; the main properties of the fibre are shown in Table 5-8;
- Sand: Chinese Standard Sand, fineness 2.13, produced in Fujian, China;
- Steel bar: Carbon steel bar (Type A3), diameter 6mm length 100mm.

<table>
<thead>
<tr>
<th>Filament Diameter (μm)</th>
<th>Density (g/cm³)</th>
<th>Elongation (%)</th>
<th>Tensile Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7±0.2</td>
<td>≥1.75</td>
<td>≥1.2</td>
<td>1950</td>
<td>175</td>
</tr>
</tbody>
</table>

5.4.2.2 Experiments

Steel bar corrosion determination: Cement: sand ratio was 1:0.7, W/C was 0.28, and the carbon fibre content 0~1.5%. The size of the specimen was 40×40×160mm. After accurate measurement of its weight \( m_0 \), a steel bar was embedded in the mortar. The specimens were subjected to standard curing conditions (20±3°C, >85% RH) for one week. Then, the specimens were immersed into 3~4% CaCl₂ solution for 28 days. Immediately thereafter, the steel bars were withdrawn from the specimens, whereupon the corroded layer on the surface was removed. Finally, the bars were treated with 12% HCl solution for 10 minutes, and then accurately weighed again \( m_i \).

5.4.3 Test results and discussions

Steel corrosion in concrete relates to electrochemical processes taking place in the system, and is influenced by the conductive property of the composite. Carbon fibres or steel fibres are conductive materials, and the resistivity of the cement composites will markedly changed with the addition of the fibres [Banthia 1992]. The change in the electrical property will affect the corrosion process of steel in concrete. The effects of conductive fibres on the electrical properties have been discussed in previous sections.

Following a direct measurement method, the corrosion degree of a steel bar in concrete can be calculated by means of the weight change before and after immersing in a salt
solution. The result can be normalized as follows:

$$\Delta m = \frac{m_0 - m_1}{m_0}$$  \hspace{1cm} (5.8)$$

where, $m_0$ and $m_1$ represent the weights of the steel bar before and after corroding.

The relationship between corrosion degrees and carbon fibre content, as well as resistivity is presented in Fig.5-7. The curves can be divided into three parts according to the fibre contents. In Part I, up to a fibre content of 0.2%, the corrosion degree decreases with an increase of the fibre content. In the Part II corresponding to fibre contents between 0.2% and 0.8%, the weight loss of the steel is minor. When the fibre content exceeds 0.8%, the corrosion degree sharply increases at rising carbon fibre contents in Part III of the curve.

The weight loss of steel bars in specimens containing 1.0% carbon fibres or more exceeds those of the plain control specimens. These results show that at low contents of carbon fibres, the cement matrix will offer an improved protection to the embedded steel bar. When the fibre content exceeds a critical limit, the protection will disappear.

It is well known that variations occur in the properties of the concrete and of the steel bar
surface layer. This will influence steel deterioration. At low fibre content, the carbon fibres protect the embedded rebar in two ways. Firstly, the carbon fibres can balance local potential difference that is caused by non-homogenous distribution of material properties, hereby eliminating local current effects. Secondly, the carbon fibres enhance the volume stability and crack-resistance, and they arrest the propagating micro-cracks in the cement matrix, restricting the penetration of aggressive compounds into the cement matrix.

5.4.4 Conclusions
Only when properly mixed at low fibre contents, the carbon fibres can distribute individually or form local fibre network elements, resulting in a decreased composite resistivity. In the range of volume contents between 0.2~0.6%, the corrosion resistance of the steel bar in the composites is marginally influenced. When the content of carbon fibre surpasses a critical value (in present study, 0.8%), the corrosion degree of steel bar increases, and will even exceed that of plain pastes.
Chapter 6

General Summary

This study deals with mechanical and electrical properties, microstructure and durability of cementitious composites reinforced by low volume content of mono- and hybrid-fibre systems.

