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STRAIN HARDENING CEMENT BASED COMPOSITE (SHCC) WITH FINE AND COARSE SAND UNDER TENSILE LOAD AND CHLORIDE ATTACK

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Abstract: The introduction of various kinds of Fibre Reinforced Concrete (FRC) has brought a new dimension in structural performance in the last few decades. The results obtained with Strain Hardening Cement Based Composite (SHCC) show improved performance especially in terms of tensile ductility and accompanied multiple cracking, and potentially reduced water and gas permeability and effective chloride diffusivity in the cracked state. Most of the published results for SHCC are based on SHCC with fine silica sand. For construction work fine silica sand is not freely available in South Africa and as a result it is often expensive to use it. Preliminary research on SHCC with coarse sand shows that it is possible to obtain more than 3% tensile strain, but up to and beyond 5% strain for SHCC with fine sand. However, a strain capacity of more than 1% will be sufficient for many applications. So, this paper reports on a research project in which SHCC with a maximum size of 300 µm of fine sand and 2.36 mm of coarse sand respectively, were developed. Dumbbell specimens were used in direct tensile tests and beam specimens were used to study chloride penetration in cracked SHCC, for both fine and coarse grained SHCC. Cracks in beam specimens were formed by flexural testing, after which chloride attack was simulated by cyclic wetting and drying with NaCl solution respectively to study the chloride penetration profiles caused by these exposures. Conclusions are drawn on the resistance to chloride penetration of fine and coarse grained SHCC under such simulated chloride exposure(s) in the cracked state.

1 INTRODUCTION

The durability of concrete is a much discussed issue worldwide in the last few decades. Researches have indicated that a large amount of money is required to repair and rehabilitate structures which have already been suffering from serious durability problems [1, 2]. Simultaneously much research has been carried out to improve structural performance against different environmental actions.

The repair and lower service of existing normal concrete (NC) structures are a burden for most countries as it impacts on the country's economy. Cracking in concrete is one of the major causes of reduced service life of structures. Cracks increase the chemical loading and reduce the lifetime of the structures. Chemical substances like chlorides $^{-}$ penetrating through cracks corrode the steel bar which has been noted as the most severe problem in concrete structures in the last 40 years. As a result, a huge amount of money is being invested for repair and rehabilitation of damaged concrete structures. Cracks in concrete structures are unavoidable and they are induced in structures in many ways, like temperature changes, creep and shrinkage, settlement of structures and lateral movement of the structure due to seismic action, or simply in its intended function subjected to operating loads. However, if it is possible to reduce the influence of cracks in structures, it may increase the life span and reducing repair cost of structures.

Cracks are indeed unavoidable in concrete structures, but, it is possible to mitigate cracks by providing sufficient ductility using reinforcement, both by fibres and steel bars. Now it is a challenging job to find out the specific pattern in structures, since the crack pattern in the composite will differ even under the same strain or loading level. Recent research results indicate that finely controlled cracks reduce the rate of permeation of water and gas in so called strain hardening cement based composite (SHCC), but the cracks do act as pathways for fast penetration under conditions of capillary absorption. SHCC came to light in 1990 by V.C.Li [3]. Typically polyethylene (PE) and polyvinyl alcohol (PVA) micro fibres are used in the SHCC widely. Through careful mix design, these fibres can control cracks to remain fine in SHCC. Being so fine, these micro cracks also appear to self heal. Continued hydration and pozzolanic activities in the SHCC causes such self healing. However it requires limited of crack width in the SHCC and best results are achieved if the crack width is lower than 0.05 mm [4]. Cracked SHCC has been shown to protect steel reinforcing bars against corrosion in patch repaired reinforced concrete beams subjected to cyclic spraying with salt solution [5]. However, several research questions remain, including the link between crack patterns, ingress, deterioration processes like corrosion, as well as which chloride exposure is more representative of the actual structural exposure, and the link to structural life.

Until now, the applications of SHCC are limited mostly to non-structural elements. Lack of information and design guidelines are the main obstacle of using SHCC structurally, or even in large repair strategies. In this research report, the main focuses are on tensile strength, cracking and chloride penetration through cracks in two specific SHCC's. Most of the existing research reported on SHCC where for SHCC containing fine sand (FS). Here, SHCC with both FS maximum particle size 300 µm) and local coarse sand (CS) (maximum particle size 2.36 mm). Their performances have been examined under tensile load, flexural load and chloride attack.

