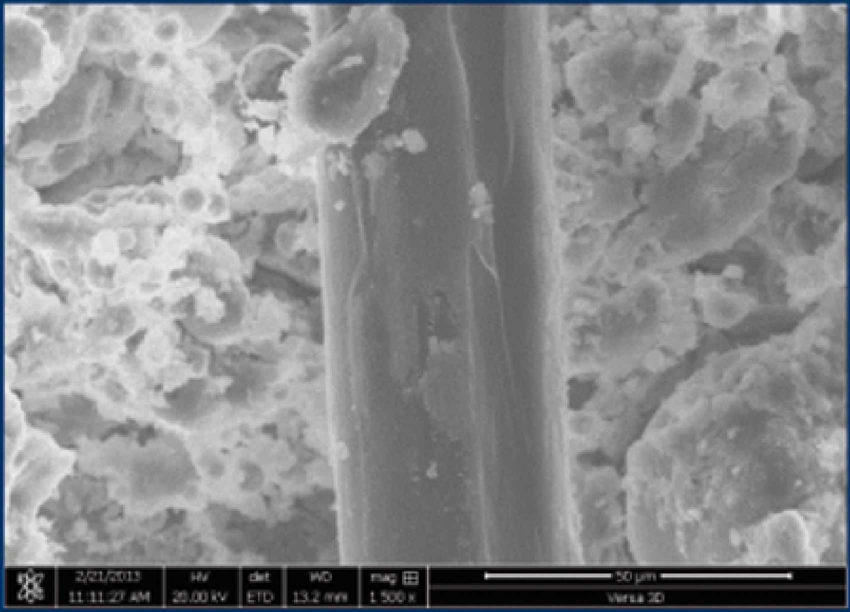
Proceedings

Joint Saudi Arabian-German Workshop on Strain-hardening Cement-based Composites

in the framework of the International RILEM Conference Application of Superabsorbent Polymers and Other New Admixtures in Concrete Construction



Edited by Viktor Mechtcherine M. Iqbal Khan

Joint Saudi Arabian-German Workshop on
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Application of Superabsorbent Polymers and Other
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- prepare state-of-the-art reports to identify further research needs,
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Joint Saudi Arabian-German Workshop on Strain-hardening Cement-based Composites

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Preface

Strain-hardening cement-based composites (SHCCs) reinforced by short PVA fibers constitute a relatively new class of building material, which exhibits pseudo-strain-hardening behavior with multiple-crack formation when tested under tension loads at quasi-static strain rates. The high ductility and strain capacity of SHCC are exceptional for cement-based materials. They give this material a marked potential for use in applications in which high non-elastic deformability is needed. Examples of promising applications include link slabs for jointless bridge decks, structural repairs, connecting beams for high-rise buildings in earthquake-prone areas, and the strengthening of masonry structures. Because of their beneficial and easily describable stress–strain behavior (similar to steel), the use of ductile cementitious composites may be advantageous and revolutionize the design of concrete structures in the near future. Based on fracture-mechanics considerations and the micromechanical modeling, strain hardening and an ultimate strain of approximately 5% (i.e., approximately 300 times greater than that of ordinary concrete) can be achieved using approximately 2% polymeric fibers by volume.

A number of research groups in different countries (USA, Germany, Japan, New Zealand, Brazil, South Africa and some others) are currently working on the further development of SHCC. The importance of this research topic can also be recognized by the fact that, in recent years, two corresponding RILEM Technical Committees have been initiated: “High performance fiber reinforced cementitious composites” and “A framework for durability design of fiber-reinforced strain-hardening cement-based composites”. In the Arabic countries, the scientific work in this area started with the joint project of the King Saud University (Saudi Arabia) and Technische Universität Dresden (Germany) funded by the King Abdulaziz City for Science and Technology (KACST), The Long-Term Comprehensive National Plan for Science, Technology Innovation (Project No.: 12-ADV2591-02). The proceedings at hand is a result of the Saudi Arabian-German workshop organized in Dresden by both institutions in conjunction with the International RILEM Conference on Application of Superabsorbent Polymers and Other New Admixtures in Concrete Construction. The organizers of the workshop and the editors of the proceedings believed that this document will considerably contribute to the international state of knowledge with respect to the material technology and structural applications of strain-hardening cement-based composites.

V. Mechtcherine, M. I. Khan

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CRACK DEVELOPMENT IN SHCC ELEMENTS REINFORCED WITH STEEL BARS AND SUBJECTED TO TENSILE LOADING

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Abstract: *The application of SHCC in structural elements can require the use of reinforcement in order to transfer tensile forces into the element or to influence post peak behaviour and secure the structural integrity even after final cracking of SHCC occurred. The design of structural members made of SHCC and containing conventional steel reinforcing rebars requires a sound understanding of the mechanical characteristics for the composite material R/SHCC under tensile loading. The goal of the research work at hand was to investigate the interaction between steel reinforcement and SHCC and thus the performance of R/SHCC elements by means of large-scale uniaxial tests. The experiments were performed on slab elements with a length of 3 m, a width of 1 m and a thickness of 0.24 m. The degree and configuration of steel reinforcement were the main parameters under investigation. The experiments proved that SHCC contributes considerably to the tensile load bearing capacity of the tension elements even after initial cracking. This stage is characterized by multiple cracking in SHCC and results in a nearly linear increase in stresses and strains up to the yielding of the steel reinforcement. It could be concluded that SHCC substantially enhances the tension-stiffening behaviour of the elements in comparison to R/C elements by contributing considerably to load transfer during the process of multiple cracking. Thus, a pronounced increase of the tensile strength of the elements was observed. This phenomenon and the reduction of the element stiffness due to multiple cracking, which might have an effect on the redistribution of internal forces, should be considered in structural design of reinforced SHCC elements.*

Keywords: SHCC, steel reinforcement, structural design, tension-stiffening, uniaxial tension test.

1 INTRODUCTION

The structural condition of many reinforced and pre-stressed concrete bridges in Germany and around the world has worsened in recent years resulting in a rising demand of rehabilitation measures. One reason for this can be found in the corrosion of the reinforcement due to the development of wide cracks. These cracks can be a result of tensile stresses due to imposed deflections or high traffic loads and thermal and hygral stresses due to restraint.

The latest developments for addressing this problem focussed on the limitation of crack widths in the state of serviceability by controlling the number, diameter and distribution of reinforcing bars. This however has influenced the economic efficiency of the concrete construction since high amounts of steel reinforcement become necessary as the result of normative requirements to achieve the desired durability.

Another approach to solve the problem of wide cracks on the material level is the use of strain-hardening cement-based composites (SHCC) [1-4]. The use of such materials seems to be especially meaningful when concrete is used in tension members of composite trusses or as the tension chord of bowstring bridges with a composite bridge deck [5] or in other non-structural parts like concrete joints or link slabs [6].

For all of these situations the designing engineer has to ensure the safety and durability of the structure. The significance of this problem becomes even more apparent when a structure is exposed to environmental impacts. This generally applies to most engineering structures like bridges, water constructions or industrial buildings. These structures are often heavily exposed to water, chemicals, chlorides, high temperature changes and dynamic loads. Especially the condition of the existing infrastructure for which all of these factors apply shows how important an effective limitation of crack widths is to maintain the durability of the structure and hence ensure the safety.

To analyse the potential capacity of using SHCC in structural tension members a series of large-scale tests with various reinforcement ratios and configurations was performed. For the tested element with a length of 3 m the bond length was sufficient to transfer the tensile load into SHCC and therefore to achieve a uniform stress distribution throughout the specimen in its central part and subsequently formation of completed crack patterns in the elements.

The material parameters of the SHCC obtained from large-scale trial mixes produced in a conventional concrete mixing plant can be found in Table 1. The compressive strength was tested on cubes with an edge length of 100 mm. The tensile tests were carried out on dumbbell-shaped specimen with a constant cross-section of 40 mm to 20 mm in the measurement zone.

Table 1: Mechanical properties of SHCC at the age of 28 days (standard deviation is given in parentheses)

Batch	Compressive strength [MPa]	First crack stress [MPa]	Tensile strength [MPa]	Strain capacity [%]	Modulus of elasticity [MPa]
S03	49.4 (1.8)	2.88 (1.09)	3.68 (0.16)	0.86 (0.30)	21,800 (490)
S04	49.3 (0.8)	3.73 (0.33)	4.02 (0.33)	0.71 (0.07)	21,630 (160)
S05	49.3 (0.1)	3.00 (0.23)	3.90 (0.41)	0.55 (0.40)	20,800 (470)

2 TESTING STRUCTURAL MEMBERS

2.1 Concept and design

The interaction of SHCC and steel reinforcement as well as the influence of SHCC on the load-deformation behaviour of the reinforced SHCC elements has been studied in [7, 8]. It could be shown that the material properties of SHCC have a significant effect on the crack formation and development compared to conventional reinforced concrete [8]. In the study at hand nine specimens were produced for the investigation on the load-deformation of reinforced SHCC elements from which 6 are presented in this article. The slab elements had a length of 3 m and a width of 1.00 m. Two different reinforcement configurations were used to analyse the influence of the distribution of steel bars on the structural response and the crack pattern.

One single layer reinforcement without and a double layer reinforcement with transversal reinforcement were produced. With a specimen thickness of 0.24 m this resulted in a concrete cover of approximately 110 mm for the single layer type and 25 mm for the double layer type. Three different configurations were chosen with a reinforcement ratio of ρ ≈ 0.65, 0.50 and 0.25. Ribbed steel bars with a yielding strength of 550 MPa were used as reinforcement. Figure 1 shows a schematic view of the specimen design.

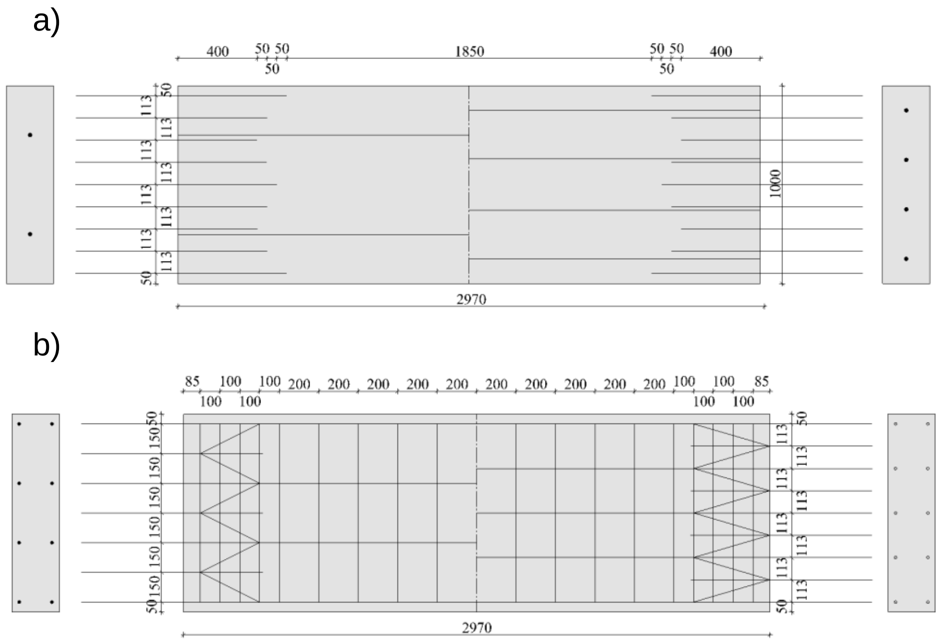

Figure 1: Schematic view of the reinforced slab elements with a) single layer reinforcement and b) double layer reinforcement

2.2 Experimental setup

A 20 MN test frame for the testing of pre-stressed steel cables was adopted for the tensile loading of the specimens. The load was applied onto a steel bar with a diameter of Ø 65.5 mm and a maximum load capacity of 1.5 MN. The steel bar transferred the load onto a stiff steel plate which ensured an even distribution of the forces on the individual steel rebars. These were attached to the embedded reinforcement with socket joints.

The global deformation was measured on the surface of the specimen with 16 LVDTs. The LVDTs were applied on both sides in the longitudinal and transverse directions. Furthermore, a 2D optical, close-range photogrammetry system was used for the measurement of local deformations on the element surface. The photogrammetrically measured surface area was 400 mm long and 300 mm wide, see Figure

2. It enabled a continuous monitoring of crack formation and quantitative evaluation of the crack development.

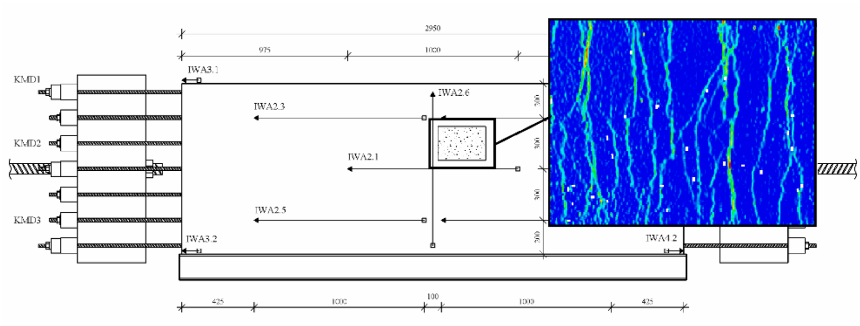

Figure 2: Test setup for uniaxial tension tests on R/SHCC slabs and location of the photogrammetric measurement field

3 EXPERIMENTAL RESULTS

3.1 Global load deformation behaviour

The elements were loaded monotonically in tension under displacement control at constant displacement rate of 0.01 mm/s.