The mechanical properties (e.g., flexural strength and toughness) of brittle cement matrices can be improved by adding fibres. Of course, the addition of fibres will lead to an increase of material costs. Also, other effects such as reduced resistivity of the composites may hinder special applications. Hence, it is important to diminish the fibre volume content in cementitious composites.

The test results in Chapter 2 show that fibre composites of similar composition but produced in a different way display quite different mechanical properties. Obviously, these technical procedures influence material structure. The "two-step" mixing procedure employed in this study was designed to properly disperse the hybrid steel-carbon fibres in the cement matrix, and to optimise the microstructure of the composites. The density analysis indirectly reveals that the modified mixing procedure led to a better fibre dispersion, resulting in improved material structure and enhanced fibre reinforcement efficiency. Hence, the critical fibre volume fraction \( V_{f,\text{crt}} \) of 3-D dispersed fibres can be reduced by means of proper production methods.

Synergy effect can be obtained in hybrid fibre systems containing steel and carbon fibres. A double effect on the mechanical properties has been achieved, employing proper proportions of uniformly dispersed fibres. The possible underlying mechanisms are:
1) different aspect ratios involved in the hybrid fibre system, enhance the fibre efficiency;
2) steel and carbon fibres can control macro and micro cracks, respectively;
3) carbon fibres can improve the steel fibre-cement interfacial bond.

However, when the hybrid fibres were not uniformly dispersed in the cement matrix, the test showed a negative effect of the reinforcement on the properties. This means that composites with hybrid fibre reinforcement will yield inferior properties as compared to those with a similar amount of mono fibre reinforcement, as demonstrated by series I in Chapter 2. Although synergy is found in series III, further improvements should be possible.

Both steel and carbon fibres are electrical conductors. The addition of these fibres to the cement matrix, even in low volume content, can largely change the electrical properties of the cementitious composites. Such changes may cause durability problems of the composites, and will also otherwise limit their application under particular conditions. The relationship between fibre content and resistivity of composites revealed a percolation phenomenon. This was more obvious when dried fibre-cement specimens were tested. The phenomenon can be considered the result of the formation of a local fibre network (or partly connected fibre network) in the cement matrix.

When fibre-cement (concrete) specimens were water-saturated or at least moist, the variation in the resistance (or impedance) with fibre contents was found only modest. In this case, fibres and the free water in the matrix simultaneously contribute to the electrical conduction. In a relatively low frequency range (0-1000Hz), impedance of the composites quickly declines with an increase of measuring frequency. Under a particular measuring frequency, such as 1000Hz in the present program, the impedance of the fibre composites and fibre content are well-correlated. This correlation can be used in structural analysis, as is demonstrated in Chapter 5.

The electrical properties of concrete reinforced by hybrid steel-carbon fibres were found basically similar to those of carbon fibre cement paste; the impedance of the material
mainly depended on the total content of the hybrid fibres. Fibre type only imposed a minor effect.

The structure and properties of fibre-cementitious composites can be studied in an indirect way by the electrical response of such materials. Three relevant cases are presented in Chapter 5.

An approximately linear relationship between fibre content and impedance of fibre-cement can be achieved under specific conditions, as stated before. This allows to assess the dispersion degree of carbon fibres in cement paste on the basis of impedance measurements obtained on small parts of the disintegrated specimen. The standard deviation and the coefficient of variation of these measured impedance values serve as main parameters reflecting the dispersion degree of carbon fibres in the cement paste.

The influences exerted by matrix composition and structure on the mechanical stress versus electrical response curve were taken into account. In particular, the effects of the structural features and the mineral composition on the compression-sensitivity were studied in detail. With the addition of a synthetic CSH gel, the ratio of crystal to gel (C/G) was reduced, whereby the number of larger pores in the cement matrix markedly decreased. As a result, the compression-sensitivity of the composites accordingly improved.