2 PROBLEM STATEMENT

The Civil Engineering Department at the Stellenbosch University has been conducting fruitful research on various fibre reinforced concrete classes like FRC, UHPFRC, SCC and SHCC for the last few years. Till now the results obtained from these materials are significant for new generation construction materials both qualitatively and quantitatively. The results also depict the future of these materials, proposing different experimental and analytical techniques for the best representation of results and explaining applications of these materials. This research paper illustrates the results obtained from SHCC containing FS and CS and explains their performance in the SHCC under tensile load and chloride attack at different ages. Most importantly, it delineates the future of CS in SHCC to achieve better structural performance at reduced cost.

3 TENSILE RESPONSE OF SHCC

Recently developed advanced concretes like high strength concrete (HSC), ultra-high strength concrete (UHSC), or high performance (HPC) and ultra-high performance (UHPC) concretes have shown drastic improvement in compressive strength, E-modulus, flexural strength as well as tensile strength [6, 7, 8]. However, one of the major disadvantages of these concretes is low tensile strain capacity or ductility. Ductility is a very important parameter for structures, especially structures in seismic regions and harsh environments. Therefore, the designer needs to provide extra reinforcement in such structures for enough ductility which is often very costly, and in some cases also not sufficient to prevent significant damage or collapse. One of the major advantages of the SHCC is that it has higher ductility than normal concrete (NC), HSC or UHSC. Using SHCC, it is possible to get more than 3-5% tensile strain at full or increased post-crack tensile resistance, while the ultimate strain in NC is about 0.015-0.02%. In spite of the fact that the initial cost of the SHCC is higher than that of NC, it may be balanced by reduced intervention cost in future. However, the 300-500% higher ultimate strain of SHCC may improve structural performance against chemical and seismic action at certain levels. So it may be possible to reduce the amount of extra reinforcement needed for ductility in structures, and the life cycle cost may be reduced in harsh environments.

Micro fibre in the SHCC improves crack bridging capacity, whereby multiple cracks form in the SHCC which are the mechanism of pseudo strain hardening. In SHCC the sustained bond and prevention of fibre breakage allows that the deformation is increased with the increase of load, leading to cracking at the next weakest point in the matrix. As a result, multiple cracks form and increased tensile stress and strain is found in SHCC [9, 10]. The strain hardening in SHCC can be achieved by fulfilling the following conditions [11]:

- Crack tip toughness should be equal or less than complementary energy ($J_{tip} \leq J_b$').
- Steady state cracking must be achieved rather than Griffith type cracks.

To realise the above, it is required that

- A critical fibre volume is used ($V_f \geq V_f^{crit}$).
- Fibres in the matrix must be pull out rather than rupture.

The basic micro-mechanical theory of SHCC can be formulated in terms of equations (1) to (5) below. The tensile response / behaviour as well as micro-crack formation in SHCC will differ in different composites because of various percentages of V_f, aggregate to binder ratio (a/b), water to binder ration (w/b), type and amount of binder and aggregate. From the specific type of SHCC mix with FS and CS investigated in this research, the tensile behaviour is discussed in subsequent sections.

The ultimate tensile strength of SHCC can be expressed as follows:

$$\sigma_{st} = \frac{1}{2} g\tau V_f \frac{L_f}{d_f} \quad (1)$$

where, g is the matrix snubbing factor,
τ is the bond strength of the matrix,
V_f is volume fraction of fibre,
L_f is the fibre length and
d_f is the fibre diameter.

The critical fibre volume is given by (reference)

$$V_f^{crit} = \frac{12 J_{tip}}{g\tau \left(\frac{L_f}{d_f} \right) w_c} \quad (2)$$

with J_{tip} the crack tip toughness and
w_c the matrix crack width at ultimate force in the fibre pullout test. The crack width

$$w_c = \frac{\tau L_f^2}{E_f d_f \left(1 + {V_f E_f}/{V_m E_m} \right)} \quad (3)$$

with E_f the fibre modulus of elasticity, E_m the matrix modulus of elasticity and $V_m = 1 - V_f$ is the matrix volume fraction. The crack tip toughness is given by

$$J_{tip} = \frac{K_m^2}{E_m} \quad (4)$$

with K_m the matrix fracture toughness. The complementary energy can be expressed as follows:

$$J_b' = V_f \frac{L_f}{d_f} \left(\frac{\tau^2 L_f^2}{6 d_f E_f} - 2G_d \right) \quad (5)$$

where G_d is the so-called chemical bond of fibre with the matrix.