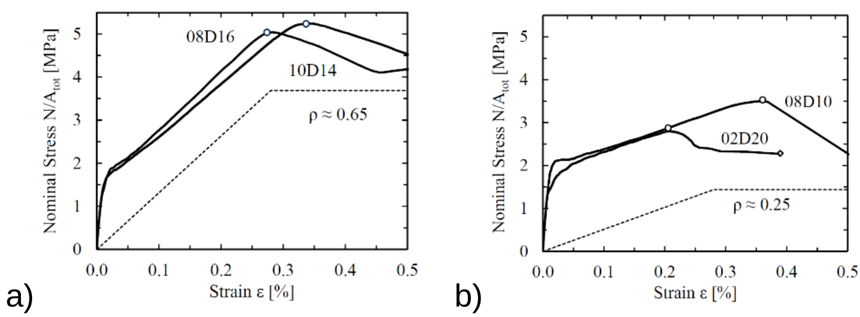

Figure 3: Stress-strain diagram for R/SHCC slabs with a reinforcement ratio of a) ρ ≈ 0.65 and b) ρ ≈ 0.25

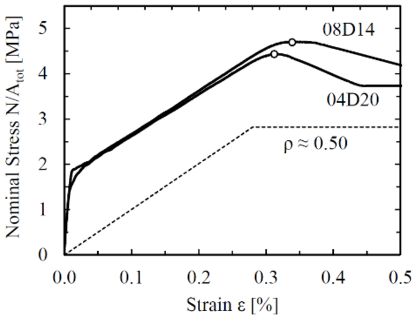

Figure 4: Stress-strain diagram for R/SHCC slabs with a reinforcement ratio of ρ ≈ 0.50

The resulting stress-strain diagrams are shown in Figures 3 and 4. The nominal tensile stress was calculated by dividing the tensile force measured with the internal load cell by the entire cross-section of the specimen. The strains were obtained from the averaged displacement measurements with LVDTs. This enabled the calculation of the overall deformation behaviour of the slab with the correction of induced eccentricities caused by the test setup.

To highlight the contribution of SHCC to the load deformation behaviour of the composite material the equivalent stress-strain responses of the plane steel rebars are shown for comparison in the same diagrams. The first cracking of the reinforced SHCC slabs was attained at a strain level of approximately 0.01 to 0.02 % with a corresponding tensile force of 450 kN which equals a nominal tensile stress of 1.9 MPa. In the following second stage the slabs exhibit a pronounced strain-hardening behaviour due to increasing development of multiple fine cracks and transfer of tensile stresses across cracks by fibres. A nearly linear increase in stress can be observed with increasing strain until the ultimate load level is reached at a strain of approximately 0.3 % which coincides with the beginning of steel yielding. After the tensile strength is reached a localization of the strains occurs, which results in the formation of a major macro-crack. The localisation is accompanied by a strain-softening behaviour of R/SHCC slabs in the yielding state.

3.2 Crack formation

During the loading of the specimen the deformations at its surface were monitored with digital close-range photogrammetry as it was used in previous studies [9]. The images were taken with a regular camera and the trigger signal was recorded so that the pictures could be synchronised with the corresponding load levels. The local strains were derived as the difference between the displacement of each facet in the measurement field at the regarded load stage and the reference stage, i.e. that for the unloaded specimen.

With a camera distance of approximately 1.0 m and a maximum camera resolution of 4032x3024 Pixel cracks with openings of more than 15 μm could be identified out of the measurement "noise". This data was used for the calculation of the number of cracks and their openings for each moment of loading. Five section lines were used in the calculation algorithm as reference for the displacement calculation of the facet coordinates. The development of crack openings as a function of strain could be calculated by taking the mean values of the crack widths at all five section lines.

The following Figures 5 to 7 show the development of the crack widths for each of the described specimens as the maximum, minimum and average crack openings calculated for increasing average strains in the element. For a better comparison the two specimen of each reinforcement ratio are displayed in each diagram.

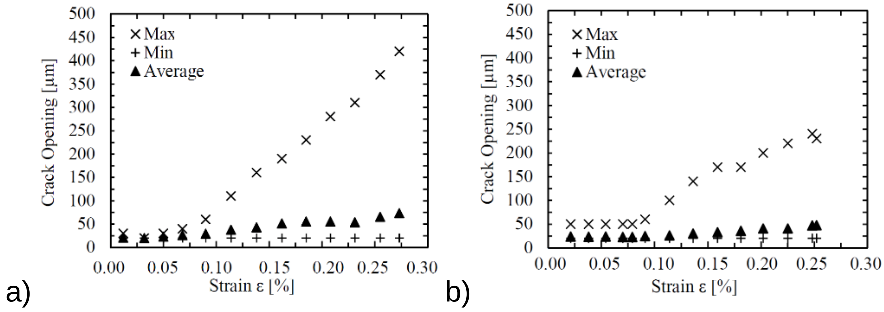

Figure 5: Development of crack widths with increasing average strain for a reinforcement ratio of ρ ≈ 0.65 with a) smaller (10D14) and b) larger (08D16) distance between rebars

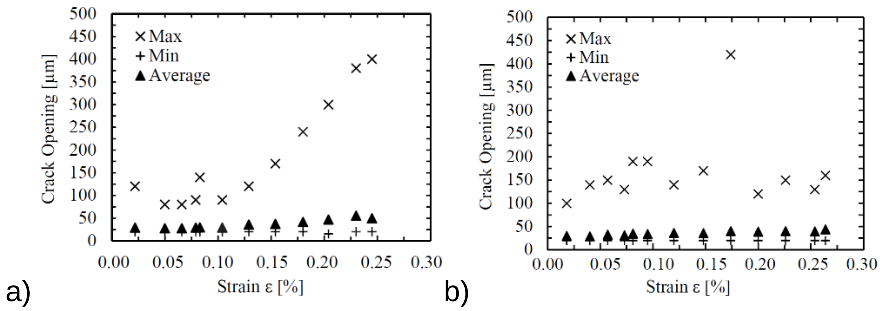

Figure 6: Development of crack widths for a reinforcement ratio of ρ ≈ 0.5 with a) large concrete cover (04D20) and b) small concrete cover (08D14)

It is apparent from these diagrams that maximum crack widths vary between 200 µm and 450 µm at the ultimate loading of the specimen. The average crack widths however remain with values below 50 µm very small until the failure of the specimen. This can be traced back to the pronounced multiple cracking. By comparing the maximum crack openings of the specimens with single and double layer reinforcement a better limitation of the maximum crack opening could be observed for the slabs with a small concrete cover (i.e. those with double layer reinforcement). It was also found that the number of cracks increases significantly if the cover thickness of the element becomes smaller.

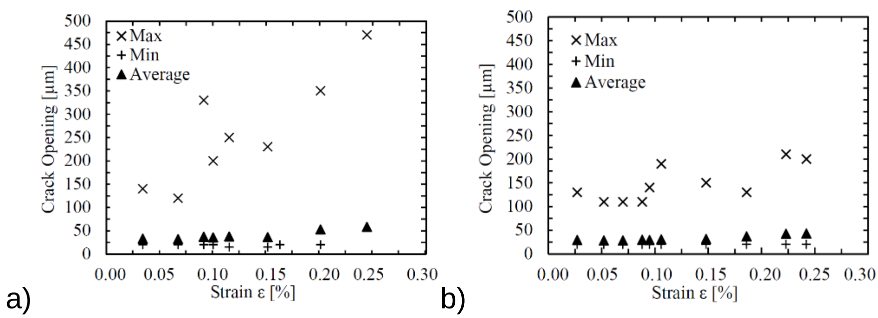

Figure 7: Development of crack openings with increasing average strain for a reinforcement ratio of ρ ≈ 0.25 with a) larger (02D20) and b) smaller (08D10) concrete cover

4 CONCLUSIONS

The research presented in the article at hand shows the influence of ductility of SHCC on the load-bearing behaviour and crack formation of structural elements made of SHCC and reinforced with steel bars. The structural response of the R/SHCC elements under tensile loading was investigated in large-scale experiments. Additionally, the average strains in the middle part of the slabs were measured and the cracking on the concrete surface was observed by digital close-range photogrammetry. Therefore, both the global and local load bearing behaviour could therefore be analysed.

The tests showed that the fibres contributed substantially to the load-carrying capacity of the structural members after formation of first cracks leading to a much more pronounced strain-hardening behaviour of R/SHCC elements in comparison to conventional R/C elements. It could also be shown that the quasi-ductile behaviour of SHCC associated with multiple cracking can be used to considerably reduce the average and to a lesser extend also maximum crack openings. The limitation of average crack widths by the use of SHCC can improve the durability of structural elements and allow an efficient design.

It is was found that the concrete cover (or, with other words, the distribution of steel bars over the cross-section) can have a pronounced influence on the crack development on the specimen surface, i.e. on the number of cracks and crack openings. This issue is a subject of a more detailed ongoing investigation.

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PRODUCTION OF SUSTAINABLE STRAIN-HARDENING CEMENT-BASED COMPOSITES USING DIFFERENT NATURAL SANDS

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Abstract: *Advanced concrete technology has taken a wide step forward in the production of ultra ductile cementitious composites. The main purpose of these composites is to be applied for different applications such as structural repairs, supporting beams under earthquake and blast loads, high impact force, etc. Strain-hardening cement-based composites (SHCC) are the output of such technology characterized with ultra ductility. Their preparation requires the use of superior contents of different combinations of materials. Cement, fine powders and fine aggregates of well-defined and uniform grain sizes as well as elevated dosages of chemical admixtures and definite amount of fibers represent these materials. The use of available local sources in the preparation of the mandated materials required for SHCC was the main aim of the present study. Dune and white sands are enormously available by nature in the Arabian Gulf region. In this study different particle size distributions from these sands were prepared, analyzed and investigated for the feasibility in the production of SHCC from the available local materials. The results have shown that dune sand is the best economical, ecological and sustainable candidate as fine material for the production of SHCC. The presence of dune sand has provided similar properties to the international and uniformly imported graded quartz. The use of dune sands has been proved to potentially reduce the overall cost of SHCC while maintaining the major strain-hardening properties intact.*

Keywords: Natural sands SHCC, sustainability.

1 INTRODUCTION

Construction technology and development move ahead and step forward to satisfy the current and future needs of this era of construction booming. The rate of the progress in construction technology and its direct applications are sometimes halted by various types of obstacles. The quality and availability of the constituting construction materials are one of the main challenges in this domain. Industrial wastes and abundantly available natural materials could be successfully used in construction. Concrete is one of the main construction element that has ever been used since long time. Development in concrete technology has led to a series of different types of concrete for specific applications. Other technologies from other domains have been brought and inserted into concrete during its development. Fiber-reinforced concrete becomes an essential part in the recent concrete technology applications due to its improved strain resistance [1, 2]. Strain-hardening cement-based composites (SHCC) are an extension to the application of fibers into a highly developed cementitious system. SHCC are known of their ultra ductility [3, 4]. SHCC has unique strain-hardening properties [5]. These exceptional properties are attributed to the nature of the mix composition, fibers technology and to the advances in research behind this type of relatively new construction technology. SHCC composition requires the presence of crystalline fine quartz which is abundantly available in the Arabian Gulf. Crystalline fine quartz is available in the form of natural sands that cover huge area in the Arabian Gulf. These natural sands are one of the best candidates for the use as fine materials in SHCC production. The mix composition of SHCC is known by its elevated contents of cement, fine powders and aggregates of well-defined and uniform fine grain sizes [4, 6 and 7]. Additionally, elevated dosages of chemical admixtures along with a definite amount of fibers are still needed. Two types of abundantly available natural sands in the Arabian Gulf can be used as fine crystalline quartz in the production of SHCC. The aim of the current investigation is to explore the effect of the presence of different types of natural sands of different grain sizes on the mechanical properties of SHCC containing PVA fibers.

2 EXPERIMENTAL INVESTIGATION

2.1 Materials

Fine powder: Ordinary Portland cement (PC) conforms the requirements of ASTM C150 specifications, was used as the available binder which was partly replaced by class F fly ash. PC has a median grain size of 14 µm while fly ash (FA) has a median grain size of approximately 10 µm. The physical and chemical properties of the above mentioned powders are summarized in Table 1. The particle size distributions of the fine powders are shown in Figure 1. The mineralogical composition and microstructure of FA is shown in Figure 2.

