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Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC)

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G.P.A.G. van Zijl • F.H. Wittmann
Editors

Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC)

State of the Art Report Prepared by Subcommittee 2 of RILEM Technical Committee 208-HFC Chaired by Professor Victor C. Li

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Contents

Durability of Strain-hardening Fibre-reinforced Cement-based Composites (SHCC) – State-of-the-art

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Foreword

This report captures the state-of-the-art of the durability of fibre-reinforced strain-hardening cement-based composites (SHCC). It has been compiled by the subcommittee on durability of the RILEM Technical Committee 208-HFC: High performance fibre reinforced cementitious composites. The subcommittee is chaired by Professor Folker Wittmann, and co-chaired by Professor Gideon van Zijl. This subcommittee has been active in the period 2005–2009, with yearly meetings in Honolulu, Hawaii (May 2005), Alexandroupolis, Greece (July 2006), Stuttgart, Germany (July 2007), Gifu, Japan (October 2008) and in Stellenbosch, South Africa (November 2009). The committee was inaugurated by its chairman, Professor Victor Li, at the first meeting in Varenna, Italy (September 2004).

In particular, the eight chapters have been compiled by the following subcommittee members:

Chapter 1 – Introduction
  Gideon P.A.G. van Zijl, Stellenbosch University, South Africa
  Folker H. Wittmann, Aedificat Institute Freiburg, Germany
Chapter 2 – Durability under Mechanical Load – Micro-crack Formation
  Gideon P.A.G. van Zijl, Stellenbosch University, South Africa
Chapter 3 – Durability under Chemical Loads
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Chapter 4 – Durability under Thermal Loads
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Chapter 5 – Durability under Combined Loads
  Folker H. Wittmann, Aedificat Institute Freiburg, Germany
Chapter 6 – Durability of Fibres
  Atsuhisa Ogawa and Hideki Hoshiro, Kuraray Co., Ltd., Japan
Chapter 7 – Durability of Structural Elements and Structures
  Viktor Mechtcherine and Frank Altmann, TU Dresden, Germany

Chapter 8 – Durability, Economical, Ecological, and Social Aspects: Life-cycle Considerations
Michael D. Lepech, Stanford University, USA

In addition to a thorough review by the editors, a critical review of the report was performed by Professor Hirozo Mihashi, of Tohoku University, Japan, and Professor Victor C. Li, Michigan University, USA, assisted by Dr. Sahmaran of Gaziantep University, Turkey. We gratefully acknowledge this review panel.

Finally, we hope that this state-of-the-art report contributes to thorough understanding and sound application of this advanced cement-based construction material in civil engineering infrastructure and buildings. It must be born in mind that, however comprehensive we have covered the current knowledge at the time of publication, active research continues to expand and modify the behaviour and characterisation data, but also to address the lack of thorough investigation and understanding of several matters clearly indicated in this report.

Gideon van Zijl
Stellenbosch, January 2010

Chapter 1
Introduction

Gideon P.A.G. van Zijl and Folker H. Wittmann

Abstract This report defines strain-hardening cement-based composites (SHCC) and describes the principles. The scope of the report is fine-grained SHCC with moderate fibre volume content, yet tight crack control over a large strain range. Durability is achieved through crack width limitation. The report layout facilitates SHCC characterisation and durability design, with chapters on durability under mechanical, chemical, thermal and combined loads, followed by durability of structural elements and structures, and finally life-cycle considerations.

Key words: strain-hardening cement-based composites (SHCC), fibre-reinforcement, multiple cracks, ductility, durability

1.1 Strain-hardening Cement-based Composites (SHCC)

It has become possible to design fibre reinforced cement-based composites to desired mechanical and non-mechanical performances. Among the various classes of high performance fibre-reinforced cement-based composites (HPFRCC) that have been developed, a particular class of generally moderate tensile strength (3–8 MPa), but with pseudo strain-hardening tensile behaviour of ultra ductility is of interest here. Fibre-reinforced strain-hardening cement-based composites (SHCC) exhibit superior crack width and spacing control in the pseudo strain-hardening phase, as depicted in Figure 1.1. Composites with such superior tensile response, yet low volumes of short fibre, can be engineered by tailoring the composite ingredients with the aid of micromechanically based formulations (e.g. Li, 1998). This has led to the terminology 'Engineered Cementitious Composites', or ECC, by Li and co-workers

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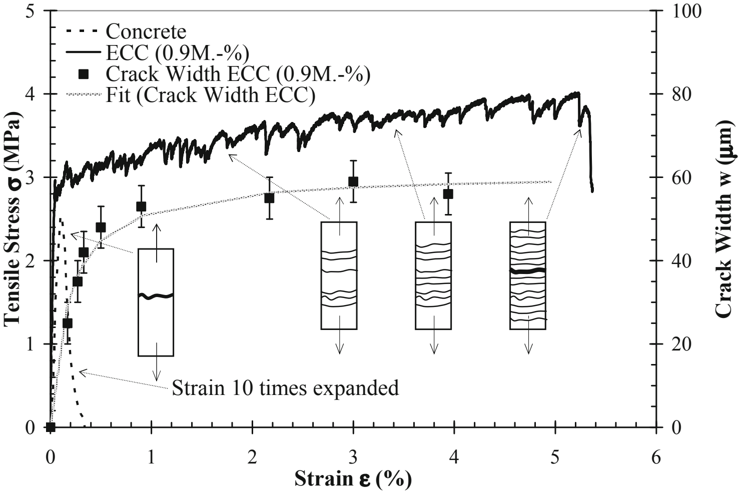

Fig. 1.1 Direct tensile stress-strain response of SHCC showing crack control to less than 65 μm (Weimann and Li, 2003).

for such SHCC materials. In this document the focus is on SHCC, distinguished by its ability to develop multiple, finely spaced cracks of tight crack widths, generally below 100 μm. This crack control may be exploited for its potential inherent durability and the durability it may afford structures (Li and Stang, 2004).

1.2 Classification and Scope

Categorization of HPFRCC may be based on tensile strength and ductility. Two classes define the extremities of tensile ductility and strength in HPFRCC. SHCC has moderate tensile strength but significant ductility (up to and beyond 3% of tensile strain). Ultra-high performance fibre-reinforced concretes (UHPFRC) have high tensile strength, flexural strength (25–60 MPa), as well as extremely high compressive strength (180–240 MPa), but reach these strengths at moderate strain levels. Examples of tensile responses of SHCC and UHPFRC are shown in Figure 1.2. Note that it has recently become possible to design these superior composites with low to moderate fibre volumes ($1\% \leq V_f \leq 3\%$).

In SHCC cracks of small, controlled width arise over a wide range in strain. Fine cracks also arise in the pre-peak region of UHPFRC. In UHPFRC the cracks are generally localised in areas of weakness or positions of maximum internal forces in structural elements, unlike in SHCC where the extreme ductility leads to large pseudo-plastic zones, containing multiple cracks. Degradation processes through a single, or a small number of fine cracks may equally apply to UHPFRC and SHCC in their respective regions of fine crack widths. However, generally these classes of HPFRCC have different mechanisms of resistance to degradation processes. For

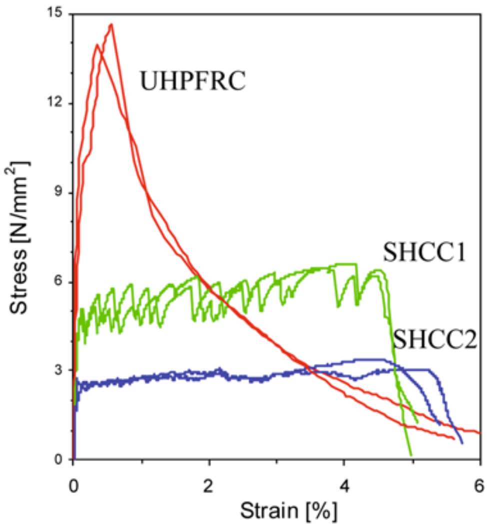

Fig. 1.2 Uniaxial tensile behaviour of classes of HPFRCC (van Zijl, 2008).

instance, UHPFRC usually has a dense matrix, which is highly resistant to capillary suction, whereas SHCC resists long term moisture and chloride diffusion through crack control to fine widths.

A traditional distinction is made between fibre-reinforced cement paste and mortars or renderings and fibre-reinforced concretes, based on the grain size of the matrix. Whereas large aggregate is desirable in several applications of FRC, fine grained matrices, which include only fine aggregates, may be required by the application, manufacturing method, or the required mechanical behaviour of the hardened material. For instance, the manufacturing method of SIMCON and SIFCON entails forcing the fresh cement-based slurry into pre-arranged, dense fibres or fibre mats. This requires a fine aggregate. Ductility, and especially inherent crack control to fine widths and spacing also requires a fine-grained matrix. This categorization in terms of grain size would group UHPFRC together with ultra ductile SHCCs, which have inherent crack control. Ductal (2007) and other UHPFRC based on reactive powder concrete (RPC) technology (Richard and Cheyrezy, 1995) or multi-scale cement composites (MSCC) and fibre-reinforcement for ductility, such as CEMTEC (Rossi, 2000), are fine-grained.

In this report, mainly fine grained SHCC is discussed.

1.3 Fundamentals of Durability Design for SHCC

Tight crack-control by SHCC has the potential of addressing an increasing trend in infrastructure internationally, namely that the portion of total expenditure for main-

Table 1.1 Examples of crack width limitation in RC structures for durability (Carino and Clifton, 1995).

Exposure condition	Tolerable crack width (mm)
ACI 224R, 90	
Dry air or protective membrane	0.41
Humidity, moist air, soil	0.30
Deicing chemicals	0.18
Seawater and seawater spray; wetting and drying	0.25
Water retaining structures	0.10
ACI 318-89	
Interior	0.41
Exterior	0.33
ACI 350R-89	
Normal	0.27
Severe	0.22
CEB/FIP Model Code 1990	
Humid environment, deicing agents, seawater	0.3

tenance and rehabilitation is growing at an alarming rate. Roughly 50% of the total expenditure for construction is needed for maintenance and repair in many countries (Wittmann and van Zijl, 2006). The largest source of damage may be attributed to moisture, gas and salts ingress in cement-based composites like concrete, whereby steel reinforcement is subjected to degradation processes.

This situation motivates great care when developing new construction materials, such as SHCC. In the first place such materials should inherently be durable, and in addition contribute to more durable structures. In this regard SHCC in particular presents a strong potential, by the very nature of pseudo strain-hardening, physically attributed to increasing load capacity during multiple micro-crack formation. It is argued that this potential of SHCC is put under the spotlight in the research efforts towards characterizing and improving the durability of these materials. Thus, this document gathers and presents the state-of-the-art regarding the inherent durability of the SHCC itself, but to a large degree, the durability afforded to structures by crack width limitation whereby ingress of moisture, gas and salts is limited.

1.4 Crack Control as Durability Measure

Crack width limitation or control is a well established concept in RC design. Design standards and codes for concrete suggest limiting values for crack widths for different environments to assure durability of structures built of RC in these environments.

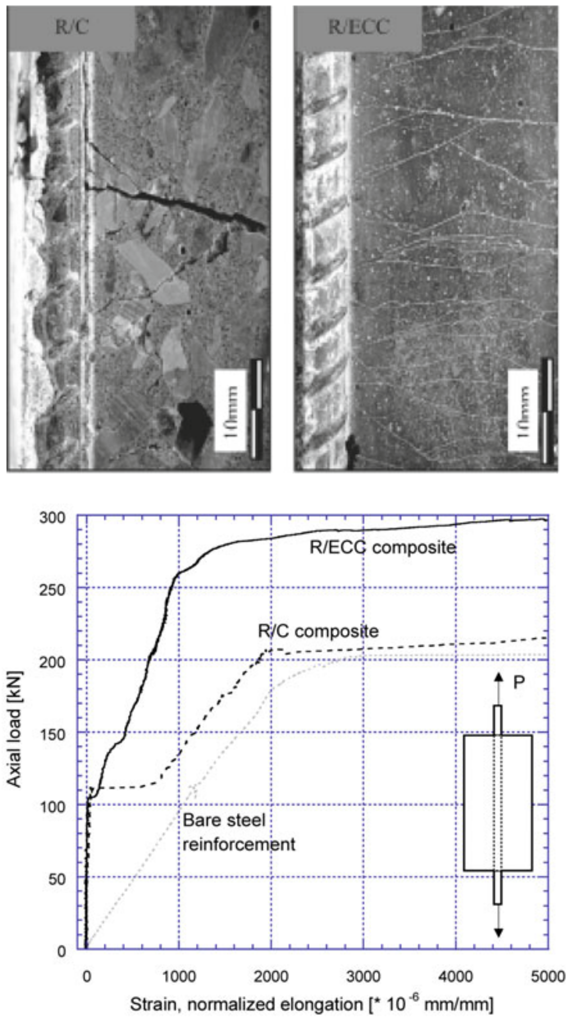

Fig. 1.3 Incompatible tensile deformation in RC vs. compatible tensile deformation in R/SHCC, through ductile, multiple cracking tensile response of SHCC (Fischer and Li, 2004).

A summary is given in Table 1.1. The pseudo strain-hardening in SHCC involves multiple cracks. Thereby individual crack widths are arrested and new cracks arise, which is a form of crack control. This has also been shown for SHCC on the material level (Figure 1.1) and also on the structural scale, steel reinforced SHCC elements (R/SHCC) – see Figure 1.3. This phenomenon may be regarded as an extension of the well-known phenomenon of crack width reduction in reinforced concrete (RC) through rebar size reduction, but increased number of bars to maintain the reinforcement level. However, it should be noted that unlike RC, the crack width in SHCC does not depend on steel reinforcement, but should be regarded as an intrinsic material property (Figure 1.1).

Researchers, for instance Li et al. (2001) and Weimann and Li (2003), have set out to measure the crack width and spacing, to confirm the crack-control in SHCC. The preliminary outcome, which will be discussed in more detail in Chapter 2 of this report, is that crack widths in particular SHCC types are arrested at widths below 80 micrometer.

1.5 Report Layout

This book collects the state-of-the-art knowledge and level of characterization of the durability of SHCC. This will assist in establishing the gaps in knowledge, and help focus research efforts.

An approach towards characterising SHCC durability has been proposed recently as a suggested guideline for the activities of RILEM TC 208-HFC, SC2 (Wittmann and van Zijl, 2006). Based on this proposal the present report shall be structured as follows:

Chapter 2: Durability under Mechanical Load – Micro-Crack Formation (Ductility)

- Ductility as compared with the sum of possibly imposed strains
- Average and maximal opening of micro-cracks during strain-hardening
- Width of micro-cracks in loaded and unloaded specimens
- Influence of width of micro-cracks on permeability and capillary suction
- Sustained and cyclic load
- Fatigue
- Abrasion
- Self-healing of micro-cracks

Chapter 3: Durability under Chemical Loads

- Chloride environments
- Hydrolysis and leaching
- Hot and humid environments
- Alkali environments
- Resistance with respect to sulphate attack
- Alkali aggregate reaction

Chapter 4: Durability under Thermal Loads

- Behaviour at elevated temperatures
- Thermal cracking at early ages
- Frost resistance and action of de-icing salts

Chapter 5: Durability under Combined Loads

- On combined loads

- Imposed strain and penetration of aggressive compounds
- Frost action and permeability
- Hydrolysis and ultimate strain capacity
- Mechanical load and alkaline environment

Chapter 6: Durability of Fibres

- Typical properties of fibres
- Durability of PVA fibre
- Durability of PVA fibre-reinforced cement-based composites

Chapter 7: Durability of Structural Elements and Structures

- Characteristic mechanical, environmental, and combined loads
- Basics for durability design
- Characteristic material properties to predict long-term durability and service-life
- Examples

Chapter 8: Durability, Economical, Ecological, and Social Aspects (Life-Cycle Considerations)

- Life-cycle impact and costs versus initial cost and impacts of construction
- Raw material recycling
- Sustainability

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Chapter 2
Durability under Mechanical Load – Micro-crack Formation (Ductility)

Gideon P.A.G. van Zijl

Abstract A significant modification of the mechanical behaviour of cement composites is brought about by fibre reinforcement. The most important feature is crack bridging by fibres. This leads to pseudo strain-hardening in SHCC. The important feature to be considered for durability design of SHCC, which is the focus in this report, is the crack-control exhibited by this class of materials in the strain-hardening phase. The crack control in SHCC subjected to mechanical actions leading to direct tension, but also shear and compression is described here. Short term monotonic actions, long-term actions as well as cyclic actions are discussed. Another mechanical degradation process, namely that of abrasion is described. Finally, self-healing of SHCC is discussed as a promising durability feature of degradation reversal.

Key words: strain-hardening cement-based composites (SHCC), durability, microcrack, mechanical load, creep, fatigue, abrasion, self-healing

2.1 Introductory Remarks

An important phenomenon of structural durability is the limitation of crack width, whereby ingress of potentially damaging salts, through media of moisture and gases may occur. In steel reinforced composites, the well-known danger of steel corrosion is a major source of rehabilitation/restoration cost in reinforced concrete (RC) buildings. By limiting crack widths, this source of damage and associated repair cost can be limited, or delayed, whereby repair/maintenance intervals may be increased and life cycle cost of such structures reduced. Carino and Clifton (1995) summarise crack widths in RC, as prescribed by various design codes for limitation of ingress.

In strain-hardening cement-based composites (SHCC) the tensile ductility is caused by the formation of multiple cracks. This is a process of crack control. The

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crack widths are limited by the fibre pull-out resistance, whereby other matrix cracks arise, rather than widening of existing cracks. This is in contrast to normal concrete or normal fibre reinforced concrete that exhibits tension-softening, wherein fracture localization occurs once a crack is formed, so that the crack width is unlimited as load capacity decreases. The micromechanical requirements for optimizing this process have been elaborated elsewhere (Li, 1998; Kanda and Li, 1998). While it is not appropriate to repeat the micromechanical base of this class of materials here in detail, it is essential to consider the main mechanisms and parameters which govern the behaviour of these materials under mechanical and environmental actions. This allows objective characterization of the durability of SHCC. In this light the influence of amongst others, fibre type and volume, fibre aspect ratio, matrix composition for its role in determining matrix toughness and strength, as well as fibre-matrix interaction is surveyed and reported. Keeping in mind these parameters, this chapter describes the current state of knowledge of tensile deformation, the possibility of expressing it as tensile strain although it manifests as multiple cracks of finite width, the influence such cracks have on permeability to moisture and gas penetration and finally, the potential of crack healing.

It must be noted that SHCC is a young class of materials in a dynamic development phase internationally. Whilst the basic principles of achieving the required, distinguishing mechanical behaviour of SHCC have been defined, many possibilities of ingredient choice and proportioning exist, rendering the complete characterization of the durability of SHCC virtually impossible at this stage of development. Nevertheless, in the light of the stated parametrisation, generality is introduced as far as possible in the discussions of the current state-of-the-art of the durability of SHCC.

2.2 Ductility as Compared with the Sum of Possibly Imposed Strains

It has been pointed out above that ductility of SHCC is not due to plastic deformation (as in ductile metal attributed to dislocation movement) but due to the formation of multiple micro-cracks. This automatically means that the material is progressively damaged in the strain hardening range. This damage can be observed as a noticeable decrease of the elastic modulus for instance. As long as the width of the micro-cracks remains below a critical value (in many cases below 40 μm), however, the permeability of the cement-based material is not substantially increased. In addition these fine micro-cracks will be closed under favourite environmental conditions again by self-healing. Therefore, with respect to durability, we have to require that the sum of all possibly imposed strains (strain-demand) does not exceed the tensile strain at ultimate load (strain-capacity) so that fracture localization is prevented. In addition, the micro-cracks formed during strain-hardening must not be wider than a critical crack width. Then and then only durability is not affected by imposed strains. The critical crack width has to be determined experimentally for a given type of environmental exposure.

In practice we have to distinguish mechanical strains and strains imposed by environmental actions. The maximum mechanical strain can be estimated from the design load and accidental additional loads. Environmental actions will usually impose hygral shrinkage and swelling strain and thermal strain. These environmentally imposed strains will often be cyclic. In the long run chemically induced strains will have to be taken into consideration in addition. Typical chemical strains are carbonation shrinkage, and swelling due to alkali silica reaction (ASR) and sulphate attack.

Hygral shrinkage strain of SHCC in a moderate climate is in the range of 0.08 to 0.12%. A temperature difference of 50°C imposes a thermal strain of about 0.05%. From these simple considerations it follows that SHCC must allow an imposed strain of at least 0.2% without formation of micro-cracks wider than the critical value. Then the sum of possibly imposed strains will not have a negative influence on durability. In many cases a more precise estimation of the possibly imposed strains will be necessary of course.

2.3 Average and Maximal Opening of Micro-cracks during Strain-hardening

The multiple crack formation, accompanied by tensile pseudo strain-hardening is illustrated in Figure 1.1 in terms of a uniaxial tension test force-displacement result, translated to stress and strain. The notions of stresses and strains are reserved for continua, but are commonly used for the macroscopical description of cement-based material, despite their heterogeneous nature, containing various phases like stone, hardened cement paste and, in the case of SHCC, fibres. Nevertheless, the SHCC with finely spaced, spread-out, fine cracks beyond the elastic range can be treated as a continuum when the stresses and strains in the constitutive description of SHCC denote averages of forces and deformation over a representative volume containing many microcracks. This is particularly justifiable when the microcrack spacings are on the mm scale, and the constitutive laws are used to describe material behaviour in structures on the cm or m scale. The artificial notion of “smeared cracking”, which is conveniently used for describing localized cracking in concrete, is in fact an actual, physical phenomenon in SHCC, justifying the expression of strain in these materials.

In Figure 1.1 the typical crack pattern development with increased tensile deformation of a SHCC specimen is shown. After the first crack arises, which indicates the end of the linear stress-strain relation, more cracks arise successively at higher deformation levels. The eventual reduced resistance is introduced by exceedance of the crack bridging capacity at a particular crack, at which location the deformation subsequently localizes.

Table 2.1 Crack width measurements in SHCC, specimen composition, size and test setup.

Li et al. (2001)[1]							Weimann and Li (2003)[2]	Wang and Li (2006)[2]
Ref. nr.	1	2	3	4	5	6	7	8
Cement	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Water	0.45	0.45	0.45	0.45	0.45	0.45	0.51	0.51
Sand	1.0	1.0	1.0	1.2	1.2	1.2	0.8	0.8
Sand grading	F110			F110				F110
Fly Ash	–	–	–	–	–	–		1.2
V_f	2.0%	2.0%	2.0%	2.0%	2.0%	2.5%	2.0%	2.0%
Fibre type	PVA							
L_f (mm)	12						12	12
d_f (μm)	39							39
E_f (GPa)	42.5							25.8
Oiling agent %	0.3	0.5	0.8	0.5	0.8	0.8		1.2
τ_0 (MPa)	3.5	2.5	2.0					
G_d (J/m^2)	3.0	2.5	2.0					
J_b' (J/m^2)	9.6	10.7	16.5					
σ_{tu} (MPa)	4.60±0.23	4.02±0.40	4.58±0.38	3.92±0.15	4.28±0.17	5.00±0.52		
σ_{fc} (MPa)	3.97±0.28	2.66±0.11	3.11±0.14	3.45±0.14	2.63±0.32	3.39±0.09		
ε_{tu} (%)	1.59±0.35	3.62±0.56	3.68±1.16	1.64±0.60	2.48±1.04	4.59±0.36		
w_c (μm)	44±7	52±10	71±9	45±19	50±9	58±10	Figure 2.1a	Figure 2.1b
Crack spacing (mm)	7.5 ± 2.8	3.5 ± 2.0	2.5 ± 0.3	6.4 ± 1.0	3.9 ± 2.4	1.8 ± 0.3		
Specimen size (mm): Length Width Thickness Gauge length	 304 76.2 12.7 180						 304 76.2 12.7 180	 304 76.2 12.7 180
Test age (days)	30							28
Curing	24h in mould, 28 d in water, 1 day air dry							
Test speed	0.15 mm / minute						0.3 mm/minute	0.3 mm/minute
Crack measurement	50 x magnifier, after unloading[1]						Single crack continuous[2]	Single crack continuous[2]

[1]The reported crack widths were measured after unloading, i.e. in the residual tensile deformation state.
[2]Individual cracks were monitored by video microscope during loading, at various strain levels.

Crack widths have been monitored in several experimental studies. The earliest report of crack width measurements is by Li et al. (2001), as part of a SHCC sensitivity study to the parameters fibre bond (varied by surface oiling), matrix toughness (varied by aggregate content variation) and, to a limited degree, fibre volume ($V_f = 2.0$ or 2.5%). The study used Polyvinyl Alcohol (PVA) fibres. Other studies that included crack width measurement were reported by Weimann and Li (2003) and Wang and Li (2006). In all of these studies PVA fibre was used. Nevertheless, the other ingredient and proportioning differences, which are summarized in Table 2.1, allow some conclusions on the crack width in SHCC as influenced by the main governing parameters. This will be discussed in the following sections.

2.3.1 Crack Width Evolution with Tensile Strain

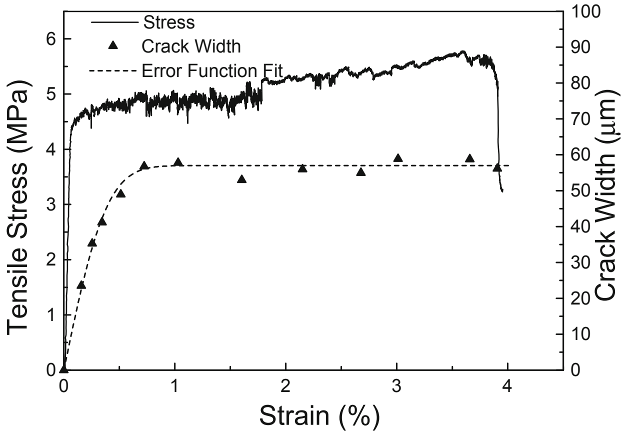
Also shown in Figure 1.1 is the crack width evolution with tensile strain. It should be noted that the crack width in that figure is that of a single crack, which was monitored throughout a uniaxial tensile test. This was done on a small rectangular tensile specimen, of dimension given in Table 2.1, as tested by Weimann and Li (2003). Similar observations were done by Li et al. (2001) and Wang and Li (2006), as shown in Figure 2.1. Note that due to fibre dispersion non-uniformity, it may be expected that crack width may vary from one crack plan to another, so that crack width on a given specimen is not a single number, but shows a statistical distribution.

It appears that, for the particular types of SHCC tested thus far, all containing PVA fibres in the range $2.0\% \leq V_f \leq 2.5\%$ and similar matrices as indicated in Table 2.1, the crack width is arrested at a strain level of less than 1% at an average value in the range of 50–60 μm. Subsequently, more cracks arise in the specimen upon increased tensile straining, while widening of the existing cracks is negligible. It is postulated that a crack width increase must take place to develop the higher crack bridging resistance demanded at increased tensile strain, to realise the pseudo strain-hardening behaviour. Either fibre slip or fibre stretching or both can lead to such increased resistance. From the shown crack measurements this effect appears to be insignificant.

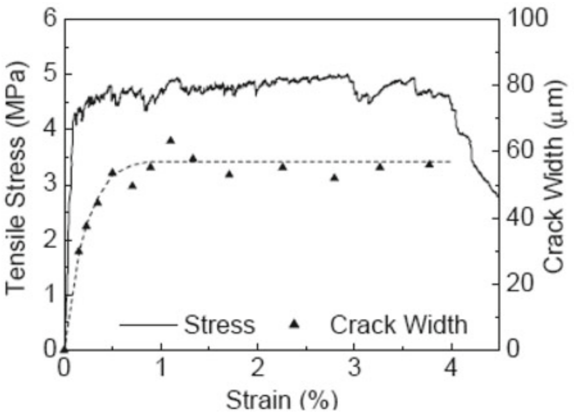
2.3.2 Fibre Volume

The only direct comparison is possible from the research results of Li et al. (2001), who tested similar PVA-SHCC specimens with $V_f = 2\%$ and $V_f = 2.5\%$, as listed in Table 2.1 under reference numbers 5 and 6. Whereas the fibre volume increase led to increases in both the ductility, in terms of the ultimate tensile strain, and the ultimate tensile strength, the crack width changed insignificantly. Note that these crack widths were measured on specimens in the unloaded state, after a monotonic tensile test up to and beyond the ultimate strength. This means that the crack widths on the lower fibre volume specimens occurred at a significantly lower residual tensile strain level, in the region of 2%, than the higher fibre volume specimens (in the region of 4%).

This result agrees with the concept of crack width arrest in SHCC, after which more cracks arise, rather than widening of individual cracks. Arguably, at a higher fibre volume the crack opening displacement to achieve the required crack bridging strength for subsequent cracks to form will be lower, due to a larger number of fibres bridging the crack in a matrix otherwise identical. If fibre interaction is ignored, the crack width reduction should be proportional to ratio of the fibre volumes, i.e. the crack width for $V_f = 2.5\%$ should reduce to 80% of that for $V_f = 2.0\%$ at the same stress level. This remains to be confirmed in future test programs.



(a) Li et al. (2001)



(b) Wang and Li (2006)

Fig. 2.1 Width evolution of an individual microcrack under uniaxial tension.

2.3.3 Fibre Bond Strength

Evaluation of this influence is possible by comparison of the results for specimens with reference numbers 1–3 in Table 2.1. For these specimens, the frictional fibre bond (τ_0) was reduced from $\tau_0 = 3.5$ MPa (0.3% coating) to $\tau_0 = 2.0$ MPa (0.8% coating), while the chemical bond (G_d) was reduced from 5.0 to 2.5 J/m^2 for the coinciding increased oil coating level. These results were established by single fibre pull-out tests (Li et al., 2001). This realises in an increased complementary energy of the fibre bridging stress-crack opening response (J_b'), Figure 2.2.

From the resulting crack width and spacing measurements in Table 2.1 for these specimen types it is clear that the reduced fibre bond leads to a reduced crack spa-

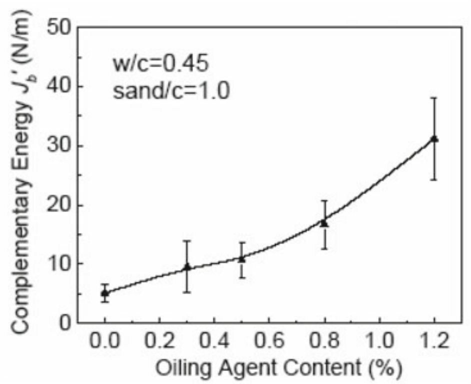


Fig. 2.2 Fibre bridging stress-crack opening complementary energy (J_b') increase with PVA fibre oil coating level increase (Wang and Li, 2006).

cing (from 7.5 to 2.5 mm), although the average crack width is increased from 44 to 71 μm. It must be noted once again that the crack widths were measured after removal of the load, which means that the residual tensile strain level was significantly lower ($\varepsilon_{tu} = 1.6\%$) for specimens with the high fibre bond than for those with weaker fibre bond ($\varepsilon_{tu} = 3.7\%$).

It is postulated that the fibre bond strength governs the ductility for this class of SHCC, rather than the crack width in the strain hardening phase. Thus, for objective characterisation of the influence of the fibre bond strength on the crack width evolution in SHCC, crack width measurements should be done at the same strain levels.

2.3.4 Influence of Matrix Composition

From the current level of micromechanical understanding and modelling, the governing parameters in the mechanical response of SHCC are the fibre factors such as fibre volume V_f, fibre length L_f, fibre diameter d_f, fibre strength and stiffness, the matrix factors such as strength, matrix toughness and maximum aggregate size (initial flaw size), and the fibre-matrix interfacial properties reflected by the frictional and chemical bond. In each of these groups of parameters, several variations are possible. In this section the influence of the matrix composition on the crack width is discussed.

Note that reference is often made to the fibre factor (FF), which combines fibre volume, length and diameter as follows

$$\mathrm{FF} = V_f \frac{L_f}{d_f} \tag{2.1}$$

2.3.4.1 Aggregate Content

Whereas the role of aggregate in the tensile mechanical behaviour of certain types of SHCC has been studied intensely (Li et al., 1995, 2001; van Zijl, 2005), not sufficient crack measurements are available to draw conclusions on its influence on crack width evolution. It has been clearly demonstrated that the matrix strength, expressed by the first cracking strength (σ_{fc}), and toughness, expressed by the crack tip toughness (J_{tip}), are increased with increased sand content. Thereby tensile ductility is reduced for a given fibre factor. It has been demonstrated theoretically that the ratio between the complementary energy (J_b') of the fibre bridging stress-crack opening, to the matrix crack tip toughness must be larger than one for strain hardening, i.e. $J_b'/J_{\text{tip}} > 1$. However, the requirement for this ratio has been measured to be $J_b'/J_{\text{tip}} \geq 3$ (Kanda and Li, 1999) for multiple cracking saturation, reflecting material variability not accounted for in theoretical models.

From the available data in Table 2.1, in particular specimens numbers 2 and 4, the reduced tensile ductility is confirmed with even a slight increase in aggregate to cement proportion from 1.0 to 1.2. Nevertheless, the average crack width is insignificantly changed, keeping in mind the different residual strain levels at which they were measured. However, the crack spacing is nearly doubled with this increase in aggregate content.