As stated earlier, the changes in electrical properties due to the addition of conductive fibres may increase durability risks of the composites. More specifically, the change of the composite’s resistivity can affect the corrosion process of the steel bars in the cementitious matrix. The test results of this study have confirmed the corrosion rate of the steel bars in concrete to vary with carbon fibre content. When the volume content of the carbon fibres was below a certain threshold value (e.g., 0.6 v.%), the carbon fibres reduced the corrosion rate, whereas corrosion rate was raised when this value was exceeded.
Despite this thorough study, the understanding of the behaviour of fibre-cementitious composites is still incomplete. Further studies are necessary in this field [Reinhardt 1995]. The following aspects are suggested as a focal point for future research:

**Mechanical Properties**

The mechanical properties of fibre-cementitious composites can be further improved by enhancing the fibre reinforcement efficiency, based on the analysis presented in Chapter 3. For this purpose, more attention should be paid to the interactions between fibres and matrix. In hybrid-fibre cementitious composites, new approach to assess the dispersion uniformity of fibres should be developed.

Fibre efficiency of hybrid fibres should be analysed theoretically as well as experimentally. Especially, understanding should be improved of the influences of micro-fibres on the macro-fibre-cement interface. Combining fibres has been found an important factor in establishing composite properties. However, what are the criteria for deciding on the appropriateness of the fibre combination?

**Electrical Properties**

World-wide, extensive studies have been performed on the electrical properties of cementitious composites. This is a very promising field of research. These studies can lead to the development of new cementitious composites, such as smart materials and shielding materials. And, new technologies and methods for the study of material structure and properties will be obtained. The relationship between electrical properties and durability of the fibre composites should be given more attention. The present study touched upon the effects of carbon fibres on the corrosion rate of steel bars in cementitious materials. But additional research is necessary. This issue should be further investigated under different conditions, i.e. under accelerated curing conditions, or when immersed in different solution media. The mechanisms of affecting the corrosion process should be further investigated.
References


References


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References

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References


[70]. Zhu, R., AR-glassfibre and its applications in concretes (I), China Concrete and