Table 2: Physical and chemical properties of cementitious materials

Oxide composition (%)	Ordinary Portland cement	Fly ash
SiO_2	20.2	50
Al_2O_3	5.49	28
Fe_2O_3	4.12	10.4
CaO	65.43	<6
MgO	0.71	<4
Na_2Oeq	0.26	1.5
SO_3	2.61	<2.5
Loss on ignition (%)	1.38	4
Specific gravity	3.14	2.3
Fineness (m^2/kg)	373	300-600

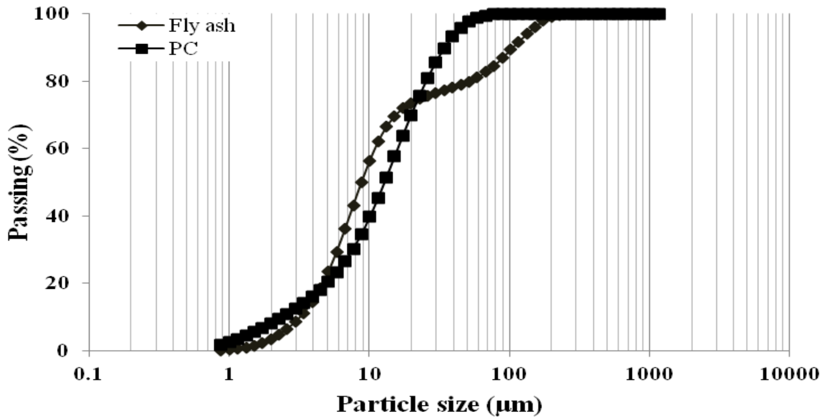


Figure 1: Particle size distribution of cement and fly ash

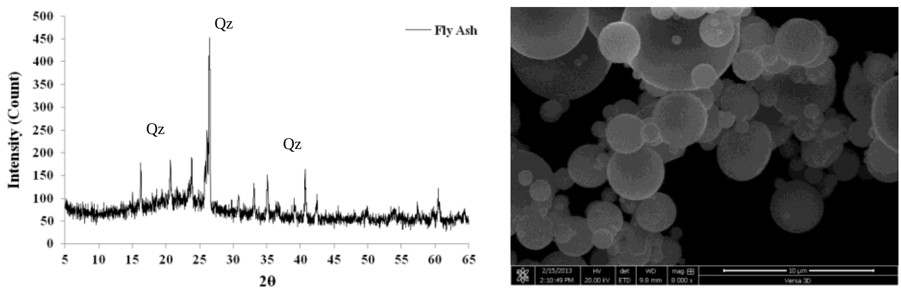


Figure 2: Mineralogical composition and microstructure of fly ash

Fine aggregates: A series of natural sands of different particles sizes originated from local white sand (WS) and dune sand (DS) and their ground powders (GWS and GDS). They are sourced from the East of Riyadh, Saudi Arabia with median grain sizes of 270, 133, 210 and110 µm, respectively, as shown in Figure 3. The microstructure of white and dune sands (WS and DS) in addition to their optimized ground forms (GWS and GDS) is shown in Figure 4. The microstructure of the natural sand shows their spherical and angular forms. Microstructural analysis shows that both WS and DS originally have a spherical structural rather than angular which should improve the rheological properties of SHCC mixtures.

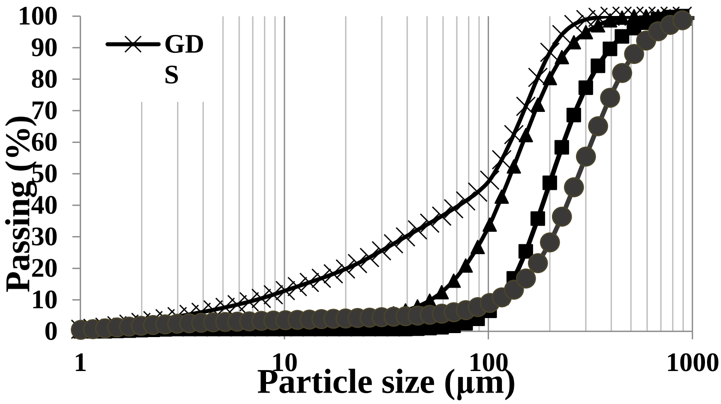


Figure 3: Particle size distribution of natural sands and their ground forms

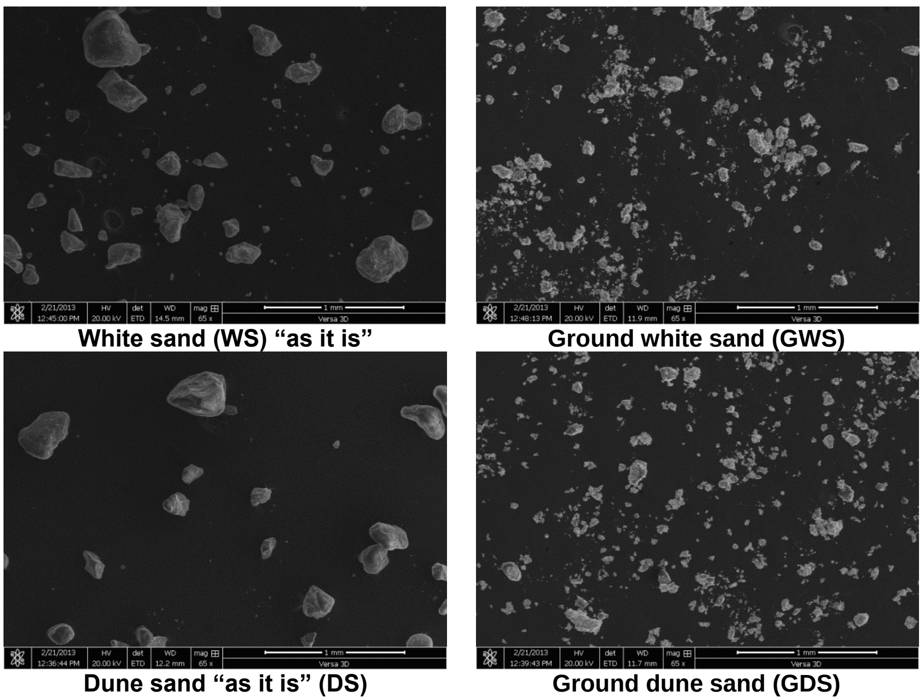


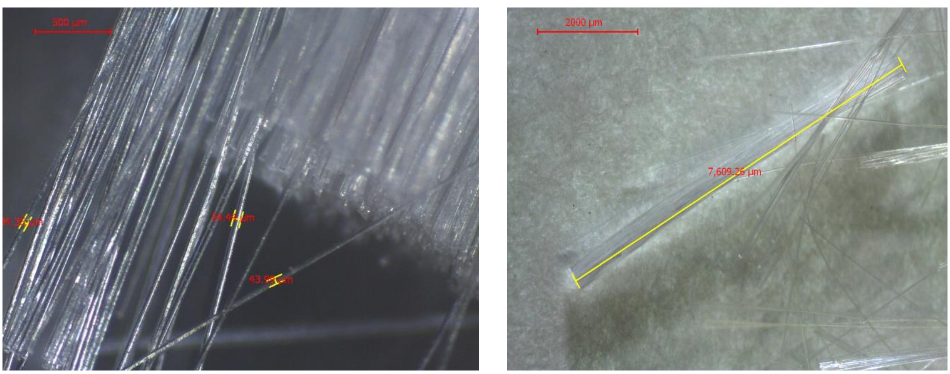
Figure 4: Photomicrographs of the used natural sand in its original and ground state

Chemical admixtures: A modified polycarboxylic ether (PE) polymer was used in the production of HSCC. It has a specific gravity of 1.1 and dry extract of 36 %. The dosage of PE is expressed as a dry extract (D.E.) per cement weight. Optimized PE dosages were determined.

PVA fibers: Poly vinyl alcohol fibers (PVA) were used in this investigation. The stereomicroscopic, geometrical and mechanical properties are shown in Table 2 and Figure 5.

Table 2: PVA fibers geometrical and mechanical properties

	Diameter (µm)	Length (mm)	Tensile strength (GPa)	Young's modulus (GPa)	Aspect ratio
PVA	~ 45	~ 7.5	1.8	46	166



23 ºC

Figure 5: Stereomicroscopic investigation of PVA

2.2 Methods

The experimental plan has begun by grinding WS and DS using Fritsch pulverisette 6 planetary mono Mill (320 RPM) to get the half value of the original median particle sizes of WS and DS. The optimization of PE dosage in SHCC mixtures with different natural sands of different particle size distributions was secondly conducted. A fixed amount of cement and class F fly ash were used.

Mixing procedures and testing: The protocol of mixing was to pour PC pre-homogenized with fly ash over fine sand then the whole mix was homogenized for few minutes. The final homogenized mix was gently poured over water premixed with the optimized PE dosage in Hobart bowl under run in speed # 1 within 4 minutes. The mixer was stopped for 30 sec to clean the wall of the ball by pushing down the flushed mix. The mixer was put on again for 5 minutes during which the required amount of fibers was slowly added while pressing fibers by fingers to disperse into separate strands. At the end of 5 minutes, the mixer was stopped and shifted to speed # 2 for 2 minutes. The final mix was then cast into the mould and pushing the different layers over each other followed by finishing the surface. Standard moulds for prisms of 16.3 x 16.3 x 40 mm and cubes of 50 mm, respectively, were used. After 24 hours, samples were demoulded and standard cured for 7 days. The prism moulds were tested for flexural strength and the cubes moulds for compressive strength. The mechanical properties of the mixtures were determined using Toni tech machine, as shown in Figure 6. The compressive strength was determined according to ASTM C 109 under a constant loading rate of 0.2 MPa/s while the flexural strength was determined according to ASATM C348 under a constant displacement rate of 1 mm/min.

Figure 6: Testing machines

SHCC mix design: The mix design of SHCC mixes investigated in this study is shown in Table 3. The amount of fiber added was equivalent to 2.2 % (volume based). Two PE dosages of 0.20 and 0.29 % (D.E., per cement weight) were used for both original sands (0.2 %) and their ground form (0.29 %), respectively.

Table 3: Mix design of SHCC mixes

	Cement [kg/m^3]	Fly Ash [kg/m^3]	Sand [kg/m^3]	Water [kg/m^3]
W29	505	613	534	324

3 RESULTS AND DISCUSSION

3.1 Effect of sand on the mechanical properties

The effect of grain size of two types of local natural sands on the compressive and flexural strengths of SHCC mixtures is shown in Figure 7. The results show that the compressive strength of SHCC mixture made with DS has the highest value whereas the other SHCC mixtures have similar compressive strengths, as shown in Figure 7a. On the other hand, the flexural strength of DS and WS show the highest values while GWS shows the lowest whereas GDS shows an average value, as shown in Figure 7b. These results reflect two concepts relying on two factors; 1) the packing effect which affect the compressive strength and 2) the bonding effect which affect the flexural and tensile strengths. These two main factors are affected by the nature of the cementitious matrix. SHCC mixture with DS seems to be the optimum which provides the highest compressive and flexural strengths due to the highest packing and bonding effect affected by the nature of DS particles.

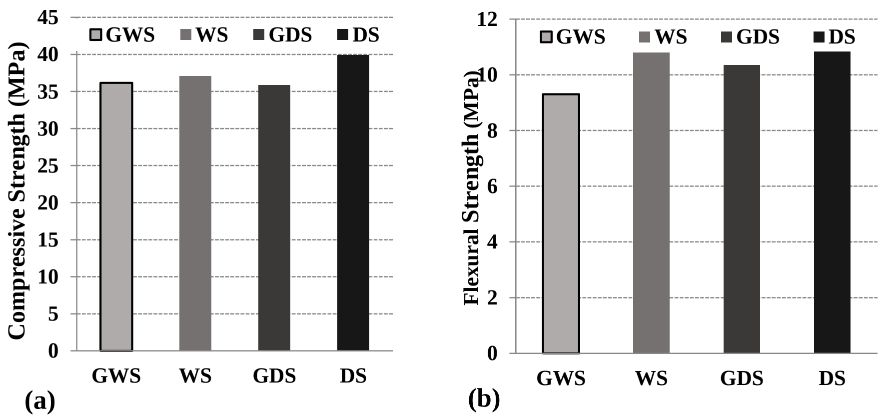


Figure 7: Test results of (a) compressive strength (b) flexural strength

Regardless of the type of sand and they are of same origin, the effect of particle size on the compressive and flexural strength is investigated, as shown in Figure 8. There is a weak relationship between median particle size and compressive strength. On the other hand, there is a direct relationship between the median particle size and flexural strength with high correlation coefficient (R^2=0.8). The optimum median particle size is equal to 210 μm.

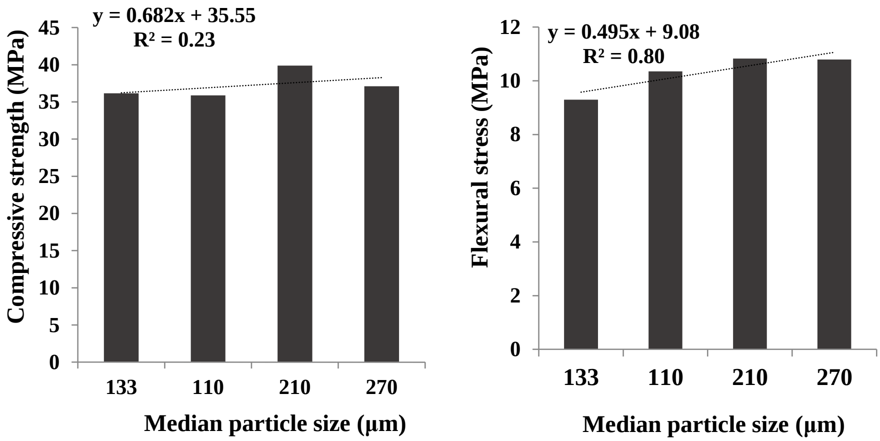


Figure 8: Effect of particle size on the compressive and flexural strengths

3.2 Effect of sand on the microstructure of SHCC mixtures

The microstructural analysis reveals and confirms the fact of the existence of packing and bonding effects. The microstructural results of SHCC mixtures after flexural strength test show that SHCC mixtures with DS and GDS have better bonding with PVA fibers than WS and GWS, as shown in Figure 9. The characteristic bonding of DS with PVA fibers and its effect on the thermal stability of PVA is covered in another work. This again proposes the existence of compatibility between the cementitious matrix and PVA fibers should be taken into account during the mix design of SHCC.