2.3.4.2 Cement Replacement by Fly Ash and Slagment

The role of fly ash (FA) in the mechanical behaviour of certain classes of SHCC has been studied by several research groups, for example Peled and Shah (2003), Song and van Zijl (2004), Wang and Li (2006). Cement replacement with FA has been shown to reduce the matrix strength, seen in Figure 2.3 for specimens with $\text{FA}/\text{C} = 1.4$. It has been postulated that the fibre-matrix interfacial zone is modified, leading to improved fibre slip from the matrix instead of fibre breakage. Measurements show reduced chemical bond but higher frictional bond with increase of fly ash. Thus both matrix and interface properties are modified, illustrated by the increased ratio J_b'/J_{tip} in Figure 2.4 (Wang and Li, 2006).

In contrast, cement replacement with large quantities (up to 50% by mass) of ground granulate Corex slagment (slag), led to a strong matrix (Figure 2.3). Of importance here is the crack patterns associated with these classes of SHCC. Although the crack widths were not measured, it is clear that the crack width and spacing are significantly larger for the slag-SHCC than for FA-SHCC. Note that the mix design for these specimens was otherwise similar in terms of fibre type (PVA, $L_f = 12$ mm, $d_f = 40$ µm) and volume (2.5%), aggregate content (aggregate/binder = 0.5) as well as water content (water/binder = 0.4).

Consider the crack width measurements for the specimens with reference number 8, Table 2.1 and Figure 2.1b. These specimens, containing large quantities of FA, show comparable crack widths with those of specimens without FA. As a general indication, the large stress fluctuations seen in Figure 2.3 (top) are indicative of lar-

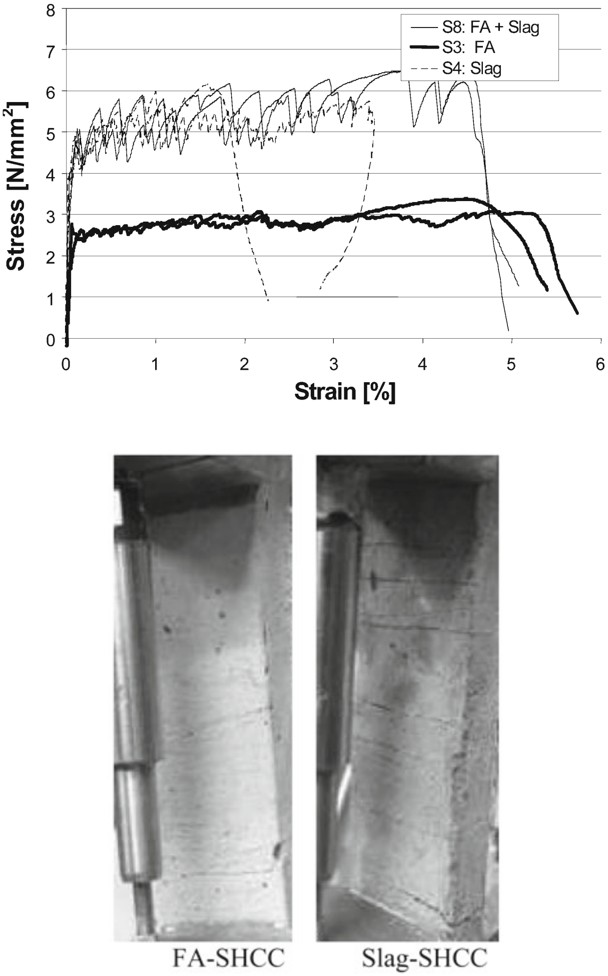


Fig. 2.3 Tensile stress-strain responses of FA-SHCC and slag-SHCC (Song and van Zijl, 2004).

ger crack widths. This may even occur in matrices without slag, but for composites with fibre volume approaching the critical level for pseudo strain-hardening.

2.3.5 Age at Loading, Curing

It must be noted that the crack width determination was on relatively young specimens, loaded 28 days after casting. There is evidence that SHCC becomes more brittle with aging, as found in the results of direct tensile testing at various ages of PVA-SHCC by Wang and Li (2005), as well as Lepech and Li (2005). Due to the

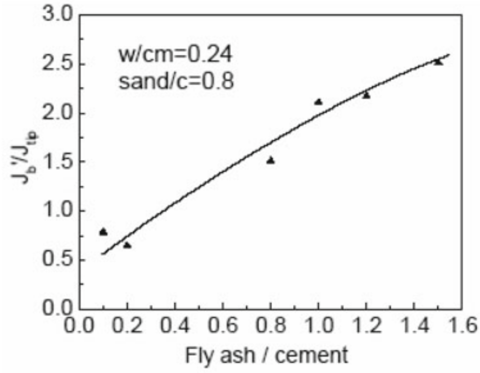


Fig. 2.4 FA content driven improvement of complementary energy: toughness ratio, critical for multiple, fine cracking (Wang and Li, 2005). The mix contained PVA fibre at $V_f = 2\%$, 1.2% oil coating.

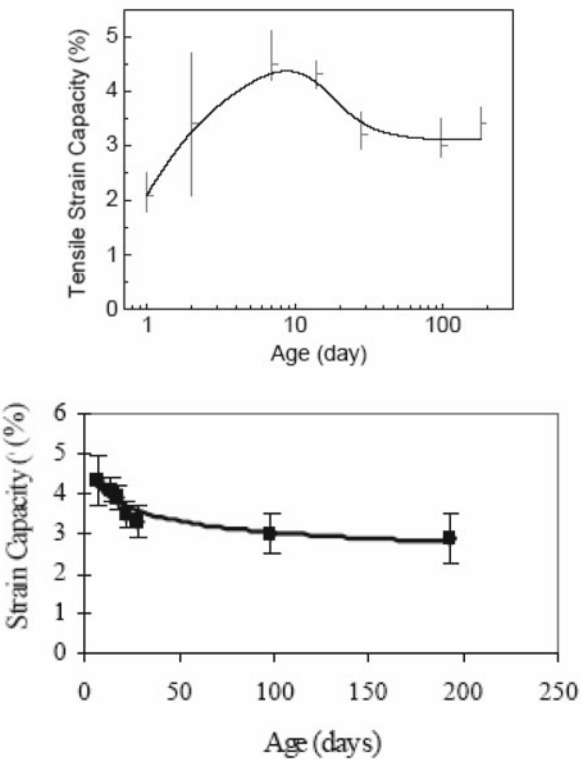


Fig. 2.5 Reduction in tensile strain capacity with aging of SHCC by (top) Wang and Li (2005) and (bottom) Lepech and (Li 2005).

delicate balance of binder matrix, fibre, and matrix/fibre interface properties, the strain capacity of SHCC changes during maturing. A gradual decrease of this value was observed by Li and Lepech (2005) from approximately 5% at the age of 10 days to approximately 3% at the age of 180 days, which is a result of the continued hydration process. Figure 2.5 shows the reduced tensile strain capacity with increased loading age of specimen reference number 8 in Table 2.1. This figure also shows that the material reaches a steady state strain capacity value at approximately 3% after about 80 days. As an important mechanism of tensile strain capacity, multiple crack formation must lie at the basis of this aging symptom. It remains to be verified on older specimens whether crack widths are indeed arrested and to what crack width level.

2.3.6 Crack Formation in Shear

The intrinsic crack control of SHCC may be beneficial in applications where tensile or pure flexural conditions dominate, but crack control also in other, more general conditions, including shear, will extend its applicability. It will be argued in subsequent sections that if cracks are controlled to within a threshold level below which ingress rates of water, gas and chlorides are insignificant, durability of cement-based composites, and particularly SHCC and R/SHCC is improved.

Li et al. (1994) executed Ohno-type shear beam tests (Arakawa and Ohno, 1957) on SHCC containing 2% by volume high molecular weight Polyethelene fibre (SPECC). This SHCC contained no sand, but only cement paste with water:cement mass ratio of 0.27. For comparison several other beams were tested, fabricated of plain concrete (PC), reinforced concrete (RC), FRC (1% by volume steel fibres) and DRECC, containing a similar cement paste as the SPECC, but with 7% by volume Dramix steel fibre (6 mm × 0.15 mm diameter, brass coated steel fibres).

Figure 2.6 shows the setup, as well as average shear stress-strain results, including crack width evolution. The PC results have been omitted, as it fails immediately at first crack. In the RC specimen two large diagonal cracks are formed at a load level approximately equal to the failure load of the PC specimen. The crack widths at this load are in the range from 0.1 to 1 mm. At the peak load, a third large crack forms suddenly due to failure of the bond between the steel shear reinforcement and the concrete. In the FRC specimen a large diagonal crack formed just after first crack, of which the width was in the range 0.1 to 1 mm, which is beyond the threshold level of insignificant penetration rate of water gas and chlorides. In the two SHCC specimens (SPECC, DRECC), cracks with width smaller than 0.1 mm developed in the strain hardening region following first cracking. In this region a large number of small cracks were formed in SPECC. Thus evidence has been presented that the multiple, controlled cracking described under tension and flexure is retained under shear.

Van Zijl (2007) derived an appropriate geometry for an SHCC Iosipescu-type shear test (Iosipescu, 1967). By the derivation of an appropriate geometry, with spe-

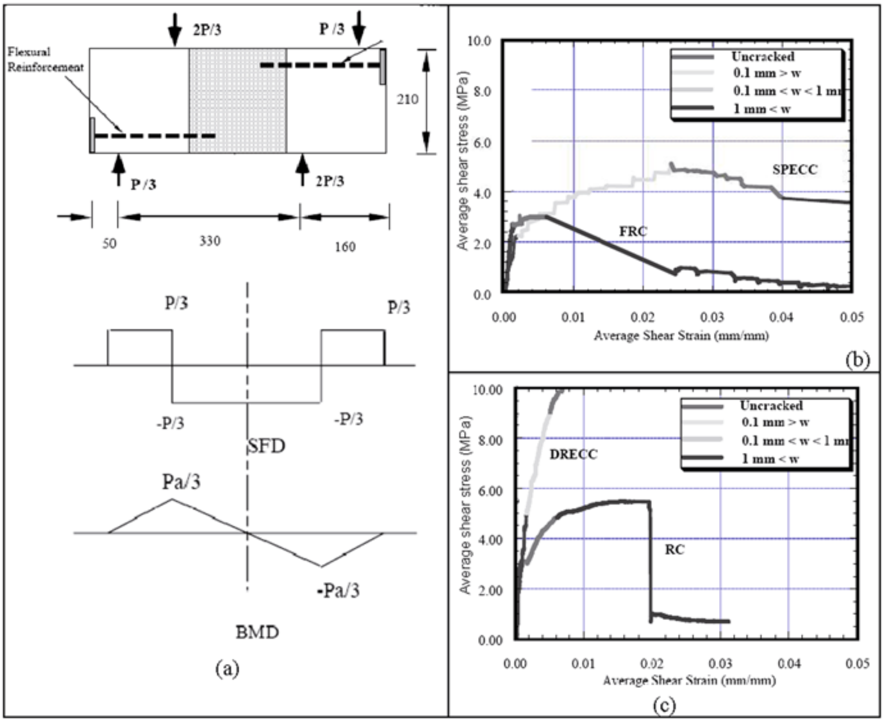


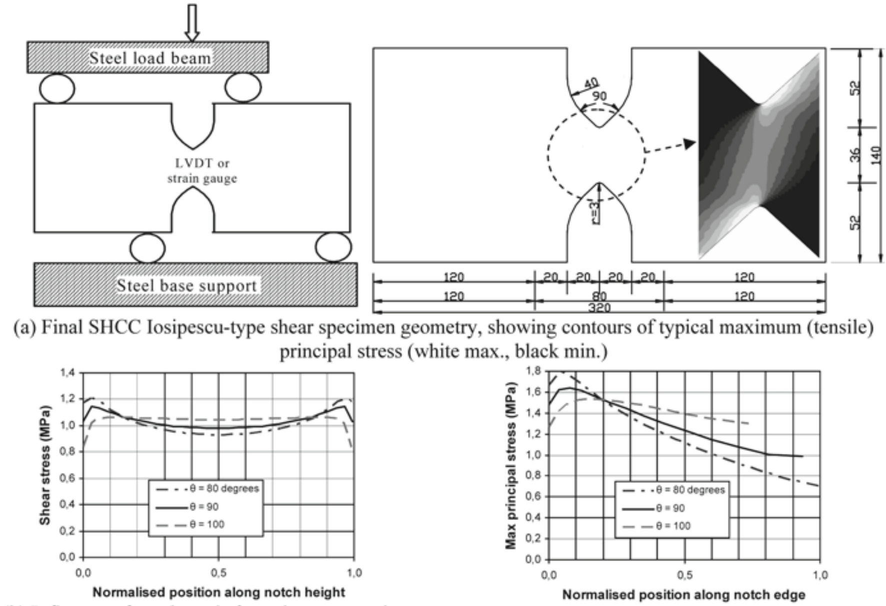
Fig. 2.6 Ohno-type shear test setup for SHCC and other beams by Li et al. (1994). Dimensions in mm.

cial care for the notch geometry, an approximately uniform shear stress distribution is induced along the specimen height at the position of pure shear (zero bending moment). In addition, the risk of failure in bending away from the pure shear section is reduced, whereby the pure shear behaviour can be studied in the elastic, but also the post first cracking region and eventual localisation in the pure shear plane. The setup is shown in Figure 2.7.

A test series was performed on specimens containing ingredients listed in Table 2.2, containing a small amount of ground granular corex slagment (GGCS) and various levels of PVA fibre volume proportions ($L_f = 12$ mm, $d_f = 40$ µm). The results clearly showed that the multiple, fine cracking to a width below the durability threshold is retained in pure shear of SHCC, i.e. for specimens with $V_f = 2\%$ and $V_f = 2.5\%$.

Table 2.2 SHCC shear specimens mix ingredients and proportions by mass (van Zijl, 2007).

	Cement	Fly Ash	GGCS	Water	Sand	V_f (%)
S1	0.5	0.45	0.05	0.4	0.5	0
S2	0.5	0.45	0.05	0.4	0.5	1
S3	0.5	0.45	0.05	0.4	0.5	2
S4	0.5	0.45	0.05	0.4	0.5	2.5



(a) Final SHCC Iosipescu-type shear specimen geometry, showing contours of typical maximum (tensile) principal stress (white max., black min.)

(b) Influence of notch angle θ on shear stress along notched section height

(c) Influence of notch angle θ on principal stress along notch edge

Fig. 2.7 Ioscipescu-type shear test setup for SHCC by van Zijl (2007).

2.4 Width of Micro-cracks in Loaded and Unloaded Specimens

The crack width measurements reported in Section 2.2 have been either on specimens in the loaded state (reference specimens numbers 7, 8 in Table 2.1) or after unloading (reference numbers 1–6 in Table 2.1). Furthermore, the measurements in the unloaded state were at different permanent deformation levels for different specimens. However, continuous monitoring of single cracks during the loading phase of reference number 6 is shown in Figure 2.1b. The crack width of the single crack monitored during loading, which stabilises at a width in the range 50–60 μm, is comparable with the average width measured in the unloaded state (58 μm). However, this effect remains to be studied in a systematic way, measuring crack widths at similar deformation levels in the loaded and unloaded state.

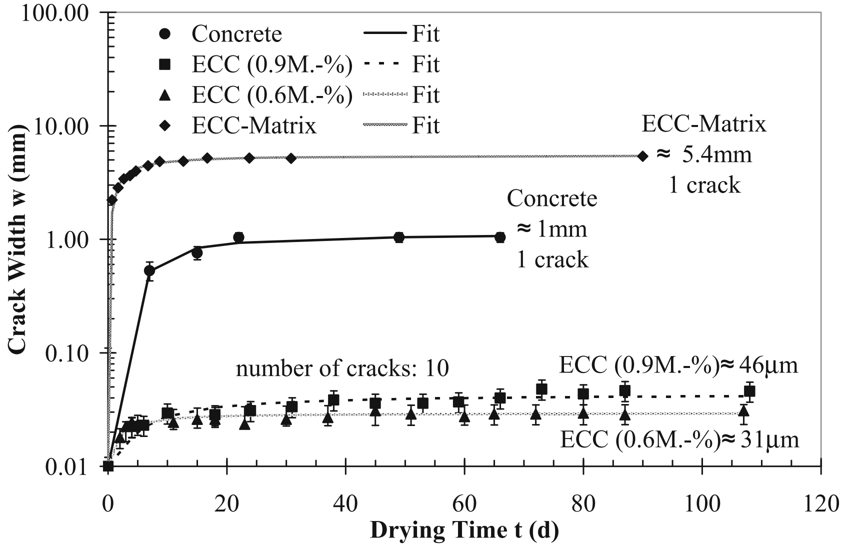
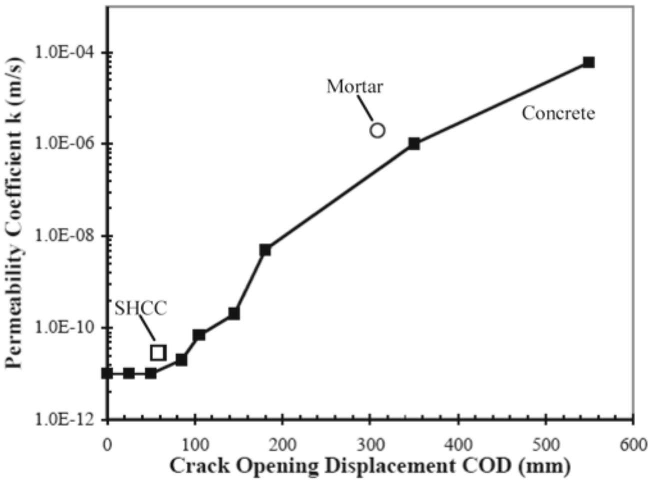


Fig. 2.8 Crack width evolution of SHCC (mix reference number 7, Table 2.1) in drying shrinkage ring test (Weimann and Li, 2003).

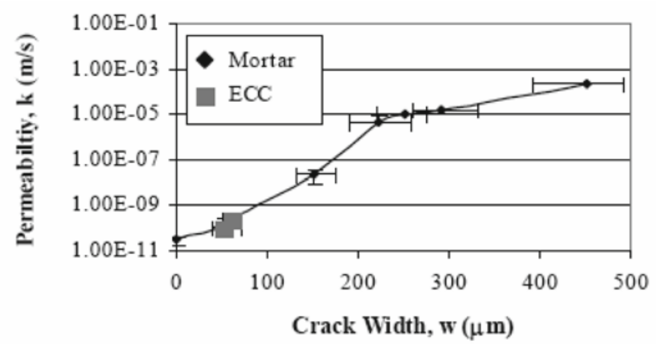
An indication of crack width under load is given by the average crack widths measured on specimens of mix reference number 7 in Table 2.1, subjected to restrained drying shrinkage in a restrained shrinkage ring test (Weimann and Li, 2003). Separate, free shrinkage tests indicated that the maximum drying shrinkage strain of this SHCC composite is in the range from 0.17 to 0.25% when drying from saturation (100% moisture content) to 0% moisture content. Under similar environmental conditions, cracks of average width 46 μm were measured for this material in the ring shrinkage test (Figure 2.8).

2.5 Influence of Crack Width of Micro-cracks on Permeability and Capillary Suction

Resistance to moisture, gas and salt penetration is an important mechanism of cement-based materials durability. Either the material degradation or reinforcing steel corrosion may be consequents of such ingress. Resistance to moisture, gas and chloride ingress is a measure of the susceptibility of SHCC to such degradation processes. General consensus exists that capillary sorption and moisture diffusion are models describing the most important mechanisms of moisture ingress and migration. In the near surface zone capillary sorption dominates moisture intake (Neithalath, 2006) while moisture diffusion governs the longer term migration of water in the material through the micro-pores (Bažant and Najjar, 1971; Neithalath, 2006). By matrix densification the capillary absorption is significantly reduced in



(a) Concrete (Wang et al., 1997) and SHCC (reference number 8, Table 2.1, Li and Stang, 2004)



(b) ECC (SHCC reference number 8, Table 2.1) and steel wire mesh reinforced mortar (Lepech and Li, 2005)

Fig. 2.9 Water permeability as function of crack width of cement-based composite materials.

UHPFRC (Kunieda et al., 2007). In SHCC diffusivity is reduced by inherent crack control (Lepech and Li, 2005; Sahmaran et al., 2007).

2.5.1 Water Permeability

Whereas permeability to water, gas and chlorides in the virgin state is an indication of material durability, exploitation of the superior mechanical qualities of SHCC will lead to microcracking in the service state in structural applications of these materials. The significance of crack width with regard to water permeability has been studied for concrete (Wang et al., 1997). The water permeability of concrete was shown to decrease by seven orders of magnitude as the crack width decreases from 550 to below 100 μm (Figure 2.9). Li and Stang (2004) found that the permeability of cracked SHCC of type reference number 8 in Table 2.1, as well as a cracked steel wire mesh reinforced (2.9%) mortar are in reasonable agreement with the permeability of cracked concrete, when both have the same laboratory controlled crack width. This is shown in Figure 2.9a. Lepech and Li (2005) also performed water permeability studies for steel wire mesh reinforced mortar cracked to various crack width levels, confirming the dominance of the crack width on permeability control, as opposed to the cement-based composite type. These results are shown in Figure 2.9b. The permeability study of cracked SHCC and mortar was performed on specimens of dimension 75 mm × 180 mm × 12 mm which had been pre-cracked in a uniaxial tensile test up to a tensile strain of 1.5%.

It must be noted that the number of cracks in the specimen represented in Figure 2.9a differ. The imposed tensile deformation resulted in 10 cracks of approximately 300 μm width in the reinforced mortar, as opposed to 50 cracks of average width 60 μm in SHCC. In Figure 2.10 the total permeability and the permeability normalised by the number of cracks in the specimen are compared for ECC (SHCC, reference number 8, Table 2.1) and reinforced mortar at various crack width levels. Note that all these permeability tests were performed on specimens after unloading of the mechanical load, with which the cracking was imposed.

In contradiction, the flow rate was found to be lower in FRC than in plain concrete by Tsukamoto (1990), ascribing it to the increased tortuosity of the cracks in the presence of fibre. However, the difference in flow rate becomes negligible when the crack width is below 100 μm. This threshold value is in agreement with results of permeability tests by Rapoport et al. (2001) on steel fibre reinforced concrete (SFRC). The steady state permeability of SFRC specimens, cracked by Brazilian split test to different levels of crack width, was insensitive to the fibre volume content level, for crack widths up to 100 μm. The crack width in the SHCC in Figure 2.10 is 60 micron.

2.5.2 Gas Permeability

Up to date no systematic study of permeability to gas penetration as a function of crack width has been performed for SHCC.

2.5.3 Chloride Permeability

Increased crack width can be related to higher chloride penetration rate in cement composites. Chloride ingress and migration in cement composites is predominantly

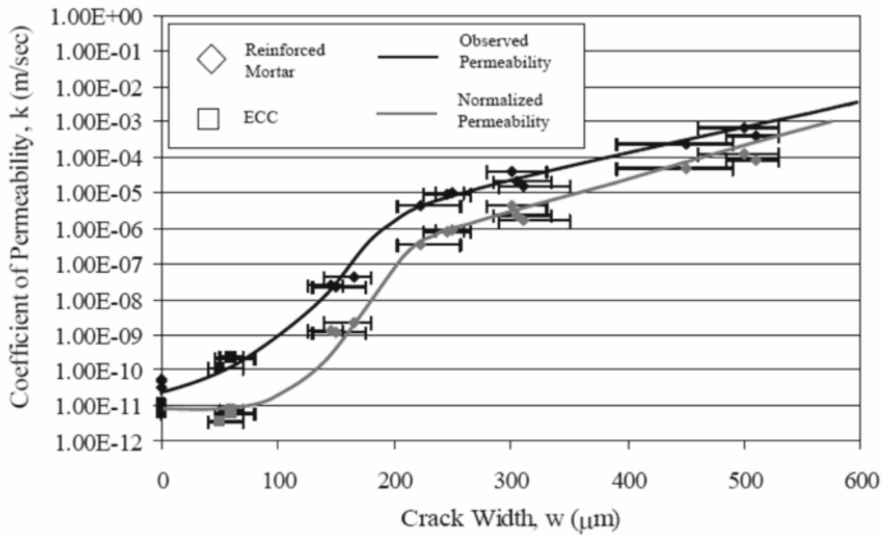
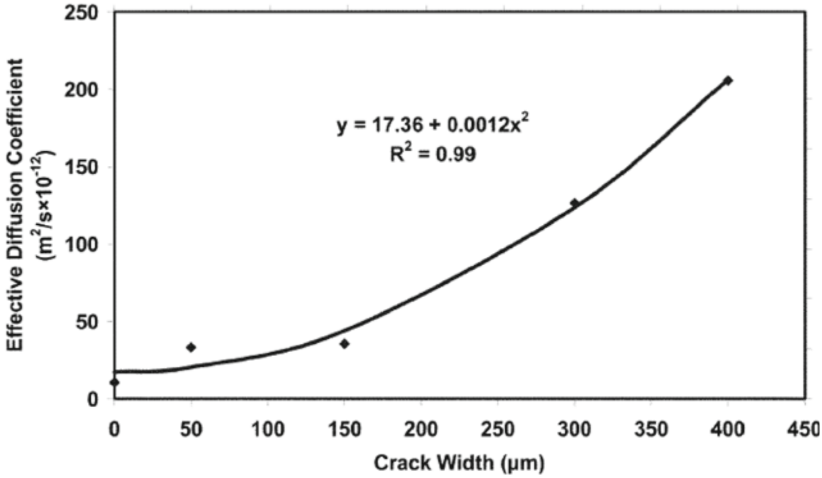


Fig. 2.10 SHCC and steel mesh reinforced mortar water permeability normalised by the number of cracks (Lepech and Li, 2005).

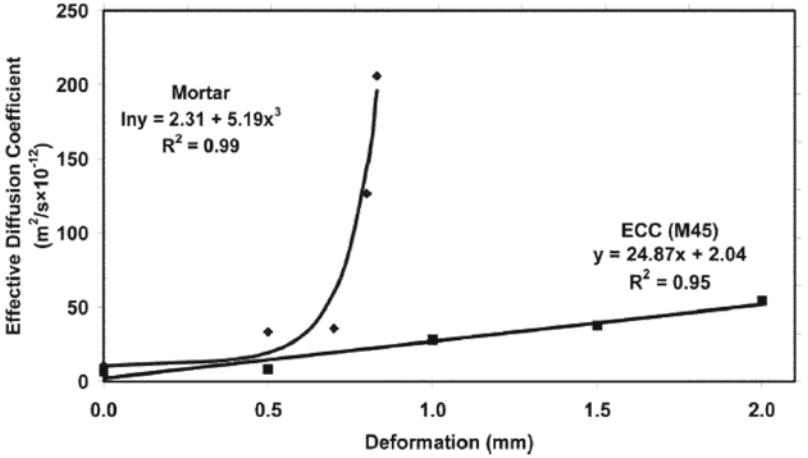
as solvent in moisture, thus sharing the driving mechanisms of absorption and diffusion. Sahmaran et al. (2007) studied chloride penetration and permeability of SHCC in comparison to mortar. Based on results of immersion tests, chloride penetration depth was found to be reduced in uncracked SHCC specimens compared to uncracked mortar. Based on ponding tests of pre-cracked specimens, the effective chloride diffusion coefficient was found to be strongly dependent on crack width in mortar (Figure 2.11a). The diffusion coefficient in SHCC was found to be comparative for equal crack widths in SHCC and mortar. However, the crack width in SHCC was found to be insensitive to the deformation level, which in this case was induced by four point bending. This explains the diversion of chloride diffusivity of mortar specimens from that of SHCC with increased deformation level (Figure 2.11b).

The reduced penetration depth in SHCC versus reinforced mortar/concrete is confirmed by observations of Maalej et al. (2002) and Miyazato and Hiraishi (2005), in comparative SHCC and concrete beams loaded in flexure to the same deflection (see Section 3.2.1).

Sahmaran et al. (2007) performed chloride diffusion tests on preloaded beams subjected to chloride solution ponding. The effective diffusion coefficient of SHCC was found to be linearly proportional to the number of cracks (see Figure 2.12), whereas the effective diffusion coefficient of reinforced mortar is proportional to the square of the crack width. Therefore, the effect of crack width on chloride transport was more pronounced when compared to that of crack number. From the results of this study, it is concluded that SHCC is effective in slowing the diffusion of chloride ion under combined mechanical and environmental (chloride exposure) loading, by virtue of its ability to achieve self-controlled tight crack width.



(a)



(b)

Fig. 2.11 Diffusion coefficient versus (a) crack width for mortar deformed under bending load, (b) deflection of SHCC and steel mesh reinforced mortar (Sahmaran et al., 2007).

Oh and Shin (2006) tested SHCC to measure chloride diffusivity in cylinder specimens that were subjected to various numbers of cyclic loadings in compression. PVA fibres with a length of 12 mm and a diameter of 0.04 mm were used in the tests. The fibre content was 2% by volume. The cylinder specimens of Ø100 × 200 mm were loaded in compression up to 55, 70 and 85% stress level of static strength for 1,000, 10,000 and 100,000 cycles, respectively.

After unloading, the specimens with the length of 50 mm were cut off from the central portions of the cylindrical specimens for chloride permeability tests. The chloride resistance was evaluated by the amount of charge passing through the specimens. The chloride penetration test used in this study is based on the standard of

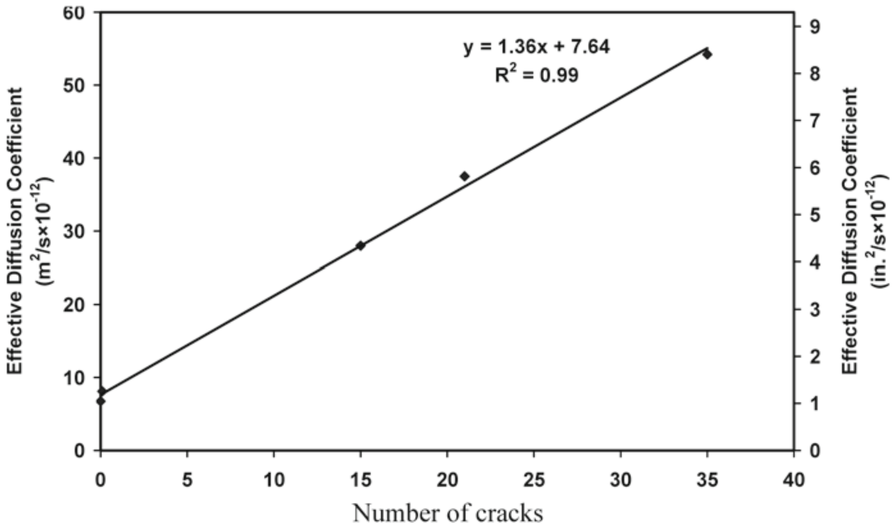


Fig. 2.12 Effective chloride diffusion coefficient versus number of cracks for SHCC (crack width at 50 micron) (Sahmaran et al., 2007).

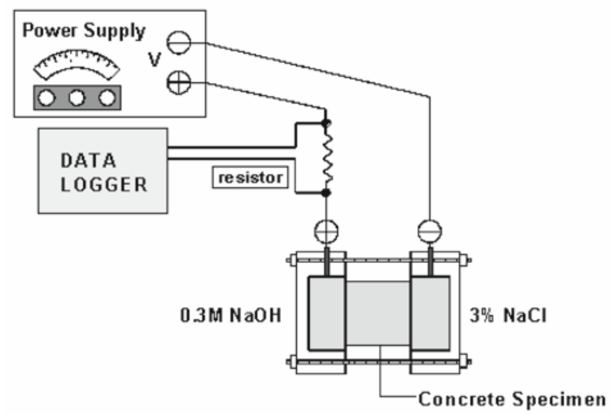


Fig. 2.13 Test setup for measurements of chloride ion penetration (Oh and Shin, 2006).

Nord Test Build 492 – Non-Steady State Migration Test (NT BUILD 492, 1999). Figure 2.13 shows the test setup for measurement of chloride ion penetration conducted by Oh and Shin (2006).

Figure 2.14 shows the test results for the relative chloride diffusion coefficients of various specimens after applied cyclic loads. Figure 2.14 exhibits the relative ratios of residual axial strains and chloride diffusion coefficients at larger load cycles of 10,000 and 100,000 cycles to those values at 1,000 cycles under the cyclic load level 55%, respectively. It can be seen that the residual strain after 100,000 cycles at the

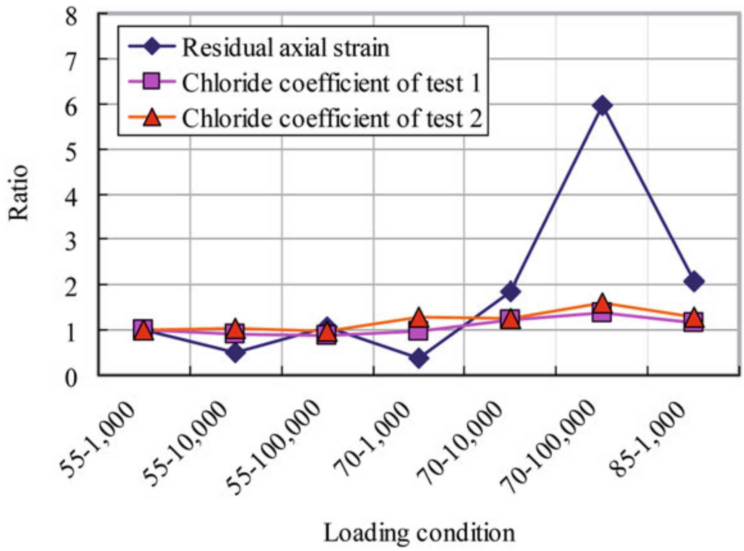


Fig. 2.14 Relative ratios of residual strains and chloride ion penetration coefficients after cyclic loadings (Oh and Shin, 2006).

stress level of 70% is 6 times as large as that after 1,000 cycles at 55% stress level, which indicates that the specimen is significantly damaged due to a large number of repeated loading under high stress level. However, the chloride permeability coefficient is not increased as significantly as can be seen in Figure 2.14, even though the residual strain due to damage is very large. This is due to the very fine internal microcracks in the specimen that do not cause any drastic increase of permeability. This is again due to the beneficial effect of fine cracking due to high performance fibres in the specimen.