4 CHLORIDE PENETRATION IN SHCC

Concrete durability serves the service life of the structures. Therefore designers must pay enough attention in this regard during the design of concrete structures. It can be achieved in many ways, viz. providing sufficient cover in concrete, higher concrete strength, adding a water repellent agent, using anti corrosion steel bars, etc. Early attention can save a lot of money for the repair or rehabilitation of structures through its life span.

In SHCC the material characteristics include a resistance to the widening of cracks. SHCC displays self-controlled crack width which is another great advantage and the cracks in SHCC are very small in comparison to NC usually used in structures [12]. In concrete structures, it appears that if cracks are controlled to a level below a certain threshold width, ingress rates of water, gas and chlorides may be insignificant [13].

Cracks in concrete are the major cause of steel corrosion in coastal environments and exposure to de-icing salts, and corrosion of steel is one of the major durability problems of infrastructure. Corrosion of steel in concrete can be clarified as carbonation induced corrosion and chloride induced corrosion. Chloride induced corrosion will start, if enough O_2 and H_2O are present in concrete for the reaction. It is said to be the most severe damaging cause of steel corrosion in concrete. In this paper only chloride penetration in unreinforced, cracked SHCC is reported. In future studies, chloride induced corrosion will be examined in both FS and CS reinforced SHCC.

5 MATERIALS AND METHODS

Table 1 shows the composition of materials used in this study. CEM I 52.5 cement and class F Fly ash supplied by the PPC Cape Town were used. Fine grain Phillippi sand (graded to ASTM F95) was used as FS and coarse natural Malmesbury sand was used as CS. The sieve analysis of both sands are shown in Figure 1. PVA fibres supplied by Kuraray Co. Ltd., Japan, of specification L_f = 12 mm, d_f = 40 µm, E_f = 40 kN/mm^2 was used. Dynamo SP1 super plasticizer (SP) was used. Dynamo SP1 is an admixture based on modified acrylic polymer supplied by MAPEI SA. To prevent segregation of the mix with the high w/c ratio, viscous agent (VA) was used together with an air-entraining agent (AEA) to ensure good fibre distribution and associated formation of multiple cracks in SHCC. Both viscous and air-entraining agents were also supplied by MAPEI SA and the specifications can be found on MAPEI website (www.mapei.co.za).

After performing several trial mixes on SHCC with FS and CS, three mix designs were chosen for FS and CS-SHCC, as shown in Table 1. The work is divided in three parts. Part one describes the SHCC performance under mechanical (compression and tension) load with FS and CS at different ages. Small dumbbell shaped specimens with cross section 30±2 x 16±2 mm^2 in the 80 mm gauge length were made for the direct tensile test. 100 mm cubes and 100 mm diameter and 200 mm long cylinders were made to determine the compressive strength and E-modulus of the matrixes. Parts two and three describe flexural and chloride penetration test results of FS and CS SHCC. Beams with dimensions of 100 x 100 x 500 mm^3 were made for the flexural test, but were subsequently used for chloride penetration testing as well. All the mixes were performed in a 50 liter pan mixer in the Stellenbosch University concrete materials lab. The maximum duration of SHCC mixes was 9 minutes. After mixing SHCC, slump flow and air content tests were also performed for both FS and CS, and their results shown in Table 2. All the specimens (dumbbells, cubes, cylinders and beams) were covered with plastic until de-moulding, approximately 48 hours after casting. After de-moulding, specimens were kept in a water curing tank at 21± 3^{o}C until the testing day.

A Zwick Z250 materials testing machine was used to perform direct tension tests of the dumbbell specimens at a constant deformation rate of 0.0075 mm/s of the 80 mm gauge length. The maximum test time period was less than 10 minutes. In total 18 specimens from each set of FS and CS at 14 and 28 days were tested respectively. The number of cracks and crack widths in the dumbbells were determined using a contactless deformation measurement system ARAMIS. The details of this measuring system can be found in Nieuwoudt [14].