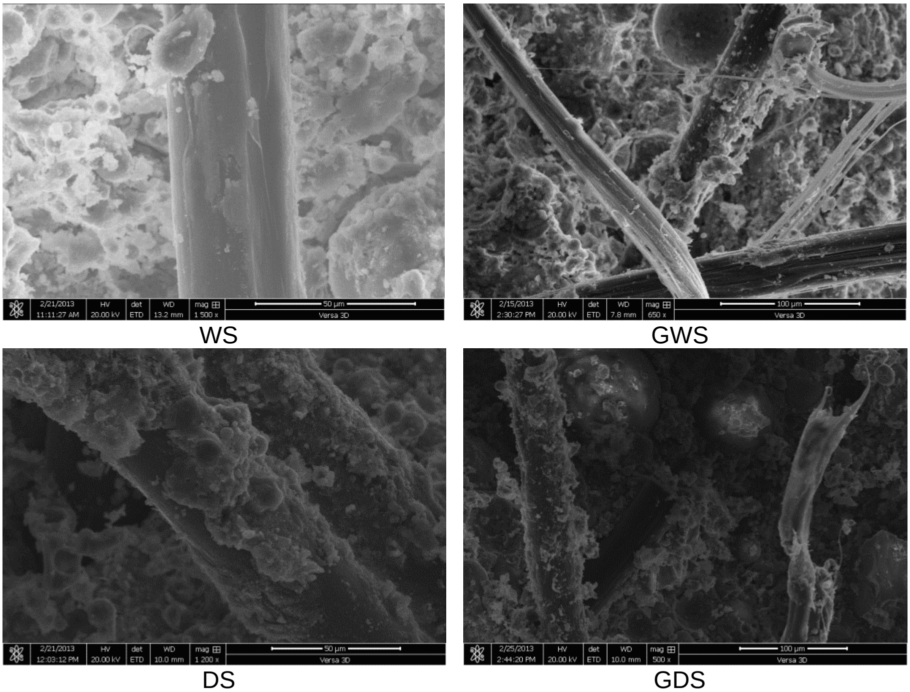


Figure 9: Photomicrographs of SHCC mixtures with different sands of different sizes after flexural strength test

4 CONCLUSIONS

Particle size distribution of dune and white sands as fine quartz and their nature not only affect the mechanical properties but also the bonding with PVA fibers. Dune sand "as abundantly available in nature" was found to hold many economical and ecological benefits. Therefore, the compatibility of the cementitious matrix and PVA fibers is of great importance that affects both the compressive and the flexural strength. Dune sand has special type of good bonding with PVA fibers that might be used as a protective layer at various temperatures. Dune sand is a good candidate for the use as fine quartz in the production of SHCC mixtures.

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FIRE-RESISTIVITY OF STRAIN-HARDENING CEMENT-BASED COMPOSITES CONTAINING NATURAL SANDS

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Abstract: *Strain-hardening cement-based composites (SHCC) are well-known for their ultra ductility. The mix composition of SHCC is characterized with superior contents of cement, fine powders and aggregates of well-defined and uniform fine grain sizes. In addition, high dosages of chemical admixtures along with a definite amount of fibers are needed. The fire-resistance of SHCC is questionable and a matter of concern specifically when non-metallic fibers are used. The most utilized non-metallic fibers are PVA. The effect of a firing temperature of 400 ^{o}C, in a short period of time on SHCC stability was investigated. Thermal analysis using DTA/TG has shown that PVA fibers have a low firing resistivity below 400 ^{o}C. PVA thermal decomposition was classified into different stages. At the critical firing temperature, PVA fibers thermally decompose and gases evolve. During the stages of thermal decomposition, different types of voids and deterioration mechanisms are created and, thus; the strain-hardening and hardened properties are significantly affected.*

Keywords: Fire-resistivity, natural sands SHCC.

1 INTRODUCTION

Great portion of the worldwide energy consumption is attributed to construction and building activities [1, 2]. These activities lead to the consumption of significant part of natural resources that should be saved for our coming generations by using other available alternatives. Several industrial wastes and abundantly available natural sources are good candidates as renewable resources [3]. The efficient use of these materials as raw building materials is the key word towards actual application of sustainability development. Natural sands available in the Arabian Gulf are one of the best candidates for the use as fine materials in concrete construction. However, they are very fine to be used alone in ordinary concrete without adding other type of crushed aggregates to adjust their fineness modulus. On the other hand, there are other techniques that do not require such modifications. Fiber-reinforced concrete becomes an essential part in the recent concrete technology applications [4, 5]. Strain-hardening cement-based composites (SHCC) are such types of technology that may successfully involve natural sands. SHCC are well-known of their ultra ductility. Their unique strain-hardening properties are mainly attributed to the nature of the mix composition and to the advances in research behind this type of relatively new construction technology. The mix composition of SHCC is characterized with superior contents of cement, fine powders and aggregates of well-defined and uniform fine grain sizes. In addition, high dosages of chemical admixtures along with a definite amount of fibers are required. Two types of abundantly available natural sands in the Arabian Gulf can be used as fine aggregates in the production of SHCC. Fibers used in SHCC production can be metallic and/or nonmetallic. The most utilized non-metallic fibers are poly vinyl alcohol fibers (PVA), which is degradable under elevated temperatures. The fire-resistance of SHCC containing PVA becomes questionable and a matter of concern. The effect of a firing temperature of 400 ^{o}C, in a short period of time on the stability of SHCC containing natural sands was investigated. Thermal analysis using DTA/TG has shown that PVA fibers have a low firing resistivity below 400 ^{o}C. PVA thermal decomposition was classified into different stages. At the critical firing temperature, PVA fibers thermally decompose and gases evolve. During the stages of thermal decomposition, different types of voids and deterioration mechanisms are created and, thus; the strain-hardening and hardened properties are significantly affected. The aim of the current investigation is to explore the effect of the presence of two types of natural sands of different grain sizes on the fire resistivity at short period of time of SHCC containing PVA fibers.

2 EXPERIMENTAL INVESTIGATION

2.1 Materials

Fine powder: Ordinary Portland cement (PC) conforms to the requirements of ASTM C150 specifications, was used as the available binder which was partly replaced by class F fly ash. PC has a median grain size of 14 µm while fly ash (FA) has a median grain size of approximately 10 µm. The physical and chemical properties of the above mentioned powders are summarized in Table 1. The particle size distributions of the fine powders are shown in Figure 1. The mineralogical composition and microstructure of FA is shown in Figure 2.

Table 3: Physical and chemical properties of cementitious materials

Oxide composition (%)	Ordinary Portland cement	Fly ash
SiO_2	20.2	50
Al_2O_3	5.49	28
Fe_2O_3	4.12	10.4
CaO	65.43	<6
MgO	0.71	<4
Na_2Oeq	0.26	1.5
SO_3	2.61	<2.5
Loss on ignition (%)	1.38	4
Specific gravity	3.14	2.3
Fineness (m^2/kg)	373	300-600

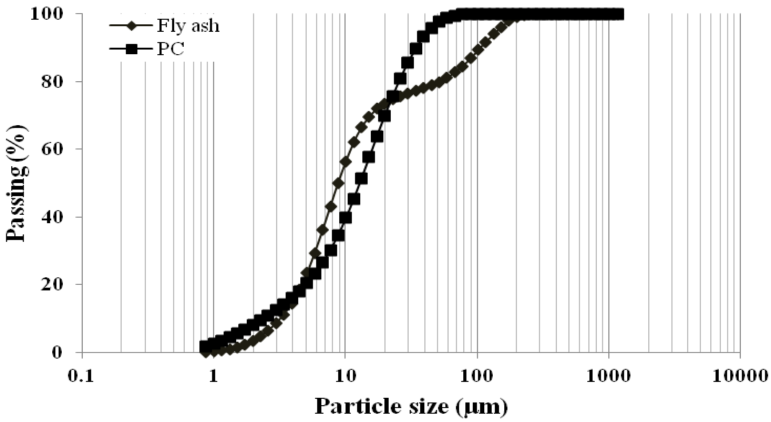


Figure 1: Particle size distribution of cement and fly ash

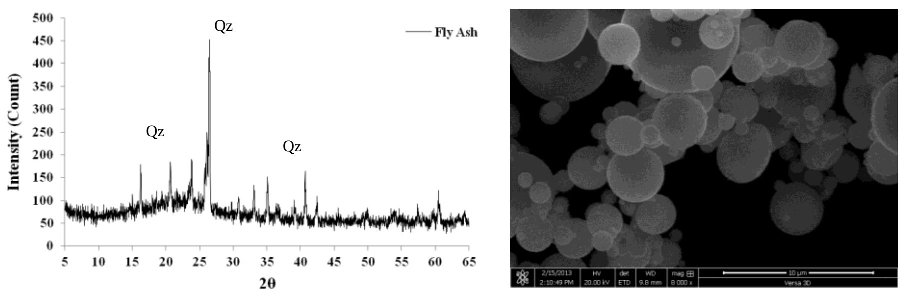


Figure 2: Mineralogical composition and microstructure of fly ash

Fine aggregates: Two types of natural sands of different particles sizes abundantly available as local sands i.e. white and dune sands (WS and DS). They are sourced from the East of Riyadh, Saudi Arabia. WS and DS have median grain sizes of 270 and 200 µm, respectively, as shown in Figure 3. The microstructure of WS and DS shows that their particles have two forms i.e. spherical and angular, as presented in Figure 4.

Chemical admixtures: A modified polycarboxylic ether (PE) polymer was used in the production of SHCC. It has a specific gravity of 1.1 and dry extract of 36 %. The dosage of PE is expressed as a dry extract (D.E.) per cement weight. Optimized PE dosages were determined.

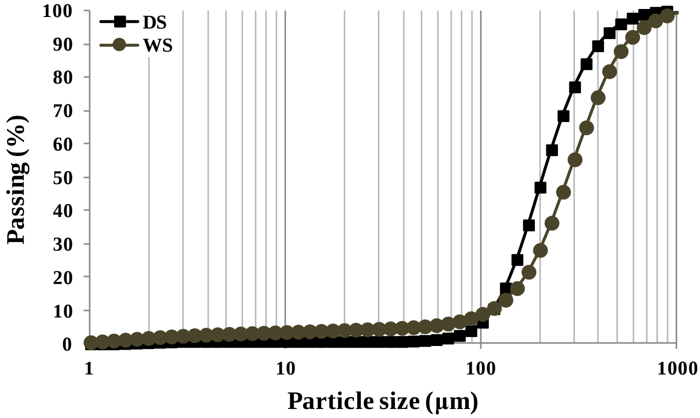
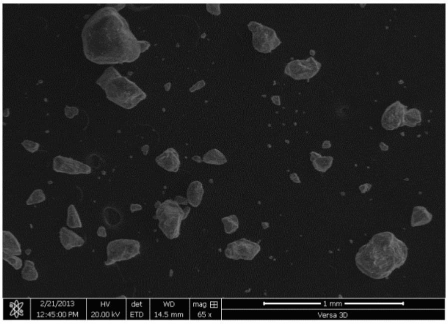
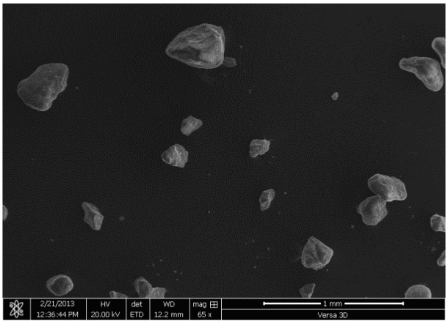


Figure 3: Particle size distribution of natural sands



White sand (WS) "as it is"



Dune sand "as it is" (DS)

Figure 4: Photomicrographs of the used natural sands

PVA fibers: Poly vinyl alcohol fibers is long time used fibers for various applications. It is thermally unstable beyond 360 ^oC, as shown in DTA-TG analysis in Figure 5. DTA-TG analysis of PVA fibers shows the presence of three temperatures at which certain critical changes to the physical and chemical composition of PVA fibers take place. The total weight loss is undertaken at 475 ^oC where PVA loses over 94 % of its original weight, as clearly shown in Figure 5 and demonstrated by stereomicroscopic investigation, as shown in Figure 6.

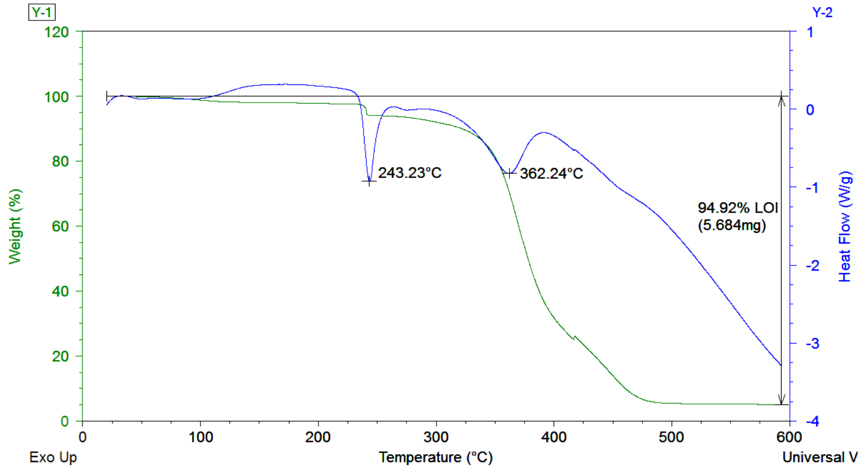


Figure 5: DTA-TG analysis of PVA fibers

The follow-up of the thermal decomposition of PVA leads to change in the color with temperature and render at the end a foam-like residue.

23 °C 250 °C 400 °C

Figure 6: Stereomicroscopic investigation of PVA during DTA/TG analysis

2.2 Methods

The experimental plan was performed in 2 phases. The optimization of PE dosage in SHCC mixtures with different natural sands was firstly conducted. A fixed amount of cement and class F fly ash were used.