2.6 Sustained and Cyclic Load

It is essential that crack control is maintained in service conditions. For structures subjected to cyclic loads, or relatively high permanent/sustained loads, cracks must remain restricted to below the threshold width beyond which highly increased moisture, gas and chlorides ingress.

Figure 2.15 schematises examples of cyclic and sustained tensile loading conditions, showing also the typical response to monotonic tensile load. Jun and Mechtcherine (2007) performed such tests on SHCC under creep, as well as force and displacement-controlled cyclic loads. The number of tests under each loading condition was limited, not sufficient to give a sound statistical base. Nevertheless, their results indicate limited sensitivity to such loading conditions of the total number of cracks that arose at the same level of total deformation. The most significant deviation was a roughly 20% lower average number of cracks under deformation controlled cyclic loading. Note that the sustained stress level and the upper tensile stress levels in the cyclic tests, are close to and above the stress at first crack.

Boshoff (2007) performed tensile creep tests on pre-cracked SHCC specimens. The specimens were subjected to a tensile deformation causing average strain of 1%. This is shown schematically in Figure 2.15b. Subsequently, tensile creep loads of 30, 50, 70 and 80% of the ultimate tensile strength were applied. This simulates a large live load which causes the SHCC member to enter the strain-hardening region, after which the live load is removed and the load drops to the respective sustained load level. In these experiments, the initiation of new cracks during the sustained load phase was observed. However, under these loading conditions, fewer cracks formed under the creep loads than under monotonic deformation-controlled tensile loading to the same level of deformation. Specifically for the high sustained load (80%), a larger crack spacing and associated wider cracks were observed. Accurate measurement of time-dependent crack width under sustained tensile load remains to be performed, and is a current research focus.

From the creep results it appears that crack initiation (see for example Figure 2.16a), width evolution as well as matrix creep contribute to creep deformation. In studying a mechanism of crack width increase under creep load, Boshoff (2007) performed single fibre pull-out tests under monotonically increasing pull-out displacement, as well as under tensile creep load. In all single fibre creep tests complete pull-out occurred, albeit delayed with up to 70 hours under a load of half the peak bond resistance. This is indication that this time-dependent fibre slip is a mechanism of tensile creep deformation, and time-dependent crack width increase.

An important further phenomenon is creep fracture, or delayed fracture of the tensile specimen subjected to sustained load. In the tests by Jun and Mechtcherine, where the tensile resistance at a strain of 1 and 2% respectively was sustained, the specimens failed after 5 and 16 hours respectively. In the tests by Boshoff (2007) creep fracture did not occur under sustained load (now already after a duration of 1.5 years), although significant deformation, beyond the monotonic tensile deformation capacity at that load, was recorded for the high sustained load cases (80% of ultimate monotonic tensile resistance). Much work still needs to be done in this area. At lower sustained load levels, it appears that creep deformation was arrested, in agreement with the so-called creep limit concept, i.e. the stress-strain response under monotonic load at infinitely slow loading rate.

2.7 Fatigue

Although limited results exist, fatigue behaviour of SHCC specimens in direct tension (Matsumoto et al., 2004), flexure (Suthiwarapirak et al., 2002), as well as of SHCC in composite action with concrete in overlay repair strategy (Zhang and Li, 2002), have been tested recently.

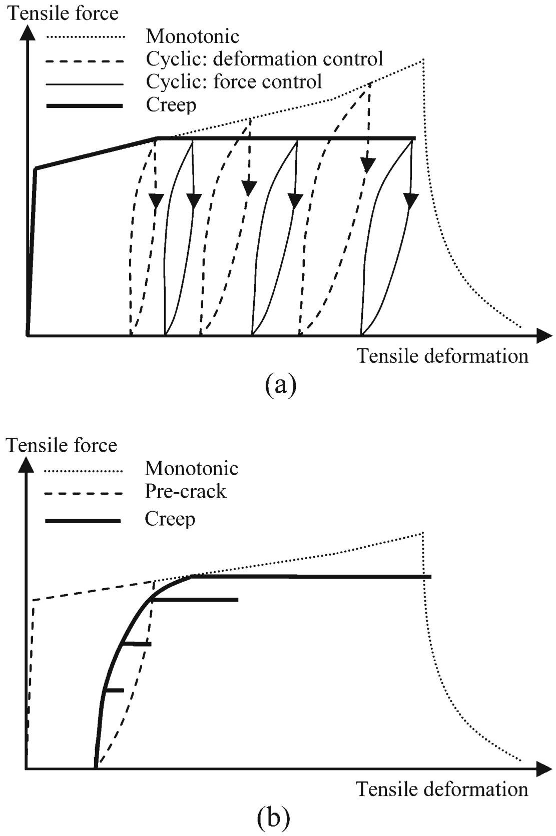
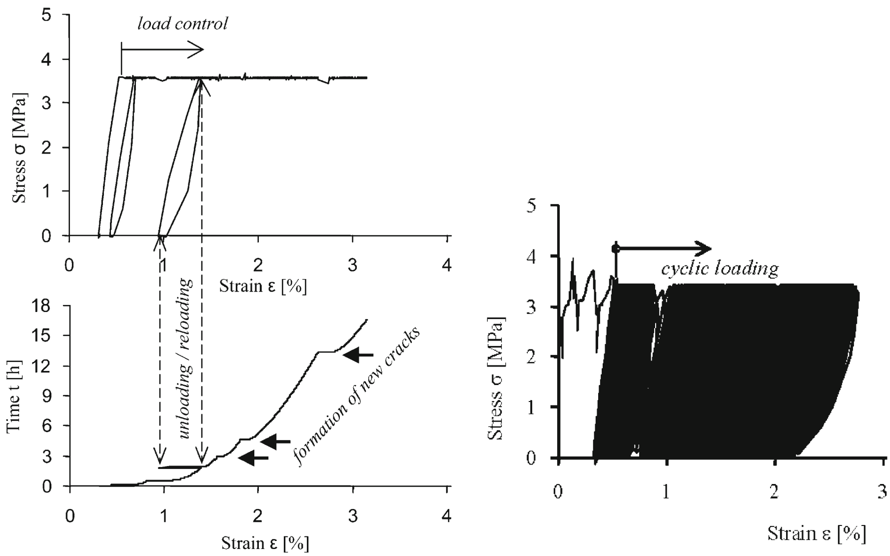


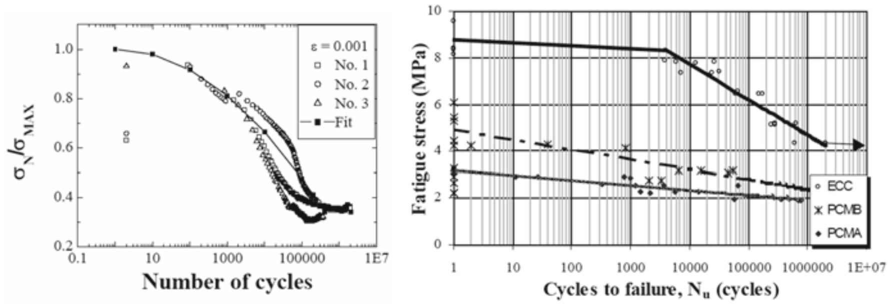
Fig. 2.15 Tensile load cases applied by (a) Jun and Mechtcherine (2007) and (b) Boshoff (2007).

For both direct tension and flexure a reduced resistance with increased number of load cycles, characteristic of most construction materials, has been reported (see Figure 2.17). Another significant trend reported by Suthiwarapirak et al. (2002), see Figure 2.18, is the gradual increased crack width with increased number of load cycles, until eventual sudden widening when failure is imminent. Note that the total crack mouth opening displacement (TCMOD) reported by these researchers is the sum of several (up to 10) crack widths, in fact including matrix deformation between cracks, as measured by an LVDT spanning all cracks at midspan at the beam farthest tensile face. The individual CMOD was measured with the aid of a microscope at the crack that caused eventual failure. In Figure 2.18b it appears that the maximum crack width is maintained below 0.1–0.15 mm for a large range in load cycles (roughly 10,000), after which the crack widens beyond this threshold level. Note that this is for a maximum flexural stress of 70% of the flexural strength. From Figure 2.18a it appears that higher stress levels cause larger total crack width than lower stress levels.



(a) (b)

Fig. 2.16 Representative (a) stress-strain and time-strain curves under sustained load, and (b) cyclic loading acc. to Jun and Mechtcherine (2007).



(a) (b)

Fig. 2.17 SHCC fatigue test results in terms of stress level – number of load cycles for (a) direct tension (under cyclic strain with strain amplitude equal to 0.1%, Matsumoto et al., 2004), and (b) flexure (four point bending, Suthiwarapirak et al., 2002). Note that the response of SHCC (ECC) is compared with two Portland cement mortars.

Zhang and Li (2002) tested an overlay repair strategy with an SHCC overlay on a concrete substrate, using simple four point bending to represent loading action on ground slabs, see Figure 2.19. A superior response to that of a concrete overlay is reported (Figure 2.19b), along with the characteristic reduced resistance with number of loading cycles.

Note that in all the above reported fatigue tests, PVA fibres of length 12 mm and diameter about 40 μm were used, at fibre volumes of 2.0% (Zhang and Li, 2002)

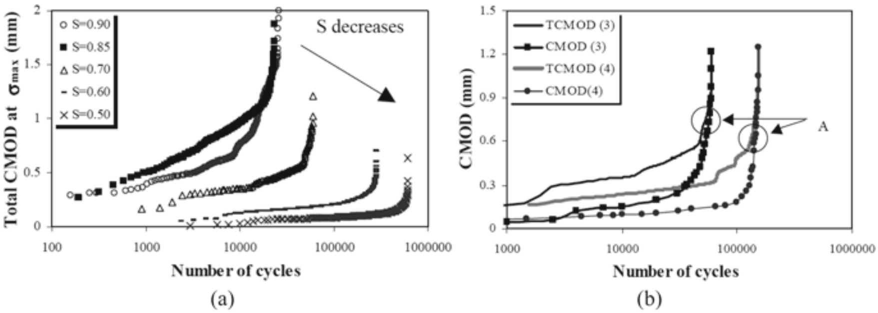


Fig. 2.18 SHCC total crack mouth opening displacement (TCMOD) under fatigue flexural load (a) at various cyclic stress amplitudes, and (b) compared with maximum CMOD for 2 particular specimens subjected to cyclic load causing a maximum flexural stress level of 70% of the flexural strength (Suthiwarapirak et al., 2002).

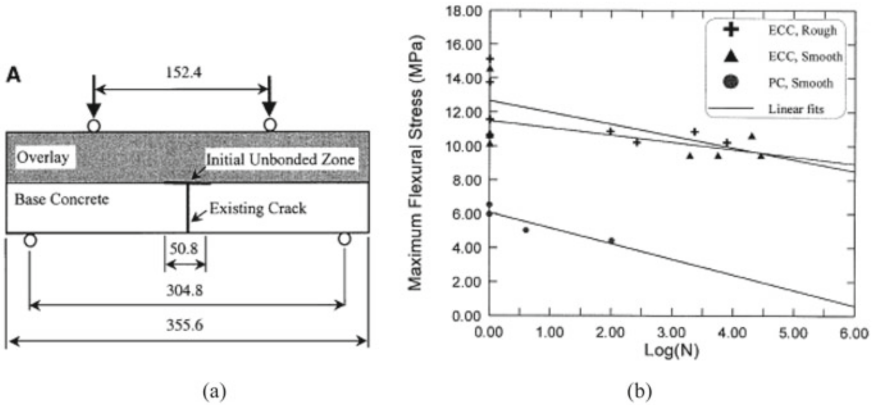


Fig. 2.19 Flexural fatigue test of SHCC (ECC) overlay repair on concrete substrate strategy, showing characteristic reduced strength with increased number of loading cycles for an SHCC overlay, compared with a concrete overlay (Zhang and Li, 2002).

and 2.1% (Suthiwarapirak et al., 2002; Matsumoto et al., 2004) respectively. The matrices were different from those given in Table 2.1, varying in water to binder (w/b) and sand to binder (s/b) content ratios as follows:

- $w/b = 0.32$; $s/b = 0.42$ (Figures 2.17 and 2.18; Suthiwarapirak et al., 2002; Matsumoto et al., 2004);
- $w/b = 0.434$; $s/b = 1.0$ (Figure 2.19; Zhang and Li, 2002).

Fig. 2.20 Grinding disc for abrasion testing according to the German standard (E DIN 52108 2006).

2.8 Abrasion

Since repair layers on horizontal concrete surfaces are a possible application of SHCC, the abrasion resistance of this material is one of the material properties to be determined.

Li and Lepech (2005) conducted both static friction testing and wear track testing according to the Michigan Test Method (MDoT, 2001). The surfaces of the tested SHCC specimens had been textured by different methods. After determining the initial static friction forces between a test tire and the wet surfaces of the test materials, the samples were subjected to 4 million tire passes. Then, the friction forces were determined again. These friction forces measured after wearing are called Aggregate Wear Index (AWI) according to the test standard (MDoT, 2001). For the differently textured SHCC samples values between 1.6 and 2.3 kN were obtained. The required minimum AWI value for Michigan amounts to 1.2 kN. It was concluded that SHCC surfaces on roadways are suitable for heavy traffic volumes.

The test method according to the German standard E DIN 52108 (2006) is significantly different from the procedure described above. It is used in European countries for measuring the abrasion resistance of cementitious materials and based upon the so-called *Böhme* grinding disc (see Figure 2.20). This testing apparatus consists of a rotating disc the specimen surface is pressed upon. Reproducible abrasion conditions are ensured by using synthetic aluminium oxide as a standardized grinding medium.

Table 2.3 Material composition.

Component	Content by mass
CEM I 32.5 R	1.0
Water	0.9
Fly ash	2.0
Fine sand (0.1–0.5 mm)	0.6
Plasticizer	0.02
Methyl cellulose	0.003

Table 2.4 Experimental results.

Age of the material	Abrasion A in [cm^3/50 cm^2]			
	SHCC		Reference mortar	
	$A_{\text{Thickness}}$	A_{Mass}	$A_{\text{Thickness}}$	A_{Mass}
14 days	17.2	17.5	19.6	19.8
28 days	16.9	16.9	21.5	21.9

The composition of the SHCC material used for abrasion testing according to the German standard is given in Table 2.3 (Wagner, 2007). PVA fibres “REC 15”, Kuraray, length 8 mm, were used with a volume content of 2.2%. This SHCC appears to have a comparably high strain capacity. It was not primarily optimized for a high abrasion resistance.

A reference mortar also tested had the same composition, but no fibre reinforcement.

The specimens had the dimensions of 71 × 71 × 71 mm^3 according to E DIN 52108 (2006). They were cut out of cubes with an edge length of 150 mm and grinded until the prescribed dimensions were reached. Before testing, the samples were dried at 105°C.

The material loss due to abrasion may be quantified either by measuring the change in specimen thickness or by measuring the mass loss. Both methods have been applied. Table 2.4 contains the results obtained at the age of 14 and 28 days, respectively. Each of the abrasion values represents the material volume loss related to the surface area and is a mean value for three individual samples. It turns out that the two methods for determining the abrasion yield almost the same results.

On the basis of the experimental results, the following conclusions may be drawn:

1. The difference between the abrasion resistance after 14 and 28 days, respectively, is insignificant.
2. The abrasion of the reference mortar after 28 days was found to be about 28% higher than the one of SHCC. The PVA fibre reinforcement leads to an increase in abrasion resistance.
3. According to the European standard DIN EN 13813 (2003), the SHCC may be assigned to abrasion class A22, see Table 2.5. This is the lowest abrasion class. Accordingly, SHCC surfaces are not recommendable for heavy roadway traffic.

Table 2.5 Abrasion classes according to DIN EN 13813 (2003).

Class	A22	A15	A12	A9	A6	A3	A1.5
Abrasion [$cm^3/50\ cm^2$]	22	15	12	9	6	3	1.5

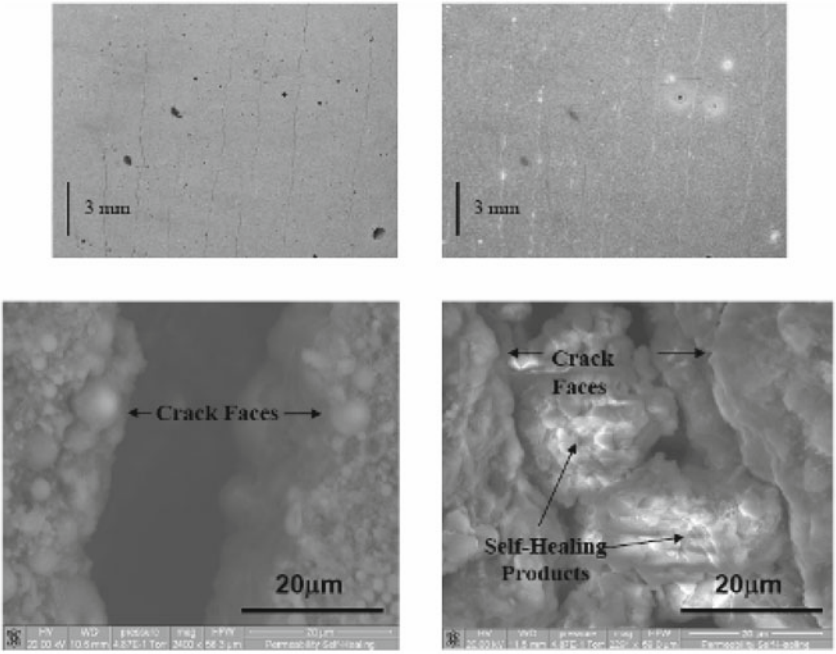


Fig. 2.21 Images indicating self-healing product formation in SHCC (Lepech and, Li 2005).

4. The results obtained with *Böhme*'s grinding disc are contradictory to those obtained in the US according to MDoT (2001). Possibly, by using the grinding disc the abrasion resistance is underestimated. The assessment according to MDoT (2001) seems to be more realistic with respect to the actual loading of real roadway surfaces.

Generally, a high abrasion resistance of cementitious materials may be achieved by a high aggregate content as well as by using hard and coarse aggregates. Hence, for the SHCC tested here a low abrasion resistance is not surprising since the material is characterized by a low aggregate content and small particle sizes.

However, an SHCC has been used in 2002 in a pilot application for repair layers on outdoor concrete surfaces which are subjected to high wheel loads (ECC, 2009). A particular repair patch was monitored for five years, without any significant abrasion observed. From this result it may be argued that in areas where vehicles travel freely, and no frequent braking occurs, SHCC performs well in terms of abrasion.

2.9 Self-healing of Micro-cracks

The fine cracks in SHCC afford these materials the potential of self-healing. It has been shown that a small crack width is imperative for self-healing of concrete (Edvardsen, 1999). Although no systematic study of this phenomenon in SHCC has been reported yet, preliminary observations indicate that SHCC specimens have a self-healing tendency. SHCC specimens of type reference number 8 (Table 2.1) used in water permeability tests (Lepech and Li, 2005) exhibit self-healing, as shown in Figure 2.21. Preliminary studies by Yang et al. (2005) and Li and Yang (2007) indicated the ability of SHCC material to regain both mechanical (strength, stiffness and ductility) and transport properties. In Chapter 3, where durability under chemical action is reported, recent research results on self-healing are discussed (in Section 3.2.3) with particular reference to a marine environment.

A systematic research program is warranted to confirm this phenomenon.

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Chapter 3
Durability under Chemical Loads

Byung H. Oh and Petr Kabele

Abstract This chapter summarizes mostly experimental findings on the effects of various types of aggressive environment on the mechanical performance of SHCC materials. In many of the reported works, a multiscale approach to durability of SHCC is adopted; consequently influence on individual constituents (matrix, fibre and interface) and behaviour on different scales of resolution are investigated.

Key words: corrosion, chloride penetration, hydrolysis, leaching, chemical exposure

3.1 Introduction

The most important advantage of strain-hardening cement-based composites (SHCC) is the capability of maintaining very narrow crack width under applied loads (Li et al., 2003, 2004; Oh and Shin, 2005). These reduced, finely-distributed cracks may provide good resistance to penetration of water and/or aggressive substances from the environment even under extensive straining. Application of SHCC is thus often seen as one of possible ways to improve durability of concrete and reinforced concrete (RC) structures, especially of those exposed to aggressive environment.

The study of SHCC durability in chemically aggressive environment involves two main aspects: first, investigation of the transport of chemical substances through the multiply cracked material, and second, clarification of the effects of chemical agents on the composite material performance, in particular its ability of multiple cracking. Since the transport phenomena have been dealt with in Chapter 2, the

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present chapter will focus mostly on the second aspect. In several works reported hereafter, authors point out that the superior mechanical properties of SHCC are often achieved through optimization of the composite microstructure. Consequently, they investigate the effects of aggressive environment on individual components or micromechanical parameters. Since these effects are usually very slow in the natural conditions, various methods of accelerated aging are often used.

3.2 Chloride Environments

The ability to protect reinforcements from corrosion greatly affects the durability of reinforced concrete (RC) members (Oh and Jang, 2003a, 2003b, 2004; Lepech and Li, 2005). The most important advantage of strain-hardening cement-based composites (SHCC) is the capability of reducing crack width under applied loads (Li et al., 2003, 2004; Oh and Shin, 2005). Refer to Chapter 2 for in depth treatment of crack width in SHCC. The reduced, finely-distributed cracks that arise in SHCC provide good resistance to chloride penetration (see Section 2.5.3) even under higher loads and thus increase durability of the structures.

Here, chloride penetration depth and corrosion of steel reinforcing bars in SHCC are reported in Section 3.2.1. The influence on SHCC mechanical properties at the micro-level is treated in Section 3.2.2, where single fibre pull-out response and results of nano-indentation after exposure to chloride environments are reported. Finally, in Section 3.2.3, observed self-healing of cracks in chloride environment is reported.

3.2.1 Chloride Penetration: Corrosion Protection of Reinforcement in Concrete

Generally, the reinforcement corrosion progresses through various stages. Initially, the concrete cover provides excellent protection. However, the passive layer protecting the reinforcement degrades due to high chloride ion content or carbonation of the concrete over time. Following depassivation, oxidation of the reinforcement ultimately cracks the cover through expansion of corrosion products. Once cracked, the decrease in cover protection spurs faster corrosion until the concrete spalls off. The exposed reinforcement then corrodes rapidly. To combat this scenario, ACI-318-02 (ACI, 2002) in Sections 4.4.1 and 4.4.2 specify a maximum initial chloride content, maximum water to cement ratio, minimum compressive strength, and minimum cover thickness in "conditions exposed to chlorides from de-icing chemicals, salt, saltwater, brackish water, seawater, or spray from these sources". Initially, the chloride content is kept low to lengthen the time to critical concentration for depassivation. The water to cement ratio, compressive strength, and cover thickness recommendations decrease transport properties, increase cracking strength, and in-

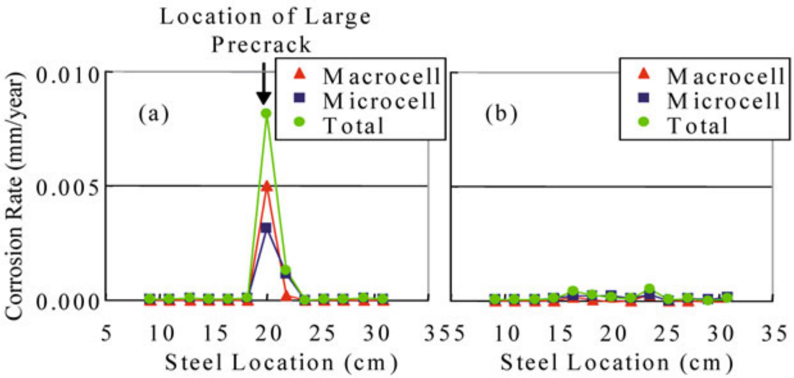

Fig. 3.1 Corrosion rate along rebar for (a) reinforced mortar and (b) R/SHCC (after Miyazato and Hiraishi, 2005).

crease ion transport distances, respectively. However, the formation of cracks due to mechanical overload and environmental conditions can negate these efforts.

In Section 2.5.3 the low chloride diffusivity in finely cracked SHCC was reported. Comparative tests on steel reinforced mortar (R/mortar) and steel reinforced SHCC (R/SHCC) beams were performed by Miyazato and Hiraishi (2005) to study the depth of chloride penetration and corrosion rate of the steel reinforcing bar. Beams of cross section 100 mm × 100 mm, reinforced by a single reinforcing bar place centrally and with 20 mm cover to the tensile surface, were subjected to three point bending with a span of 350 mm. All beams were loaded to 20 kN, causing a single crack in the R/mortar of width 300–400 μm, but several cracks in the R/SHCC beams of width below 100 μm. These beams, while kept under load, were subjected to accelerated chloride exposure conditions, with alternating wet and dry cycles. The results indicate chloride penetration to a depth through the total 100 mm depth of the R/mortar specimen, while it was restricted to 30 mm in the R/SHCC specimen. They also showed corrosion rate (Figure 3.1) differences. The dependence on the matrix type of the chloride penetration speed and arrest of the penetration depth remains to be verified. Whether this mechanism of durability impairment is also crack width dominated, remains to be studied.

Along with the ability of SHCC to reduce the transport of corrosives through the cover even after cracking, enhanced durability may be provided through the high ductility of the material itself. The presence of cracks increases the rate of deterioration of RC members, which is further increased after cover spalling. With a tensile ductility on the order of 3%-5%, the spalling of SHCC cover is highly unlikely (Lim, 1996; Kabele et al., 1999; Li and Stang, 2004). By preserving low transport properties after cracking, and eliminating spalling through high ductility, the ability of SHCC material to effectively protect reinforcement from corrosion significantly longer than concrete is expected. This protection is further supported by the work previously mentioned by Miyazato and Hiraishi (2005) in which SHCC material was effective in reducing the rate of corrosion of steel embedded in SHCC after cracking when compared to concrete. Sahmaran et al. (2008) present results of experimental investigation on steel-reinforced SHCC beams subjected to accelerated corrosion by an electrochemical method. An accelerated corrosion test method, which was carried out by imposing a constant potential, was used to induce different degrees of corrosion into the reinforcement embedded in SHCC prismatic specimens. Mortar specimens that have an equal compressive strength to the SHCC specimens were also used as reference specimens. After inducing different degrees of accelerated corrosion, the cracks and the residual flexural load capacity of the test specimens and the mass loss of reinforcing bars embedded in specimens were determined. From the results of this study, it was concluded that due to its high tensile strain capacity and microcracking behaviors, SHCC significantly prolonged the corrosion propagation period while enhancing the ability to maintain the load capacity of the beam.

3.2.2 Effects on Micromechanical Properties

The effects of chloride exposure on various micromechanical parameters of SHCC were investigated by Kabele et al. (2006b, 2007). Natural chloride attack was simulated in an accelerated manner by 10 cycles of 5-days immersion in a saturated solution of NaCl at 20 ^{o}C and 2-days drying in an oven at 50 ^{o}C. Reference samples were kept in room conditions. One of the microscale mechanisms that have a dominant influence on achieving the desirable mesomechanical behaviour such as multiple cracking is fibre-matrix interfacial bond. A series of tests was performed, in which a single PVA fibre was pulled out from cementitious matrix under displacement control. Both chemical and frictional bond were calculated from the measured load-displacement curves (Figure 3.2).

The tests revealed that cycles of exposure to chlorides and drying significantly reduced the chemical bond strength, while frictional bond showed a slight increase (Figure 3.3). Microscopic inspection of the pulled-out fibres showed that in the control specimens, fibres tended to rupture with little pull-out. On the other hand, fibres in samples exposed to a chloride environment and drying underwent more pull-out; in this process the fibre surface was damaged (scratched) which resulted in hardening response and subsequent rupture, however, at larger pull-out displacement (as also seen in Figure 3.2).

To gain a better understanding of the phenomena observed in the pull-out tests, nano-indentation of the fibre-matrix interfacial transition zone (ITZ) was carried out (Němeček et al., 2007; see also Section 3.3.1). As seen in Figure 3.4, in control specimens (O), the local elastic modulus increases as the distance from the fibre increases, before attaining a stable value at about 30 μm from the fibre. This can be attributed to higher porosity of the ITZ close to the fibre. This tendency is almost unaffected by chloride environment (S). The exposure to leaching environment was

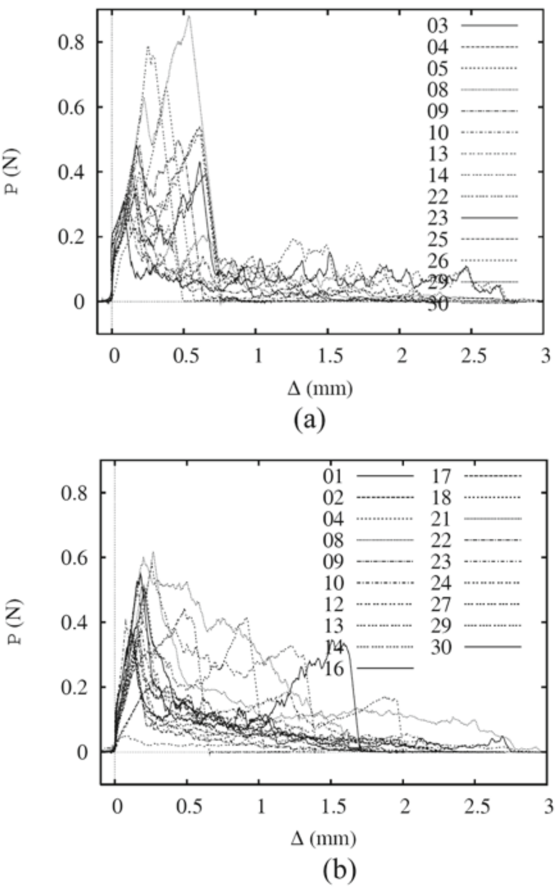

Fig. 3.2 Effects of accelerated deterioration conditions on the results of single-fibre pull-out tests (Kabele et al., 2006b). (a) Reference specimens kept in room conditions; (b) S-series: exposure to chloride exposure and drying.

accelerated by immersing samples for 70 days into 3 mol/l (N3-series) or 6 mol/l (N6-series) water solution of NH_4NO_3 at room temperature.

Matrix fracture toughness is another important micromechanical parameter, since it controls initiation of multiple cracks from matrix defects. Kabele et al. (2007) conducted fracture tests on small 3-point bending notched beams (150 × 20 × 12 mm) with notch size close to the largest intrinsic flaw (5 mm). The material was a cementitious composite with short PVA fibres. From the load at initiation of matrix crack propagation, the matrix fracture toughness was estimated. Figure 3.5 shows that the fracture toughness was almost unaffected by chloride treatment. From the peak loads attained in these tests, the modulus of rupture was calculated. Since the peak load is mostly determined by the cohesive traction acting between crack surfaces, this quantity can be interpreted as an indicator of the effectiveness of fibre

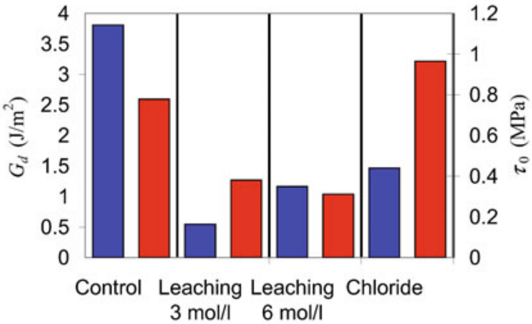

Fig. 3.3 Effects of chemical exposure on chemical bond (left columns) and frictional bond (right columns) (Kabele et al., 2007).

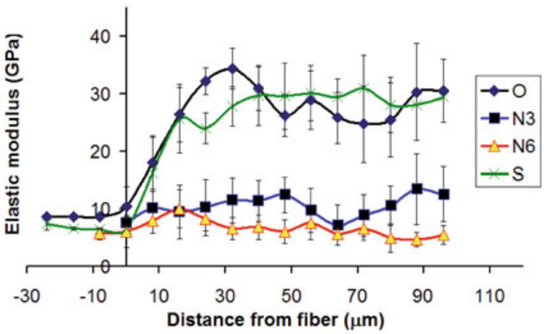

Fig. 3.4 Effect of chemical exposure on the local elastic modulus of fibre-matrix ITZ (Němeček et al., 2007).

bridging on a single crack. Figure 3.5 shows that chloride treatment causes some decrease in the fibre-bridging effectiveness.