Table 1: Materials used in this study

	FS-SHCC (kg/m^3)			CS-SHCC (kg/m^3)		
Materials	1	2	3	1	2	3
Cement	450					
Fly-ash	670					
Sand	550					
Water	395					
Fibre	28.6	19.5	13	26	19.5	13
SP	2.7	-	-	3.6	-	-
VA	1.13	1.35	1.35	1.35	1.35	1.35
AEA	0.45	0.45	0.45	0.45	0.45	0.45

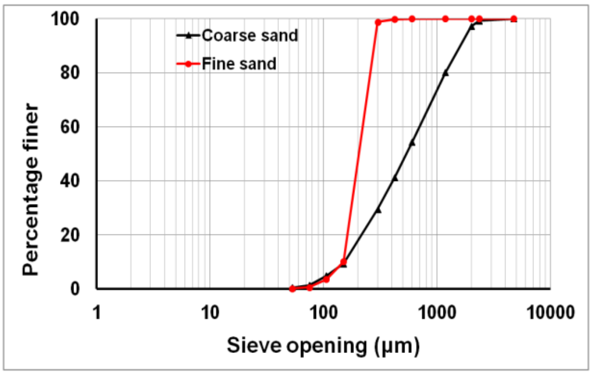

Figure 1: Grading of fine and coarse sand in this study.

Flexural beam testing was performed (loading span length of 300 mm) as the preparation of chloride penetration testing in SHCC. The same Zwick Z250 materials testing machine was used for the flexural test (three point bending) at a constant rate (force control) of 0.03 kN/s and the maximum test time period was 12 minutes.

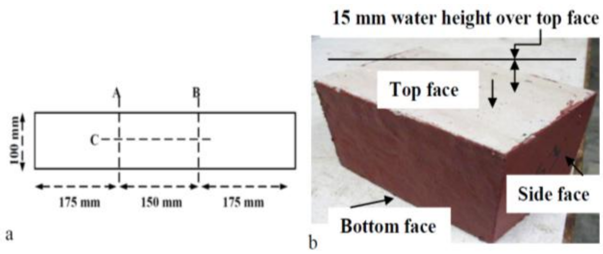

Figure.2: Preparation of specimens for chloride penetration test.

An HBM 20 ton load cell was used to record the force and one 10 mm linear variable differential transformer (LVDT) was used to record deflection of the beam. In total 9 specimens were tested at the age of 28 days for both FS and CS, which were further used in chloride penetration tests of duration 30, 60 and 90 days respectively, i.e. 3 specimens were used on each duration of chloride testing. Besides these 9 specimens, another 3 specimens of each SHCC type were tested to determine the ultimate flexural resistance. For the preparation of the chloride test specimens, approximately 60% of the ultimate flexural load was applied to cause pre-cracks in the specimens. The reason behind the application of 60% load is to simulate in-service loading conditions, as opposed to ultimate limit state, failure loads. For the chloride penetration test, a 150 mm length of each cracked specimen was prepared by saw-cutting it from the middle portion of the each beam - see Figure 2. The figure shows that the specimen was collected between lines A and B. After the chloride penetration test, it was sawn along the C line to observe the chloride penetration. Five faces of the specimens were sealed with a layer of waterproofing repellent (plascon roofseal product), leaving the cracked face open for penetration (top face in Figure 2b). Presently there is no specific method for chloride penetration into SHCC, so, different methods were followed by different researchers [5, 15, 16, 17]. In this research paper, only one method was followed which was cyclic wetting (1day submerged) and drying (5 days). The specimens were submerged into a 3.5% solution of NaCl in water by weight. After 1 day, the specimens were removed and kept in ambient laboratory conditions for 5 days. This cyclic wetting and drying procedure was followed until the specimens were ready for testing at 30 days (5 wet and dry cycles), 60 days (10 cycles) and 90 days (15 cycles) respectively. The NaCl solution concentration was not checked to ensure that it remained at 3.5% in time, but a new mix was made after 30 days to ensure the solution quality. On the above mentioned day of chloride testing, each specimen was sawn through the middle along the line C in Figure 2 (left). After that, 0.1N of $AgNO_3$ solution was painted on the cutting surface to observe the chloride penetration into SHCC specimen. It is worth mentioning that, only two types of SHCC (FS-SHCC1 and CS-SHCC1) were used for the flexural test and further chloride penetration test. Detail results of chloride penetration are given in the next section.