Mixing procedures and testing: The protocol of mixing was to pour PC pre-homogenized with fly ash over fine sand then the whole mix was homogenized for few minutes. The final homogenized mix was gently poured over water premixed with the optimized PE dosage in Hobart bowl under run in speed # 1 within 4 minutes. The mixer was stopped for 30 sec to clean the wall of the bowl by pushing down the flushed mix. The mixer was started again for 5 minutes during which the required amount of fibers was slowly-slowly added while pressing fibers by fingers to disperse into separate strands. At the end of 5 minutes, the mixer was stopped and shifted to speed # 2 for 2 minutes. The final mix was then cast into the mould and pushing the different layers over each other followed by finishing the surface. Standard moulds of prisms and cubes of 40 x 40 x 160 mm and 50 mm, respectively, were used. After 24 hours, samples were demoulded and standard cured for 7 days. The prism moulds were split into two groups. At 7 days, the first group was tested for flexural strength while the other group was added into an electric furnace where the temperature was brought from ambient to 400 ^oC within 15 minutes and kept for another 15 minutes then brought to less than 100 ^oC within 15 minutes. This group of prisms was then tested for flexural strength and compared to these samples tested under ambient temperature. The protocol of thermal treatment is demonstrated, as shown in Figure 7. The particle-size distribution of SFL measured using laser scattering particle size distribution analyzer (LA 950V2, Horiba). Microstructural investigation was performed using field emission dual beam Versa 3D scanning electron microscope (FESEM) from FEI. Thermogravimetric and differential thermal analyses (TGA/DTA) were performed using a TA instrument (model SDT Q600). Microscopic investigation was done under Leica EZ4 stereomicroscope.

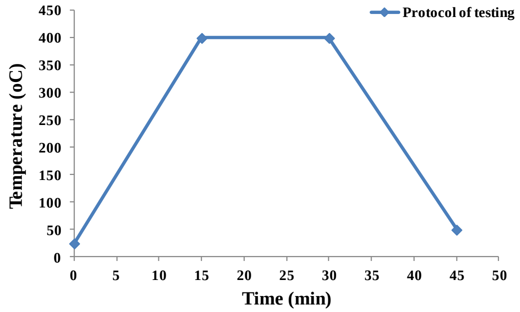


Figure 7: Protocol of thermal treatment

SHCC mix design: The mix design of SHCC mixes investigated in this study is shown in Table 2. The amount of fibers added was equivalent to 2.2 % (volume based).

Table 2: Mix design of SHCC mixes

	Cement [kg/m^3]	Fly Ash [kg/m^3]	Sand [kg/m^3]	Water [kg/m^3]
W29	505	613	534	324

3 RESULTS AND DISCUSSION

3.1 Mechanical properties

PVA thermal decomposition was previously investigated in different studies [6-8]. The presence of PVA in any cementitious matrix generally improves its mechanical properties under tension. When PVA is subjected to thermal decomposition inside the cementitious matrix, it loses the mechanical properties under tension. The tested samples with DS and WS show different behaviors at different temperatures, as shown in Figure 8. The compressive strength of DS samples at ambient temperature is higher than these samples with WS by approximately 7 %. On the other hand, the compressive strength of DS samples at 400 ^oC is lower than these samples with WS by approximately 5 %. This might be attributed to the stimulated pozzolanic reactivity of pure silica quartz in WS samples which is higher than this in DS samples. However, both DS and WS samples have similar flexural strength at ambient temperature as they do have much difference in their compressive strength. However, at 400 ^oC the flexural strength of DS is much higher than this of WS by approximately 17 %. Pieces of these samples were taken after testing to investigate their microstructure to interpret and explain this difference.

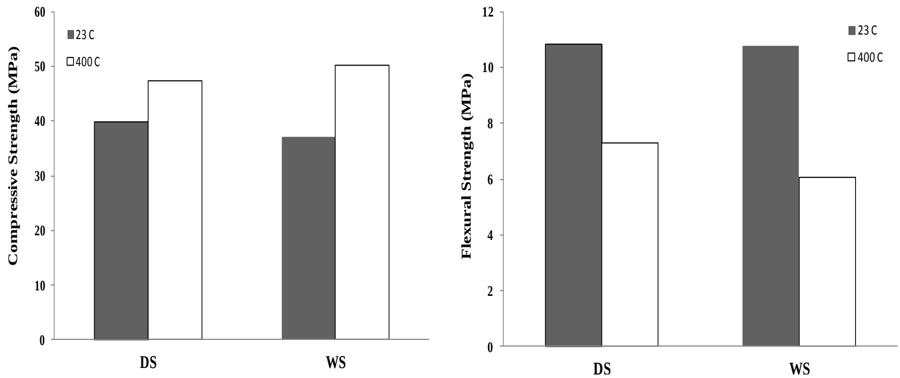


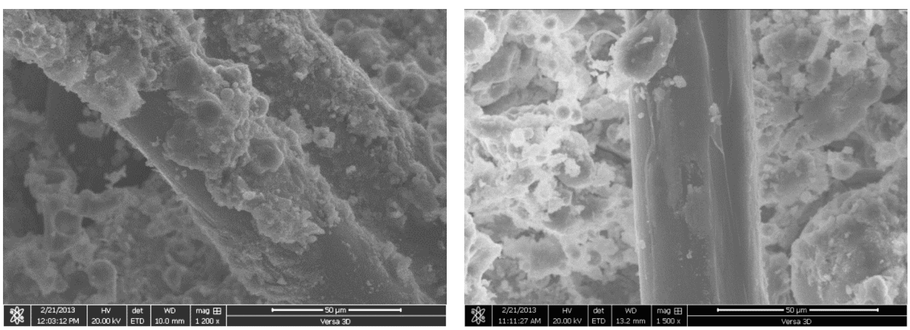
Figure 8: Mechanical properties of DS and WS samples tested at ambient and after subjected to 400 °C

3.2 Microstructural analysis

Microstructural analysis was conducted on the samples tested at both temperatures 23 and 400 °C. The features of interest are the nature of bonding between PVA fibers and the cementitious matrix under both testing conditions.

3.2.1 At ambient temperature

The microstructure of tested samples at ambient temperature shows that the cementitious matrix in DS samples is attached to PVA fibers better that this in WS samples, as obviously shown in Figure 9. The microstructure of WS sample fibers reveals that PVA fibers seem to be intact and free of cementitious matrix.

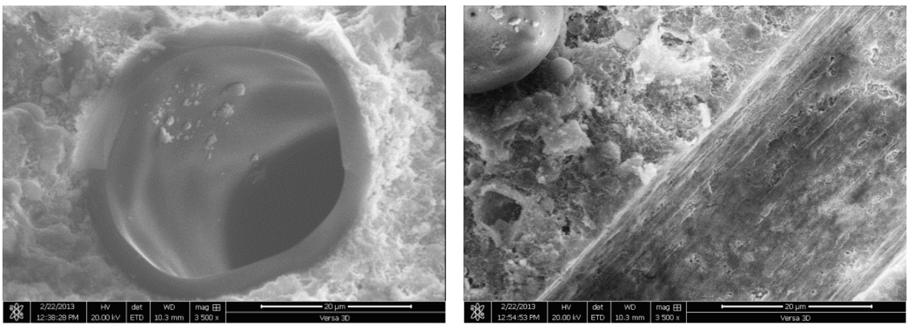


DS WS

Figure 9: Photomicrographs of DS and WS samples cured at 23 °C

3.2.2 AT 400 ^{O}C

The microstructure of the samples tested under the effect of elevated temperature of 400 ^{o}C is shown in Figure 10. The results reveal the presence of tunneling effect which is lined with melted PVA fibers as an indication to the need for higher activation energy to completely eliminated PVA fibers out of the cementitious matrix as the case with WS samples, as shown in Figure 10. This clearly explains the reason for the difference in their flexural strengths. The improved bond between DS cementitious matrix and PVA fibers seems to work as an insulating layer that protects PVA fibers from charring. The bond between WS cementitious matrix and PVA fibers seems to be weak as it did not show a similar effect.



DS WS

Figure 10: Photomicrographs of DS and WS samples treated at 400 ^{o}C

Previous investigations have shown that there is a kind of bonding between PVA fibers and silica particles in nano silica or clayey compounds [8, 9]. These results are encouraging and raise the need for insight investigation on the effect of different other particles sizes of these types of natural sands on the tensile properties of SHCC samples. This effect will be covered in another study.

4 CONCLUSIONS

The abundantly available natural sands are effective in the production of relatively fire resistant SHCC samples based on PVA fibers. Dune sand was proved to have improved bonding with PVA fibers. This type of interaction between the dune sand, cementitious matrix and PVA leads to the formation of an insulating layer that prevents the charring of PVA. Moreover, it leads to the formation of PVA lined tunneling effect, which improves the flexural strength.

ACKNOWLEDGEMENTS

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HIGH-CYCLE FATIGUE OF STRAIN-HARDENING CEMENT-BASED COMPOSITES (SHCC)

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Abstract: *The safe use of Strain-hardening Cement-based Composites (SHCC) for structural and non-structural applications often requires a solid knowledge of the mechanical performance of this material under cyclic loading. In the previous investigations the behaviour of SHCC subjected to a relatively moderate number of loading cycles was studied in the tension regime. The article at hand presents the experimental results obtained from the fatigue tests performed with a considerably higher number of cycles both in tension regime and alternating tension–compression regime. The varying parameters under investigation were upper strain level, lower stress level and the deformation rate. The experiments were performed on uniaxially loaded dumbbell-shaped specimens. The loading regime was deformation controlled up to the upper reversal point, by an incremental increase in strain. The bottom reversal point was at zero stress or at a stress level corresponding to 25 % and 50 % of the compressive strength, respectively. It was observed that the tensile strength and even more so the ultimate strain of SHCC decreased with increasing number of loading cycles and with increasing frequency of them. Furthermore, the crack patterns at surfaces of the specimens were analysed and optical investigations of the SHCC fracture surfaces were performed to provide insights into the failure mechanisms specific for the fatigue behaviour of SHCC. The experimental results are discussed in particular with respect to the identification and description of the determinant physical phenomena influencing the material performance.*

1 INTRODUCTION

Strain-hardening Cement-based Composites (SHCC) are a particular type of Fibre Reinforced Concrete (FRC), which exhibits a tensile strain capacity of several percent [1]. The name SHCC describes a specific stress-strain behaviour of this material in monotonic uniaxial tension tests. After a linear-elastic stage prior to first cracking, a stress-strain curve changes its inclination dramatically due to gradual formation of a great number of fine cracks bridged by polymeric fibres. The increase in stress and formation of new cracks continues until the crack-bridging capacity of the fibres in the “weakest” crack is reached. Then the final crack forms and the material exhibits strain-softening behaviour characteristic for the most types of FRC.

While the mechanical performance of SHCC under monotonic quasi-static and partly dynamic loading has been extensively investigated over the last two decades, see e.g. [2, 3], only little research has been performed on the behaviour of SHCC subject to cyclic loading. In tension-compression experiments by Fukuyama et al. [4] only about five cycles were needed until the strain capacity was exhausted, while the cyclic tension response accurately reflected the corresponding curve obtained from a monotonic tension test. In contrast, Douglas and Billington [5] found that the envelope of the stress–strain curve from the cyclic tests lay below the relationship measured in the monotonic regime. The difference was particularly pronounced in the experiments with high strain rates. Jun and Mechtcherine [6] did not observe any pronounced effect of tensile cyclic loading on material performance in terms of stress-strain response. The analysis of the hystereses of the stress–strain curves showed a decrease in the material stiffness with an increasing number of loading cycles. The hystereses further revealed a considerable partial inelastic deformation in every loop. However, the maximum number of loading cycles in the experiments was about 2000, which is not representative for most structural and non-structural applications with cyclic loading as the relevant scenario. In the project at hand, the behaviour of SHCC under a reasonably high number of loading cycles was investigated. Furthermore, both tension regime and alternating tension-compression regime were used as loading scenarios.

2 EXPERIMENTAL SETUP AND TEST PROGRAMM

2.1 Material

The composition of SHCC under investigation is given in Table 1. The binder was a mix of Portland cement type 42.5 R-HS and fly ash. Only very fine aggregates, quartz sand with particle sizes ranging from 0.06 mm to 0.20 mm, were used. Such small grain sizes were necessary to achieve a uniform distribution of fibres. The mixture contained 2 % by volume of polyvinyl-alcohol (PVA) fibre with a length of 12 mm and a diameter of 40 microns. The adequate workability was achieved by using a superplasticizer and a viscosity agent.

Table 4: Composition of SHCC in kg/m³

Cement CEM I 42.5 R-HS	Fly ash	Water	Quartz sand 0.06-0.20 mm	Superplasticizer	Viscosity agent	PVA fibres
505	621	338	536	8.5	3.2	26.0

2.2 Processing

When producing the SHCC, first, all dry components were homogenized in a mixer. Subsequently, the water and superplasticizer were added and mixed until a fluid consistency of SHCC was achieved. Finally, the fibers were added during continuous relatively slow mixing, followed by intensive mixing needed for a good distribution of fibres.

All specimens were cast horizontally in dumbbell shaped metal forms with the dimensions of 24 mm (40 mm at the ends) x 40 mm x 240 mm. After casting the moulds were covered with plastic sheets and stored for two days in a room under controlled temperature (T = 22 °C). After de-moulding, the specimens were placed in plastic boxes and stored under controlled temperature (T = 20 °C) until testing. Caused by the fibres, a plane levelling of the fresh mix in the mould was not achievable. In order to produce flat surfaces, the superfluous material was cut off with a circular saw after SHCC hardened.

The specimens were prepared in different batches. To prevent singular mix influences, specimens from each batch were used for each load regime.