3.2.3 Self-healing and Effects on Performance in Uniaxial Tension

After a brief introduction to self-healing of cracks in SHCC in Section 2.9, particular research about SHCC self-healing in chloride environment is reported here. Li et al. (2007) conducted an experimental research, which primarily targeted self-healing phenomena of SHCC materials in marine environment. Coupon specimens were first pre-loaded by uniaxial tension up to overall strain of 0.5, 1, and 1.5% to induce multiple cracking, then exposed to a chloride environment for 1, 2, and 3 months, and then loaded to failure. Self-healing of the induced microcracks was observed, which demonstrated itself not only by formation of a distinct deposit inside the cracks, but also by almost complete recovery of the pre-cracking stiffness.

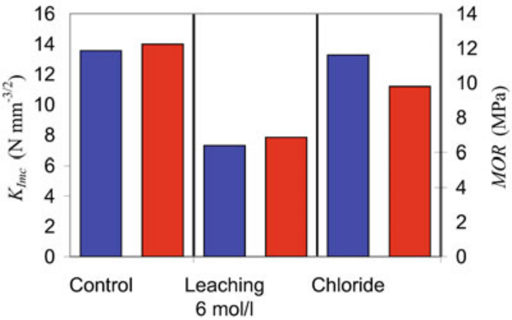

Fig. 3.5 Effect of chemical exposure on matrix fracture toughness K_{Imc} (left columns) and composite modulus of rupture (right columns) (Kabele et al., 2007).

Compared to control specimens treated at laboratory air, specimens stored in NaCl showed about 10% reduction of ultimate tensile strength, which was attributed to leaching of calcium hydroxide and damage on the fibre/matrix interface due to immersion in humid environment. The ultimate tensile strain capacity of the latter samples ranged between 2.4 and 3.8%, which was higher than for the air-cured specimens (2.5 to 2.8%). Also, the pieces exposed to chloride environment showed larger average crack width ($\sim$100 μm, as opposed to $\sim$45 μm for air-cured ones).

It should be noted that the observations by Li et al. (2007) are consistent with the earlier-mentioned study by Kabele et al. (2007): the reduction of chemical bond and improvement of frictional bond may lead to reduction of fibre rupture and enhancement of fibre pull-out, which may result in larger crack width and overall strain capacity.

Sahmaran and Li (2007) reported on the durability performance of non-air-entrained SHCC with different fly ash content when subjected to mechanical loading and freezing and thawing cycles in the presence of de-icing salt. Besides demonstrating good durability of SHCC in terms of scaling resistance and residual tensile behaviour after freeze-thaw cycles, it was also discovered that multiple micro-cracks due to mechanical loading would heal sufficiently under freezing and thawing cycles in the presence of salt solutions to restore nearly the original stiffness.

3.3 Hydrolysis and Leaching

3.3.1 Effects on the Fibre-matrix Interfacial Transition Zone

Cementitious composites and particularly their CSH phases are known to be sensitive to calcium leaching. Calcium leaching can be found in natural conditions in structures exposed to soft water (low ion concentrations) or to water containing sulphur or ammonium ions. In such water, cementitious matrix is decalcified and mechanical properties are degraded together with partial loss of chemical bonds and internal integrity of the material. Not only chemical composition but also mechanical properties are homogeneously degraded throughout the hydrated products as shown in Constantinides and Ulm (2004). Numerical results from sophisticated models of microstructure development also indicate a change in elastic modulus due to calcium leaching in ordinary cement pastes (Kamali et al., 2004).

The degradation processes caused by the calcium leaching on SHCC were studied by Němeček et al. (2005). Special attention was paid to the properties of interfacial transition zone (ITZ) between fibre and matrix. Němeček et al. (2005) prepared SHCC samples in the form of 20 mm thick plates and cured them for 28 days in water. The composition of test materials consisted of Portland cement, fly ash, fine sand and 12 mm long PVA fibres. The plates were cut into 5 mm slices and two types of specimens were prepared. The first series was left at room conditions without any treatment and the second series was put into the 1.4 mol (139.9 g/l) KNO_3 solution to induce accelerated leaching. The period of nitrate curing was 16 days. During this period, the specimens were partially decalcified. The leaching process dissolved Portlandite $Ca(OH)_2$ and decalcified CSH gels. The calcium Ca^{2+} ions were released from the specimens and bonded to OH^- ions resulting in Portlandite precipitation. The dissolution was measured by means of pH change. It showed that the nitrate ions were not chemically bonded to the matrix during the given period while calcium ions were dissolved out of the specimens.

Nano-indentation technique was employed to measure the change of material properties. Before the testing, the samples were mechanically finely-polished on a series of emery papers to achieve a flat surface suitable for indentation and ESEM analysis. After the selection of a suitable indentation area next to the fibre, the indenter was positioned. Indents formed a matrix having 6 rows and 15 columns. The distance between indents was 5 μm. Each indent was approximately 400 nm deep. The matrix of indents was perpendicular to the fibre and the first column of indents lay in the fibre. This configuration allowed observing the change of properties in the transition zone between fibre and the surrounding bulk materials

It can be seen from Figure 3.6 that the elastic modulus is progressively growing with an increase of distance from the fibre and stabilizes at the distance of 60 μm for the chemically non-treated sample. However, the results show only a very small increase in elastic modulus for chemically-treated samples, i.e., calcium leached ones, as shown in Figure 3.7. This means that the elastic properties were degraded in the farther distance from the fibre in the case of calcium leached material. The present findings proved the existence of transition zone around fibres and the potential degradation of micromechanical properties due to calcium leaching. Němeček et al. (2005) indicated that there was a considerable scatter in the evaluation of material properties, especially for SHCC materials due to high complexity in microstructure and porosity.

In a subsequent study (Němeček et al., 2007), the nano-indentation technique was used on a composite with matrix with lower w/c ratio. The accelerated leaching was induced by immersing samples for 70 days into 3 mol/l (N3-series) or 6 mol/l

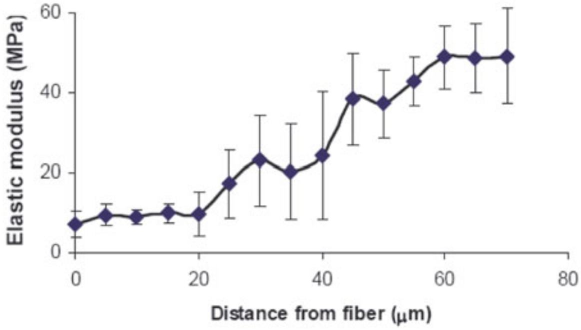

Fig. 3.6 Change of elastic modulus measured in perpendicular direction from the fibre on the chemically non-treated sample (Němeček et al., 2005).

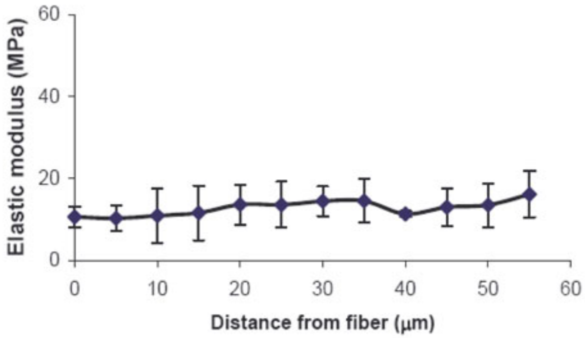

Fig. 3.7 Change of elastic modulus measured in perpendicular direction from the fibre on the chemically treated sample (Němeček et al., 2005).

(N6-series) water solution of NH_4NO_3 at room temperature. As seen in Figure 3.4, the study qualitatively confirms the earlier results of Němeček et al. (2005).

3.3.2 Effects on Micromechanical Properties

In the work by Kabele et al. (2006a) and as a part of the earlier-reported studies by Kabele et al. (2006b, 2007), the effects of calcium leaching on cementitious composites with short PVA fibres were investigated by the same methods as those reviewed in Section 3.2.1. In Kabele et al. (2006b, 2007) the exposure to leaching environment was accelerated in the same way as in Němeček et al. (2007), i.e. by immersing samples for 70 days into 3 mol/l (N3-series) or 6 mol/l (N6-series) water solution of NH_4NO_3 at room temperature.

Figure 3.8 shows that, compared to the control samples (Figure 3.2a), the ultimate forces measured in single-fibre pull-out tests were significantly lower for both leached series N3 and N6. As seen in Figure 3.3, both chemical and frictional bond strengths calculated from these pull-out curves show significant reduction against those of the control samples. Microscopic observations confirmed that fibres in the leached specimens usually did not rupture but were pulled out with very little damage to their surfaces. This, together with the nano-indentation results, indicates that leaching severely damages the interface on the matrix side.

Results from the small-scale fracture tests plotted in Figure 3.5 indicate that exposure to leaching environment caused almost 50% decrease of both matrix fracture toughness and single-crack ultimate bridging strength (expressed by MOR). These results are consistent with the findings from the finer-scale experiments (fibre pull-out, nano-indentation).

3.4 Hot and Humid Environments

The hot water immersion tests have been conducted to simulate hot and humid environments by Li et al. (2004). The hot water immersion was performed on individual fibres, single fibres embedded in SHCC matrix, and composite SHCC specimens. Specimens for individual fibre pull-out and composite SHCC were cured for 28 days at 60°C prior to hot water immersion for 26 weeks. After 26 weeks, little change was seen in fibre properties such as strength, modulus, and elongation. Interfacial properties, however, experienced significant changes, particularly between 13 and 26 weeks. Figure 3.9 shows the effect of hot water immersion on: (a) frictional bond; (b) chemical bond; and (c) apparent fibre strength, respectively. During this time, the chemical bonding between fibre and matrix strengthened, while the fibre apparent strength dropped. These two phenomena caused fibres within HPFRCC to delaminate and break under load after 26 weeks, rather than pull-out intact as seen in specimens immersed 13 weeks or less. Figure 3.10 shows the effect of hot water immersion on tensile stress-strain curve of composites with: (a) 0 weeks; (b) 4 weeks; (c) 13 weeks; and (d) 26 weeks of exposures. The change in interfacial properties resulted in a drop of strain capacity from 4.5% at early age to 2.75% after 26 weeks of immersion as seen in Figure 3.11, which shows the influence of hot and humid environmental loading on composite tensile strain capacity of SHCC.

While accelerated hot weather testing results in lower strain capacity, the 2.75% capacity, over 250 times greater than concrete, seen after 26 weeks of accelerated conditioning (equivalent to 70+ years of hot and humid exposure) is acceptable for nearly any application.

Figure 3.12 shows the result of acceleration test of PVA and AR glass fibre reinforced mortar (Horikoshi et al., 2005). Specimens were soaked into 60°C hot water at 28 days. PVA fibre reinforced mortar keeps its MOR, but AR glass fibre reinforced mortar gradually loses its MOR to 70% of the initial value.

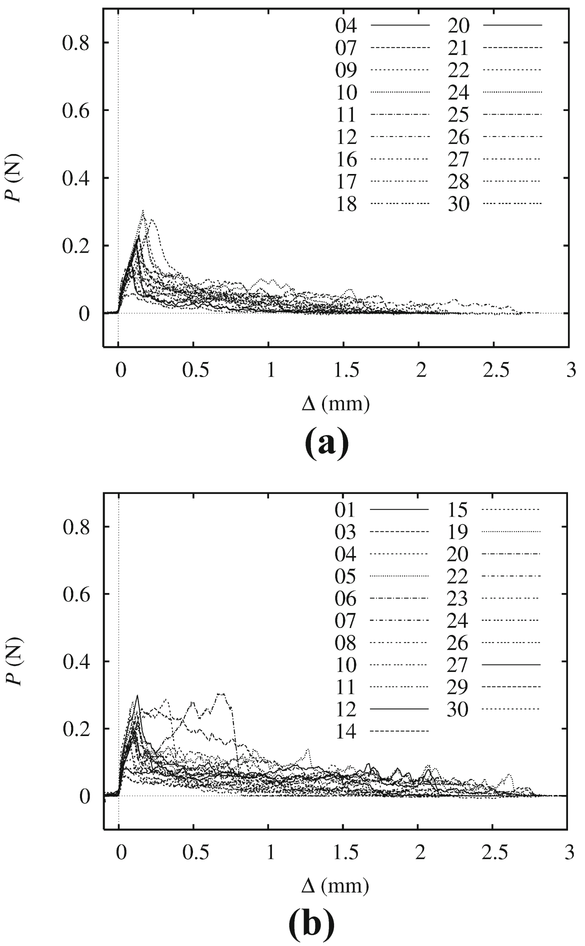

Fig. 3.8 Effect of accelerated deterioration conditions on the results of single-fibre pull-out tests (Kabele et al., 2006b). (a) N3-series: calcium leaching by immersing the samples for 70 days into 3 mol/l water solution of NH_4NO_3 at room temperature; (b) N6-series: ditto in 6 mol/l solution.

3.5 Alkali Environments

Some companies recognized over a decade ago the advantages of using PVA fibres for external roof and wall cladding. It is recognized that PVA fibres will not degrade in highly alkali cement. Studies show that even with 17% to 19% zirconium infused into the glass fibres, they still degrade over time in the highly alkaline environment. Figure 3.13 shows the result for acceleration test of PVA, polyester, alkali resistance AR glass and E glass fibres, respectively (Horikoshi et al., 2005). These fibres were soaked into hot (80°C) and high alkaline water. PVA fibre (KURALON) maintains

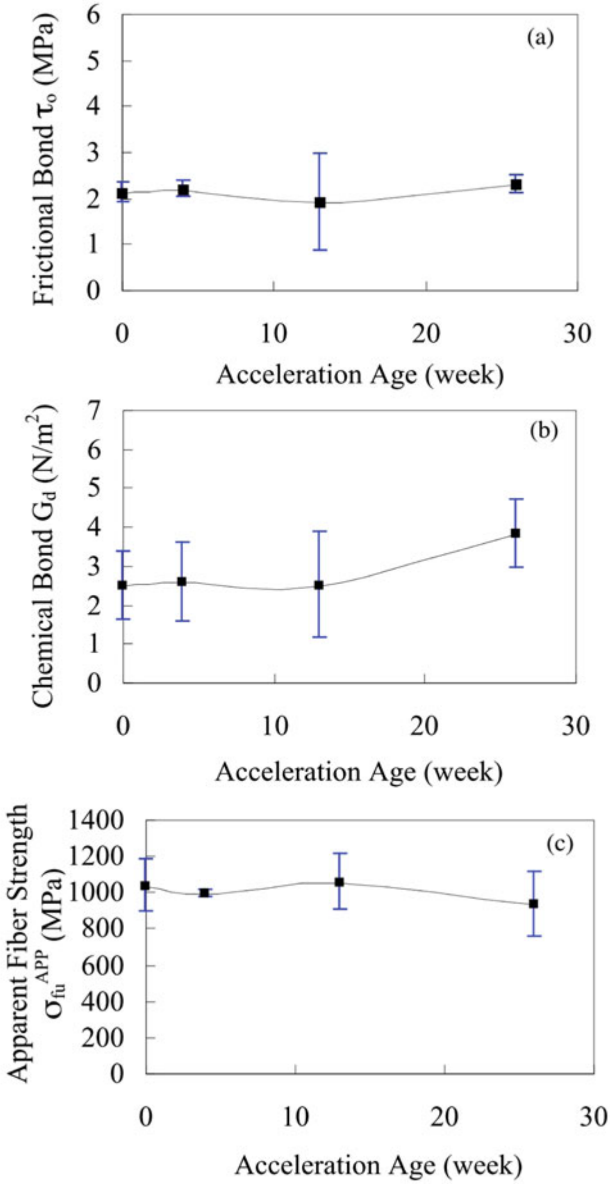

Fig. 3.9 Effect of hot water immersion on: (a) frictional bond; (b) chemical bond; and (c) apparent fibre strength (Li et al., 2004).

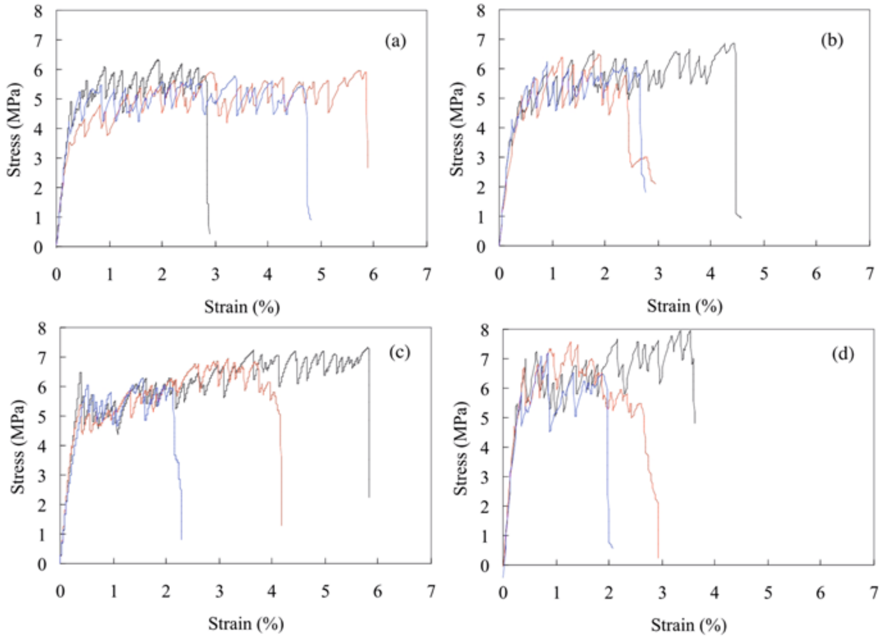

Fig. 3.10 Effect of hot water immersion on tensile stress-strain curve of composites with: (a) 0 weeks; (b) 4 weeks; (c) 13 weeks; and (d) 26 weeks of exposures (Li et al., 2004).

tensile strength even after 14 days soaking. However, the strengths of polyester, AR glass and E glass fibres were decreased by alkali attacks.

3.6 Resistance with Respect to Sulphate Attack

For structures contacting soil, specifically foundations and concrete piles, resistance to sulphate attack is essential (Lepech and Li, 2005). This is addressed in section 4.3 of ACI-318-02. Adequate resistance to sulphate attack is achieved through limiting the water-to-cement ratio within the concrete, requiring a minimum compressive strength, and using either Type II or Type V cement specially blended for sulphate resistance. Within ACI-318-02 (ACI 2002), appropriate preventative recommendations are given for the levels of sulphate exposure ranging from negligible to very severe. With limited C_3A content, Type II and V cements have proven very effective in minimizing the effect of sulphates on concrete. While no research has been done on the durability of SHCC in sulphate rich environments, the use of these cements should prove effective in maintaining durability. However, the effect of these cements on micromechanical properties of the matrix, fibres, and matrix/fibre interface will have to be investigated. The use of fly ash, especially low-lime fly ash, can

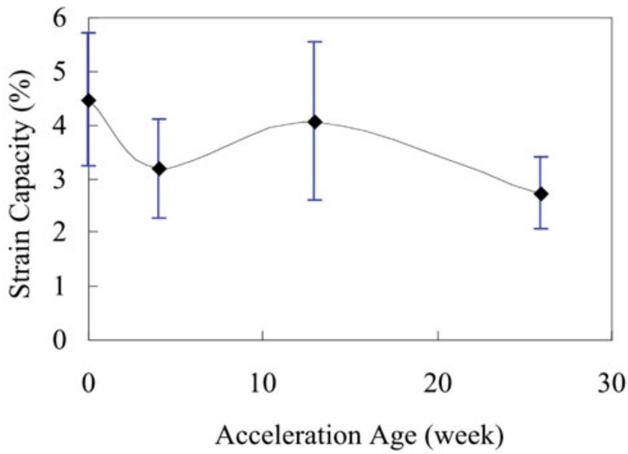

Fig. 3.11 Influence of hot and humid environments on composite tensile strain capacity (Li et al., 2004).

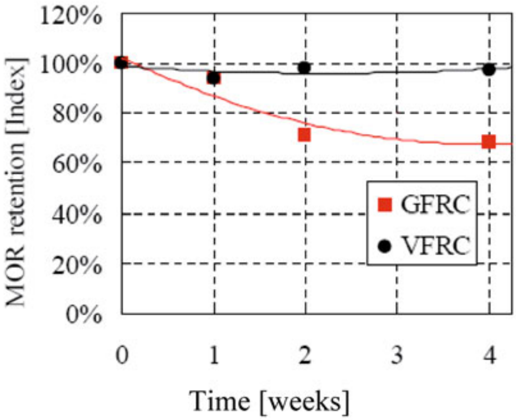

Fig. 3.12 Acceleration test for PVA and glass fibre reinforced composites (Horikoshi et al., 2005).

also be successfully used to prevent the deterioration due to sulphate attack. Fly ash is already the main component of many SHCCs.

3.7 Alkali-aggregate Reaction

The alkali-aggregate reaction (AAR) is caused by the use of reactive aggregates in inherently alkaline cementitious composites.

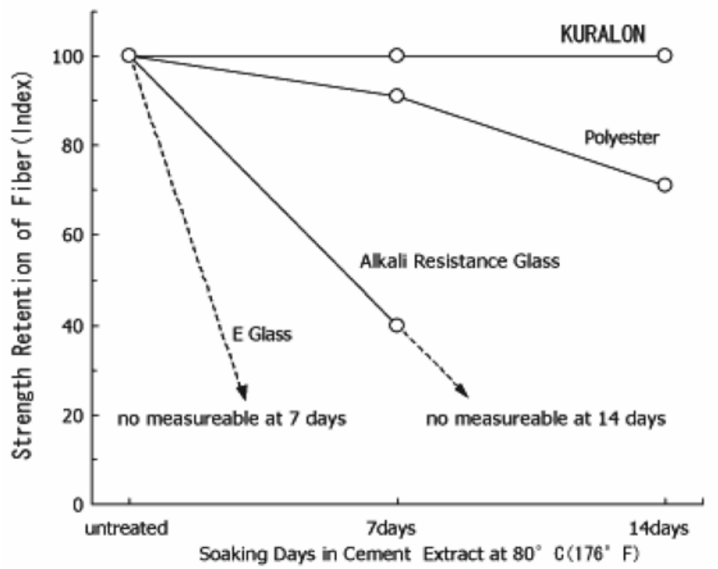

Fig. 3.13 Results of accelerated tests on various fibres for alkali resistance (Horikoshi et al., 2005).

Sahmaran and Li (2008) investigated the durability of SHCC under high alkaline environment. The performance of SHCC under high alkaline medium was tested according to ASTM C1260. The length change of the SHCC bars was measured up to 30 days. Figure 3.14 shows expansive behaviour of the SHCC. The classification ranges given from the ASTM C 1260 are illustrated graphically in Figure 3.14 by horizontal gridlines. The results obtained from accelerated mortar bar test indicated that SHCC did not show any expansion at the end of 30 days soaking period probably due to non-reactive silica sand. However, even if reactive silica sand and alkalis are present in SHCC, it cannot be expected to develop deleterious expansion due to alkali-silica reaction (ASR) because of the high volume fly ash content, small sand particle size and micro-fibres in SHCC. No further study is needed for the ASR performance of SHCC, if high volume fly ash is used in its production.

Even though no deleterious expansion has been observed due to alkali silica reaction (Sahmaran and Li, 2008), alkalis will penetrate through micro-cracks or even the uncracked matrix that could lead to modifications in the material microstructure and hence changes in the composite properties. For this reason, Sahmaran and Li (2008) evaluated the mechanical performance of both virgin and mechanically-loaded SHCC under high alkaline environments. Pre-loaded SHCC specimens with microcracks with width of about 50 μm induced by mechanical loading and then exposed to high alkaline solution at 38°C almost fully recovered their elastic stiffness when re-tested in direct tension. Moreover, self-healing of microcracks in SHCC specimens subjected to alkali solution is evident from the microstructural observations. On the other hand, alkali solution exposure at 38°C leads to a reduction of about 20% in the tensile strain at the end of the 90 days exposure period. Moreover,

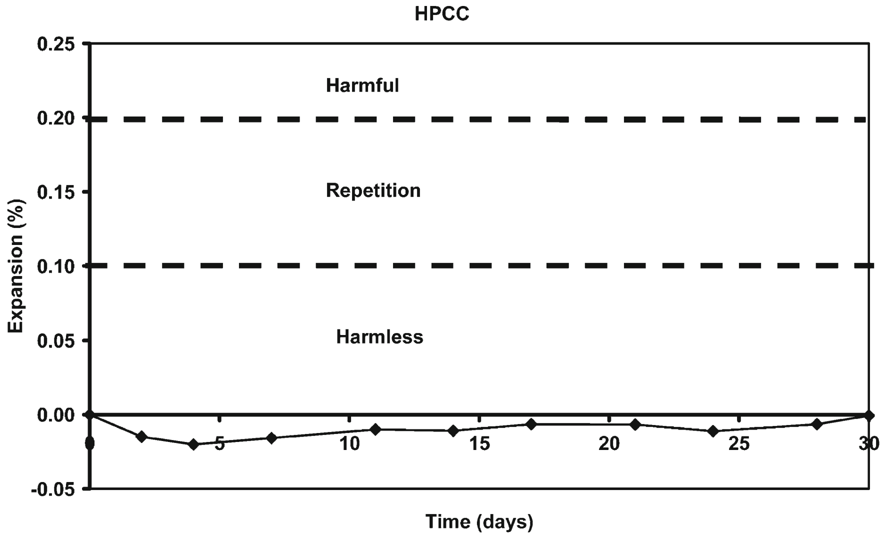

Fig. 3.14 Expansion time histories for SHCC (ASTM C1260-94).

the crack width increased to around 100 μm compared with 40 μm in air curing condition. This phenomenon suggests possible change in the fibre/matrix interface bond properties. Apart from the slight reductions in ultimate tensile strain capacity and higher residual crack width, the results presented in this study largely confirm the durability performance of SHCC material under high alkaline environment, even in cases where the material experiences mechanical loading that deforms it into the strain-hardening stage prior to exposure.

3.8 Conclusions

The most important advantage of strain-hardening cement-based composites (SHCC) is the capability of reducing crack width under applied loads. The finely-distributed microcracks may provide good resistance to penetration of deleterious substances even under higher strains and thus increase durability of the structures.

In this chapter, the durability characteristics of SHCC under chemical loads have been summarized including the effects of chloride attack, leaching, sulphate attack, and alkali-aggregate reaction.

The present study indicates that the SHCC materials exhibit much better performance under these aggressive environments. However, test data are very limited and thus further intensive studies are needed in various area of durability under chemical loads to generally come up with more solid conclusions, which can be used for the practical design of actual structures with SHCC materials.

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Chapter 4
Durability under Thermal Loads

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Abstract Three main topics related to the durability of strain hardening cementitious composites (SHCC) under thermal loads are discussed: (i) high temperatures induced either by service loads or by fire possibly causing damage to the microstructure of the material; (ii) heat released during cement hydration that causes thermal gradients and may lead to cracking; and (iii) low temperatures which cause freezing and can degrade the durability of the structure.

Considering that at present only few results are available in the literature for the durability of SHCC under thermal loads, further research will be necessary to fully understand the behaviour of SHCC under these loading conditions. In concluding remarks, some recommendations for future investigations are given.

Key words: durability, thermal load, thermal gradient, hydration heat, freeze-thaw resistance, de-icing salt

4.1 Introduction

Concrete structures when exposed to thermal gradients or extreme temperatures (including fire and freeze-thaw cycles) may be subject to modifications of their properties. This might degrade their efficiency and consequently their durability. The mechanism of concrete deterioration due to thermal loads is characterized by the build-up of differential internal stresses which will promote the initiation of cracks. The latter tend to form fracture surfaces or a network of connections between the pores increasing the concrete permeability and making it more vulnerable to aggressive agents.

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The determination of thermal properties such as hydration heat, thermal conductivity, specific heat, coefficient of thermal expansion as well as of the resistance to high temperatures or freeze-thaw cycles is very important for predicting the behaviour of the structure when subjected to thermal loads. For SHCC, however, only few results are available in the literature.

This review will cover three main topics related to the durability of SHCC under thermal loads: (i) the behaviour under high temperatures induced either by service loads or by fire; (ii) the behaviour under thermal gradients resulting from hydration heat; (iii) the resistance to freeze-thaw cycles.

4.2 Behaviour at Elevated Temperatures

Two fundamental aspects should be considered when studying the behaviour of concrete subjected to high temperatures. The structure can be subjected to a more or less stable high temperature, reached in a gradual way, such as found in chimneys, industrial vats, etc; or it can be subjected to a great fluctuation of high temperatures within a short time, for example, when it is subjected to an accidental fire and thermal shocks of cooling when the fire is extinguished. In the first case, when the structure is already destined to operate under high temperatures it can behave in an acceptable way if properly designed. In the second case, when the structure is subjected accidentally to severe aggressive conditions, it can resist well or badly, according to its characteristics and the gravity of occurrence.

It is known that concrete undergoes significant chemical and micro-structural changes at temperatures beyond 105°C (Bažant and Kaplan, 1996), leading to loss of stiffness and strength due to dehydration. In the event of rapid heating, high pore pressure may arise and lead to spalling. One cannot find in the specialized literature reports of researches concerning SHCC at elevated temperatures. However, it is known that polypropylene fibres have a twofold effect regarding thermal loadings. On one hand, they can reduce the effects of spalling (Nishida and Yamazaki, 1995; Kalifa et al., 2000, 2001; Velasco et al., 2004) because when the polypropylene fibres are melted at about 170°C they create relief channels and also micro-cracks that allow the vapour to escape through the cement mass avoiding the spalling phenomenon that occurs between 190 and 250°C. On the other hand, it was verified that polypropylene fibres have a minimum or negative effect in the residual performance of heated concrete (Poon et al., 2004; Chan et al., 2000; Li et al., 2004). The property deterioration could be attributed to fibre melting or softening, dehydration of cement hydrates, and porosity increasing during the heating process (Li et al., 2004).

As far as fire temperatures are concerned, Yoshitake et al. (2006) used the setup shown in Figure 4.1 to compare the response of specimens made of plain concrete with the one of three types of fibre reinforced concrete (medium fibre content 0.5 to 0.75% by volume): steel, polypropylene and PVA fibre reinforcement. While it should be noted that these composites are unlikely to exhibit strain hardening tensile behaviour, an indication of fire heat resistance of SHCC is given by the test results

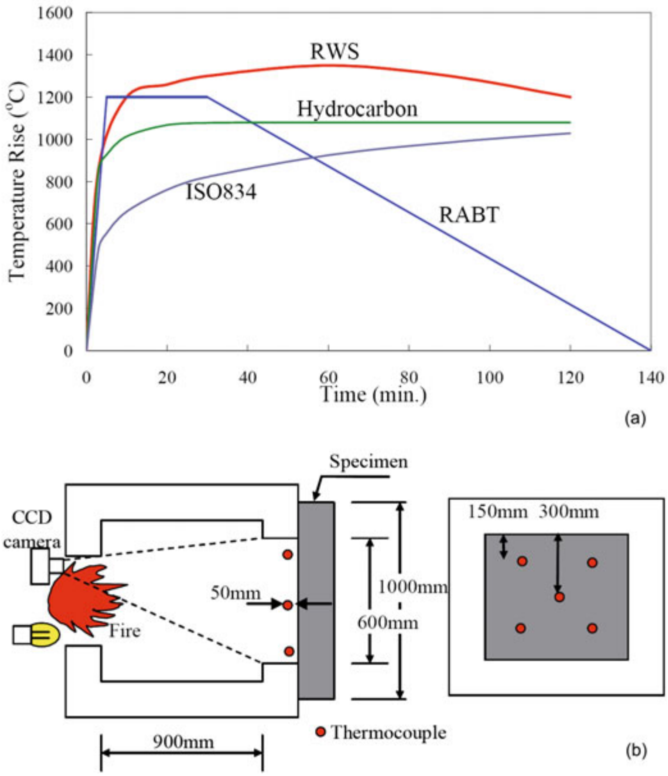

Fig. 4.1 (a) Temperature evolution curves from fire simulation and (b) experimental fire heating setup (Yoshitake et al., 2006).

shown in Figure 4.2. It can be observed that the surface temperature nearly instantly follows the heating, but the heating is delayed with increasing depths. With additional data concerning the temperature dependence of mechanical material parameters, the duration under fire loading before structural collapse may be estimated from such test results. An extreme situation will occur when the thermal decomposition temperature (for polypropylene 271°C and for PVA 263°C) of the fibre materials is reached at a significant depth in the structural element. Elaborate testing is required to confirm the retardation of heat evolution in the case of FRC containing polymeric fibres, as indicated by Figure 4.2.

A systematic study is required to verify whether these mechanisms act also in SHCC. In addition, fibre integrity at elevated temperature is a concern and must be verified through an investigation of the fibre's thermal stability. Research on the mechanical and physical properties of SHCC at elevated temperatures, on the residual mechanical and physical properties after the exposure to high temperatures, as well as on the gas permeability at high temperatures also needs to be performed.