6 EXPERIMENTAL OUTCOME

The compressive strength range of SHCC was 31 to 39 MPa and the E-modulus was 13 to 20 GPa. See Table 2. The detail procedures of testing and are given in Paul and van Zijl [18]. Only the tensile strengths of SHCC are discussed here together with other parameters like crack width and number of cracks.

Table 2: Fresh and mechanical properties of SHCC at 28 days (and at 14 days in brackets).

	FS-SHCC			CS-SHCC		
	1	2	3	1	2	3
Slump (mm)	170-200	185	190	170-200	185	173
% of Air	4.5-6.5	-	-	4.5-8.9	-	-
f_{cu} (MPa)	39	33.6	34.4	35.1	31.2	36.7
E-mod (GPa)	19.9	15.8	17.7	18.1	12.9	19.1
$\sigma_{u,st}$ (MPa)	4.05 (3.61)	3.47	2.46	3.42 (3.64)	3.27	2.28
$\varepsilon_{max\ (\%)}$	1.48 (3.4)	1.16	0.86	1.46 (4.1)	1.14	0.76

6.1 Tensile stress and strain of SHCC

The typical responses of SHCC's containing various fibre volumes to direct tension at different ages are shown in Figures 3 to 6. In total 10 FS-SHCC1 specimens (5 at 14 days and 5 at 28 days age), 4 FS-SHCC2 specimens and 4 FS-SHCC3 specimens were tested. Their average ultimate strength ($\sigma_{u,st}$) and strain (ε_{max}) at different days have given in Table 2. CS-SHCC1 shows lower cracking strength than the CS-SHCC2, but at that stage the ultimate strain was higher for CS-SHCC1 than others. Figures 3 and 4 also show the results for FS and CS-SHCC1 at 14 days. In both cases, the ultimate strain was much higher than at the age of 28 days. Maximum tensile strength of 3.61 MPa and 3.64 MPa was found for FS and CS-SHCC1 respectively, which is close to the 28 days strength. However, in case of ultimate strain, maximum 3.4% and 4.1% were found for FS and CS-SHCC1 at that age. So the experimental results show that SHCC becomes more brittle in direct tensile testing at higher age (14 days to 28 days). This trend was also shown by Wang and Li

[19] and Yang et al. [20]. The complex behaviour of binder, sand, fibre and matrix/fibre interface properties, influence the strain capacity of SHCC during aging [13]. However, no major changes in ultimate tensile strength are observed at different ages.

6.2 Number of cracks and crack width in SHCC

As mentioned earlier the major advantage of SHCC to NC is the formation of multiple fine cracks. These fine cracks delay ingress of liquids and salts into the SHCC. This is why it is thought that SHCC may delay the corrosion of steel in structures and increase the total life span. This paper only reports detailed crack information as found in FS-SHCC1 and CS-SHCC1 specimens tested at the age of 14 days. Figure 7 shows the formation of cracks in FS-SHCC1 and CS-SHCC1. Figures 8 and 9 show the average number of cracks (NOC), crack width (ACW) and maximum crack width (MCW) from 3 specimens of FS-SHCC1 and CS-SHCC1 at 14 days. In Table 3, the NOC, ACW and MCW at strain level 1% of each type of FS-SHCC and CS-SHCC at 28 days. It is worth mentioning that the cracks were counted at the intersections with three lines drawn vertically along the 80 mm gauge length of the dumbbell specimen, shown in Figure 7. Also, all the results shown here are the average value of 3 sections from a total of 3 specimens for each type of SHCC.

Higher fibre volume leads to higher NOC, lower ACW and MCW in the all SHCC's except CS-SHCC3. In this study it was assumed that deformations exceeding 15 µm (measuring with ARAMIS during testing) between two points (roughly 1 mm apart) in the direct tensile test were cracks.