Caused by the relatively long duration of each individual test, the test series for one produced batch took one week. To avoid influences, resulting from the different age of the samples at the time of loading [3] all specimens were tested at an average age of 8 weeks.

The cyclic tests were performed in a testing machine under stable climatic conditions (20 °C and 65 % RH). All tests were performed with non-rotatable fixing conditions, achieved by using stiff metal adapters and special fast-hardening glue. Two LVDT's were used to measure the deformation of the specimen at a gauge length of 100 mm. Additionally, the data for force, crosshead displacement and time were collected.

2.3 Test program

All uniaxial tension and tension-compression tests were performed with a strain rate of 10^{-2} s^{-1}. This strain rate corresponds to low-speed dynamic regime characteristic for traffic loads. Note that in comparison to quasi-static testing regime lower strain capacity and higher tensile strength can be expected for testing at the chosen stain rate [7, 8].

The lower reversal point was load controlled. Three different load levels were investigated: σ = 0 MPa, σ = 25 % of the compressive strength and σ = 50 % of the compressive strength.

The upper reversal point was deformation controlled. A particular incremental increase in strain in each cycle was chosen and kept constant over the experiment. Figure 1 shows an example of loading regimes as used in this study. The overview of the experimental parameters is given in Table 2.

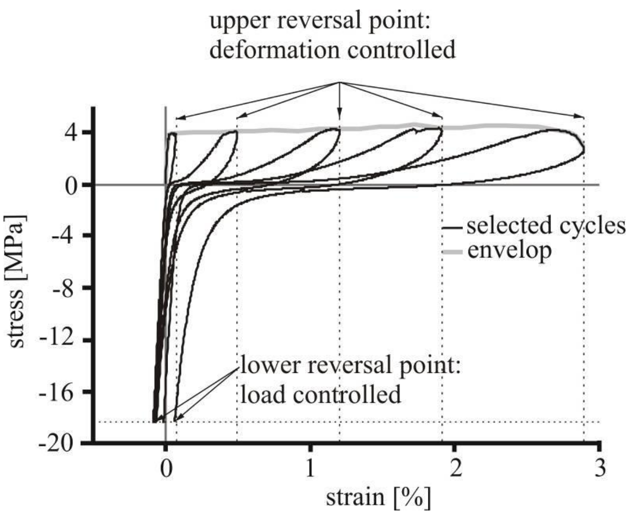


Figure 1: An example of testing regimes

Table 2: Parameters under investigation, loading regimes

		Deformation increment [%]		
		0.2	0.002	0.00002
Lower reversal point	σ_u = 0 MPa	Regime 0-0.2	Regime 0-0.002	Regime 0-0.00002
	σ_u = 25 % of σ_{cc}	Regime 25-0.2	Regime 25-0.002	Regime 25-0.00002
	σ_u = 50 % of σ_{cc}	Regime 50-0.2	Regime 50-0.002	Regime 50-0.00002

3 TEST RESULTS

Figures 2 and 3 show representative stress-strain curves obtained for each loading regime with a bottom reversal point at 25 % (Figure 2) and of the compressive strength of the SHCC, respectively 50 % (Figure 3). From these plots it can be seen that SHCC is sensitive to the magnitude of the strain increment and herewith to the number of loading cycles.

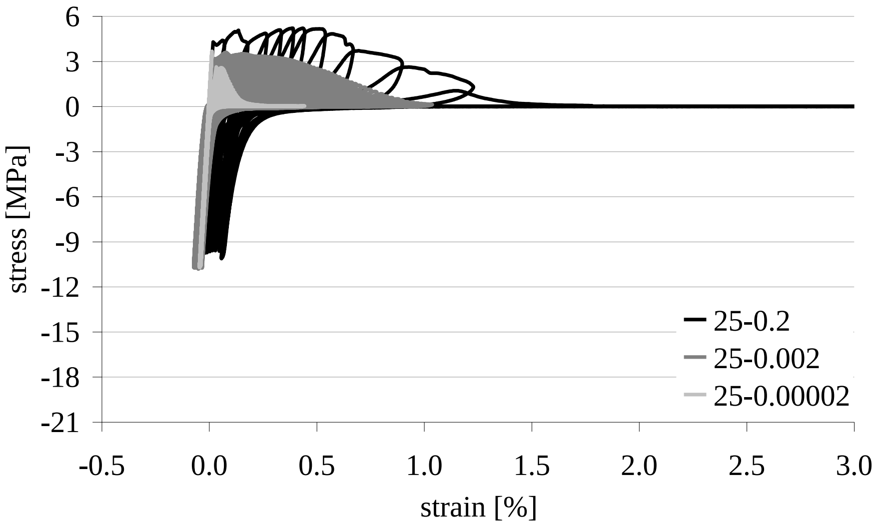


Figure 2: Representative stress-strain curves obtained for testing regimes with the bottom reversal point at 25 % of the compressive strength

The summary of the results with respect to the mechanical performance of SHCC is given in Table 3. The average tensile strength and standard deviation were calculated from the peak tensile stresses measured in individual test series. The strain corresponding to the peak stress was regarded as strain capacity. In some cases the localisation of failure occurred out of the gauge length. If the number of the reliable experimental results was just one or two no standard deviation was calculated.

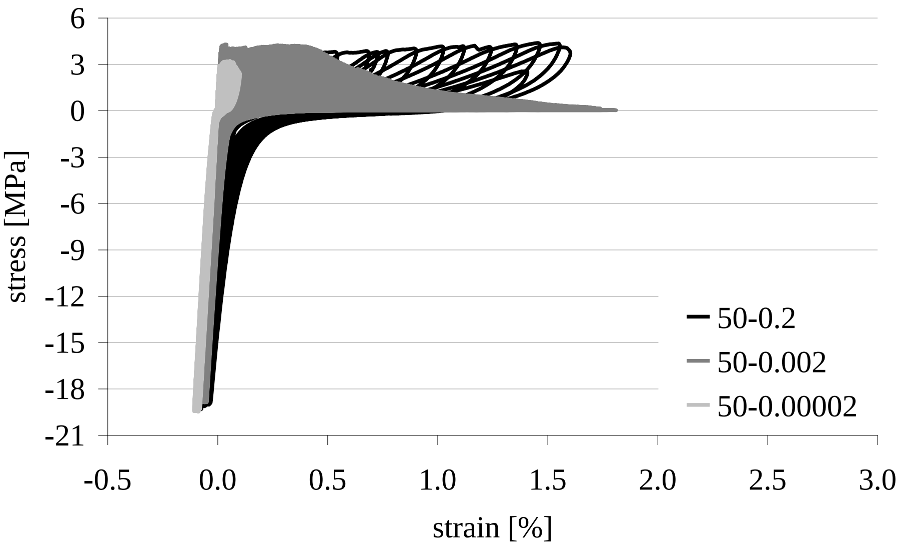


Figure 3: Representative stress-strain curves obtained for testing regimes with the bottom reversal point at 50 % of the compressive strength

For loading regimes with the bottom reversal point of σ_u = 0 MPa only minor increase in the tensile strength and a hardly noticeable decrease in the strain capacity was measured with decreasing magnitude of the strain increment, while the standard deviations in the tests with the individual parameter combinations were higher than the measured changes due to the change in the increment. However, for the loading regimes with the bottom reversal point in the compression region a pronounced decrease in both the tensile strength and strain capacity could be observed with decreasing strain increment.

The measured changes in mechanical performance with decreasing strain increment can be most likely explained by increasing number of loading cycles up to reaching the same strain level during the test. A high number of cycles may cause various degradation processes of the fibres. On one hand, the fibre material itself exhibits fatigue behaviour. On the other hand, due to repeated opening and forcible closing of the cracks in tension-compression cyclic regime, the fibres might be subject to buckling and crushing between the crack edges. The likely damages of fibres lead to a reduction in the tensile strength of the fibres in the first place, which subsequently results in a premature failure of the composite.

Table 3: Summary of the results, average values (standard deviations are given in parentheses)

	Tensile strength [MPa]	Strain capacity [%]
Regime 0-0.2	4.13 (0.24)	0.38 (0.22)
Regime 0-0.002	4.16 (0.57)	0.35 (0.08)
Regime 0-0.00002	4.67 (-)	0.34 (-)
Regime 25-0.2	4.71 (0.54)	0.23 (0,22)
Regime 25-0.002	3.60 (0.90)	0.03 (0.03)
Regime 25-0.00002	2.52 (1.15)	0.01 (0.01)
Regime 50-0.2	4.51 (0.11)	1.28 (0.54)
Regime 50-0.002	4.29 (-)	0.03 (-)
Regime 50-0.00002	2.10 (1.59)	0.03 (0.03)

Another interesting effect can be shown when comparing of the results obtained for the loading regimes with a low number of cycles and varying bottom reversal point (i.e., regimes 0-0.2, 25-0.2 and 50-0.2): The tensile strength does not seem to be affected negatively by the magnitude of the compressive stress at the reversal point. The strain capacity was found to be even higher for the testing regime 50-0.2 (higher compressive stress) then for the regime 25-0.2 (lower compressive stress at the bottom reversal point). A possible explanation can be that a higher level of compression leads to more pronounced deterioration of the matrix in the crack area. This may cause degradation of the fibre-matrix bond which may be associated with increasing free deformation length of the fibre and consequently with larger crack openings. Wider cracks cause high measured deformations and therefore higher strain values for the composite.

4 CRACK PATTERN AND MICROSCOPICAL INVESTIGATION

A macroscopic observation of samples' surfaces revealed that specimens subject to a small number of cycles (large strain increment) had a pronounced multiple cracking, while the specimens tested with a higher number of cycles developed just one or two cracks before failure. Figure 4 shoes characteristic crack patterns for various testing regimes.

a)

b)

c)

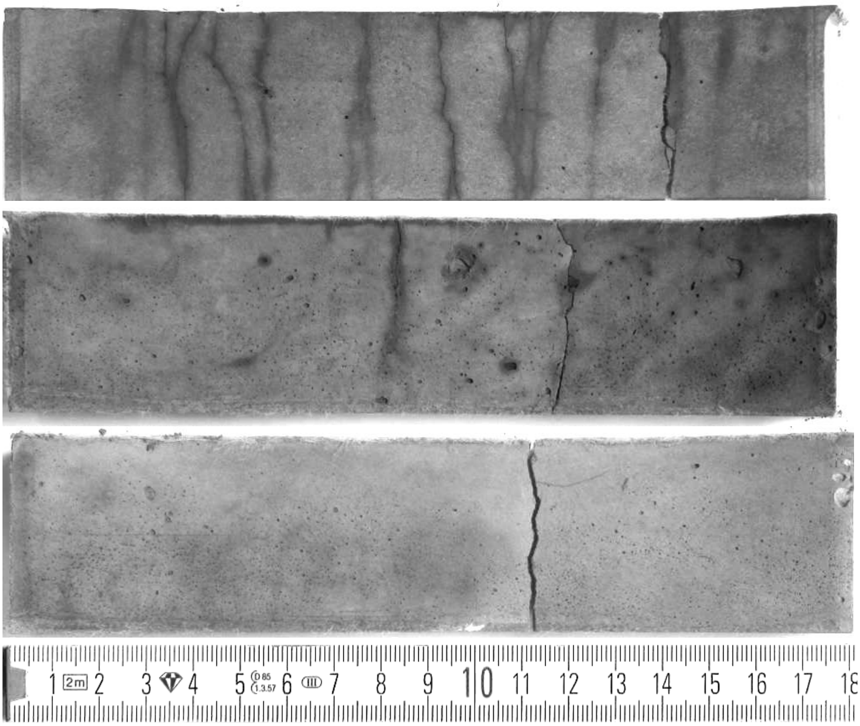
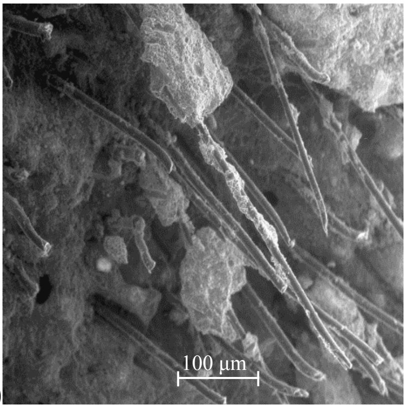
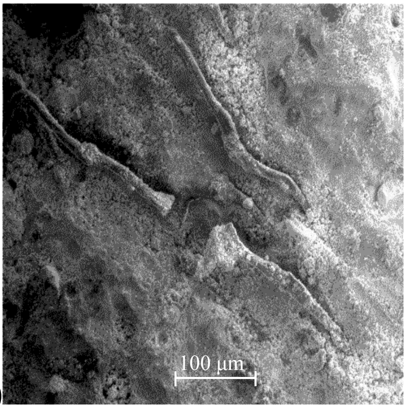


Figure 4: Crack pattern of selected specimens tested in a) Regime 50-0.2, b) Regime 50-0.002 and c) Regime 50-0.00002

To explain why smaller magnitude of strain increments and therefore increasing number loading cycles prevents multiple cracking at least two deterioration mechanisms should be considered. On one hand, the possibility of (additional) fibre damage increases with each load cycle which finally causes a premature failure of the composite. On the other hand, the formation of a new crack needs an increase in tension stress level. Such an increase does not occur in the tests with a very small increase in strain per cycle. Loading cycles with low strain magnitude seems to cause deterioration (non-uniform plastic deformations) of fibres and probably fibre-matrix bond in the cracked area, so that new loading cycles lead to the further opening of the existing crack(s) rather than to formation of the new ones.

a) 

b) 

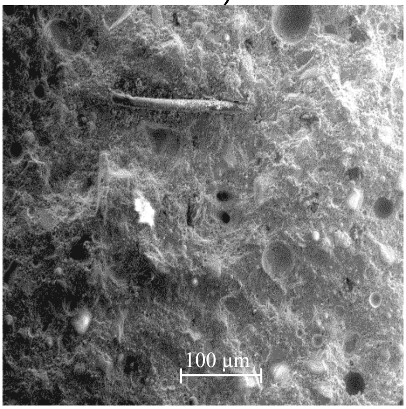
c) 

Figure 5: Microscopic images of fractured surfaces of selected specimens tested in a) Regime 50-0.2, b) Regime 50-0.002 and c) Regime 50-0.00002 (magnification 150x)

Microscope investigation of the crack surfaces supports this hypothesis. Figure 5 shows crack surfaces of the specimens subject to the loading regimes 50-0.2, 50-0.002 and 50-0.00002. For the regime 50-0.2 with a low number of cycles, the fibres on the crack surface are quite long, the majority of them are pulled out, just a few fibres failed or show buckles. The crack surface of the specimen tested in the regime 5-0.002 shows a more pronounced deterioration of the fibres like buckles or bruises. No undamaged fibre is there and most of the fibres failed during the experiment. On the fracture surface of the specimens subject to the regime 50-0.00002 with the highest number of loading cycles nearly no fibre could be found. Just empty fibre channels or channels filled with fibre leavings can be found. To become empty fibre channels a pull-out process is necessary. Based on findings in non-cyclic experiments it's expected to see the pulled out fibres on the other crack surface. But the more cycles are applied less fibres can be found. A possible reason may be the grinding of the pulled or partially pulled out fibre in the fracture plane.