## Notations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>Notch depth of beam</td>
<td>2</td>
</tr>
<tr>
<td>$a_j \ (j=1,2,...)$</td>
<td>Aspect ratio of $j$ fibre</td>
<td>2, 3</td>
</tr>
<tr>
<td>$A$</td>
<td>Section area of specimen</td>
<td>2, 4</td>
</tr>
<tr>
<td>$A_{lg}$</td>
<td>Ligament area of specimen</td>
<td>2</td>
</tr>
<tr>
<td>$b$</td>
<td>Width of specimen</td>
<td>2</td>
</tr>
<tr>
<td>$C$</td>
<td>Capacitance</td>
<td>4</td>
</tr>
<tr>
<td>$C_{d}$, $C_{d'}$</td>
<td>Solid-liquid interfacial capacitance</td>
<td>4</td>
</tr>
<tr>
<td>$C_{int}$</td>
<td>Capacitance of interfacial zone</td>
<td>4</td>
</tr>
<tr>
<td>$C/G$</td>
<td>Ratio of crystal to gel phase</td>
<td>5</td>
</tr>
<tr>
<td>$d$</td>
<td>Diameter of fibres</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>$d_c$</td>
<td>Actual density of composite</td>
<td>3</td>
</tr>
<tr>
<td>$d_0$</td>
<td>Ideal composite bulk density</td>
<td>3</td>
</tr>
<tr>
<td>$E_c$</td>
<td>Elastic modulus of fibre composite</td>
<td>2, 3</td>
</tr>
<tr>
<td>$E_f$</td>
<td>Elastic modulus of fibre</td>
<td>2, 3</td>
</tr>
<tr>
<td>$E_{fj} \ (j=1,2,...)$</td>
<td>Elastic modulus of $j$ fibre</td>
<td>2, 3</td>
</tr>
<tr>
<td>$E_m$</td>
<td>Elastic modulus of matrix</td>
<td>2, 3</td>
</tr>
<tr>
<td>$f$</td>
<td>Coefficient of friction of crack edge</td>
<td>2</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity, 9.81 (m/s$^2$)</td>
<td>2</td>
</tr>
<tr>
<td>$G_i$</td>
<td>Conductance of composite</td>
<td>4, 5</td>
</tr>
<tr>
<td>$G_{fibre}$</td>
<td>Conductance of fibres</td>
<td>4, 5</td>
</tr>
</tbody>
</table>
### Notations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$G_t$</td>
<td>Conductance of liquid</td>
</tr>
<tr>
<td>$G_F$</td>
<td>Fracture energy of fibre composite</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of specimen</td>
</tr>
<tr>
<td>$I$</td>
<td>Electrical current</td>
</tr>
<tr>
<td>$I_k$ ($k=5, 10...$)</td>
<td>Toughness indices in flexure</td>
</tr>
<tr>
<td>$\bar{j}$</td>
<td>Imaginary unit, $j^2 = -1$</td>
</tr>
<tr>
<td>$K_t$</td>
<td>Coefficient of variation</td>
</tr>
<tr>
<td>$l$</td>
<td>Length of fibre</td>
</tr>
<tr>
<td>$L$</td>
<td>Total length of beam (or distance between two electrodes)</td>
</tr>
<tr>
<td>$l_c$</td>
<td>Critical fibre length</td>
</tr>
<tr>
<td>$l/d$ (or $a_y$)</td>
<td>Fibre aspect ratio</td>
</tr>
<tr>
<td>$m$</td>
<td>Load of specimen</td>
</tr>
<tr>
<td>$m_1$</td>
<td>Mass of beam between two supports</td>
</tr>
<tr>
<td>$m_2$</td>
<td>Mass of those parts of the loading frame that are not attached to the machine</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass of specimen</td>
</tr>
<tr>
<td>$p$</td>
<td>Porosity of composite</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>Additional porosity of composite</td>
</tr>
<tr>
<td>$P_{\text{max}}$</td>
<td>Ultimate load</td>
</tr>
<tr>
<td>$r$</td>
<td>Linear correlation coefficient</td>
</tr>
<tr>
<td>$R$</td>
<td>Electrical resistance (or gas constant)</td>
</tr>
<tr>
<td>$R_{2s}, R_2'_{s}$</td>
<td>Solid-liquid interfacial resistance</td>
</tr>
<tr>
<td>$R_{\text{fibre}}$</td>
<td>Apparent fibre resistance</td>
</tr>
<tr>
<td>$R_l$</td>
<td>Resistance of liquid</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Resistance of solid</td>
</tr>
<tr>
<td>$R_{\text{int}}$</td>
<td>Resistance of interfacial zone</td>
</tr>
<tr>
<td>$S$</td>
<td>Span of beam specimen</td>
</tr>
<tr>
<td>$S_e$</td>
<td>Specimen cross-sectional area normal to electrical field</td>
</tr>
</tbody>
</table>
### Notations