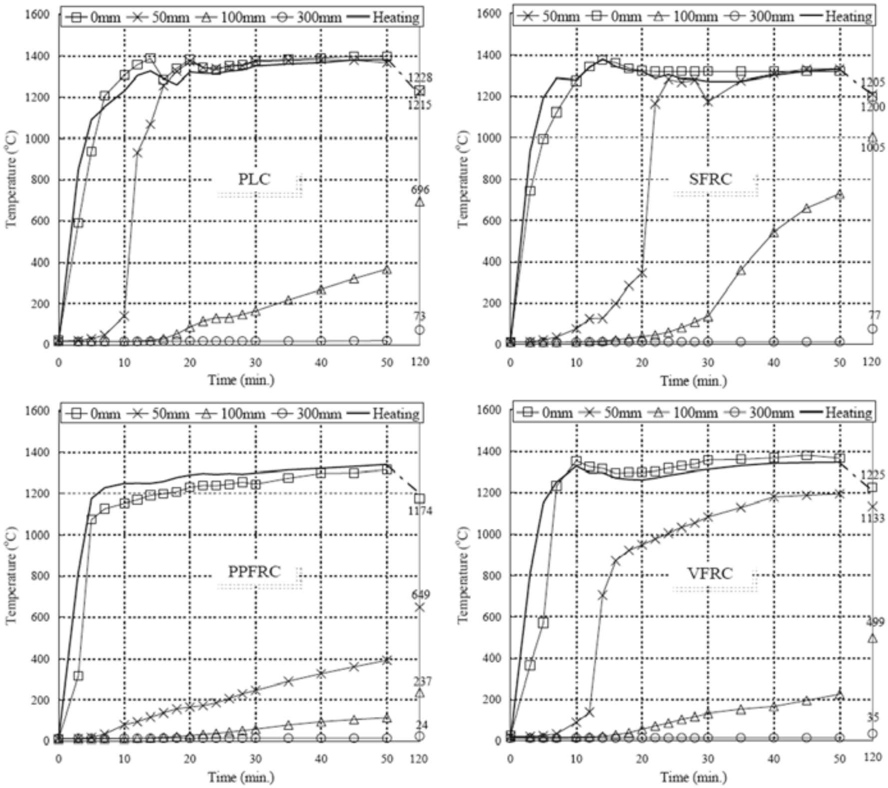

Fig. 4.2 Temperature evolution at various depths in plain concrete, SFRC, PPFRC and PVA-FRC specimens, subjected to (RWS) fire temperature simulation in Figure 4.1.

4.3 Thermal Cracking at Early Age

Cracking at early age is a problem that involves strains imposed by both thermal gradients and autogenous shrinkage. Both phenomena originate from the hydration reaction of the cement. This reaction is exothermic as well as thermally activated and the properties of the material (e.g., strength, Young's modulus, autogenous shrinkage and creep) are dependent on its extent. In what concerns the heat generation, thermal activation introduces a second-order effect, since the rate of heat generated by a unit mass at a given time depends on the extension of the reaction, which varies as a function of the thermal history of the structure (Fairbairn et al., 2004).

The properties of concrete that allow a good understanding of the early age material behaviour should be determined in a way that all the effects of hydration as well as of the mechanical and thermal material behaviour are considered (Fairbairn et al., 2006). This can be done experimentally by coupling an adiabatic calorimeter to a cure chamber which will receive the temperature signal from the calorimeter. An example of this experimental setup is shown in Figure 4.3.

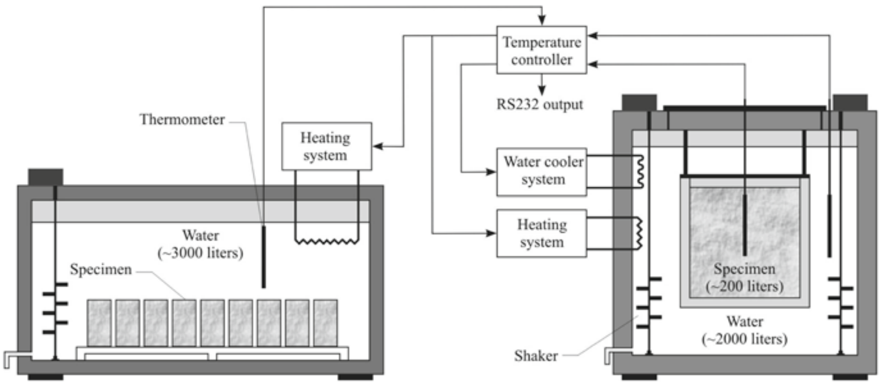

Fig. 4.3 Experimental setup to determine thermo-chemo-mechanical properties (Fairbairn et al., 2006).

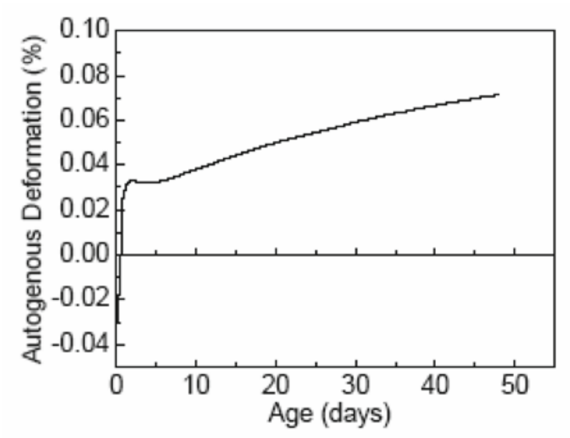

Fig. 4.4 Autogenous shrinkage (Wang and Li, 2005).

The following properties should be determined for SHCC as a function of the hydration degree: adiabatic temperature rise; autogenous shrinkage; coefficient of thermal expansion; specific heat; heat conductivity; creep; Young's modulus; compressive strength; tensile strength.

There are few references concerning the thermo-chemo-mechanical properties of SHCC. shows the autogenous deformation of SHCC immediately after casting up to an age of 47 days. Positive deformation means shrinkage. The zero deformation was defined at the moment of setting, which occurred about 11 hours after casting. Rapid autogenous shrinkage was recorded within the first two days, which may be attributed to the chemical reaction. Afterward, the development tends to exhibit a plateau (Wang and Li, 2005).

4.4 Frost Resistance and Action of De-icing Salts

Cyclic freezing and thawing is one of the most damaging environmental conditions for concrete. To combat the effects of freeze thaw cycles, ACI-318-02 (ACI 2002) stipulates in Section 4.2 both a minimum entrained air content and a maximum water to cement ratio. By adhering to these recommendations, along with proper placement and curing, very durable concrete can be cast. However, concrete durability remains very sensitive to the amount of air entrainment and to the curing conditions. Therefore, if this sensitivity can be overcome through the use of SHCC materials, the desired structural durability can be achieved.

There are indications that the stiffness (dynamic modulus of elasticity) and tensile ductility of SHCC are not significantly degraded by this mechanism (Li et al., 2003; Ogawa et al., 2005). This may be due to the relatively high air content of the SHCC because of fibre addition, which should be confirmed in systematic testing and characterization of the SHCC resistance to this potential degradation mechanism.

4.4.1 SHCC Freeze-thaw and De-icing Resistance as Tested According to ASTM

Freeze-thaw testing, in accordance with ASTM C666A, was performed by Li et al. (2003) with companion series of SHCC and normal concrete specimens (both without deliberate air entrainment). In addition to typical dynamic modulus testing of prism specimens outlined in C666A, a series of SHCC tensile specimens was also subjected to freeze-thaw cycles. The results of the tensile tests were compared to those with reference samples of identical age cured in water at 22°C. These tests allowed to evaluate the effect of freeze-thaw exposure on the composite strain capacity. Testing of SHCC and concrete prisms was conducted concurrently over 14 weeks. After 5 weeks (110 cycles), the concrete specimens had severely deteriorated, requiring removal from the test. However, all SHCC specimens survived 300 cycles with no degradation of dynamic modulus. This performance results in a durability factor of 10 for concrete compared to 100 for SHCC, as computed according to ASTM C666. It is noted that this high durability was achieved without deliberate air entrainment into the SHCC. In the uniaxial tension tests performed on wet cured and freeze-thaw exposed SHCC specimens, no significant drop in strain capacity was experienced after 300 cycles. Both sets of specimens exhibited a tensile strain capacity of roughly 3%, well above the capacity needed for most applications.

Salt scaling resistance of non-air-entrained sound (uncracked) and mechanically pre-loaded (cracked) SHCC specimens was evaluated in accordance with ASTM C672 by Sahmaran and Li (2007). Non-air-entrained mortar specimens with and without fly ash were also tested as reference specimens. The SHCC specimens contained approximately 2% PVA fibres by volume, with a fibre length of 8 mm and

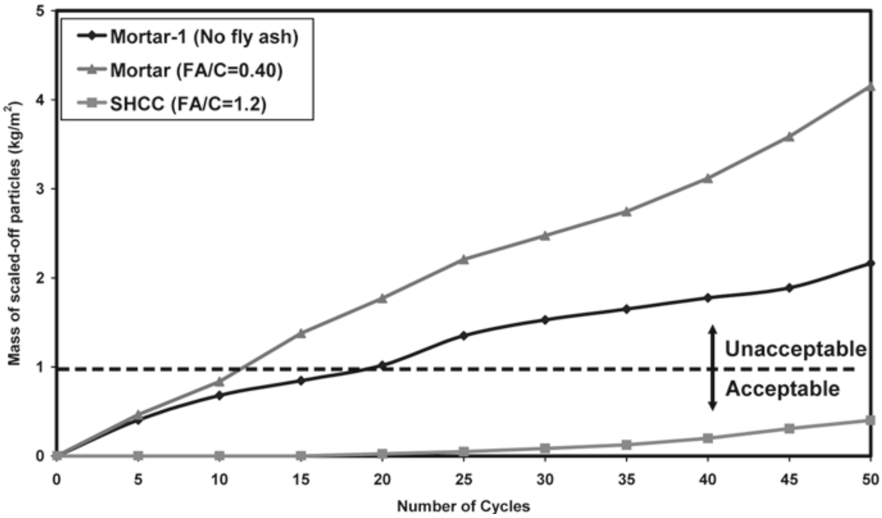

Fig. 4.5 Mass of scaled-off particles versus number of cycles for virgin mortar and virgin SHCC prisms (Sahmaran and Li, 2007).

a fibre diameter of 39 μm. The composition differed from those given in Table 2.1 also by the water to binder (w/b) ratio, which at $w/b = 0.27$ was significantly lower than those in Table 2.1. After 50 freezing and thawing cycles in the presence of de-icing salt, the surface condition, visual rating and total mass of the scaling residue for SHCC specimens, even for those with high volume fly ash content (fly ash (FA) – cement (C) ratio of up to 2.2), remained within acceptable limits according to ASTM C 672, see Figure 4.5. This level of durability holds true even for SHCC specimens pre-loaded to high deformation levels and exhibiting extensive microcracking. In comparison, reference mortar specimens under identical testing conditions deteriorated severely. Moreover, the replacement of fly ash with cement in the mortar further exacerbated deterioration due to freezing and thawing cycles in the presence of de-icing salt.

In a separate test, both pre-loaded (cracked) and sound SHCC specimens were exposed to freeze-thaw cycles in the presence of de-icing salt for 25 and 50 cycles in order to evaluate the residual tensile strength and the ductility of reloaded SHCC specimens (Sahmaran and Li, 2007). The reloaded specimens showed negligible loss of ductility and retained the multiple micro-cracking behaviour and a tensile strain capacity of more than 3%. It was also discovered that microcracks formed under mechanical loading will heal sufficiently under freeze-thaw cycles in the presence of salt solutions, restoring nearly the original stiffness. These results confirm that SHCC, both sound and micro-cracked, remains durable despite the exposure to freeze-thaw cycles in the presence of de-icing salts.

Table 4.1 Material composition.

Component	Content by mass
CEM I 32.5 R	1.0
Water	0.9
Fly ash	2.0
Fine sand (0.1–0.5 mm)	0.6
Plasticizer	0.02
Methyl cellulose	0.003

4.4.2 SHCC Freeze-thaw and De-icing Resistance as Tested with the RILEM TC-117 Procedure

The freeze-thaw and de-icing resistance of SHCC has been assessed in comparison to a reference mortar by using the test method proposed by RILEM TC 117 – FDC (Setzer et al., 1996). This so-called CDF test procedure (capillary suction of de-icing solution and freeze-thaw test) allows the determination of the material loss per unit surface area due to repeated well-defined freeze-thaw cycles in the presence of de-icing salt.

The composition of the SHCC test material is given in Table 4.1. PVA fibres "REC 15", Kuraray, length 8 mm, were used with a volume content of 2.2%. This SHCC appears to have a comparably high strain capacity. It was not primarily optimized for a high freeze-thaw resistance.

The reference mortar had the same composition, but no fibre reinforcement.

The specimens had the dimensions of 150 × 150 × 75 mm^3. A number of five samples was prepared and tested for each material, i.e. for the SHCC as well as for the reference mortar.

Specimen preparation and tests were undertaken according to the RILEM Recommendation (Setzer et al., 1996). The procedure started at the age of 7 days with 21 days of dry storage. Then, the specimens were subjected to a pre-saturation with the test liquid for 7 days. The test liquid consisted of demineralised water with 3% sodium chloride content by mass. Subsequently, twelve-hour freeze-thaw cycles with maximum and minimum temperatures of +20 and –20°C, respectively, were applied, see Figure 4.6. During the freeze-thaw cycles, the front faces of the specimens were in contact with the test liquid. Before pre-saturation, the side faces of the specimens had been sealed with an epoxy resin. The mass loss was determined after 8, 14, 21 and 28 freeze-thaw cycles and related to the surface area of the samples. In order to remove loosely adhering particles from the samples, an ultrasonic cleaning was undertaken according to Setzer et al. (1996).

The results are presented in Table 4.2 as well as in Figure 4.7. It may be seen that the mass loss of the reference mortar is significantly higher than the one of the SHCC. Figure 4.8 shows the samples after 28 freeze-thaw cycles and Figure 4.9 two representative specimen surfaces.

On the basis of the experimental results, the following conclusions may be drawn:

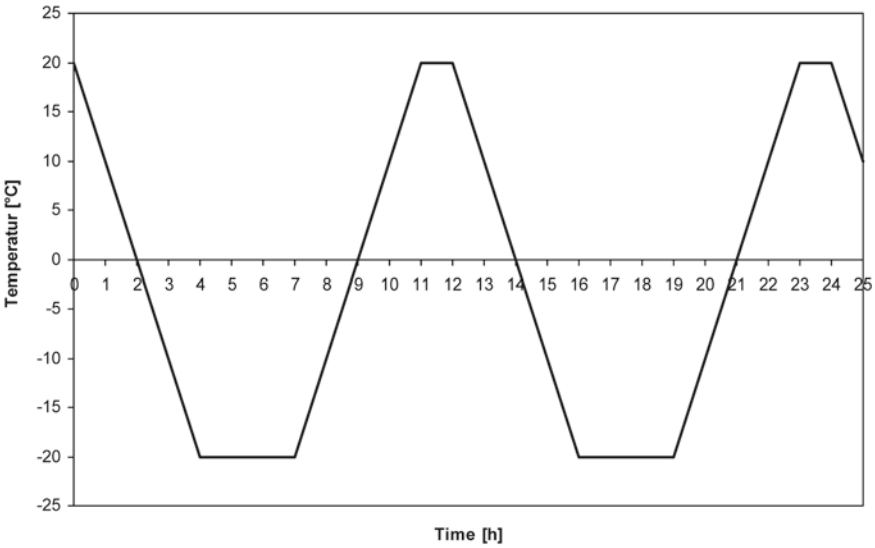

Fig. 4.6 Freeze-thaw cycles according to RILEM TC 117 – FDC (Setzer et al., 1996).

Table 4.2 Mass loss per unit surface area due to freeze-thaw cycles.

Number of cycles	Reference mortar specimens [kg/m^2]	SHCC specimens [kg/m^2]
8	2.1	0.3
14	4.1	0.7
21	7.5	1.4
28	10.9	2.2

1. The presence of the PVA fibres causes a significant reduction of the mass loss per unit surface area during the CDF test. At the first view, the SHCC appears to have a significantly higher freeze-thaw and de-icing resistance as compared to the reference mortar.
2. The mass loss of 2.2 kg/m^2 after 28 freeze-thaw cycles measured for the SHCC exceeds the generally accepted limit value of 1.5 kg/m^2 (Setzer and Auberg, 1995). Accordingly, the freeze-thaw and de-icing resistance appears to be insufficient when determined by this method.
3. The examination of the surfaces after the freeze-thaw cycles revealed distinct differences between the SHCC and reference mortar samples, see Figure 4.8. Whereas the surfaces of the reference mortar samples are comparably smooth, see Figure 4.9a, those of the SHCC samples appear to be rough and fissured, see Figure 4.9b. At the SHCC surfaces, some pieces of the material are almost completely separated from the sample. They are only lightly adhering to the surface by the help of the PVA fibres. On the basis of this observation, it is concluded

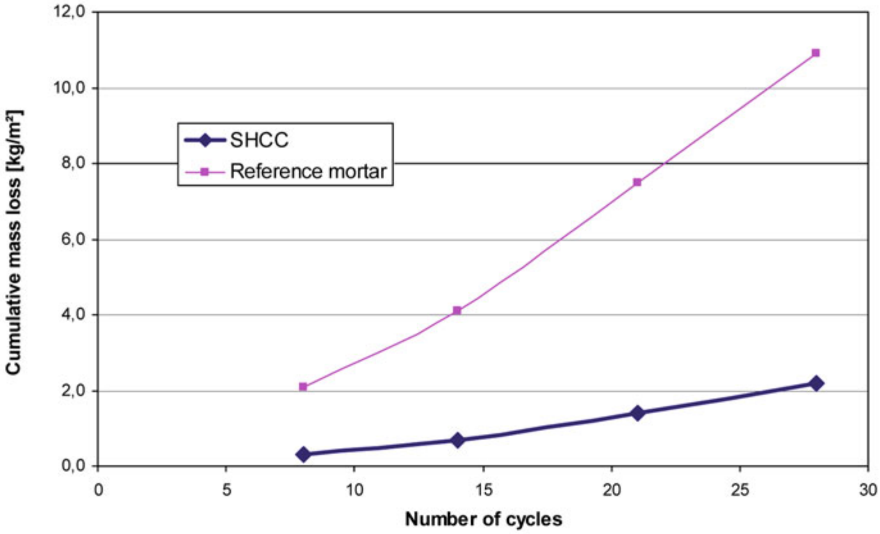

Fig. 4.7 Mass loss per unit surface area due to freeze-thaw cycles.

Fig. 4.8 Specimens after 28 freeze-thaw cycles, left side: SHCC specimens, right side: reference mortar specimens.

that by measuring the mass loss during the CDF test the actual damage caused by the freeze-thaw cycles might be underestimated.

It has to be taken into account that the investigated SHCC was not optimized for a high freeze-thaw and de-icing resistance.

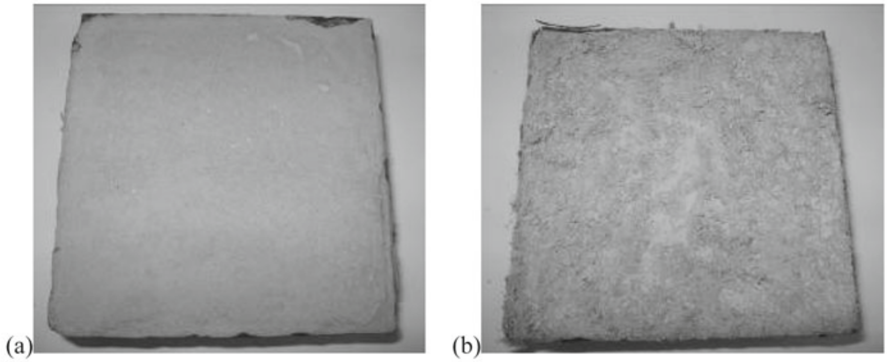

Fig. 4.9 Reference mortar (a) and SHCC (b) surface after 28 freeze-thaw cycles.

In a pilot application, the SHCC tested here has been used for repair layers on outdoor concrete surfaces in Germany. The repaired surfaces are about 3.5 years old now and have survived three cold seasons without any freeze-thaw damage.

Furthermore, experience in Ann Arbor shows no freeze-thaw damage on a bridge deck exposed to freeze-thaw cycles over five cold Michigan winters.

4.5 Concluding Remarks

Thermal loading is a very general concept that may include several aspects of the material and structural behaviour of a cement based composite implicating its durability. At present, few results are available concerning the durability of SHCC under thermal loads. Further investigations will be necessary to fully understand the damage processes taking place in the material under this type of loading. It is believed that several topics should be addressed including: (a) thermo-chemo-mechanical behaviour of SHCC (heat of hydration – kinetics and amplitude – using an adiabatic calorimeter; specific heat, thermal conductivity and coefficient of thermal expansion; autogenous shrinkage; mechanical properties of SHCC as a function of its degree of hydration and creep of SHCC as a function of temperature); (b) mechanical and physical properties of SHCC under high temperatures (mechanical behaviour at elevated temperatures; residual mechanical properties after exposure to high temperatures; residual physical properties after exposure to high temperatures; porosity and gas permeability at high temperatures for different crack widths); (c) behaviour of SHCC under thermal gradients (crack width measurement under thermal cycling as well as under thermal shock; thermal stability of PVA fibres and SHCC using thermo-analysis; spalling resistance of SHCC); and (d) behaviour under freeze-thaw cycles (comparison of the material behaviour under different standardised test conditions; influence of the SHCC air content; effect of air-entraining admixtures).

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Chapter 5
Durability under Combined Loads

Folker H. Wittmann

Abstract So far deterioration of cement-based materials has been studied in most cases under single actions. In reality, however, materials are exposed to mechanical and environmental load combinations. Actions of combined loads on building materials can be subdivided into simultaneous actions and successive actions. Chloride penetration into SHCC under sustained load is an example for simultaneous actions and carbonation after frost damage is an example for successive actions. On ordinary concrete aggravating synergetic effects of combined loads could be observed. Chloride penetration for instance is accelerated if the material is simultaneously under tensile stress. The influence of combined loads on durability of cement-based materials is of particular significance if the service life of a structural element is to be predicted. Service life is overestimated in general, if design is based on a single selected environmental load as for instance carbonation or chloride penetration. So far few results of investigations into the behaviour of SHCC under combined loads are available. It is suggested to set up a coordinated research program in order to identify most serious combined loads as soon as possible.

Key words: combined loads, durability, service life

5.1 Introduction

The new class of cement-based materials with pronounced strain hardening has interesting mechanical properties for a series of applications. But it is likely that the durability of SHCC will be even more important for future applications. Service life of concrete structures is often limited by crack formation in the rather brittle concrete cover. It should be noted here that the "skin" of concrete is particularly brittle. So far durability of concrete and other cement-based materials has been considered

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under one or several isolated actions such as carbonation, chloride penetration or frost action most often. In reality, however, materials are usually exposed to a combination of mechanical and environmental loads and hence durability of a structural member depends essentially on the specific combination of loads in its environment. It has been shown, that service life of concrete structures under the influence of combined loads can be considerably shorter than under the influence of individual loads (Zhao et al., 2005a; Wittmann et al., 2006b). Few results are available so far from tests on durability of concrete under combined loads and even fewer on durability of SHCC under these complex conditions. For this reason this chapter must be considered to be a preliminary first step with the major aim to point out the practical relevance of durability under combined actions and to initiate more research in this specific field.

If the influence of combined loads on durability of cement-based materials is to be studied, two different situations have to be distinguished at least:

1. Simultaneous actions: a typical example is the combination of mechanically imposed sustained strain and simultaneous carbonation or chloride penetration.
2. Successive actions: a typical example is damage induced by frost action followed by carbonation or chloride penetration.

This subdivision may be useful for a better understanding of the processes involved but in reality we may often be confronted with a mixed situation. Then, of course, the situation becomes even more complex. In any case simplifying assumptions have to be introduced if service life of a reinforced construction is to be estimated on the basis of laboratory test results.

We can take full advantage of the enormous ductility of SHCC only under strain-controlled conditions but not under stress-controlled conditions. In practice a series of different strains may be imposed on cement-based structural elements. Non-mechanical strains lead to stresses if a structural element is fixed at both ends or if strain gradients are generated (Alvaredo and Wittmann, 1995; Wittmann, 2002). Some possibly imposed strains and their typical origin are listed in Table 5.1. Let us have a quick look into the order of magnitude of different strains. The ultimate tensile strain capacity of unreinforced cement-based materials is approximately 0.015%. In comparison hygral strain alone (shrinkage) can be easily 0.08% and thermal strain may reach up to 0.04% under usual climatic conditions. A combination of thermal and hygral strains is frequently much higher than the ultimate tensile strain capacity of unreinforced cement-based materials. This is the reason why crack formation due to imposed strains often limits the service life of reinforced concrete structures. SHCC, however, can absorb a usual combination of strains by multiple micro-crack formation, and this type of micro-cracks should have no influence on durability if the material is optimised. In addition Lepech and Li (2005) and Yang et al. (2005) found that micro-cracks in SHCC under moist conditions are closed again by self-healing. Both mechanical properties and permeability are re-established in this way.

Some synergetic effects of combined actions are obvious, others are not. In Table 5.2 some examples for actions, which may damage the composite structure

Table 5.1 Major imposed strains and their typical origin.

Imposed strain	Typical origin
Mechanical	Dead weight, service load, accidental load
Hygral	Drying shrinkage, wetting swelling, autogenous drying
Thermal	Heat of hydration, climatic temperature changes, fire
Chemical	Carbonation shrinkage, ettringite and delayed ettringite formation, AAR

Table 5.2 Examples for synergetic effects of combined actions. Damage may be induced by various actions, which lead to acceleration of deteriorating processes.

Damage induced by	Acceleration of deteriorating processes
Mechanical load; compressive, tensile, or dynamic	Carbonation
Frost action	Chloride penetration
Chemical reactions; hydrolysis, AAR, or sulphate attack	Sulphate ammonia penetration

of cement-based materials are compiled. If a compressive load higher than 60% of the ultimate load is applied, additional micro-cracks are formed and the bulk volume increases. Under tensile stress the same happens at even lower stress levels. Damage can also be induced by frost action. In this case the pore space is increased. $Ca(OH)_2$ in the concrete structure can be dissolved if the surface of concrete is in contact with pure water or carbonic acid. Again new pore space is created.

We can expect that these actions will accelerate all deteriorating processes, which depend on diffusion or migration, such as carbonation or chloride penetration. In reality the interactions are more complex, however. Each of the three actions mentioned in Table 5.2 has an influence on the other two. That means it will take us some time to find out what are the most critical load combinations.

5.2 Imposed Strain and Penetration of Aggressive Compounds

Let us briefly consider the combination of an imposed strain and the simultaneous penetration of an aggressive agent such as chloride. If the stress in SHCC reaches the tensile stress of the cement-based matrix multiple micro-cracks are formed as the imposed strain increases. This crack formation obviously means damage of the composite material. This damage can be observed by measuring the elastic modulus for instance. It has been shown, however, that the permeability of the material with respect to chloride penetration is not increased by crack formation if the maximum crack width remains below a critical value. In Figure 5.1 experimental results obtained by Takewaka et al. (2003) are shown. Several authors have reported similar results in the meantime.

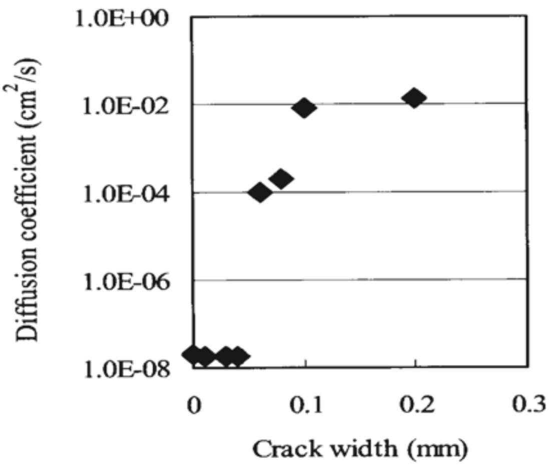

Fig. 5.1 Diffusion coefficient as function of crack width according to Takewaka et al. (2003).

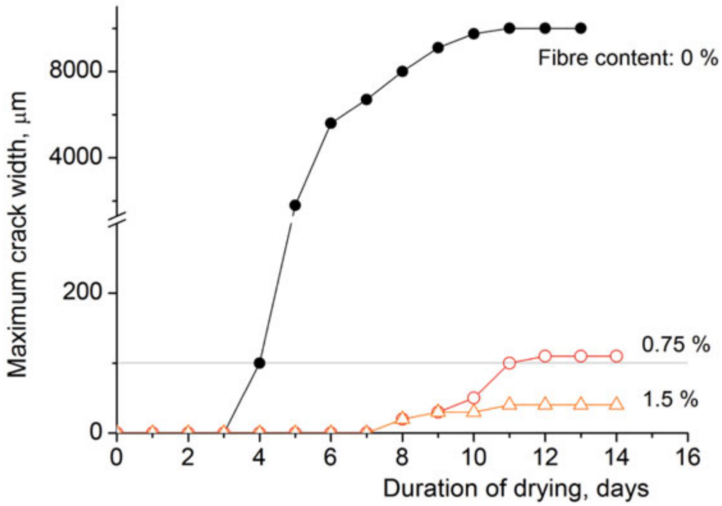

Fig. 5.2 Maximum crack width as observed by means of a ring test on the SHCC matrix (0%) and on SHCC with 0.75 and 1.5% of PVA fibres added. If 1.5% of PVA fibres are added, the maximum crack width remains below 0.05 mm (Wittmann et al., 2006a; Zhao et al., 2005b).

If we succeed to optimise SHCC to such a degree that no cracks wider than 0.05 mm are being formed in the strain hardening range, chloride penetration will not be accelerated. In Figure 5.2 results of ring tests with SHCC matrix (0%) and with SHCC containing 0.75 and 1.5% of PVA fibres are shown. With the mortar matrix used in these test series, 1.5% of PVA fibres are sufficient to reduce the maximum crack width to a value below 0.05 mm. As a consequence, this material should be able to absorb all strains imposed by combined environmental loads without negative influence on durability. Further studies will be necessary to elucidate these results completely.

5.3 Frost Action and Permeability

Mechanisms of frost action in porous materials such as concrete have been studied for a long time and they are reasonably well understood by now (Setzer, 2000, 2005). Damage induced by frost action into concrete coarsens the pore structure and as a consequence rate of carbonation and of chloride penetration can be considerably accelerated (Wittmann et al., 2006b). It has become obvious that service life of a reinforced concrete structure can be considerably shortened by combined frost action and chloride attack.

Lepech and Li (2006) have tested frost resistance of SHCC. They could not observe any measurable damage during their tests. The high ductility probably prevents damage of the composite structure up to 300 freeze-thaw cycles. Exact limits of the safe region of combined frost action and chloride penetration are still to be investigated carefully.

5.4 Hydrolysis and Ultimate Strain Capacity

It is well known that cement-based materials have limited durability in contact with water (Wittmann and Gerdes, 1996; Wittmann et al., 2000). The degradation by hydrolysis can actually be considerably accelerated by certain aqueous solutions and by an electric field.

Nemecek et al. (2006) have observed by nano-indentation technique that the interface between PVA fibres and the cement-based matrix can be substantially weakened by hydrolysis and in presence of a chloride containing solution. In this way the ultimate tensile strain of the composite material will be reduced. Most probably the width of micro-cracks will grow under combined mechanical load and hydrolysis. The significance of these complex interactions for long-term durability of SHC will have to be clarified in detail by further studies.

5.5 Mechanical Load and Alkaline Environment

SHCC is primarily of interest because of its extraordinary strain capacity. But to which extent can this strain capacity really be used without jeopardizing durability and service life?

Sahmaran and Li (2009) have investigated the effect of combined mechanical and chemical loads on the performance of SHCC. They determined the complete stress strain diagram under strain controlled conditions. Some specimens were pre-strained up to 1 and 2% respectively. Then they were exposed to 1N Na(OH) aqueous solution for 30 respectively 90 days. It turned out that the strain capacity had decreased by about 20% and the crack width increased from 40 to about 100 μm. But this reduction in performance was nearly independent on the extent of pre-straining. Partial self-healing of the induced cracks has also been observed. The authors explain their findings by a damaging effect of the high alkalinity on the interface between PVA fibres and the cement-based matrix.

5.6 Conclusions

There is evidence that some loads lead to synergetic effects when acting in combination. Then damage under combined actions is more severe than the sum of damage if acting separately.

This aggravating effect of combined loads has to be taken into consideration if service life is to be estimated in a realistic way.

At present we are at the beginning of studying service life under combined actions only. Serious efforts will be necessary to fully understand the significance of damage under combined actions for the service life prediction of SHCC structural members.

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Chapter 6
Durability of Fibres

Atsuhisa Ogawa and Hideki Hoshiro

Abstract Whereas previous chapters have reported on durability of SHCC composite as a whole, this chapter addresses the durability of the fibres. In particular, the durability of the fibres in the alkaline paste environment, at elevated temperature and exposed to various chemical substances is considered here. It is noted that various fibre types can be used to produce SHCC. However, due to limited test results on fibre durability in SHCC, the discussion here is limited to a few fibre types, notably Polyvinyl Alcohol (PVA) fibre.