5 CONCLUSIONS

SHCC behaviour under high-cyclic loading differs from that observed in monotonic tension tests, specifically when alternating tensile and compressive loads are applied. With increasing number of loading cycles the tensile strength and strain capacity decrease considerably. Furthermore, a transition from multiple cracking in the tests with low number of load cycles (large strain increment) was observed to one or two crack pattern in the tests with high number of load cycles. As a reason for such behaviour higher deterioration of the fibre and fibre-matrix bond for high number of alternating loadings was suggested. The microscopic investigations confirmed increasing signs of fibre deterioration with increasing number of load cycles. Further research is ongoing to clarify the deterioration mechanisms in more details.

ACKNOWLEDGEMENTS

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WATER INTAKE AND RELEASE IN COMPOSITE SPECIMENS MADE OF CRACKED ORDINARY CONCRETE AND STRAIN-HARDENING CEMENT-BASED COMPOSITE (SHCC) AS CHARACTERISED BY NEUTRON RADIOGRAPHY

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Abstract: *Composite specimens of steel-reinforced concrete (RC) strengthened with a strain-hardening cement-based composite (SHCC) were characterised according to their water uptake and release kinetics by neutron radiography imaging. The specimens were cracked in well-defined patterns, and some cracks were hydrophobised at the RC/SHCC interface. Qualitative and quantitative image evaluation revealed that capillary suction was very intense; within 1.2 minutes the cracks in both SHCC and RC filled with water completely, deep into the interior. Capillary transport through the matrices followed and led to moisture distribution throughout the body up to an elapsed time of 27 hours. When drying, only macro-sized cracks emptied within about one hour. Up until 46 hours the original water frontier progressed approximately 1 mm further into the matrix. In parallel the specimen dried from its bottom face. Hydrophobisation of cracked areas prior to application of the SHCC proved a highly efficient measure to inhibit the ingress of water deep into the structure.*

Keywords: Concrete repair, SHCC, capillary suction, desiccation, hydrophobisation, neutron radiography, image analysis.

1 INTRODUCTION

Strain-hardening cement-based composites (SHCC) have recently been developed as a very promising material for new construction as well as for strengthening and repair of steel-reinforced concrete structures [1]. In this context, the effect of SHCC as a protective layer against the ingress of liquid media into retrofitted, reinforced concrete (RC) structures is of prominent significance. Due to multiple crack formation with narrow individual crack widths in SHCC, one can expect that the transport of water and corrosive solutes through such toppings is considerably retarded [1, 2]. A major target of the present study is to verify this expectation and provide a guideline as to how to promote this protective functioning. Neutron radiography imaging at PAUL SCHERRER Institut [3-5] was chosen to monitor the water migration and distribution kinetics in the porous solid material. With respect to principal specimen design, the study at hand is a direct transfer from composite specimens made of cracked RC with textile-reinforced concrete (TRC) as the topping layer [5]. The RC/SHCC interface was hydrophobised in some instances in the cracked areas.

2 EXPERIMENTAL INVESTIGATION

The RC was prepared as that used by LIEBOLDT and MECHTCHERINE [5] and the SHCC accorded to recipe M68a published by MECHTCHERINE *et al.* [6]. RC slabs were cast of ordinary concrete 1,000 mm in length, 300 mm in width and 60 mm in thickness with the reinforcement bars placed the tensile zone, the concrete cover was 15 mm. The RC slabs were pre-cracked by four-point bending loading at an age of 15 months after casting. The crack pattern on the surface of the slabs was as expected for this kind of concrete and coincided with that observed in [5]. A subset of crack mouths was hydrophobised on the cracked RC surface which later represented the interface to SHCC. The crack openings were treated twice with a stroke of the brush using a commercial hydrophobising agent (MEM Super-Tiefgrund, MEM Bauchemie, Leer/Ostfriesland, Germany). The visually hydrophobised area spread for about 1 cm from the flanks of each crack into the surrounding region; the further areas between the cracks remained unaffected. The cracked RC surface was coated with a layer of SHCC by spraying, replicating a practical repair or strengthening approach. The layer thickness amounted to about 15 mm. The slabs reinforced with SHCC were cured for 28 days (20 °C, RH 65 %). They were subsequently subjected to four-point bending loading. Multiple crack formation occurred in the SHCC in the form of a delta originating in close proximity to the RC crack mouths. Nominal deflection at the maximum force of 40.4 kN was 19.8 mm.

Characteristic specimens with respect to the states of cracking and hydrophobisation were extracted by sawing. From among them one of each kind was selected, in which no reinforcement bar was present. A reference specimen with no observable cracks was taken from a non-hydrophobised area and designated as “uncracked”. Figure 1 shows a schematic of the slices visualising relative alignments of concrete layers, crack orientation, suction direction and the projection line of the neutrons.

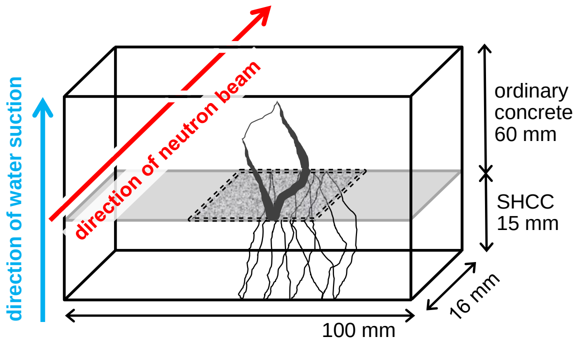

Figure 1: Schematic of the specimens extracted from the slabs to be inserted in the neutron beam (not to scale); the inlay at the RC/SHCC border represents the hydrophobised area

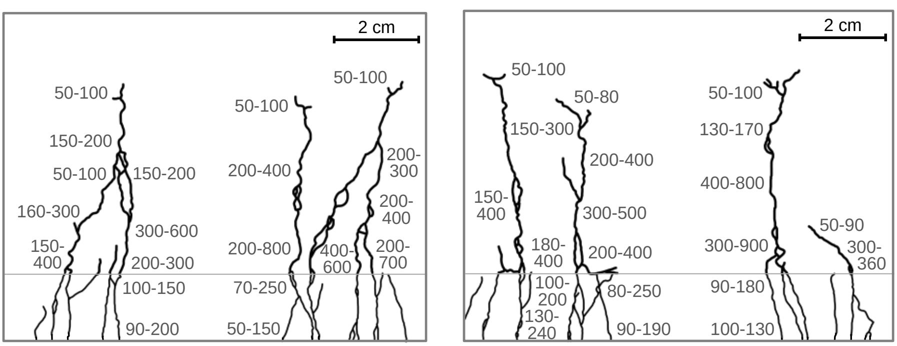

Figure 2: Sketches of the crack patterns visible on the front- and backsides of the cracked non-hydrophobised specimen; numbers indicate the observed crack opening width in µm

The crack patterns of the specimens bound for neutron radiography were visualised by a light microscope (Axio Tech, Zeiss, Jena, Germany). They were re-drawn and the crack widths visible on the front- and backsides were quantified (Figures 2 and 3).

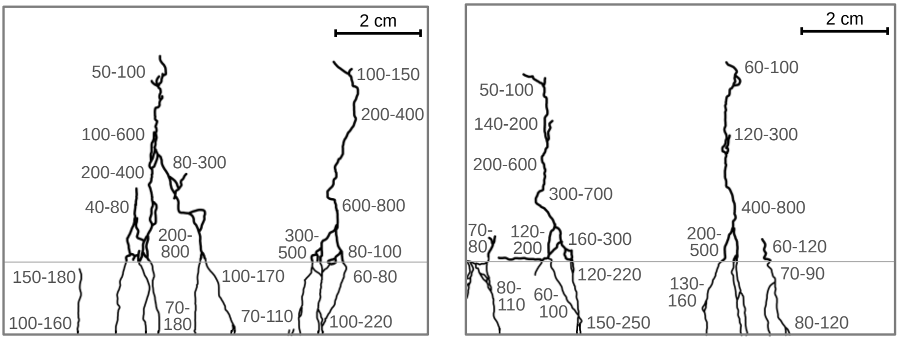

Figure 3: Sketches of the crack patterns visible on the front- and backsides of the cracked hydrophobised specimen; numbers indicate the observed crack opening width in µm

After slice extraction from the slabs, the specimens were stored in standard laboratory atmosphere (temp. 19-23 °C, 60-70 % RH) until neutron radiography. The moisture content reached equilibrium during this period of several days. All vertical faces of the specimens were tightly sealed with self-adhesive Al tape, which is almost transparent to neutrons.

Capillary suction kinetics of water by the RC/SHCC specimens were visualised and quantified at the neutron imaging and activation group of PAUL SCHERRER Institut (PSI) in Villigen/Aargau, Switzerland, with their beam line NEUTRA [3-5]. The suction experiments were equivalent to DIN EN ISO 15148, but some geometrical and statistical aspects had to be modified to obtain scientifically most appropriate results from neutron radiography during the available beam time slot. The suction period observed was 27 hours. Imaging of water release had to be performed seven months later due to restricted beam time allocation (storage in laboratory conditions, temperature 19-23 °C, 60-70 % RH). Short before imaging, it was gravimetrically verified that they had regained equilibrium moisture content. They were subject to 27 hours of capillary suction, but outside the beam. The SHCC surface, through which suction had taken place, was immediately swept with a dry cloth. Surplus water was removed but no significant amount of water was extracted. Imaging started at the earliest convenience of some very few minutes.

Image recording and processing accorded to previously published procedures and methods [3-5, 7]. To quantify the differential water content in spatial resolution, rectangular stripes of 25 pixels in height and over the entire specimen’s width were laid into the images by ImageJ [7]. The temporal water content in comparison to the original state was quantified over the specimen width and at four or five heights, respectively, and plotted in diagrams.

3 RESULTS AND DISCUSSION

Uncracked composite specimen

Although the selected slice was supposed to be uncracked, some presumably very narrow cracks appeared to be present in the SHCC layer. These cracks took up water quickly, but the impact with regard to ingress into the specimen was moderate. Some boundary effects seemed to occur at the corners of the specimen. Most probably, the self-adhesive Al tape was not absolutely tightly attached there, allowing some water uptake through wrinkles. In any event, the dominant suction mechanism was matrix transport through first the SHCC followed by that in the RC. The wetting front in RC reached a distance of 5 to 10 mm from the interface.

In the desiccation part of the tests, the same specimens that had been used previously in the capillary suction experiments were investigated. The image series of the uncracked specimen showed, as expected, that the desorption of water was significantly slower than the water intake. After 1.5 to 2 hours, a dark rim – representing some increased water content in time – at the former suction border became visible. The water content remained constant above it since the wetting front had never reached this region during the conditioning of the sample. Below that boundary, a very minor decrease of water content started and proceeded slowly in both matrices. This process continued until the end of neutron imaging at 46 hours. In parallel, after as long as six hours from the beginning of desorption imaging, the first unambiguous traces of surface drying from the bottom into the interior became evident. The apparent cracks and edge regions dried from the same time onward. From these starting points the drying front proceeded into the soaked area, i. e. directed into the matrix. It progressed to about 3 mm after 46 hours from the bottom of the specimen. During this time, the water content dropped by about 20 g/dm^3 close to the surface. In the matrix regions farther inwards, decreasing water content was clearly visible; the quantification disclosed that it was 5 to 10 g/dm^3. Thus, efficient drying only came into sway in the surface neighbourhood within 46 hours, whereas the water content in the inner parts was still considerably higher than that before water intake.

Cracked non-hydrophobised composite specimen: Capillary suction

Figure 4 visualises and quantifies the water uptake in the cracked non-hydrophobised specimen. The numerous cracks in SHCC take up water as intensely and quickly that the RC cracks adjacent to them activate their capillary suction force. The water content in the cracks amount to 50 to 60 g/dm^3 in SHCC and 40 to 90 g/dm^3 in RC. The distinct value of this peak height at the (lateral) locations of the cracks depends on the crack alignment with respect to the direction of projection. If a crack was freely penetrated by the beam, only water attenuates the neutrons. This can only be the case if the crack is aligned in-line with the neutron beam pervading the specimen. Otherwise, some rims of neighbouring matrix are penetrated as well and the apparent amount of water detected is significantly lower.