- $S_i$: Standard deviation of impedance
- $S_f$: Area faction of liquid phase
- $S_s$: Area fraction of solid phase
- $S_f$: Area fraction of fibres
- $V$: Voltage
- $V_f$: Fibre volume fraction (%)
- $V_f(j=1,2,...)$: Volume fraction of $j$ fibre (%)
- $V_i$: Volume fraction of a material component
- $V_m$: Matrix volume fraction (%)
- $V_{f(crit)}$: Critical fibre volume fraction (%)
- $V_w$: Air (or free water) volume fraction in composite
- $V_w$: Area under load-deflection curve
- $W_i(i=1,2,3...)$: Weight of $i$ material component
- $W_w$: Weight of water filling in pores
- $x_f$: Impedance of a specimen
- $\bar{x}$: Average impedance of a series
- $Z$: Complex impedance
- $\chi(i=1,2,3...)$: Density of $i$ material component
- $\chi_w$: Density of water
- $\delta_0$: Displacement in bending test
- $\varepsilon$: Strain
- $\varepsilon_c$: Strain of fibre composite
- $\varepsilon_f$: Strain of fibre
- $\varepsilon_f(j=1,2,...)$: Strain of $j$ fibre
- $\eta_l$: Length efficiency factor of fibres
- $\eta_l(j=1,2,...)$: Length efficiency factor of $j$ fibres
- $\eta_0$: Orientation efficiency factor of fibres
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_j) ((j=1,2,...))</td>
<td>Orientation efficiency factor of (j) fibres</td>
<td>2, 3</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Resistivity</td>
<td>4</td>
</tr>
<tr>
<td>(\sigma_b)</td>
<td>Flexural strength of composite</td>
<td>2, 3</td>
</tr>
<tr>
<td>(\sigma_c)</td>
<td>Tensile strength of fibre composite</td>
<td>2, 3</td>
</tr>
<tr>
<td>(\bar{\sigma}_f)</td>
<td>Mean stress along fibre</td>
<td>2</td>
</tr>
<tr>
<td>(\sigma_{fu})</td>
<td>Fibre tensile strength</td>
<td>2, 3</td>
</tr>
<tr>
<td>(\sigma_{ji}(j=1,2,...))</td>
<td>Tensile strength of (ji) fibre</td>
<td>2, 3</td>
</tr>
<tr>
<td>(\sigma_i)</td>
<td>Compressive stress</td>
<td>5</td>
</tr>
<tr>
<td>(\sigma_{mi})</td>
<td>First crack strength</td>
<td>2, 3</td>
</tr>
<tr>
<td>(\sigma_{mu}^i)</td>
<td>Tensile strength of cement matrix</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>(\sigma_{ST})</td>
<td>Splitting strength of composite</td>
<td>2, 3</td>
</tr>
<tr>
<td>(\omega)</td>
<td>Degree of fibre orientation (or angular frequency of the A.C)</td>
<td>2 (4)</td>
</tr>
<tr>
<td>(\omega_b)</td>
<td>Specific angular frequency, (\omega_b = 1/C_{\mu}^b R_2)</td>
<td>4</td>
</tr>
<tr>
<td>(\tau_{fu})</td>
<td>Fibre-cement interfacial shear strength</td>
<td>1, 2, 3</td>
</tr>
</tbody>
</table>
Samenvatting

Deze studie houdt zich bezig met mechanische en elektrische eigenschappen, met de microstructuur en met de duurzaamheid van cementachtige composieten, voorzien van een gering percentage van enkelvoudige of hybride vezels.

De mechanische eigenschappen van brosses cementmatrices (zoals de buigtreksterkte en de taaïheid) kunnen worden verbeterd door vezeltoevoegingen. Natuurlijk zal dit tot een prijsverhoging leiden. Andere effecten kunnen evenzeer specifieke toepassing van dergelijke composieten bemoeilijken. Het is daarom belangrijk de vezelhoeveelheid in cementachtige materialen beperkt te houden.

De proefresultaten in Hoofdstuk 2 laten zien dat vezelcomposieten met dezelfde samenstelling onderscheiden mechanische eigenschappen kunnen bezitten wanneer op verschillende wijze geproduceerd. Klaarblijkelijk beïnvloeden dergelijke technische processen de materiaalstructuur. Met de "twee-steps" mengprocedure die gehanteerd is in deze studie werd daarom beoogd een goede verdeling van de staal- en koolstofvezels te bevorderen teneinde de microstructuur van deze composieten te optimaliseren. Het bereiken van een goede vezelverdeling leidt tot een maximale wapeningsefficiëntie en een goede, dichte structuur. Dit wordt op indirecte wijze weerspiegeld in de gepresenteerde resultaten met betrekking tot de ruimteverdeling van de volumieke materiaal dichtheid.