Key words: accelerated aging, alkaline exposure, tensile strength retention, fibre bond aging

6.1 Introduction

Polyvinyl Alcohol (PVA) has a relatively simple chemical structure with a pendant hydroxyl group shown in Figure 6.1. PVA is produced by the polymerization of vinyl acetate to polyvinyl acetate (PVAc), followed by hydrolysis of PVAc to PVA. In 1939, Sakurada's research group at Kyoto Imperial University in Japan developed PVA fibre, and in 1950 Kuraray Corp commenced the manufacture and sale of the PVA fibre. PVA fibres have been widely used for industrial, agricultural, fishing applications, seaweed farming nets, ropes, hoses, belts, tire codes, paper making felts, but also as reinforcement in cement-based construction material.

PVA fibre has suitable characteristics as reinforcing materials for cementitious composites. In this chapter, typical characterizations of PVA fibre are reviewed on the basis of comparison with other fibres used for cement reinforcing material.

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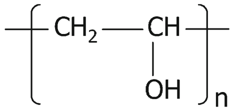


Fig. 6.1 Typical chemical structure of PVA macromolecule.

Table 6.1 Properties of fibres for use in cement-based construction materials.

	Tensile strength (N/mm^2)	Young's modulus (kN/mm^2)	Elongation Capacity (%)	Density (g/cm^3)
PVA fibre	880–1600	25–40	6–10	1.30
Polypropylene fibre	600	5	25	0.91
Polyamide fibre	750–900	3.4–4.9	13–25	1.10
Polyethylene fibre	250–700	1.4–2.2	10–15	0.95
High performance polyethylene fibre	2700	120	5	0.97
Steel fibre	1200	200	3–4	7.85
AR glass fibre	2200	80	0–4	2.78
Asbestos fibre	620	160	–	2.55

6.2 Typical Properties of Fibres

Table 6.1 shows typical mechanical properties of fibres used in construction materials. Like steel and glass fibres, PVA fibres have a relatively high Young's modulus, equal to or greater than that of normal concrete. Through this mechanical property, and the fibre strength, PVA fibre holds particular potential for effective crack bridging in cement-based construction materials.

There are several types of PVA fibres as shown in Table 6.2. Finer type of PVA fibre "RM182" has been used for cement board roofing as asbestos fibre replacement. Coarser fibres have been widely used in civil engineering applications, including tunnel lining, industrial floors, road overlays and various kinds of shotcrete. Recently, new types of PVA fibres, the REC series, have been developed. REC15, one of the new types of PVA fibre, has been designed for SHCC based on micromechanics theory, resulting in surface treatment for bond control (Kanda and Li, 1998, 1999). This fibre is currently used widely in SHCC applications.

6.3 Durability of PVA Fibre

6.3.1 Accelerated Test in Alkaline Environment

Accelerated durability testing on PVA fibre in cementitious alkaline environment has been performed by Hoshiro et al. (2006). PVA fibre tenacity change and the

Table 6.2 Properties of Kuralon PVA fibres.

Types	Product Name (mm)	Diameter (MPa)	Tensile strength (GPa)	Young's modulus (%)	Elongation capacity	Main application
Standard	RM182	0.014	1500	36	7	Cement Board, Mortar
	RSC15	0.040	1400	36	6.5	Mortar, Concrete
	RF400	0.20	975	27	9	Mortar, Concrete
	RF1000	0.31	975	26	6	Mortar, Concrete
	RF4000	0.67	900	23	9	Concrete
Ductile	RECS7	0.027	1560	39	6.5	Cement Board, Mortar
	REC15	0.040	1600	41	6.5	Mortar
	RECS100	0.10	1200	28	12.5	Mortar, Concrete

oxidation mechanism have been observed during the accelerated test, which entailed soaking of fibres in cement extracted alkaline water at various temperatures.

The experimental study was done with PVA fibre filament. The filament yarn was twisted 80 turns per meter to prevent feazing. The twisted yarn was wound on a stainless steel frame. The wound PVA filaments were subsequently soaked in the cement extracted alkaline water at various temperatures. The results are shown in Figure 6.3 and suggest a threshold temperature of 50°C. Below 50°C full strength is retained, but beyond this threshold, strength loss is evident in Figure 6.3.

Hot alkaline conditions reduce the viscosity and discolor PVA. On the other hand, under nitrogen, it does neither. With regard to the viscosity change and discoloration of PVA, Shiraishi et al. (1962) pointed out the chemical reaction shown in Figure 6.3. The generation of the -CO-C=C- group, the circled group in Figure 6.2, causes discoloration and can be measured by UV absorption at 235 nm (Yamaguchi et al., 1959).

From the experimental study Hoshiro et al. (2006) suggested a method of estimating tensile strength retention of PVA fibre after accelerated degradation in hot alkaline water by estimating the relation between tensile strength change and UV absorption. Figure 6.4 shows the relation between tensile strength retention and the UV absorption.

This b-linear relation can be approximated by the following equation:

$$\text{Tensile strength retention (\%)} = \begin{cases} -505(\text{UVabs.}) + 143 & \text{for UV abs.} > 0.085 \\ 100 & \text{for UV abs.} \leq 0.085 \end{cases} \tag{6.1}$$

Considering the relation between tensile strength retention and soaking time (h in hours), they obtained following equation:

$$\text{Tensile strength retention (\%)} = \begin{cases} -1.3\text{E} - 05h + 111.2 & \text{for } h \geq 8.58\text{E}5 \\ 100 & \text{for } h < 8.58\text{E}5 \end{cases} \tag{6.2}$$

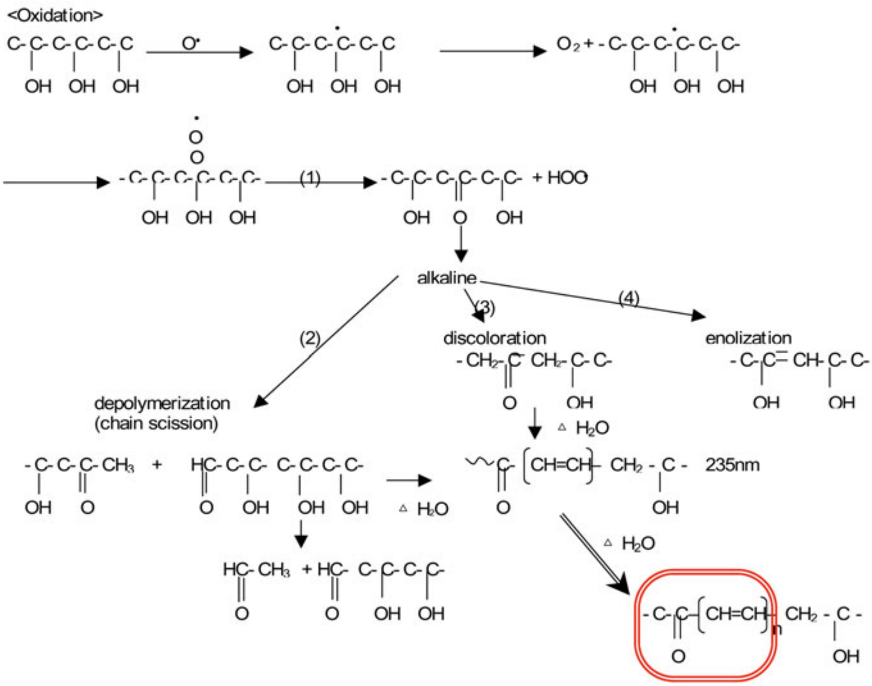


Fig. 6.2 Oxidation reaction of PVA molecule under alkaline condition.

From equation (6.2) the estimated tensile strength retention after 60, 100 and 120 years can be calculated to be 100, 99.8 and 97.5%, respectively. Based on this accelerated test, the long-term durability of PVA fibres is evident.

Figure 3.13 (Section 3.5) shows another result of accelerated testing of PVA, polyester, alkali resistance AR glass and E glass fibre. These fibres were soaked in hot (80°C) and high alkaline water. PVA fibre maintains its tensile strength even after 14 days of soaking.

6.3.2 Accelerated Tests in Chemical Exposure

The chemical stability of PVA fibre was studied in similar way as above, with the results shown in Figure 6.5. PVA filament was also applied for this study. The PVA filament yarn was wound with 80 turns per meter of twist on a stainless steel frame. Subsequently the wound PVA filaments were soaked in various chemicals at various temperatures. Especially in dilute acid solution case, strength retentions are marginally decreasing, however chemical stability of PVA fibre is demonstrated in these results.

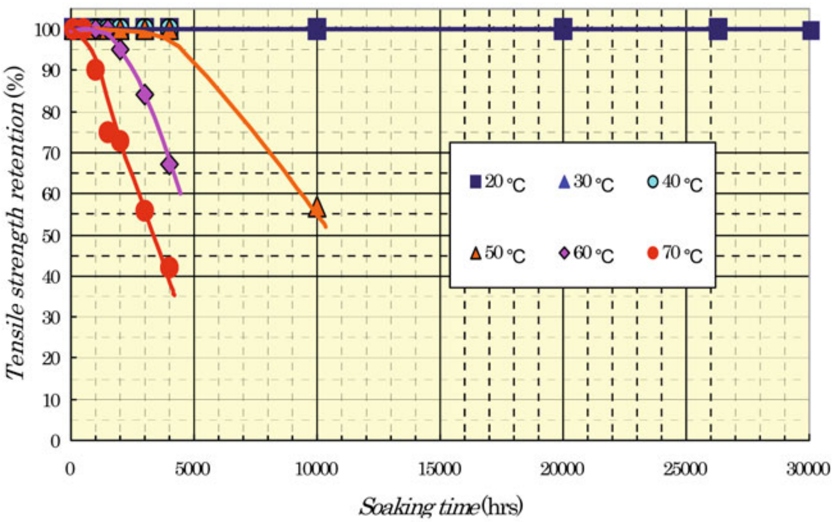


Fig. 6.3 Effect of soaking time on tensile strength.

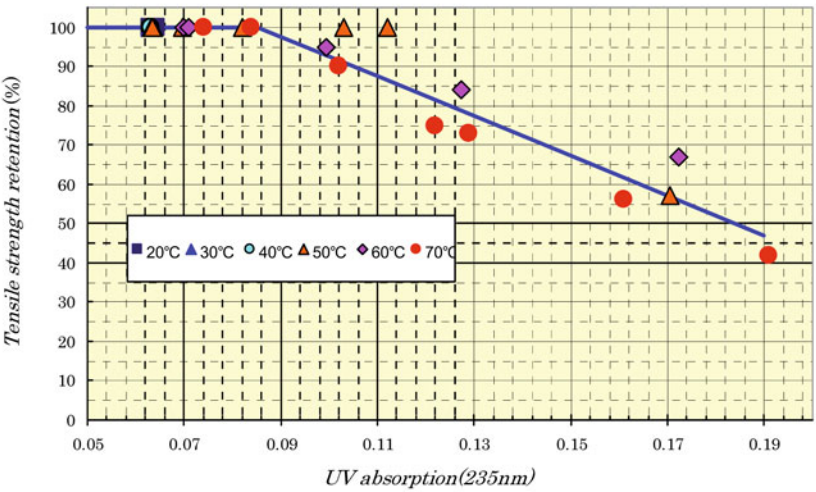
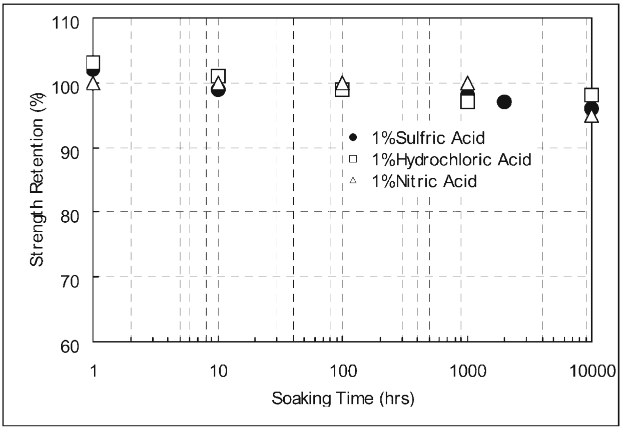


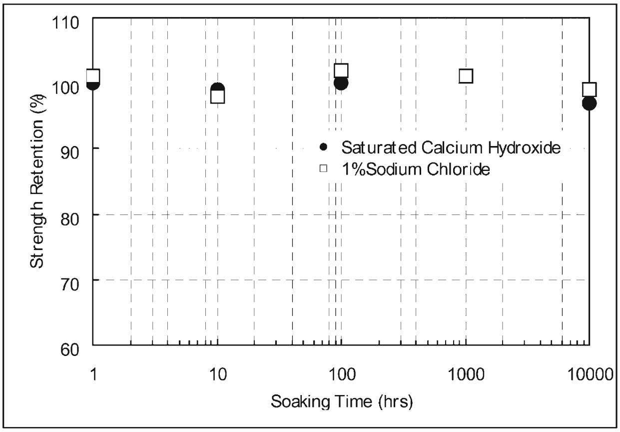
Fig. 6.4 Effect of soaking time on tensile strength.

6.4 Durability of PVA Fibre-reinforced Cement-based Composites

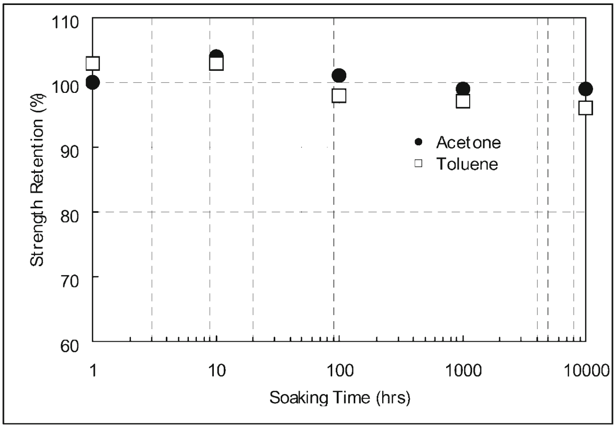
For over 20 years, PVA fibre has been successfully used in various parts of the world. The use and shipping of PVA fibre reinforced cement board products for roofing started in 1983. The long experience in the field has provided excellent data on the



a) Acid Solutions



b) Alkaline Solutions



c) Organic Solvents

Fig. 6.5 Chemical stability test results.

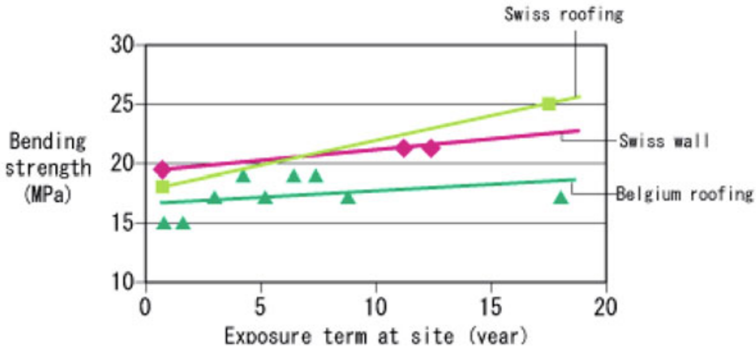


Fig. 6.6 Flexural strength evolution of cement board during outdoor exposure in Belgium and Switzerland.

longevity of PVA fibres and their suitability as an asbestos replacement (Lhoneux et al., 2002). Figure 6.6 shows fibre-cement strength evolution during natural weathering in Belgium and Switzerland. It was found that PVA fibre-reinforced cement slates maintain their strength or develop increased strength than before aging. Also it is found that from tensile strength, crystalline and molecular weight determinations, no sign of degradation could be observed on the fibres, which were extracted from fibre cement sheet exposed to outdoor weathering. For many years PVA fibres have also been used by international manufacturers of curtain walls, and for external roof and wall cladding.

The test results in Figure 3.12 (Section 3.4) also reflect the durability of SHCC composite, when subjected to accelerated testing. There it is shown that the immersion of PVA and AR glass fibre reinforced mortar in 60°C hot cement extracted alkaline water for 28 days leads to no reduction in MOR in PVA fibre-reinforced mortar. However, AR glass fibre reinforced mortar gradually loses its MOR to 70% of the initial value.

Tests were also performed on PVA SHCC to determine the influence of accelerated aging on model parameters of the micromechanics-based models proposed by Li et al. (2004). The accelerated aging test here entailed immersion of SHCC specimens in 60°C hot water. Both single fibre pull-out tests and single fibre tensile tests were performed. In this study, REC15, SHCC suitable surface-treated PVA fibre, was applied. The results are shown in Figure 3.9 (Section 3.4) in terms of frictional and chemical bond, as well as apparent fibre strength. Twenty-six (26) weeks of hot water immersion, corresponding to over 70 years of natural weathering, lead to a reduction of the tensile strain capacity by the change of interfacial parameters. However it retained a tensile strain capacity of 2.7% on average, see Figure 3.11. All these results suggest that PVA-SHCC composites are durable under long-term hot and humid environmental loading as long as this long-term value of strain capacity is used in structural design.

6.5 Conclusions

PVA fibre itself has good durability under ordinary chemical environment. From accelerated aging tests in cementitious alkaline water environment, the PVA fibre tensile strength is predicted to be maintained at more than 95% over 100 years. Accelerated aging tests on the composite indicate that the interface bond properties of appropriately coated PVA fibre in SHCC are maintained.

On the other hand, PVA fibre-reinforced cement-based composites have been applied in various civil/architectural structures, some of which are already more than two decades old, demonstrating the durability practically.

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Chapter 7
Durability of Structural Elements and Structures

Viktor Mechtcherine and Frank Altmann

Abstract Strain-hardening cement-based composites (SHCC) have a great potential for the application in structures exposed to severe mechanical or environmental loading. This chapter summarises the current knowledge on the durability of the composite components as well as steel reinforcement when used in combination with SHCC.

Based on those considerations, the transport properties in the cracked state, the long-term strain capacity and the resistance in aggressive environments are identified as critical parameters. Current knowledge indicates that SHCC shows a high long-term strain capacity and favourable transport properties in the cracked state. The composite also exhibits superior resistance to aggressive environments compared to ordinary concrete. However, there is little information available on the effects of aggressive environments on the mechanical properties of the material.

A selection of field applications is presented, showing that the superior laboratory performance can be replicated in the field. However, since SHCC is a new material, there is no information available on its long-term field performance. To be able to fully utilise the superior qualities of this new material, it will be necessary to develop a realistic and reliable performance based durability design concept for SHCC structures.

Key words: strain-hardening cement-based composites (SHCC), structural elements, steel-reinforced SHCC, durability, service life

7.1 General Remarks

Most current applications of SHCC are non-structural. Fibre reinforcement is primarily used in controlling shrinkage cracks as well as cracks induced by tem-

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perature changes. However, considerable laboratory research has been performed in the last few years on the behaviour of structural members made of SHCC, and the number of structural applications is increasing. Based on these first insights, some major tendencies may be deduced already.

From the current point of view, fibre reinforcement will be combined with conventional steel reinforcement in the majority of structural elements made of SHCC (R/SHCC). Thus the protection of steel from corrosion must be considered with regard to durability of such structures. This also holds true for the repair of reinforced concrete structures using SHCC. According to Li (2003), at least three broad classes of target applications can be discerned based on the observed characteristics of R/SHCC structural elements:

1. Structures requiring collapse resistance under severe mechanical loading.
2. Structures requiring durability even when subjected to harsh environmental loading.
3. Structures in which the application of SHCC is expected to support enhanced construction productivity.

Even this general classification indicates that durability requirements for different structures made of SHCC may vary significantly. To best meet these requirements, the material composition may also vary considerably. This implies that only a general framework for dealing with the problem of durability of such structural elements and structures can be provided in this chapter.

7.2 Characteristic Mechanical, Environmental, and Combined Loads

The wide variety of potential applications for SHCC means, that the range of mechanical and environmental loads as well as their possible combinations may be very broad. Table 7.1 gives a general classification of perspective structural applications of SHCC according to the loading mode and the performance modification by using SHCC.

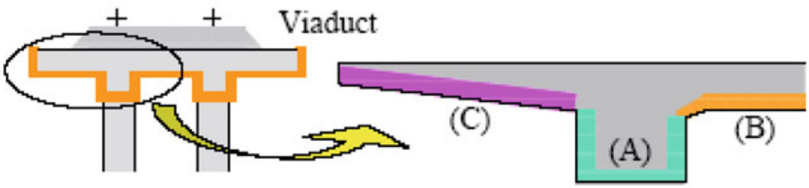
Particular performance requirements may vary even for different parts of one structural member, as was shown by Inaguma et al. (2006) for the repair of a viaduct using SHCC, see Figure 7.1.

Considering the durability of structures, the mechanical loads are of particular interest with regard to the cracking, since cracks dramatically increase the transport of fluids and gases in concrete and consequently the corrosion process. Apart from the mode of loading (e.g. tension, shear, bending), which affects crack pattern and crack widths, the loading type should be considered, since for instance single overloading, fatigue loading or high sustainable loads can affect the cracking behaviour of SHCC (crack width and crack distribution).

However, crack formation and propagation often begin before any crack inducing mechanical loads are applied. Cracks resulting from thermal movements, re-

Table 7.1 Perspective structural applications of SHCC according to Li (2002).

Structural member/load	Example application	Performance modification by using SHCC
Flexural members	Tunnel linings, beams, slabs	Bending strength, pre-peak and post-peak ductility
Shear members	Bridge decks, corbels, keys in segmental construction, steel anchors in concrete members	Shear capacity, post-cracking safety
Torsional members	Poles, bridge decks	Torsional capacity, post-cracking safety
Uniaxial tension members	Pavements	Expand joint spacing
Beam-column connections	Building frames	Seismic resistance, reduce reinforcement and congestion
Column	Building columns, bridge	Seismic resistance, reduce spalling and enhance steel reinforcement



Part name	Member characteristic	Required performance of the surface coating
(A) Beam	Mainly support train loading	Crack-bridging ability
(B) Centre slab	Thin and easily affected by water from above	Water permeability
(C) Overhang slab	Often located above roads	Prevention of falling concrete fragments

Fig. 7.1 Required performance of SHCC repair for individual parts of a viaduct, according to Inaguma et al. (2006).

strained drying shrinkage, or autogenous shrinkage can be eventually exacerbated, for example by fatigue loading. A number of typical examples for combinations of mechanical and environmental loads is given in Chapter 5. These load combinations for R/SHCC structures are generally the same as for steel reinforced concrete structures.

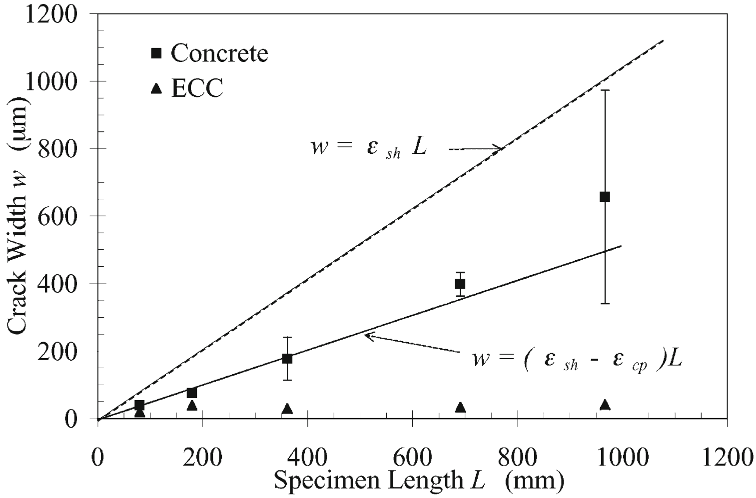


Fig. 7.2 Crack width as a function of specimen dimension for concrete and SHCC, according to Li and Stang (2004).

Restrained drying shrinkage might be the main cause of tensile stresses and cracking of SHCC prior to any mechanical loading. Li and Stang (2004) theoretically demonstrated that the restrained shrinkage crack width w depends on the cracking potential $p = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_{cp})$ and characteristic material length l_{ch} according to Hilleborg et al. (1976), with ε_{sh} being the shrinkage strain, ε_e the elastic strain, and ε_{cp} the tensile creep strain. Due to its ductile behaviour and subsequently very high values of l_{ch}, SHCC possesses a high material resistance to the widening of cracks. As long as p remains negative, the microcrack width is an intrinsic material property, and will not depend on the structural dimension. This independence of the crack widths from the member size for SHCC applications was also confirmed experimentally through a series of simple restrained drying shrinkage tests, see Figure 7.2.

In most cases, cracking is inevitable in concrete structures and generally essential for an effective usage of reinforcement, both by steel bars and fibres. A great advantage of SHCC is that this material displays a self-controlled crack width, which is very small in comparison to conventionally reinforced structures. This enables, at least theoretically, full decoupling of steel reinforcement from the crack control. Steel reinforcement is used only for ensuring adequate load capacity, while SHCC controls the cracking behaviour. This constellation opens new opportunities for structural design, allowing a more effective use of both types of reinforcement. An example of where this decoupling has been taken advantage of, is an SHCC link-slab connecting between two bridge deck spans (Kim et al., 2004).

In this chapter the “mechanical part” of the design will not be directly addressed (this is the task of the SC 3), while the mechanical performance of SHCC will be considered with regard to the durability of SHCC structures.

7.3 Basics for the Durability Design

7.3.1 General Remarks

While discussing basics of the durability design for SHCC structures, reference will be made to existing durability design rules for steel reinforced concrete structures. The descriptive design rules of current standards are unlikely to be suitable for taking full advantage of the new class of materials discussed in this report. A performance-based durability design approach will likely be much more appropriate. While such an approach exists for crack-free ordinary concrete (DuraCrete 2000, fib bulletin 34, 2006; Schießl and Gehlen, 2005), significant efforts will be required to develop a similar approach suitable for cracked and crack-free SHCC. Recently Altmann et al. (2008) took a first step towards such a design concept by developing a fuzzy-probabilistic approach to forecast chloride ingress in SHCC. This approach allows the quantification of parameters based on limited data and expert knowledge. More research will be required to further develop and expand this approach until it allows a reliable durability design for cracked and crack-free SHCC under environmental loads. Only then it will be possible to fully utilise the inherent durability of SHCC for the construction of more sustainable structures.

In order to ensure structure durability, the durability of the applied materials should first be assured. Since a combination of steel reinforcement and SHCC seems to be most promising for most structural applications, the following requirements arise with regard to the durability of individual system components and consequently of the system as a whole:

1. Protection of steel reinforcement from corrosion.
2. Durability of the SHCC matrix.
3. Fibre durability.
4. Durability of fibre-matrix bond properties.

7.3.2 Protection of Steel Reinforcement from Corrosion

Ordinary steel reinforcement requires protection against corrosion, which the alkaline environment of the cementitious matrix provides. If aggressive agents such as chloride or carbon dioxide ingress into the matrix and reach the reinforcement, however, the steel may corrode. This chapter provides an overview of how the fundamental differences between ordinary concrete and SHCC may affect the protection of embedded steel reinforcement, while details regarding the current knowledge on individual transport properties of SHCC are covered in Section 7.4.

In the established codes and regulations (e.g. Eurocode 2, DIN 1045), three measures are demanded to protect steel reinforcement: limitation of the maximum crack width, sufficient concrete cover, and appropriate concrete quality defined by corresponding threshold values (minimum compression strength, maximum water-cement ratio, minimum cement content). In principle, these requirements also hold true for R/SHCC structures; however, the weighting and the thresholds values change (see also Section 1.3).

Li and Stang (2004) suggested two levels of protection of the structural element with regard to the steel corrosion. The first level relies on the tight crack width control of SHCC ($< 100\ \mu m$), which delays the penetration of aggressive agents from reaching the steel reinforcement. Hiraishi et al. (2003) showed that the corrosion rate in an R/SHCC beam is significantly lower than that of a reference ordinary reinforced concrete (RC) beam preloaded to the same level. The second level of protection afforded by SHCC is the prevention of radial crack formation even if the steel rebar corrodes and expands. This anti-spall ability of SHCC has been demonstrated in experiments (Kanda et al., 2003).

Comparing this approach with the existing codes, the following considerations can be made:

- Intrinsically small crack widths in R/SHCC structures are much smaller than threshold values allowed by codes for RC structures. The question arises if adjustments should be made concerning the other two protection measures of the steel reinforcement, namely thickness of the concrete cover, and concrete quality.
- The requirement of a particular minimum value of concrete cover is based on numerous considerations including the carbonation of concrete, transport of aggressive agents through the concrete layer to steel reinforcement, as well as the concrete resistance against spalling. For ordinary concrete, the spalling resistance increases with increasing thickness of the concrete layer (Müller et al., 2003). In the case of SHCC, a much higher spalling resistance than that of ordinary concrete can be achieved with only a very thin overlay.
- The lack of coarse aggregates means that there are no vast aggregate-matrix interfaces with higher porosity than aggregate-free hardened cement paste, which might serve as "highways" for the transport of fluids and gases. However, due to a higher binder content, the overall porosity of SHCC is higher than that of ordinary concrete. To which extent the presence of fibres influences the transport properties must still be investigated in more detail.
- SHCC usually possesses higher binder content than ordinary concrete. The associated higher ability to bind aggressive substances such as chlorides and carbon dioxide is advantageous with regard to preventing steel corrosion.

In conclusion, it can be stated that for the same exposure classes (e.g. XC carbonation, XD de-icing salt or XS seawater according to CEN EN 206-1) the threshold values for SHCC would probably differ significantly from the corresponding values for ordinary concrete, if the established approach for durability design was applied to R/SHCC structures.

7.3.3 Durability of the SHCC Matrix

Frost attack, chemical attack by aggressive substances, as well as abrasion in some cases must all be considered with regard to the durability of the SHCC matrix. Basic effects of matrix composition on concrete resistance against these exposures are reasonably well known for ordinary concrete. However, they can not be transferred to predict the behaviour of SHCC because of its very particular mixture composition: absence of coarse aggregates, high binder content and presence of fibres. The fine, well distributed fibres might lower the deterioration of the composite even if the matrix is severely loaded.

The first results on the durability of SHCC under frost and chemical attack (the details are given in previous chapters of this report) display a sufficient resistance of the matrix, if it has an appropriate composition, especially concerning the water-binder ratio and the binder type. With regard to abrasion, the results of laboratory experiments are contradictory, with the suitability of the matrix and thus the composite SHCC for heavy roadway traffic depending not only on the mixture composition but also on the test method (see Chapter 2.8). Nonetheless, the results in field applications are encouraging. Further, it was found that the mechanical performance of SHCC remained practically unaltered (Li and Lepech, 2005) upon being exposed to frost attack. However, a chemical attack might very well affect the mechanical properties of the matrix, which would then lead to a change in SHCC strength and particularly its ductility. A substantial amount of research is still required to investigate the material behaviour under further exposures as well as statistically ensure observed characteristic material performance.

Another issue is the aging process and associated hydration, altering the mechanical performance of SHCC by changing the composition of the hardened binder paste phases as well as the microstructure and the properties of the bond between matrix and fibres (refer to Section 7.3.5).

7.3.4 Fibre Durability

In principle, different types of fibre can be used for the production of SHCC. As of yet, the best results have been obtained by using polyethylene (PE) and polyvinyl alcohol (PVA) fibres. Since PE fibre is very expensive, PVA fibre has been used in many research works on SHCC as well as for most applications.

Eternit Corp. began delivering PVA fibre reinforced roofing slates in 1983. This experience has provided reliable data on the longevity of PVA fibres (De Lhoneux 2002). Furthermore, it was discovered that from tensile strength, crystallinity and molecular weight determinations, no sign of degradation could be observed among the fibres, which were extracted from fibre cement sheets exposed to outdoors weathering (Horikoshi et al., 2006).

The effects of environmental exposure have also been examined using hot water immersion (see Section 3.4 and Li et al., 2004). For an equivalent of 70 years of natural weathering, little change has been observed in fibre properties such as strength, elastic modulus and elongation.

Apart from investigations on the behaviour in highly alkaline environments (see Section 3.5), no results on the chemical resistance of PVA fibre in aggressive environments are known. However, PVA groups of materials are generally considered to be resistant against chemical attacks.

7.3.5 Fibre-matrix Bond Durability

Like for the fibre, the effects of aging (see Section 2.3) and environmental exposure to hot and humid environments on interfacial properties have been examined using hot water immersion (see Section 3.4). It was found that the chemical fibre-matrix bond increased while the apparent fibre strength decreased. This reduces the overall strain capacity of the composite, which nonetheless generally remains at a level high enough to ensure the desired performance.

There is little specific information on the changes of the bond properties under chemical attack. As outlined in Sections 3.4 and 3.5, both chloride attack and calcium leaching reduce the fibre-matrix bond. Kabele et al. (2006) found that the case of calcium leaching this reduction may be so severe that multiple cracking of the material can no longer be guaranteed. It should be noted, however, that those experiments were carried out on specimens with high water-cement ratios. According to Sahmaran and Li (2008) a highly alkaline environment may lead to changes in the fibre-matrix bond, resulting in reduced tensile strain and – to a lesser degree – tensile strength (see Section 5.5). Other forms of chemical attack may very well affect the mechanical properties of the fibre-matrix bond as well. There is great need for further research on the changes of fibre-matrix bond properties due to chemical attack.

7.4 Characteristic Material Properties to Predict Long-term Durability and Service Life

7.4.1 General Remarks

Based on the considerations regarding the durability of individual components outlined in Section 7.3, the following characteristic properties of the composite material seem to be decisive with regard to long-term durability and service life of R/SHCC structures:

- Transport properties of SHCC material in a cracked state.
- Strain capacity of SHCC.
- Resistance of SHCC in aggressive environments.