From the specimen bottom as well as from the crack walls, permeation through the capillary pore system thoroughly wets the matrices. Due to the quick and deep suction through the cracks and subsequent distribution through the RC matrix, the intake frontier reached the upper border of the specimen.

Cracked non-hyrophobised composite specimen: Water release

The release sequence for the cracked non-hydrophobised specimen shows Figure 5. The drying process of intact matrix regions is equivalent to that of the uncracked specimen. But new aspects need to be considered due to the cracks and the suction frontier reaching the top surface of the specimen. The widest cracks, which are located in the middle of the RC substrate, are the first regions to dry out. At all previous suction frontiers, some progress of water into the matrix is visible as a dark rim. Surface drying from the bottom occurs over the long term. At the conclusion of neutron imaging after 46 hours, the water content in the near-surface region of the SHCC decreased by approximately the same amount as it had increased during the suction. However, the intact matrix areas in the upper region of the SHCC layer as well as those in the middle of the RC substrate did not dry significantly. There, decreasing amounts of water are visible only in the nearest vicinity of the crack flanks. Since the suction frontier had pervaded up to the top surface, drying from that interface to the surrounding atmosphere occurred. Yet, at places of overlapping suction frontiers, the water content did not decrease but even slightly increased in the course of time.

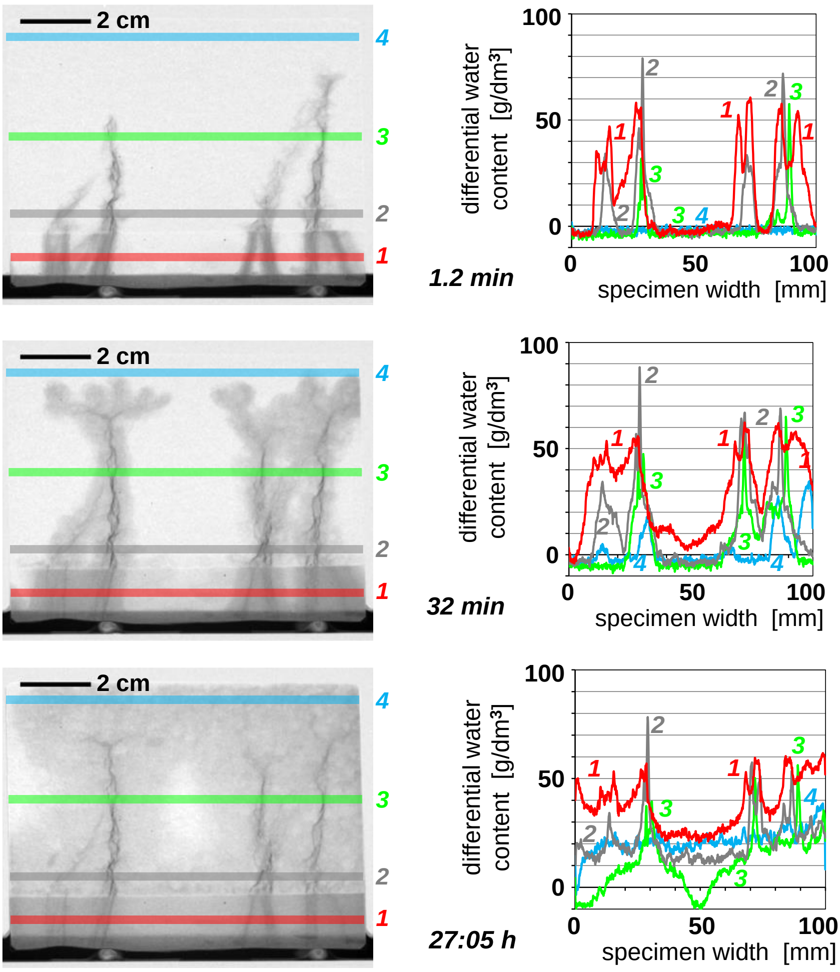

Figure 4: Neutron radiography differential suction images of the cracked non-hydrophobised specimen and differential water content at the four heights indicated in the pictures

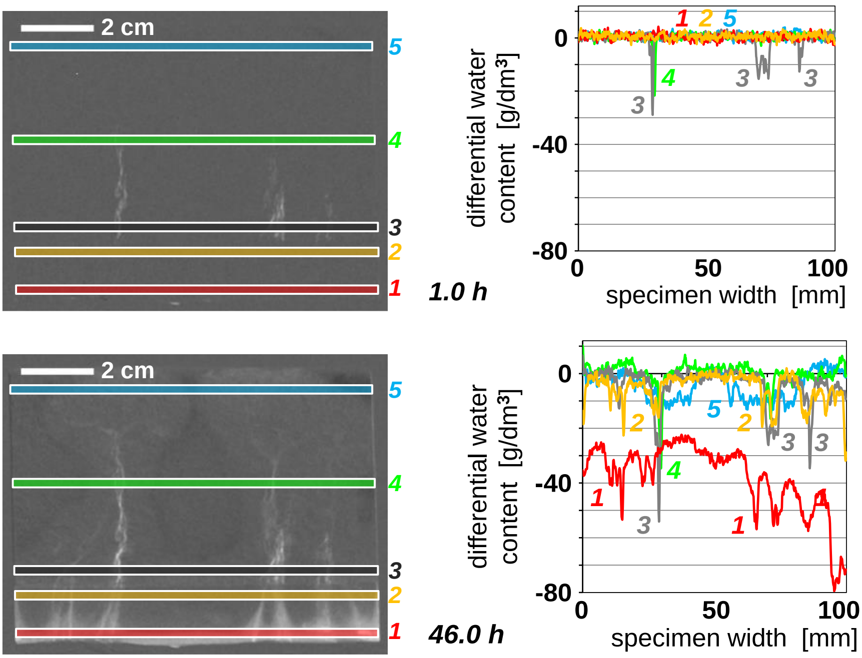

Figure 5: Neutron radiography differential release images of the cracked non-hydrophobised specimen and differential water content at the five heights indicated in the pictures

Cracked hydrophobised composite specimen: Capillary suction

Figure 6 shows the water uptake into the cracked specimen with hydrophobised regions around the crack mouths in the RC. Hydrophobisation presents itself as impenetrable barrier, at least in the short and intermediate terms. It is evident which areas of the RC/SHCC interface were hydrophobised in contrast to those that were left out. Purposely, only obvious and macro-sized crack mouths on the RC had been hydrophobised prior to SHCC application. When deciding on the hydrophobisation, no cracks at about 20 mm from the left were seen and thus, hydrophobisation was not applied here as well as the visibly uncracked areas 60 to 70 mm and 80 to 100 mm. From 40 to 75 mm, two stripes were consciously hydrophobised.

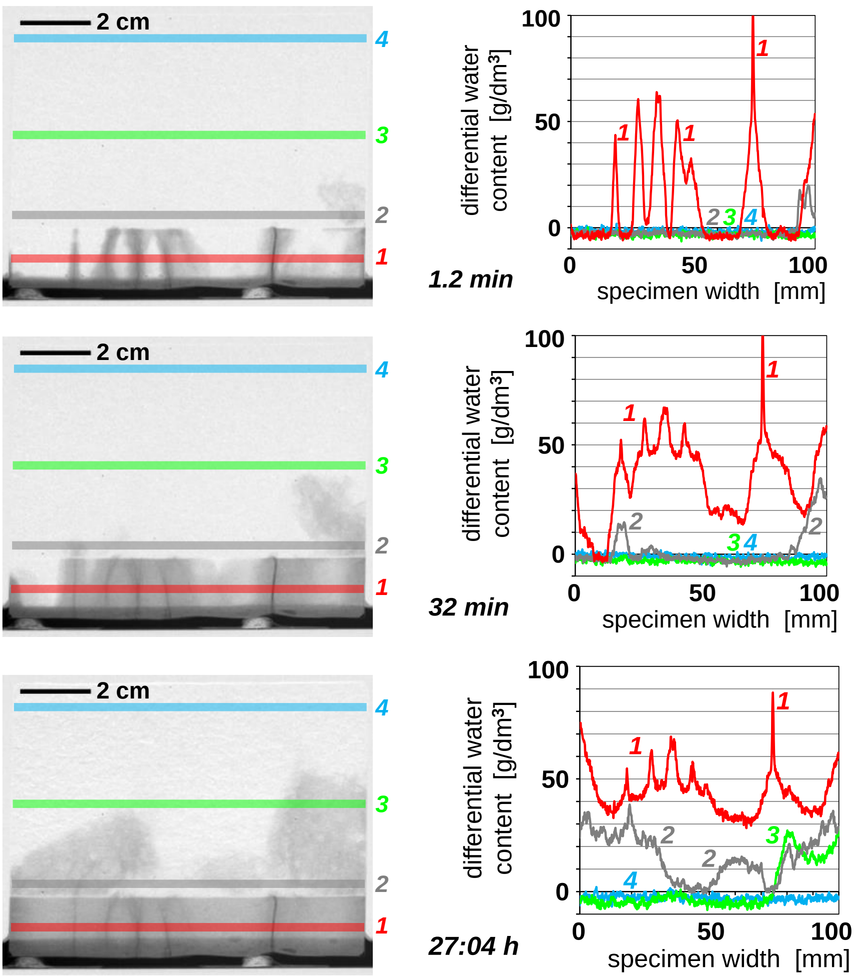

Figure 6: Neutron radiography differential suction images of the cracked hydrophobised specimens and differential water content at the four heights indicated in the pictures

The cracks in SHCC, which opened on top of the macro-cracks in the RC substrate, showed intense and quick capillary suction. While the hydrophobisation effect is obvious in the regions of the treated cracks in RC, some capillary suction through wrinkles of the Al tape could obviously take place at the right rim of the specimen. 32 minutes after beginning the test, water ingress in the non-hydrophobised RC crack at 20 mm could be detected. Water was transported from the SHCC's crack flanks as well as into the non-hydrophobised RC crack and from this crack sidewards into the RC matrix. This mode of matrix transport lets water migrate to back regions of the hydrophobised areas in the long term.

Cracked hydrophobised composite specimen: Water release

Consistent with the results discussed above, no changes occurred in non-soaked areas in this specimen as well. Deeply penetrated water remains in the interior region of the RC and does not migrate to the outside within 46 hours (duration of neutron radiography). Taking into account the amount of water taken in, some 10 up to 30 g water/dm³ remain in this region.

4 SUMMARY AND CONCLUSIONS

Composite specimens representing typical features of steel-reinforced concrete repaired with SHCC were investigated with regard to a protective function of the SHCC layer. The objective was to visualise and quantify the kinetics of water ingress and release depending on the state of cracking and a partial hydrophobisation of cracks. It was found that the capillary suction forces in cracked, non-hydrophobised specimens are so strong that within 1.2 minutes the vast majority of cracks in both SHCC and RC fill with water deep into the interior of the specimen. Capillary transport through the matrices follows. In an ongoing project the authors are developing a high-strength SHCC with stiffer and stronger fibre and stronger bond between fibre and a dense cement-based matrix. Due to these changes the crack pattern in SHCC will become finer. A better barrier function of a repair layer made of such SHCC should be expected. The present study demonstrated that hydrophobising the crack mouths of the RC prior to SHCC application can be a highly efficient measure to inhibit the ingress of water deep into the structure. After stopping the access of water to the SHCC-RC composite specimens, the cracks empty quickly over the entire height of the specimen. In the long term, the original frontier of water suction progresses a little further into the body (up to 1 mm within 46 hours). In parallel the matrix dries slowly via the bottom surface.

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Strain-hardening cement-based composites (SHCCs) reinforced by short PVA fibers constitute a relatively new class of building material, which exhibits pseudo-strain-hardening behavior with multiple-crack formation when tested under tension loads at quasi-static strain rates. The high ductility and strain capacity of SHCC are exceptional for cement-based materials. They give this material a marked potential for use in applications in which high non-elastic deformability is needed. Examples of promising applications include link slabs for jointless bridge decks, structural repairs, connecting beams for high-rise buildings in earthquake-prone areas, and the strengthening of masonry structures. Because of their beneficial and easily describable stress–strain behavior (similar to steel), the use of ductile cementitious composites may be advantageous and revolutionize the design of concrete structures in the near future. Based on fracture-mechanics considerations and the micromechanical modeling, strain hardening and an ultimate strain of approximately 5% (i.e., approximately 300 times greater than that of ordinary concrete) can be achieved using approximately 2% polymeric fibers by volume.

A number of research groups in different countries (USA, Germany, Japan, New Zealand, Brazil, South Africa and some others) are currently working on the further development of SHCC. The importance of this research topic can also be recognized by the fact that, in recent years, two corresponding RILEM Technical Committees have been initiated: “High performance fiber reinforced cementitious composites” and “A framework for durability design of fiber-reinforced strain-hardening cement-based composites”. In the Arabic countries, the scientific work in this area started with the joint project of the King Saud University (Saudi Arabia) and Technische Universität Dresden (Germany) funded by the King Abdulaziz City for Science and Technology (KACST), The Long-Term Comprehensive National Plan for Science, Technology Innovation (Project No.: 12-ADV2591-02). The proceedings at hand is a result of the Saudi Arabian-German workshop organized in Dresden by both institutions in conjunction with the International RILEM Conference on Application of Superabsorbent Polymers and Other New Admixtures in Concrete Construction. The organizers of the workshop and the editors of the proceedings believed that this document will considerably contribute to the international state of knowledge with respect to the material technology and structural applications of strain-hardening cement-based composites.

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