Synergie kan worden bereikt door hybride vezelwapening waarbij van staal- en koolstofvezels gebruik wordt gemaakt. Een dubbel effect op de mechanische eigenschappen werd experimenteel waargenomen bij een optimale mengselsamenstelling en uniform verdeelde vezels. De volgende mechanismen spelen daarbij een rol:
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1) hybride vezels kunnen door hun onderscheiden slankheden de wapeningsefficiëntie verbhogen;
2) de staal- en koolstofvezels kunnen respectievelijk de macro- en de microscheurvorming beïnvloeden;
3) de koolstofvezels kunnen de hechtsterkte aan het staalvezel-cementgrensvlak bevorderen.

Bij een niet-uniforme vezelverdeling in dit hybride vezelsysteem werd echter experimenteel een negatieve beïnvloeding van de mechanische eigenschappen waargenomen. Dit houdt in dat slechtere resultaten werden geboekt in vergelijking tot cementcomposieten met een gelijke hoeveelheid enkelvoudige vezelwapening, zoals weergegeven in Hoofdstuk 2 (serie I). En hoewel synergie werd waargenomen bij serie III, behoren verdere verbeteringen tot de mogelijkheden.

Zowel staal- als koolstofvezels zijn elektrische geleiders. Dergelijke vezels kunnen daarom zelfs bij geringe toevoegingen van grote invloed zijn op de elektrische eigenschappen van de vezelcompositiet. Zulke veranderingen kunnen tot duurzaamheidproblemen leiden en ook anderszins specifieke toepassingen van deze vezelcomposieten bemoeilijken. De relatie tussen vezelhoeveelheid en elektrisch weerstandsvermogen vertoond in dit onderzoek een percolatiefenomeen. Dit was overduidelijk bij droog materiaal. Een dergelijke percolatie kan geacht worden te zijn veroorzaakt door het ontstaan van een lokaal vezelnetwerk (of gedeeltelijk gekoppeld netwerk) in de cementmatrix.

Onder vochtige condities of bij volledige waterverzadiging werd slechts een beperkte variatie waargenomen in de weerstand (of impedantie) bij wisselende vezelgehaltes. In dat geval is het geleidingsvermogen terug te voeren op de bijdrage van de vezels en van het poriewater. De impedantie van een dergelijke vezelcomposiet daalt snel met een toenemende meetfrequentie onder relatief laagfrequente omstandigheden (0-1000 Hz). Onder bepaalde omstandigheden kunnen impedantie en vezelhoeveelheid gecorreleerd worden. Dit was in het beproevingsprogramma het geval by 1000Hz. Deze correlatie kan bij kwantitatieve structuuranalyse gebruikt worden, zoals behandeld in Hoofdstuk 5.
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De elektrische eigenschappen van met hybride staal-koolstofvezels gewapend beton bleken in principe gelijk aan die van met koolstofvezels gewapende cementsteen: de impedantie van de systemen hing in hoofdzaak af van het totale vezelgehalte. Het vezeltype was van tweede importantie.

De structuur en de eigenschappen van vezelgewapende cementcomposieten kunnen op indirecte wijze bestudeerd worden aan de hand van de elektrische eigenschappen. Drie relevante voorbeelden worden behandeld in Hoofdstuk 5.

De hiervoor aangeduide relatie tussen impedantie en vezelgehalte bleek bij een meetfrequentie van 1000 Hz nagenoeg lineair te zijn. Dit maakte het mogelijk de ruimtelijke verdelingsgraad van koolstofvezels in cementsteen te onderzoeken. Daartoe werd een proefstuk van deze vezelgewapende cementsteen in kleinere delen verzaagd. De standaarddeviatie en variatiecoëfficiënt van de impedantiewaarnemingen, die aan deze kleinere eenheden ontleend werden, dienen daarbij als parameters die de verdelingsgraad van de koolstofvezels in de cementsteen weerspiegelen.