Table 3: Number of cracks and crack width (µm) in SHCC at 28 days at 1% strain level

	Strain 1.0%		
SHCC	NOC	ACW	MCW
FS-1	18	41.9	88.7
FS-2	12.78	62.1	129.4
FS-3	6.67	122.0	260.9
CS-1	12.33	64.9	140
CS-2	10.67	88.9	187.3
CS-3	10.67	70.9	156.4

6.3 Micromechanical behaviour of SHCC

As mentioned before, the behaviour of SHCC differs from one mix to another. For the specific SHCC's reported here, the micromechanical parameters in eqs (1) to (5) for FS and CS-SHCC1 are shown in Table 4.

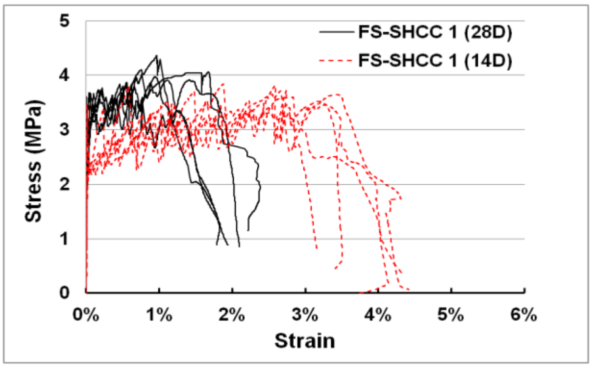

Figure 3: Tensile stress strain response of FS-SHCC1 at 14 and 28 days.

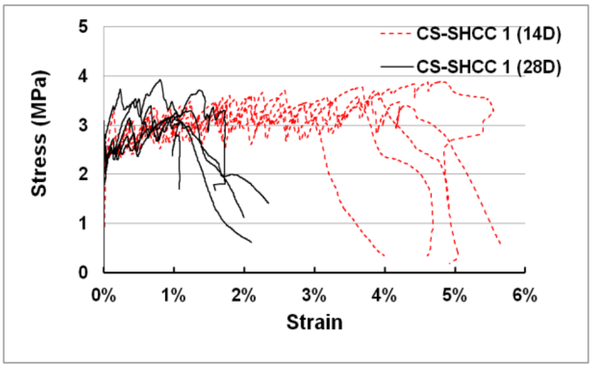

Figure 4: Tensile stress strain response of CS-SHCC1 at 14 and 28 days.

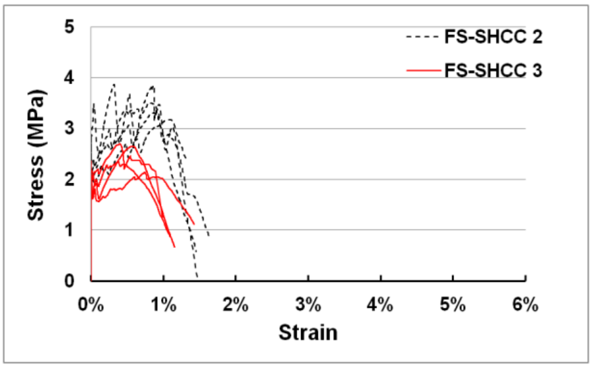

Figure 5: Tensile stress strain response of FS-SHCC2 and 3 at 28 days.

The results presented in the Table 4, were determined by assuming that the critical fibre volume (V_f) is 1% for both FS and CS-SHCC and the mechanical properties K_I, E_m and J_{tip} were taken from 28 days response of FS and CS mortar notched beam tests More details are given in Paul and van Zijl [18]. Coarse sand leads to increased K_I and J_{tip} in this specific SHCC mix.

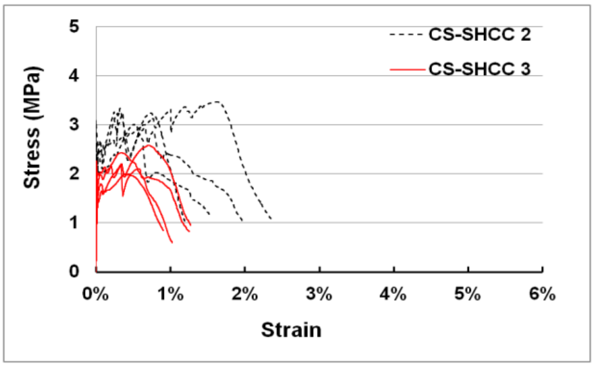

Figure 6: Tensile stress strain response of CS-SHCC2 and 3 at 28 days.