On the material level these issues are discussed in detail in previous chapters. The following sections provide a brief overview as well as special considerations for elements and structures made of SHCC.

7.4.2 Transport Properties

The key question is what effect a considerable number of fine, distributed cracks have on the transport properties of SHCC (see Section 2.5). Average crack width has been used routinely as a reference parameter. However, for SHCC with multiple cracks of self-limiting width an approach using the cumulative crack length seems to be more appropriate (Mechtcherine et al., 2007). Where this is not practical, the average strain may serve as a useful reference. It can however be assumed that the fine fibres in combination with a fine grain matrix also affect the condition of crack profiles and the continuity of the entire crack system, which of course influences the transport of fluids and gases through the material. There is significant need for research into reliable and practical methods to describe the crack system in SHCC both in the laboratory as well as in field applications.

7.4.2.1 Air Permeability

There is very little information available on the air permeability of cracked SHCC, but it seems that the air permeability of uncracked SHCC is well within the range of typical values for ordinary concrete. For material strained to up to 1%, an increase of almost two orders of magnitude has been observed (Mechtcherine et al., 2007). While this may no longer be comparable to sound concrete, it should be noted that the specimens were tested at an age of 45 to 50 days and the mix had a high content of fly ash. Thus it can be expected, that in field applications with similar mixes ongoing hydration and self-healing will have a mitigating influence over time.

7.4.2.2 Water Transport Properties

As outlined in Section 2.5, the water transport properties of various cracked cementitious materials have been studied by a number of researchers. These investigations demonstrated the significance of the crack width w and the cumulative crack length in controlling the permeability and water absorption of cracked SHCC. A comparison with values for ordinary concrete (Adam, 2006) shows, that for strain levels up to 0.5% the water absorption of SHCC is comparable to that of sound concrete. It should be noted, however, that the reported crack widths in SHCC are typically between 50 and 100 μm. While capillaries of this width may not transport water very far into the material, the process is rather fast. In conjunction with the natural porosity of SHCC and sub-microcracks (Wittmann et al., 2007), the water may be transported deep into the material over time. Further research in this area is required.

7.4.2.3 Chloride Permeability

So far, very little information is available on the chloride permeability of SHCC. Miyazato and Hiraishi (2005) observed no macro-cell corrosion in cracked R/SHCC specimens with steel corrosion due to chloride penetration and a penetration depth that was significantly lower than for cracked reinforced mortar specimens (refer to Sections 2.5 and 3.2).

More recently Sahmaran et al. (2007) conducted immersion and ponding tests on SHCC and reinforced mortar specimens. The observed chloride penetration depth and diffusion coefficient both in cracked and uncracked SHCC specimens was much lower than that of the mortar specimens. The authors found the chloride diffusion coefficient to be proportional to the square of the crack width and linearly proportional to the number of cracks in the case of multiple cracking. The observed higher resistance of cracked and uncracked SHCC against the ingress of chloride ions can be attributed to a higher content of cementitious materials, a low w/c-ratio, the self-limiting crack width and, as a result of this, self-healing of the cracks (refer to Sections 2.9 and 3.2). While this is promising, more research is required.

7.4.2.4 Other Transport Properties

For sound ordinary concrete, numerous correlations were experimentally and in part also theoretically derived between different transport mechanisms (diffusion, permeation, absorption) and for different transport media (e.g. water, air, CO_2) (Hilsdorf et al., 1997; Lawrence, 1986). For cracked concrete, however, such comparisons have not yet been performed, as is the case for SHCC. The knowledge of possible correlations is essential for the prediction of the SHCC durability for different applications, if it is based on the results of just one or two particular test methods. There is a great need for research in this area.

7.4.3 Strain Capacity of SHCC

7.4.3.1 Long-term Strain Capacity and Aging Behaviour

Since a high strain capacity is a decisive property with regard to the durability of SHCC, this material and members or structures made of it, can only be considered as truly durable if their strain capacities do not negatively alter at a substantial rate over time.

In laboratory experiments SHCC long term strain capacities of 3% compared to initial ultimate strain levels of 5% were observed (see Section 2.3). While both values are far above the deformation demand imposed by many applications, average strain capacities in large scale SHCC production outside the laboratory are likely to be significantly lower. Kanda (2005) reported values between 1.18 and 3.80%, depending on the test method. Furthermore, the binder composition, the type of cement and the cement replacing materials as well as hygral and thermal ambient conditions should be considered (see Section 2.3). More research is required in order to be able to predict the long term mechanical performance of SHCC.

7.4.3.2 Cyclic Loading and Fatigue

As outlined in Section 2.6 the available information on the behaviour of SHCC under cyclic loading indicates that cracking behaviour is comparable to the behaviour under monotonic loading. The material stiffness decreases significantly with an increasing number of load cycles, but there is no evident influence of cyclic loading on the ultimate strain level (the details may be found in Jun and Mechtcherine, 2007, as well as in Mechtcherine and Jun, 2007).

There is little information available on the fatigue behaviour of SHCC in field applications. Zhang and Li (2002) investigated SHCC in high cycle fatigue scenarios, such as highway repairs. Both SHCC/concrete and concrete/concrete overlay specimens were tested in flexural fatigue. The tests showed that the load capacity of SHCC/concrete specimens was twice that of concrete/concrete specimens, the deformability of SHCC/concrete specimens was significantly higher, and the fatigue life was extended by several orders of magnitude. It should be noted, however, that under certain fatigue load conditions ordinary FRC may yield better durability results. Kunieda and Rokugo (2006) found, that while SHCC has a longer fatigue live than ordinary FRC at higher fatigue stress levels, its fatigue life at lower stress levels is shorter. This can be attributed to the fact that for low stress levels only a few cracks can propagate in the specimen. Thus the cracking state under fatigue load is an important factor for fatigue resistance of SHCC.

7.4.3.3 Behaviour under Sustained Loads

As described in Section 2.6, creep of SHCC consists of matrix creep, time-dependant crack development accompanied gradual delamination of fibres from the matrix and subsequent pull-out. As is the case with ordinary concrete, high sustained loads will lead to time-dependant failure (Jun and Mechtcherine, 2007).

There is little information on the creep behaviour of SHCC in field applications. Rokugo et al. (2005a) have reported increasing crack widths of up to 0.12 mm after 24 months for the patch repair of a concrete retaining wall suffering from ASR. However, it is unclear if this is due to increasing crack widths in the substrate, relaxation in the SHCC or both.

7.4.4 Resistance of SHCC in Aggressive Environments

The composite resistance of SHCC when exposed to aggressive environments is a function of the durability of matrix, fibre and fibre-matrix bond as well as their possible combinations. The durability of the individual phases is briefly summarised in Section 7.3, while the current knowledge on the effects of combined loads on the composite is presented in Chapter 5.

SHCC generally exhibits an equal or superior resistance in aggressive environments compared to ordinary concrete. However, little to no information is available on the effects of chemical attack on the mechanical properties of SHCC or the long-term behaviour in real-life applications with their complex load combinations.

7.4.5 Size Effect

There is only little and contradictory information available on the size effect in SHCC. Lepech and Li (2003a, 2003b) conducted three-point bend tests on SHCC and R/SHCC beams with lengths from 175 to 2800 mm. All specimens had a length to height relationship of seven; they were 75 mm wide and tested at an age of approximately 10 days. The material composition and the mechanical properties in direct tension are given in Table 7.2. The authors reported flexural tensile strengths from 11.28 to 15.13 MPa for 175 mm long specimens and from 10.18 to 15.19 MPa for 2800 mm long specimens. They concluded that there is negligible size effect for structural members made of SHCC or R/SHCC compared to RC members.

Mechtcherine and Schulze (2005) investigated the size effect in uniaxial tension on two batches of dumbbell-shaped specimens cast at different times and with cross-sections of 60 mm × 100 mm and 24 mm × 40 mm. They also conducted three- and four-point bending tests on prisms with the dimensions 450 mm × 100 mm × 100 mm and 160 mm × 40 mm × 40 mm. In both cases the SHCC was placed horizontally in steel moulds and the specimens were either sealed (bending and uniaxial tension tests) or stored in water (uniaxial tension tests) until being tested at an age of 28 to 35 days.

In case of the uniaxial tension tests the authors found no pronounced size effect for tensile strength and stress at first crack. The average ultimate strain, however, was found to be significantly lower for the larger specimens (see Table 7.3). In the second test series the authors recorded significantly higher stresses at first crack and tensile strength, with the tensile strength measured for the small specimens being larger than that of the large specimens. The differences in ultimate strain were smaller than in the first series but exhibited the same tendency. In contrast to Lepech and Li (2003a, 2003b) the authors found flexural strength to be significantly influenced by specimen size. In four-point bend tests it decreased from 19.4 to 11.3 MPa, in three-point bend tests from 17.6 to 12.7 MPa with increasing specimen size.

In a further test series using SHCC made of Kajima Co. premix, Mechtcherine (2007) performed tensile tests using the same geometries of dumbbell-specimens as

Table 7.2 SHCC compositions and mechanical properties in direct tension.

	Lepech and Li (2003a)	Mechtcherine and Schulze (2005)	
Composition			
	[weight proportions]	[kg/m^3]	[weight proportions]
Cement	1.0	320	1.0
Fly ash	0.1	750	2.34
Quartz sand	1.0	535	1.67
Water	0.45	335	1.05
SP	0.02	16.1	0.05
VA	0.0015	3.2	0.01
PVA fibres	0.02*	29.3	0.022*
Mechanical properties in direct tension			
		First batch	
Stress at first crack [MPa]	2.8	2.30–2.79**	
Ultimate tensile strength [MPa]	4.0	2.57–3.47**	
Ultimate compressive strength [MPa]	60	30	
E-Modulus [MPa]		16,000	
Ultimate strain [%]	4.9	1.92–4.75**	

*Percent by volume, **Depending on specimen size and curing conditions.

Table 7.3 Results of displacement controlled uniaxial tension tests with non-rotational loading plates, average values of the first test series by Mechtcherine and Schulze (2005).

Curing conditions	Specimen size	Stress at first crack [MPa]	Tensile strength [MPa]	Ultimate strain [%]
Sealed	small	2.41	3.45	4.75
	large	2.60	3.47	1.96
Stored in water	small	2.30	2.57	2.57
	large	2.79	2.84	1.92
		COV = 20%	COV = 10%	COV = 25%

explained above. In this case nearly no change was observed with increasing specimen size with regard to the average values of the stress at first cracking (small specimens: 3.6 MPa, large specimens: 3.5 MPa) and the ultimate strain (small specimens: 2.1%, large specimens: 2.0%). However, a considerable decrease of the tensile strength was measured (small specimens: 5.0 MPa, large specimens: 4.0 MPa).

The contradictory results of Lepech and Li (2003a, 2003b) and Mechtcherine and Schulze (2005), Mechtcherine (2007) indicate the need for systematic research in this area to clarify the mechanisms that cause size effect in SHCC, and its implications for structural design using SHCC. In light of the findings by Mechtcherine and Schulze (2005) a careful statistical interpretation of test data, especially with regards to repeatability and reproducibility, will be necessary. Parameters that may influence size effect include the skin effect, composition and rheology, mixing and casting procedure, curing, ageing, load regime. Furthermore, the behaviour of full-scale SHCC members should be investigated to confirm any findings made for smaller-scale specimens.

7.5 Examples

7.5.1 General Remarks

In Sections 7.1 and 7.2 possible applications for SHCC and R/SHCC members and structures were outlined. While by far not all of these have been realised in full-scale projects, there has been a number of SHCC field application in recent years (see Table 7.4).

In the following, two well-published examples of structures under severe mechanical or environmental loading are presented. They may be instructive for both researchers and practitioners by drawing attention to the complexity of load combinations in field applications and the remarkable performance of SHCC in those conditions.

7.5.2 Patch Repair of Bridge Deck; Michigan, USA

To verify the durability of SHCC in field applications, in 2002 a section of a deteriorated bridge deck in Michigan was repaired using SHCC (Lepech and Li, 2006). To facilitate a comparison with the durability of ordinary repair products, parts of the bridge deck section in question were also repaired with the commercial concrete patching material commonly used by the local authorities.

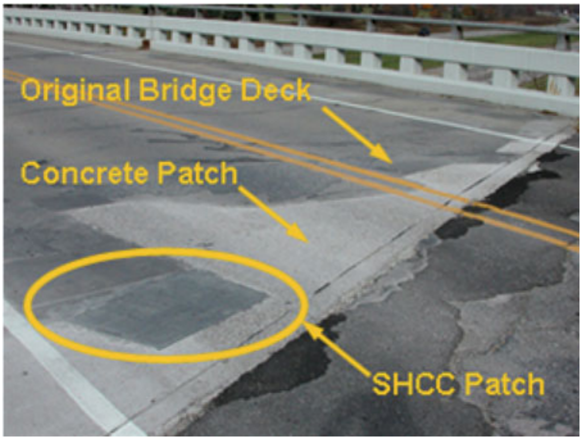
After five years including harsh winter cycles of freezing and thawing in addition to live loads it was found that the crack width in the SHCC was limited to 50 μm, and no significant abrasion could be observed. In contrast to that, the cracks in the ordinary repair material had widened to up to 2 mm after two years and after three years it had to be partly replaced (Li, 2007).

In Altenburg, Germany, similar positive experiences were made with patch repairs of the concrete slab of a petrol station exposed to freeze-thawing cycles as well as heavy, chained traffic: The observed cracks were much smaller than in the PCC-mortar used as reference material and no significant abrasion could be observed after 1.5 years (Slowik, 2007; Wagner, 2008).

Table 7.4 Overview of realized SHCC applications (Source: ECC Technology Network, 2009).

Application	Location	Year	Comments
Patch repair of bridge deck	Michigan, USA	2002	See Section 7.5.2
Repair of Mitaka Dam with sprayable SHCC	Japan	2003	A 30 mm layer of SHCC was applied over an area of 500 m^2 to improve the dam's resistance against water ingress (Kunieda and Rokugo, 2006)
Surface repair of retaining wall	Gifu, Japan	2003	See Section 7.5.3
Mihara bridge	Hokkaido, Japan	2004	Steel/SHCC composite bridge deck. The 40 mm thick SHCC layer increases the load bearing capacity, stiffness and fatigue resistance of the structure (Kunieda and Rokugo, 2006)
R/SHCC coupling beams in high-rise residential building	Tokyo, Japan	2004	While not addressing durability as discussed in this chapter, the R/SHCC members increase the fatigue and earthquake resistance of the structure, thus increasing its service life
Patch repair of waterways	Shiga and Toyama, Japan	2005	Deteriorated and cracked concrete surfaces were repaired with SHCC layers, which were between 6 mm (walls) and 10 mm (bottom slab) thick. In conventional and ultra high-strength polymer cement mortar repair layers applied for comparison, cracks were observed one month after application, whereas none were found in the SHCC (Kunieda and Rokugo, 2006)
Surface repair of railway viaduct	Shizuoka, Japan	2005	A 10 mm layer of SHCC was applied to increase the structure's resistance against carbonation (Kunieda and Rokugo, 2006)
SHCC link slab retrofit for bridge deck	Michigan, USA	2005	Expansion joints of a highway bridge were replaced by an SHCC link slab, which is expected to have a much longer service life (Lepech and Li, 2005)

(a)



(b)

Fig. 7.3 Patch repair in 2002 (a) and 2007 (b) (Li, 2007).

7.5.3 Surface Repair of Retaining Wall; Japan

In 2003 a gravity concrete retaining wall in the Gifu Prefecture, Japan was repaired with sprayed SHCC to restore a satisfactory visual appearance. Constructed in the 1970s, the 18 m long and 5 m high wall exhibited cracking due to alkali-silica reaction (ASR). A previous rehabilitation in 1994 had been unsuccessful, with cracks re-occurring after only a few years (Rokugo et al., 2005a).

To study the performance of SHCC, two types of this material as well as a conventional repair mortar were applied with a thickness of 50 to 70 mm in combination with different types of crack pre-treatment as well as reinforcement. For this purpose, the wall was divided into 1.8 m wide and 5 m high sections. The specific rehabilitation method for each block is given in Table 7.5 (Rokugo et al., 2005a).

Fig. 7.4 Self-consolidating casting of SHCC patch (ECC Technology Network, 2009).

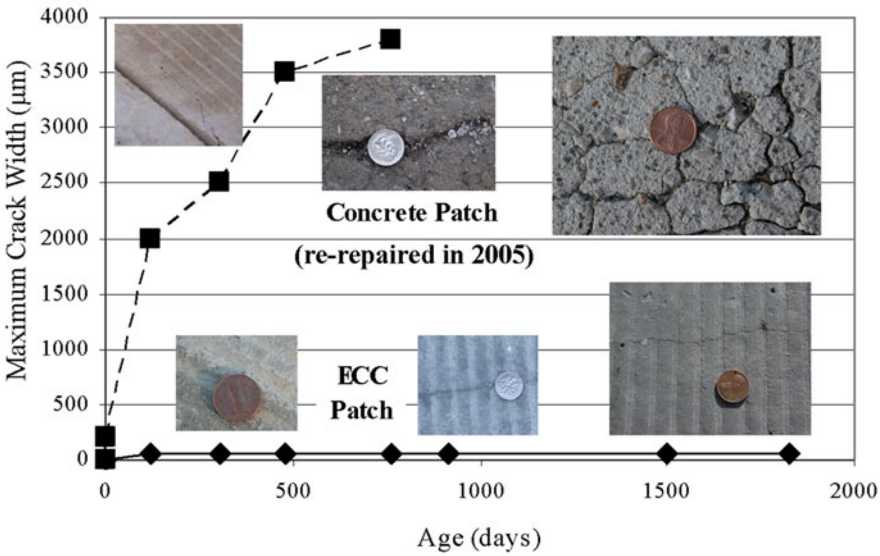


Fig. 7.5 Maximum crack width development over time (Li, 2007).

In two instances (blocks 4 and 8) the existing cracks were sealed with a polyurethane sealant to prevent bonding between the SHCC and the substrate over a width of 30 mm, see Figure 7.6. Additionally, the surface of all blocks up to a height of 2 m from the bottom was coated with an acrylic paint to prevent water ingress (Rokugo et al., 2005a).

Fig. 7.6 Existing cracks are being sealed with a polyurethane sealant to prevent bonding with the SHCC and the substrate over a width of 30 mm (Rokugo et al., 2005b).

Fig. 7.7 Surface repair of retaining wall. Counter-clockwise: appearance before rehabilitation, surface preparation with high-pressure water-jet, application of SHCC, after rehabilitation (Rokugo, 2005).

Table 7.5 Repair methods for the different wall sections (Rokugo et al., 2005a).

Repair materials	Block No.	Reinforcement	Unbonded region at crack
Repair material A	1	Welded bar mesh	No
Fibre: 1.5% (by vol.) high-strength PE	2	Expanded metal	No
Matrix: Premixed polymer cement mortar	3	None	No
	4	None	Yes
Repair material B	5	Welded bar mesh	No
Fibre: 2.1% (by col.) high-strength PVA	6	Expanded metal	No
Matrix: Premixed cement mortar	7	None	No
	8	None	Yes
Repair material C			
Fibre: None	9	Welded bar mesh	No
Matrix: Premixed cement mortar			
No repair	10	None	No

In the following two years a fine mesh of cracks developed at the surface of the SHCC layer with the crack widths growing from 50 μm after 10 months to up to 120 μm after two years. In the ordinary repair mortar the cracks grew much faster and up to a width of 300 μm after two years (Kunieda and Rokugo, 2006).

Figure 7.8 shows the crack pattern 12 months after repair from 1 m below to 1 m above the boundary between coated and uncoated repair material. It was found that cracks were randomly distributed for blocks without reinforcement or with expanded mesh. However, where welded bars were used, the crack patterns resembled the mesh geometry irrespective of the repair material. Furthermore, little cracking could be observed for a combination of SHCC and acrylic surface paint (Rokugo et al., 2005a).

7.6 Summary and Conclusions

There is great potential for the application of SHCC in structural elements and structures exposed to severe mechanical or environmental loading. Current knowledge indicates that SHCC shows a high long-term strain capacity and favourable transport properties in the cracked state. On top of that, the composite exhibits superior resistance to aggressive environments compared to ordinary concrete. However, with the exception of exposure to alternating freezing and thawing, which does not alter the mechanical properties significantly, there is no information available on the effects of aggressive environments on the mechanical properties of the material.

Since SHCC is a new material, there is no information available on the long-term field performance of SHCC elements. However, the experiences outlined in Section 7.5 indicate, that the superior performance in a laboratory environment as

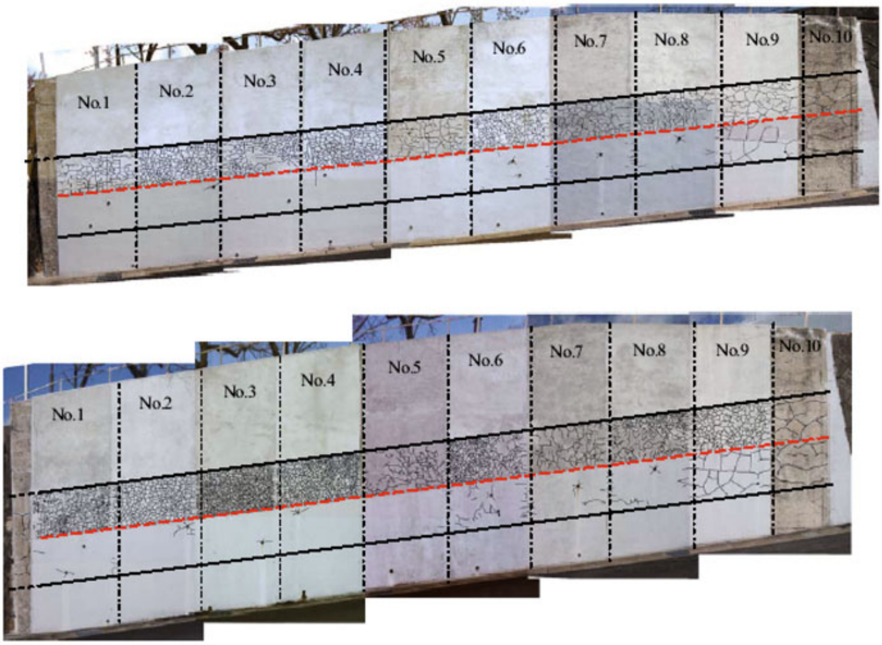


Fig. 7.8 Crack patterns 12 (top) and 24 (bottom) months after repair (Kunieda and Rokugo, 2006).

discussed in previous chapters and summarised above, does indeed translate to superior field performance.

There is significant research need to understand the long-term behaviour of SHCC and R/SHCC elements under complex combined loads as encountered in field applications. To be able to fully utilise the superior qualities of this new material, it will be necessary to develop a realistic and reliable performance based durability design concept for SHCC structures.

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Chapter 8
Durability, Economical, Ecological, and Social Aspects: Life-cycle Considerations

Michael D. Lepech

Abstract Concerns over global climate change, nonrenewable resource consumption, energy depletion, and sustainable development are increasingly coming to the forefront of large infrastructure and building projects worldwide. The ability to design materials, structures, and building systems that improve the sustainability of built environments is becoming an essential tool for engineers. This chapter frames the challenge of a sustainable built environment, highlights the role of SHCC materials in meeting that challenge, and details specific design approaches for the incorporation of green SHCC materials in sustainable infrastructure.

Specifically, the use of SHCC bridge elements to replace failing expansion joints in the USA results in a one third reduction in bridge life-cycle energy consumption when compared to a traditional bridge. Total economic costs are reduced by 15% as a result of less maintenance, lower construction traffic congestion, and fewer environmental impacts. Similarly, using SHCC rigid pavement overlays (rather than concrete or asphalt) to rehabilitate existing rigid pavements can reduce total greenhouse gas emissions by nearly one third. The incorporation of life cycle assessment with design to measure sustainability can greatly improve the sustainability of built environments. Accordingly, SHCC materials can play a significant role in improving the sustainability of these environments and systems.

Key words: strain-hardening cement-based composites (SHCC), sustainability, life-cycle assessment (LCA), life-cycle cost (LCC), durability

8.1 Introduction

As global natural resource stockpiles shrink, population grows, and concerns over environmental damage and global climate change increase, sustainable design con-

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cepts within the civil engineering and infrastructure design community are becoming increasingly important. As a highly versatile material with greater durability than concrete, SHCC can play a large role in the development of sustainable construction and operation of society's infrastructure and other built environments.

To begin designing SHCC materials for sustainable infrastructure and building systems, a common definition of sustainability must be established for use by the SHCC community. In 1987 a commonly used global definition for sustainable development was formulated within the report by the World Commission on Environment and Development (WCED, 1987):

> *Sustainable development* is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

In 1989 this report was debated in the United Nations General Assembly and formed the foundation for the United Nations Conference on Environment and Development. As a worldwide definition for sustainability, this definition can be adopted to guide sustainable design, construction, operation, and demolition of civil infrastructures.

In addition to this broad definition for global sustainability, numerous working definitions which are narrower in scope have been used to direct sustainable initiatives globally. For concrete specifically, the Nordic Network (2003) suggests:

> A sustainable concrete structure is a structure that is constructed so the total environmental impact during the entire life cycle, including use of the structure, is reduced to a minimum. This means that the structure shall be designed and produced in a manner which is tailor-made for the use, i.e. to the specified lifetime, loads, environmental impact, maintenance strategy, heating needs, etc. This shall be achieved by utilizing the inherently environmentally beneficial properties of concrete, e.g. the high strength, good durability, and high thermal capacity. Furthermore, the concrete and its constituents shall be extracted and produced in an environmentally sound manner.

While this definition may be used narrowly for concrete materials and structures, often when referring to the complex infrastructure and building systems in which concrete is used, sustainability generally encompasses three broad main issues; minimization of environmental cost, economic cost, and social cost (Keoleian et al., 1994). Environmental costs, such as depletion of nonrenewable raw materials, are issues typically associated with sustainable environmental practices. Economic costs, such as financial resources saved by taking total life cycle cost into consideration, are also important. Finally, social costs, such as reduced levels of public health as a result of increased pollution, are the least tangible of the costs yet may likely encompass the greatest immediate impacts to an individual. As a whole, these three sets of indicators serve as a comprehensive measure of the overall sustainability of many complex societal systems.

Based on this "triple bottom line" of economic, environmental, and social costs, development of more sustainable infrastructure and built environments using SHCC materials can be accomplished. Such design requires a holistic approach toward infrastructure design along with integration among numerous design disciplines.

8.2 Life-cycle Impacts and Costs versus Initial Costs and Impacts of Construction

Using indicators of economic, environmental, and social cost to determine the overall sustainability of an infrastructure system, it is essential to assess these costs over the entire life-cycle of the structure or system. This includes natural resource extraction, construction material processing, construction of infrastructure facilities, operation and maintenance of the structure, and end of life considerations. Without accounting for each phase of service life, incomplete and likely misleading conclusions may be drawn with regard to the full cost burden on infrastructure owners and society in general.

Early efforts to standardize life cycle costing were first introduced in the United States in 1971 by the United States Department of Defence for purchase of large defence systems (US DOD, 1971). Similar concepts were taking root globally during the same period due to the global energy crisis of the 1970s. Currently, environmental sustainability metrics, reporting, and standards are codified globally through ISO 14000 and 15000 series standards. Within ISO are international standards in the field of environmental management (ISO 14000), environmental life cycle assessment (ISO 14040), environmental declaration (ISO 14025) and international standards on service life planning (ISO 15686 series).

Apart from these environmental sustainability standards, a number of researchers have examined the life-cycle economic costs of infrastructure and building systems. These have included Grivas and Rivala (1995), who looked at determining life cycle costs for highway management and included traditional agency costs, such as construction and traffic control, as well as user delays (costs incurred by those waiting in construction traffic). Ehlen has undertaken several studies that expand the definition to include costs due to environmental effects and those imposed upon business affected by construction (Ehlen, 1997, 1999).

Recently the European Commission has undertaken an effort to incorporate life cycle costing into planning for building refurbishment (LCC-REFURB). This project is aimed at making use of existing life cycle cost (LCC) knowledge for building and construction applications. Within this project, the costing of life cycle of building structures is captured in Figure 8.1 from initial construction, through operations, reconstruction, and ultimately end of life (Caccavelli et al., 2005).

Still, many of these life cycle costing models fail to account for external or social costs. The extraction, processing, use, and disposal of concrete materials in infrastructure has been shown to lead to global climate change, ecosystem degradation, diminished water quality, and other environmental effects (Langer, 1999, 2001). While difficult to quantify, these costs should be incorporated to allow decision makers to achieve more socially efficient and responsible outcomes.

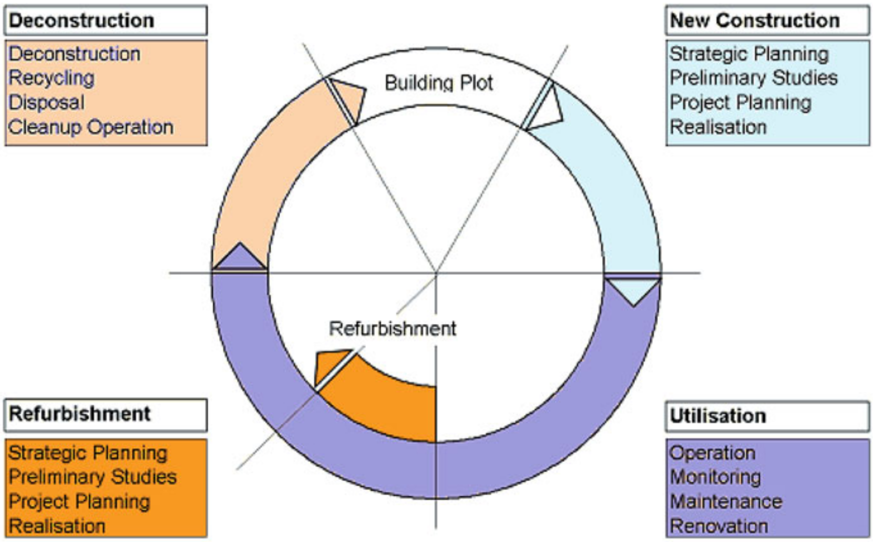

Fig. 8.1 Life-cycle of building and infrastructure systems.

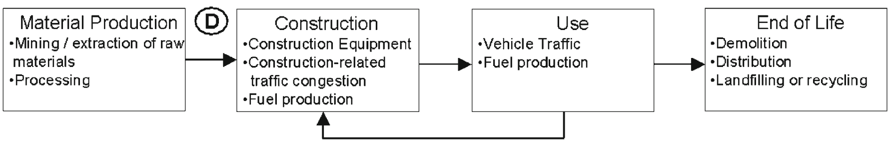

Fig. 8.2 Bridge deck life cycle phases (D = distribution).

To account for the full range of economic, environmental, and social costs Keoleian et al. (2005a) have proposed a life cycle cost model that examines the cost of infrastructure systems and built environments through each phase of the life cycle. In this case the model is shown for a bridge deck which transports automobile traffic during the "use" phase. This framework is shown in Figure 8.2.

This simple model is expanded to account for economic costs placed upon the agency or owner (i.e. department or ministry of transportation) for construction and maintenance, societal costs associated with traffic delays, traffic noise, and decreased public health, and environmental costs stemming from natural resource depletion, energy use, and global warming potential. Each cost is accounted throughout each service life phase as shown in Figure 8.3.

While life cycle cost models have been developed for many infrastructure systems, existing models may be difficult to use when evaluating SHCC systems. This is primarily due to the lack of knowledge regarding service life performance of new SHCC materials. Innately connected with durability and deterioration of these new materials, the ability to accurately predict end of service life and rehabilitation events for SHCC structures is critical. Yet without predictive modeling which ac-

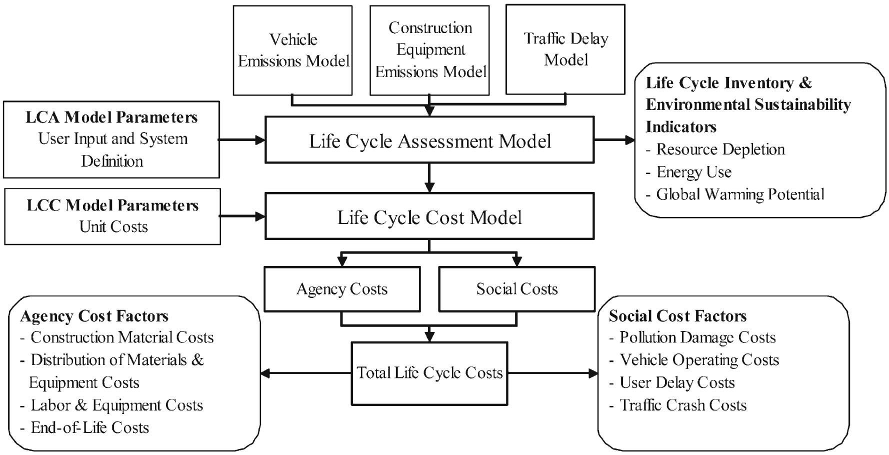

Fig. 8.3 Integrated LCA-LCC Model Flow Diagram (Keoleian et al., 2005b).

counts for the greater durability and highly ductile nature of SHCC materials, life cycle cost analysis becomes an educated guess at best. Detailed models of SHCC material deterioration are needed for this purpose. With development of such models, life cycle assessment and costing can be more widely practiced. Such deterioration modelling is addressed in Chapter 5 of this book.