De mate van invloed uitgeoefend door de matrixsamenstelling en de structuur op de relatie tussen de mechanische spanning en de elektrische respons zijn expliciet meegenomen. In het bijzonder werden de invloed die de structurele eigenschappen en de minerale samenstelling sorteren op de drukspanningsgevoeligheid van de elektrische respons in detail bestudeerd. Door toevoeging van een synthetische CSH gel is de kristal/gel-verhouding gereduceerd, waardoor het aantal grotere poriën in de cementmatrix significant afnam. Dientengevolge nam de bovengenoemde drukspanningsgevoeligheid zeer sterk toe.

De modificatie in de elektrische eigenschappen door toevoeging van geleidende vezels kan, zoals eerder genoemd, de duurzaamheidsrisico’s verhogen. De veranderingen in het elektrisch weerstandvermogen kunnen in het bijzonder het proces van wapeningscorrosie beïnvloeden. Experimenteel is aangetoond dat de corrosiesnelheid van wapeningsstaven inderdaad gekoppeld is aan het gehalte aan koolstofvezels. De koolstofvezels bleken de corrosiesnelheid te verminderen wanneer het vezelgehalte beneden een grenswaarde bleef van 0.6 vol.%. Boven deze waarde werd de corrosiesnelheid echter vergroot.
Ondanks bijdragen van deze grondige studie is het inzicht in het gedrag van vezelgewapende cementachtige composieten nog incompleet. Aanvullende studies zullen nodig zijn op dit gebied [Reinhardt 1995]. De volgende aandachtsgebieden kunnen daarbij onderscheiden worden:

**Mechanische eigenschappen**

Naar verwachting kunnen de mechanische eigenschappen van vezelgewapende cementachtige composieten een verdere verbetering ondergaan door opvoeren van de vezellefficiëntie, volgens de principes uiteengezet in Hoofdstuk 3. Daartoe zal meer aandacht moeten worden geschonken aan de interactie tussen vezels en matrix. In cementcomposieten met een hybride vezelwapening zal een nieuwe methode moet worden ontwikkeld en gehanteerd voor het vaststellen van de wijze waarop de vezels verdeeld zijn in het materiaal.

De vezellefficiëntie behoeft theoretische als wel experimentele aandacht. Daarbij zal in het bijzonder aandacht moeten worden geschonken aan de invloed van de micro-vezels op het grensvlak tussen macro-vezels en de cementmatrix. Mechanische eigenschappen zijn gebaat, zo is aangetoond, bij combinaties van vezels. Maar wat zijn de criteria die aan het mengselontwerp ten grondslag moeten worden gelegd?

**Elektrische eigenschappen**

Aan de elektrische eigenschappen van cementcomposieten is wereldwijd in uitgebreide studies aandacht besteed. Dit moet als een veelbelovend gebied van onderzoek worden gekenschetst. Deze studies zullen leiden tot de ontwikkeling van nieuwe cementcomposieten, zoals 'zelfdenkende' (smart) en beschermende materialen. Ook zullen nieuwe technologieën en methodes voor onderzoek aan materiaalstructuur en -eigenschappen langs deze weg beschikbaar kunnen komen. De relatie tussen elektrische eigenschappen en duurzaamheid van vezelcementcomposieten verdient meer aandacht. De onderhavige studie besteedt aandacht aan het effect van de toelaging van koolstofvezels op de corrosiesnelheid van wapeningsstaven in beton. Aanvullend onderzoek is hier echter nodig. Daarbij zal herhaling van dit onderzoek moeten plaatsvinden onder verschillende omstan-

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digheden, waarbij aan versnelde verharding en aan verharding in verschillende vloeistoffen moet worden gedacht. De daarbij optredende mechanismen behoeven verdere studie.
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