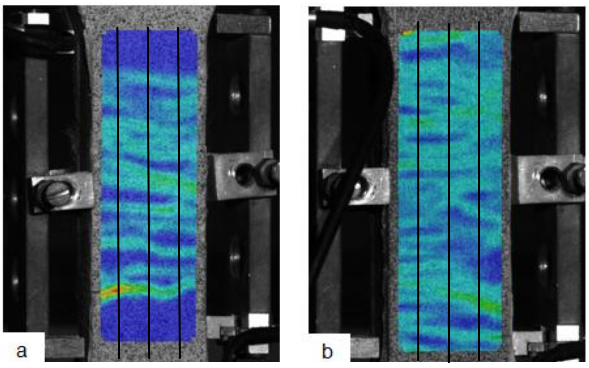

Figure.7: Formation of cracks in (a) FS-SHCC1 and (b) CS-SHCC1.

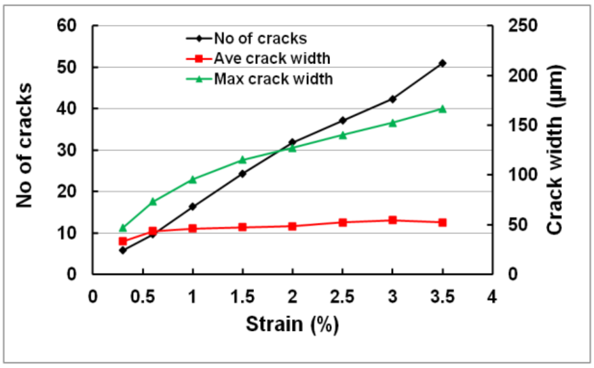

Figure.8: No. of cracks and crack width at 14 days in FS-SHCC1.

Table 4: Micromechanical properties of the matrix of SHCC [18]

SHCC	K_I	E_m	J_{tip}	τ	g	w_c
FS-1	0.82	17	0.04	1.55	0.79	0.13
CS-1	1.12	17	0.08	3.18	0.36	0.27

Note the units of K_I is in $MPa.m^{1/2}$, E_m is in GPa, J_{tip} is in $J.m^2$, and τ is in MPa.

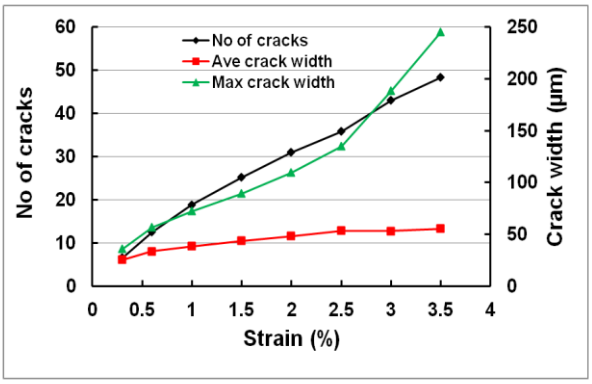

Figure.9: No. of cracks and crack width at 14 days of CS-SHCC1.

6.4 28 days Flexural behaviour of SHCC

A maximum ultimate flexural strength of 11 MPa with coefficient of variation (CoV) 9.7% was found for FS-SHCC1 and 9.5 MPa with CoV 4.6% was found for CS-SHCC1. The cracking strengths were 4.74 MPa (CoV 8.4%) and 4.61 MPa (CoV 3.0%) for FS and CS-SHCC1 respectively. The flexural test responses of both SHCC are shown in Figure 10. Figure 11 shows SHCC beam responses up to 15 kN load which have been used for pre-cracking the chloride penetration test specimens. In this particular type of SHCC mix, at ultimate flexural load state, only 4 cracks were found at the tensile face with maximum width about 2 mm (see Figure 12a). It was proved in 28 days direct tensile test that number of cracks reduce with the maturity of SHCC. At the 15 kN load state, a maximum of 2 cracks were found per specimen and the crack width was about 0.02 mm at the widest part, i.e. at the furthest tensile face (see Figure 12b).