8.3 Raw Material Recycling

Currently, there are a number of academic, industrial, and government initiatives worldwide which are working to improve the overall sustainability of built environments. Individually, these focus on various forms of green building materials development and procurement, promotion of low energy intensity building products, architectural designs for low energy demand, and construction methods which produce less waste, use fewer resources, and require less energy (USGBC, 2005; GBC-A, 2005; JSBC, 2005).

Recycled material is quite common in concrete materials. Two widespread approaches toward greening concrete materials, which have undergone significant laboratory development and met general industry acceptance, are the use of fly ash (Siddique, 2004; Su and Miao, 2003) and blast furnace slag (Manso et al., 2004; Mindess and Young, 1981) as supplementary cementitious materials. But, as will be seen in Section 8.4, the simple replacement of virgin materials with waste products does not necessarily translate to increased sustainability.

Unlike concrete however, the incorporation of industrial waste materials into SHCC materials has been limited. Due to their high performance and exceptional raw material requirements (i.e. higher cement content, special fibre requirements,

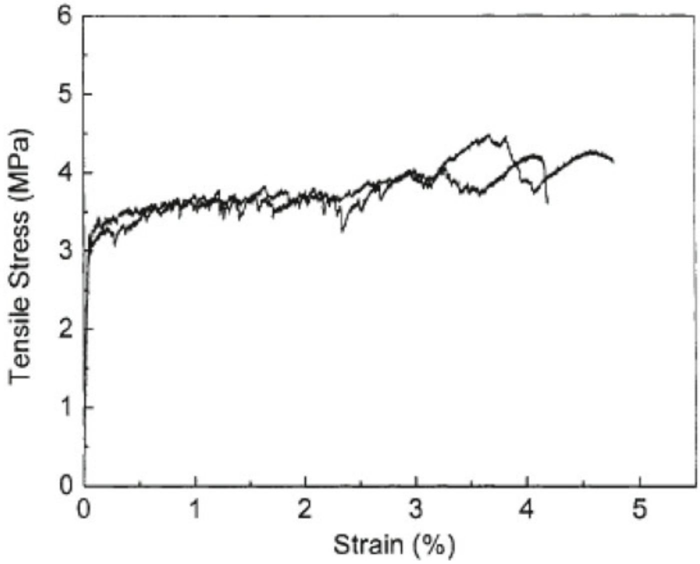

Fig. 8.4 Tensile behaviour of SHCC with high volume fly ash content (FA/C = 2.2).

Table 8.1 Mixing proportions for concrete, PE-ECC, and high volume fly ash ECC.

Material	Cement (kg/m^3)	Aggregate (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)	HPMC (kg/m^3)	SP (kg/m^3)	Fiber (kg/m^3)
Concrete	390	1717	–	166	–	–	–
PE-ECC	1205	603	–	314	0.6	12	17
ECC (FA/C = 2.2)	318	701	701	289	0.24	19	26

small particle sizes, etc.), the incorporation of waste materials is difficult in many SHCC composites. Therefore, SHCC materials must be carefully designed for incorporation of recycled waste streams as not to degrade their exceptional performance.

Wang (2005) has successfully incorporated high volumes of fly ash in polyvinyl-alcohol SHCC materials for the purpose of materials tailoring. Micromechanics tools were used to guide the design for maximized tensile strain capacity. The resulting composite with a fly ash to cement ratio of 2.2 to 1 demonstrated robust tensile strain capacity at 3–4% (Figure 8.4) and tensile strength above 4.5 MPa while lowering harmful environmental indicators as compared to SHCC materials (polyethylene fibres) without fly ash. Mix designs are shown in Table 8.1 while material sustainability indicators are shown in Table 8.2. In Table 8.2, fly ash is counted as negative solid waste since it would be landfilled otherwise.

Kim et al. (2005) has successfully incorporated ground granulated blast furnace slag into SHCC materials. The mix proportions for this SHCC material are shown in Table 8.3 along with uniaxial tensile response in Figure 8.5.

Table 8.2 Material sustainability indicators for concrete, PE-ECC, and high fly ash ECC.

Material	Total energy (MJ/L)	Solid waste (kg/L)	Carbon Dioxide (g/L)	Chemically polluted water (L/L)
Concrete	2.46	0.2	373	0.0126
ECC	7.55	0.361	870	0.0243
ECC (FA/C = 2.2)	4.58	–0.541	390	0.0099

Table 8.3 Mix proportions of ordinary concrete, FRC, and SHCC by weight (fibre by volume) and corresponding material compressive strength.

Material	C	W	S	G	HRW	HPMC	V_f (%)	f'_c (MPa)
Concrete	1.0	0.69	2.5	3.8	0	0	0	24
FRC	1.0	0.69	0.8	0	0.02	0.001	1	25
ECC	1.0	0.69	0.8	0	0.02	0.001	2	25

(C: Type I Portland cement; W: water; S: silica sands for SHCC, regular sand for concrete; G: coarse aggregate with a maximum size of 15 mm; Slag: ground granulated blast furnace slag; V_f: fibre volume fraction; f'_c: compressive strength)

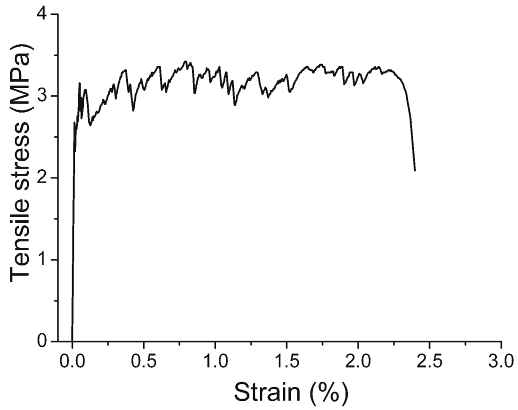

Fig. 8.5 Tensile stress versus strain curve of SHCC with ground granulated blast furnace slag.

In order to incorporate numerous waste streams into SHCC materials, Lepech et al. (2008) have proposed a methodology that allows for incorporation into SHCC composites. This is shown in Figure 8.6.

This methodology begins with a large pool of potential waste materials and eliminates candidate materials through a series of preliminary tests including grain size distributions and chemical analysis. Material design (i.e. microstructural tailoring and optimization design) is then completed to appropriately incorporate the waste material into the composite without sacrificing exceptional SHCC material properties (i.e. tensile ductility). This methodology has been used in the incorporation of waste foundry sand into SHCC composites (Lepech et al., 2008).

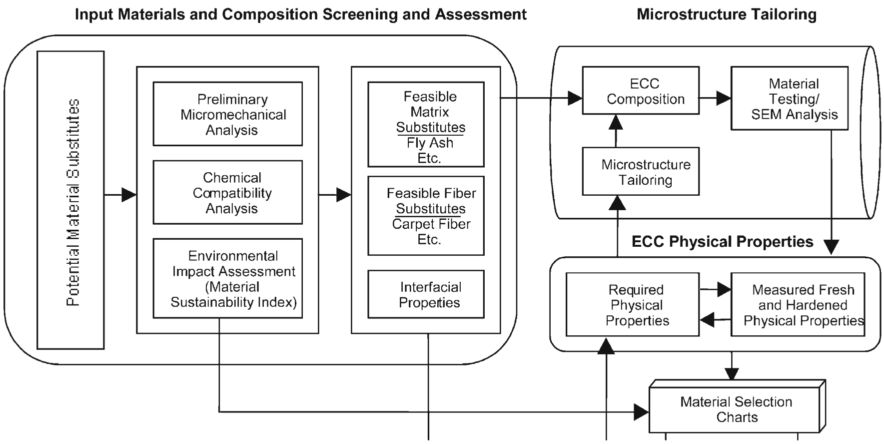

Fig. 8.6 Materials development approach for recycled waste streams in SHCC materials.

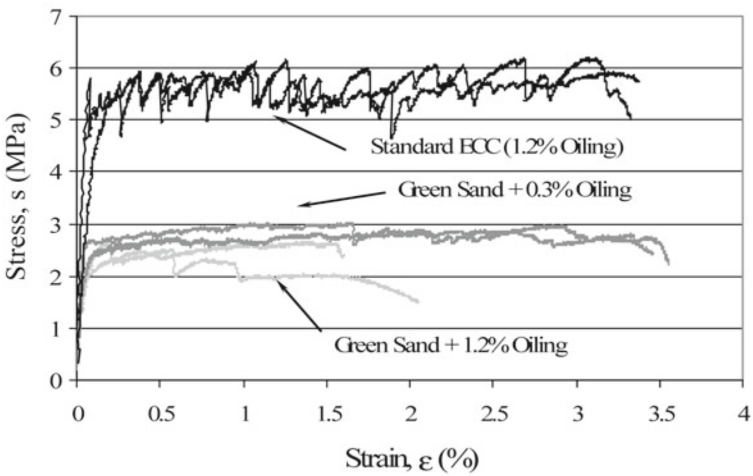

Fig. 8.7 Effect of excess carbon and oiling content on tensile strain capacity.

Demonstrating this work, after passing the predefined set of preliminary material requirements, foundry waste sand (commonly called green sand) was tested as a replacement for natural sand typically used in SHCC materials. When tested, the composite (M45-Green) showed a large loss of tensile strain capacity over the conventional SHCC mixture (Figure 8.7). After further micromechanical investigation, this was found to be due to residue on the green sand particles.

To be used in the casting process, virgin sand is coated with finely ground coal to produce a smoother casting finish. However, when mixed into SHCC material, the excess carbon on the sand surface accumulates on the fibres, as shown in Figure 8.8. This excess carbon effectively acts as a sleeve, preventing the necessary bond between fibre and matrix from forming.

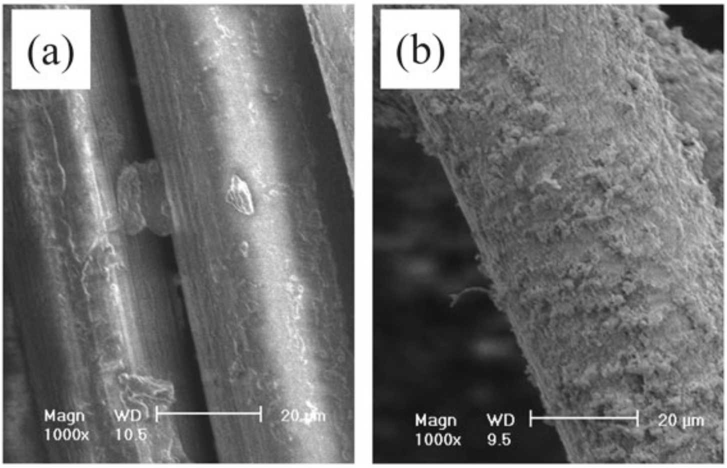

Fig. 8.8 (a) Virgin PVA fibre and (b) PVA with carbon residue coating.

During the original development of SHCC material, it was discovered that the strong bond between PVA fibres and the cement matrix was preventing strain hardening (Li et al., 2002). Therefore, the fibre surface was oiled to decrease the bond and improve the tensile response. Using the oiled fibres along with the foundry sand, the bond is too weak. Currently, PVA fibres used in SHCC have 1.2% (by volume) oiling content on the fibre surface. By reducing this to 0.3%, and thereby restoring the proper bond, the green SHCC material utilizing the waste sand shows ductility performance equivalent to standard SHCC (Figure 8.7). The substantial loss of tensile strength is due to lower matrix toughness as a result of incorporating the carbon coated sand particles. Only tensile strain capacity was considered in this work.

Following the methodology for incorporation of high volumes of fly ash, ground granulated blast furnace slag, and waste foundry sand, there exist countless opportunities for introduction of waste materials into SHCC materials. Due to the unique performance of these materials, this incorporation should be done while retaining large material performance advantages over concrete or other FRC materials.

8.4 Sustainability

While the sustainability of cement products and concrete materials, along with concrete and other infrastructure have received significant research attention recently, little work has been undertaken to specifically evaluate the sustainability performance of SHCC materials or SHCC structures. As emerging sciences, both SHCC materials themselves and the industrial ecology and life cycle analysis tools needed to evaluate the sustainability of SHCC structures are still in the developmental phase.

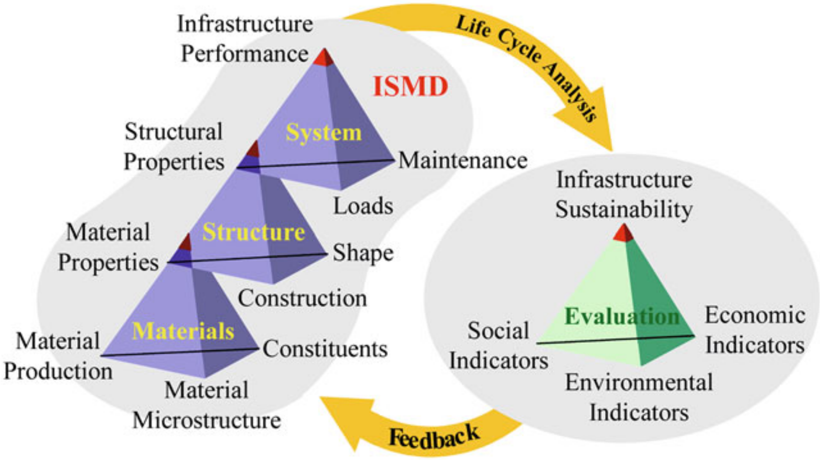

Fig. 8.9 Integrated materials design framework for sustainable infrastructure.

Most prominent among these are a set of environmentally friendly or "green" SHCC composites and the service life prediction models needed to complete a full life cycle analysis of SHCC structures. Built from these tools, Lepech (2006) and Keoleian et al. (2005a) proposed a framework for the design of sustainable infrastructure using SHCC materials. This framework is shown graphically in Figure 8.9.

The civil engineering portion of this framework is embodied in the Integrated Structures and Design Philosophy (ISMD) first proposed by Li and Fisher (2002). This multi-scale design philosophy links materials engineering, structural engineering, and infrastructure system operations through common design parameters thereby enabling engineers a greater flexibility in meeting overall infrastructure system performance requirements.

At its base, this design concept is rooted in materials science and engineering through the combination of various constituent materials, processing techniques, and microstructure formations to develop SHCC materials which display a designed set of material properties which can range from minimum strength to stiffness to water permeability. Structural engineers then use these materials properties, in conjunction with a particular structural shape and construction technique to design a particular structural property such as minimum load carrying capacity, deflection, or length of time until corrosion begins. Finally, system operators or owners account for structural properties in combination with the loads placed on the system and operational considerations to achieve a desired infrastructure performance level. This performance level is typically a multi-objective function depending upon numerous factors.

Taking advantage of this systematic approach toward SHCC structural design and management, Keoleian et al. (2005b), have expanded this theory by integrating efforts specifically aimed at increasing sustainability at each level of design and

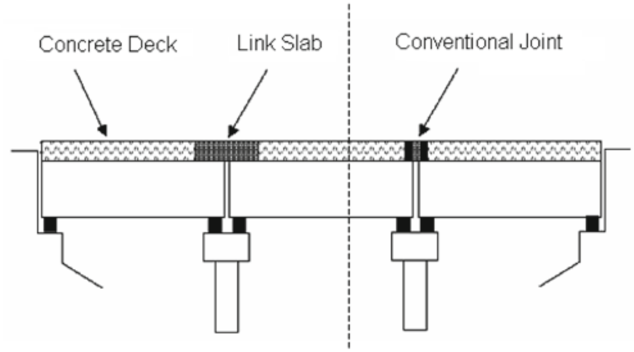

Fig. 8.10 Bridge deck schematic showing SHCC link slab and conventional expansion joints.

operation. This is accomplished using standardized life cycle analysis techniques to produce a set of sustainability indicators for the infrastructure system which accounts for contributions by each *material*, *structure*, and *system* design choice. This set of sustainability metrics, made up of social, economic, and environmental indicators, are ultimately used as feedback into the design process for iterative increases in overall infrastructure sustainability.

A unique bridge deck system was chosen by Keoleian et al. (2005a) to calculate the impacts SHCC materials may have on the sustainability of an infrastructure system. The bridge system studied incorporated SHCC link slab elements to eliminate problematic expansion joints on multi-span vehicle bridges. Using a green version of SHCC similar to those discussed in Section 8.3, a bridge was designed with SHCC link slabs replacing conventional joints (Figure 8.10). Critical within this design was the linking of material properties, particularly tensile strain capacity, with structural demands due to thermal expansion and contraction. This system is further described by Lepech and Li (2005).

Using the material proportions provided for green SHCC and an assumed service timeline for both conventionally jointed bridges and SHCC link slab bridges, the sustainability of the two systems was compared. The assumed timelines are shown in Figure 8.11. Within this timeline, the performance of SHCC link slabs was assumed to be double that of conventional joints. Durability testing is ongoing to verify these assumptions.

Results from Keoleian et al. (2005a) show that PVA-SHCC material is significantly less sustainable than conventional steel reinforced concrete (1% reinforcement ratio) material per litre. This is due to the higher cement content of SHCC material along with the energy associated with production of polymeric fibres. The energy consumption by material component is shown in Figure 8.12.

When considering the entire structure life cycle rather than material consumed during material production however, SHCC link slab bridges far outperform the conventional bridge deck. This is shown in Figure 8.13.

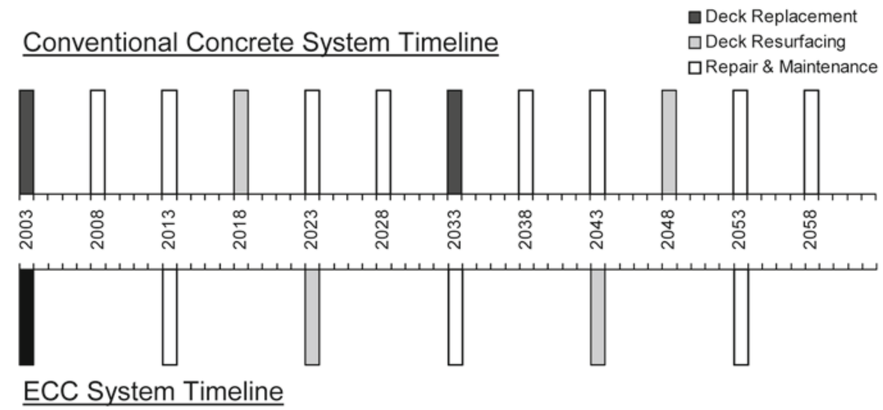

Fig. 8.11 Timeline of construction events for conventionally jointed bridge and SHCC link slab bridge.

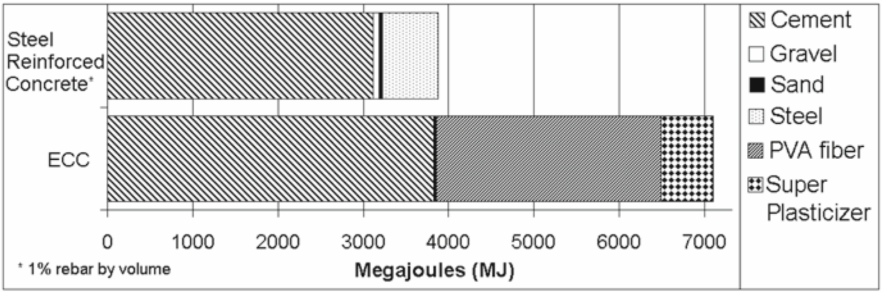

Fig. 8.12 Energy consumption per cubic meter of conventional steel-reinforced concrete and SHCC.

Due to the reduction in construction events over the entire life cycle of the bridge, significant energy is saved over the 60 year bridge timeline. As seen in Figure 8.13 the majority of these savings are in the "traffic" portion of the energy consumed. This is due to the elimination of traffic congestion as a result of construction bridge closures. With fewer construction events, less fuel is consumed over the entire service life by vehicles in cue.

Keoleian et al. (2005b) also found substantial economic savings associated with the SHCC link slab bridge in comparison with the conventionally jointed bridge. This is summarized in Table 8.4.

Key conclusions from Keoleian et al. (2005b) associated with the use of SHCC materials for improvement of sustainability were:

- Life cycle modelling is critical to enhance the sustainability of infrastructure systems.
- Construction related traffic (use phase) was dominant in determining the environmental performance of conventional and SHCC infrastructure systems.

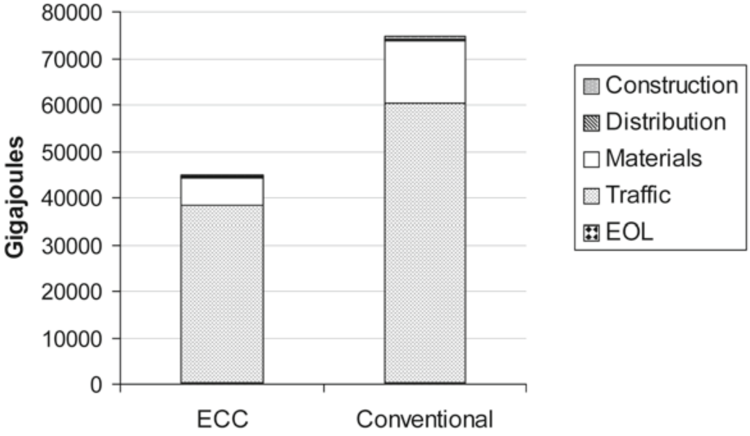

Fig. 8.13 Total primary energy consumption by life cycle stage for and SHCC link slab bridge and conventional jointed bridge.

Table 8.4 Total life cycle costs.

	Conventional system	ECC linkslab system	ECC cost advantage
Agency cost	$640,000	$500,000	22%
User cost	$21,300,00	$18,200,00	14%
Environmental costs	$34,000	$26,000	22%
Total costs	$22,000,000	$19,000,000	15%

- Accurate prediction of maintenance schedules and end of service life is critical in evaluating the performance of SHCC materials.

Similar findings were recently published from the 2003 Nordic Network "Concrete for the Environment" conference such that life cycle analysis is critical to the design of sustainable concrete structures, the use of highly durable concretes are needed to increase service life, and concrete materials must be designed and produced in ways which are tailor-made for the intended use for a specified lifetime, loads, environmental impact, and maintenance strategy (Glavind et al., 2006).

As a follow up to this bridge deck link slab study, Qian (2007) and Zhang et al. (2007) have investigated the use of SHCC materials for more durable, smoother, and therefore more sustainable, rigid pavement overlays. To evaluate the sustainability of rigid pavement overlay designs, Zhang et al. developed an integrated life cycle assessment and life cycle cost analysis model to calculate the environmental impacts and costs of overlay systems resulting from material production and distribution, overlay construction and maintenance, construction-related traffic congestion, overlay usage, and end of life management. An unbonded concrete overlay system, a hot mixed asphalt overlay system, and an alternative engineered cementitious composite (SHCC) overlay system were examined.

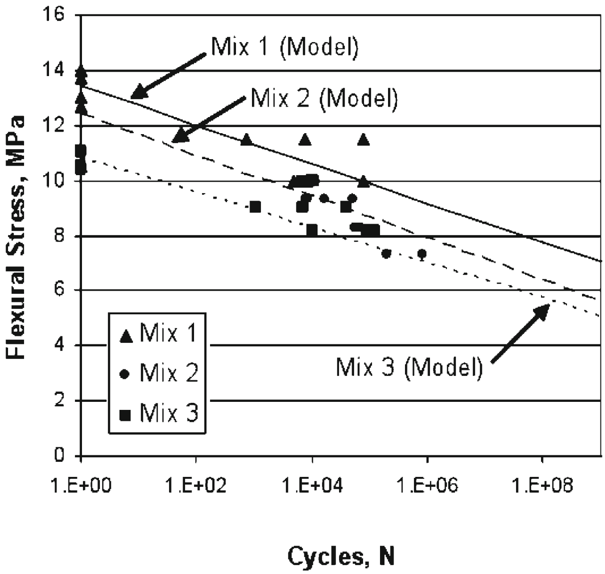

Fig. 8.14 Fatigue performance of three SHCC mix designs (flexural strength versus number of flexural load cycles).

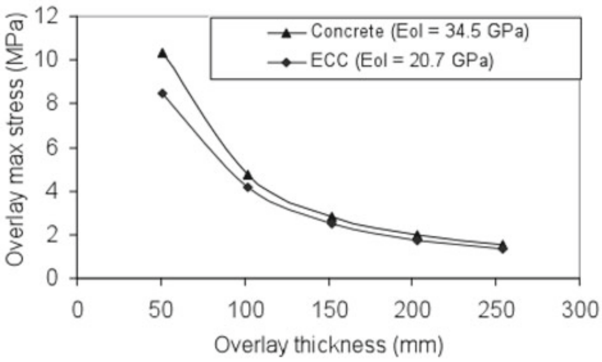

Fig. 8.15 Overlay slab maximum tensile stress versus overlay thickness.

As part of this work, Qian et al. (2007) along with Lepech et al. (2008) developed a set of deterioration models that can be used to predict SHCC pavement overlay deterioration over time and estimate the end of service life. This framework begins with individual material fatigue response in the form of traditional S-N curves (Figure 8.14). FEM analysis of the actual overlay structural system is used to determine a maximum stress level within the overlay, accounting for the unique material properties of SHCC materials (Figure 8.15). Combining these two, an estimation can be made which relates design choices of SHCC material and overly thickness to pavement deterioration rates and end of service life calculations.

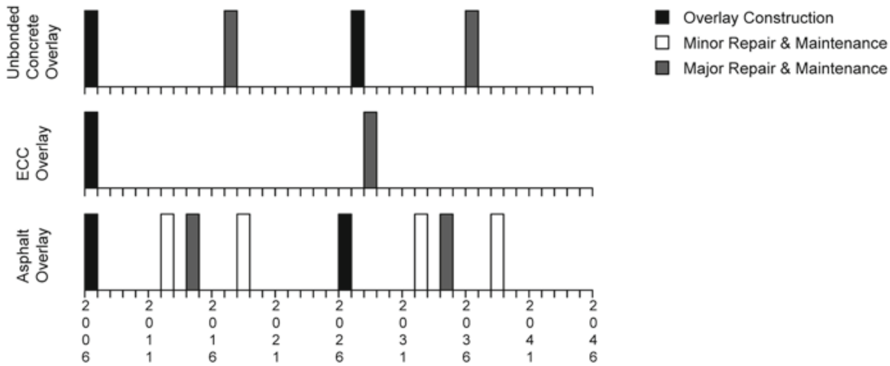

Fig. 8.16 Timeline of construction events for unbonded Concrete, SHCC, and hot mix asphalt overlays.

Similar to the timeline for bridges shown in Figure 8.11, a life cycle maintenance timeline has been developed which captures the improved performance of the overlay structural system resulting from the improved material properties of SHCC materials. This comparative timeline is shown in Figure 8.16. (Reference maintenance timelines were taken from Michigan Department of Transportation standard operating practices.)

Similar to results from Keoleian et al. (2005a), Zhang shows that PVA-SHCC material is significantly less sustainable than conventional steel reinforced concrete (1% reinforcement ratio) material when compared on a per litre basis. This is due to the higher cement content of SHCC material along with the energy associated with production of polymeric fibres. However, SHCC is more sustainable than hot mixed asphalt (HMA) material due to the large amount of feedstock energy (petroleum) used in the production of asphalt. The energy consumption by material component is shown in Figure 8.17.

Similar once again to Keoleian et al. (2005a), when considering the entire structure life cycle rather than material consumed during material production however, SHCC overlays outperform both HMA and concrete overlays. This is shown in Figures 8.18 and 8.19.

Zhang et al. (2007) found that due to the reduction in construction events over the entire life cycle of the overlay along with reductions in surface roughness leading to greater fuel economy, significant energy resources and global warming potential is saved over the 40 year overlay timeline. Unlike the link slab example however, the majority of energy and global warming reductions are due to savings in the materials production stage of the life cycle. Due to the much larger quantities of materials used in overlay applications as compared to bridge link slabs, the impacts of materials greening (i.e. incorporating industrial waste streams) are more prevalent. However, durability aspects remain important because more durable SHCC overlay materials require fewer replacement events (Figure 8.16) and thereby consume less material over their entire service life.

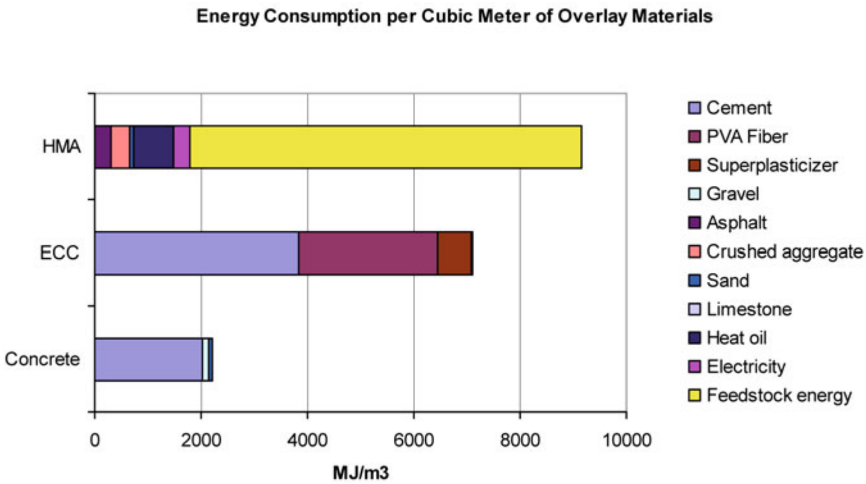

Fig. 8.17 Primary energy consumption of hot mixed asphalt, SHCC, and concrete materials per volume of each material produced.

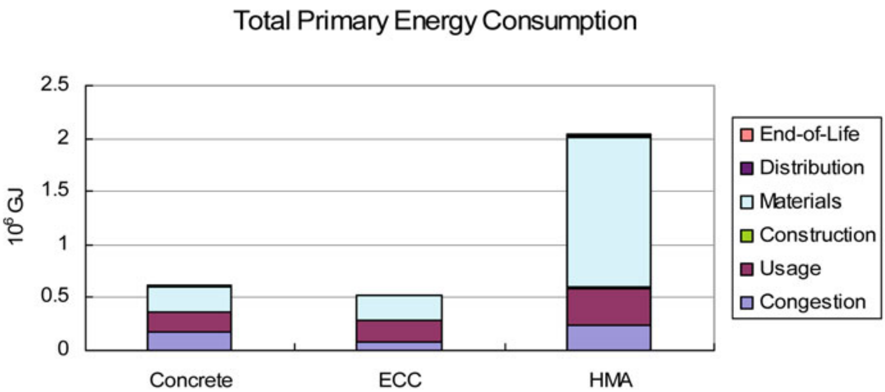

Fig. 8.18 Total primary energy consumption of concrete, SHCC, and hot mixed asphalt overlays by life cycle phase.

8.5 Conclusions and Future Research

It is well known that SHCC materials are often more expensive than traditional concrete materials when measured on a per cubic meter basis. While some cost advantages may arise due to smaller designed size of SHCC members or elimination of reinforcing steel, these savings are often not enough to entice builders to use SHCC materials. There is profound evidence that through complete life cycle costing of structures incorporating SHCC materials, significant cost savings can be realized. This is demonstrated in a life cycle cost savings of 22% to bridge owners in the USA when implementing SHCC bridge deck elements to replace failing

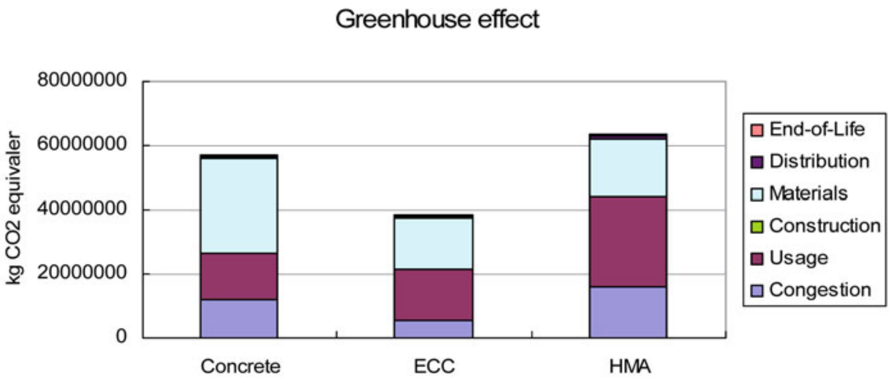

Fig. 8.19 Total global warming potential of concrete, SHCC, and hot mixed asphalt overlays by life cycle phase.

expansion joints. In addition to these economic costs borne individually by the infrastructure owner, life cycle costing can also address the environmental and social costs associated with construction and quantify any savings resulting from SHCC implementation. These may prove to be significant drivers in the wider adoption of SHCC materials.

Many of the materials development tools are in place to incorporate industrial waste streams into SHCC composites to reduce their environmental impact. Using these tools, work remains in the identification of new waste streams for additional greening of SHCC materials while preserving the unique material properties which set them apart from other concrete and FRC composites. Significant work also remains to be done in the development of service life prediction models for both SHCC structures and composite structures which adopt SHCC materials in strategic locations. Without such predictive models, efforts to estimate the improvements in sustainability through the use of SHCC materials remain difficult. Once this work is complete, an iterative design loop for increasingly more sustainable infrastructure using SHCC materials, shown above in Figure 8.9 can be more fully implemented.

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