The small cracks (0.02 mm) in the SHCC at about 60% of ultimate load brings another issue of self healing, because at this crack level self healing of SHCC is expected. The crack depth in the specimens are different from one to another, as illustrated in Figures 13 and 14 by the white-gray colours indicating NaCl penetration.

6.5 Chloride penetration in SHCC

Chloride penetrations through cracked FS-SHCC1 and CS-SHCC1 specimens' depth were monitored at the three different durations of cyclic wetting and drying exposure (30, 60, 90 days). Figures 13 and 14 show the penetration of chloride in the specimens. The white-gray colour represents the chloride penetration in the specimens. It is clear from the figures, that the waterproofing repellent used here did not work at all. As a result penetration through the sealed faces was observed as well.

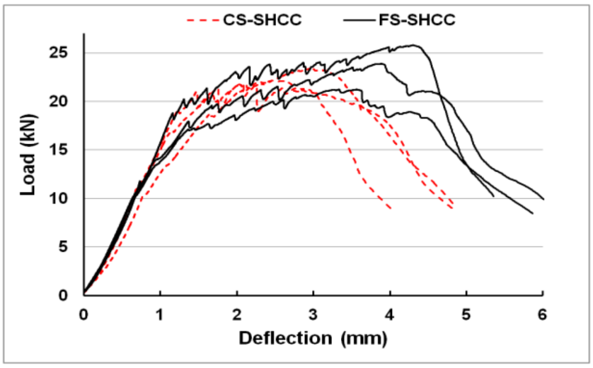

Figure.10: 28 days flexural load vs deflection of FS-SHCC1 and CS-SHCC1.

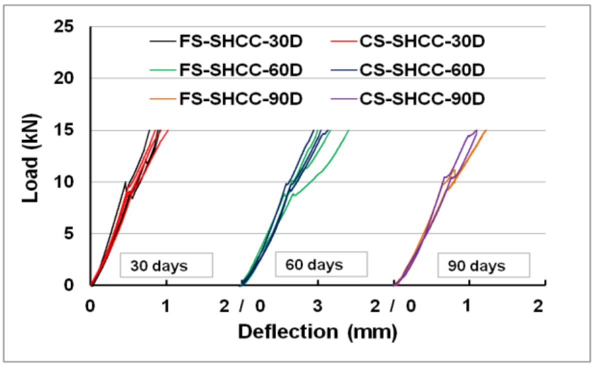

Figure.11: Applied flexural load vs deflection in FS and CS-SHCC1 specimens for chloride penetration test.

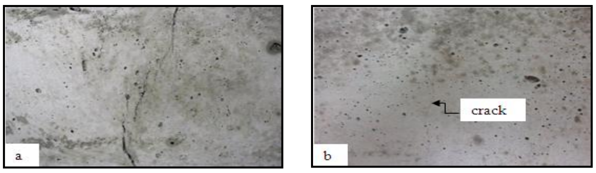

Figure.12: 28 days SHCC beam, a) cracks at ultimate load state, b) cracks at 15 kN load.

The chloride penetration depth in SHCC specimens was measured manually using normal scale and their results are shown in Table 5 as the average values of three specimens of each type of SHCC. A maximum of 13 mm and 14.5 mm penetration of chloride is found along the top face in FS-SHCC1 and CS-SHCC1 respectively at 90 days. From the Table 5 it is clear that the number of wetting and drying cycles influence the penetration depth.

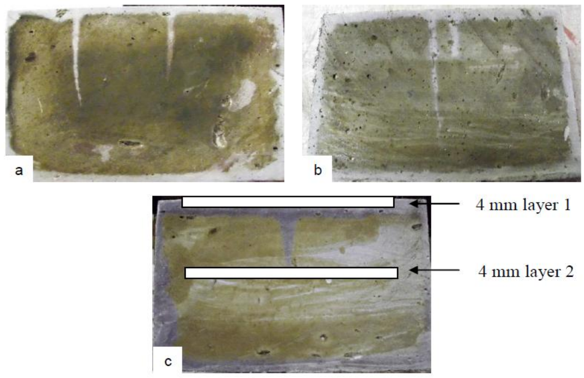

Figure.13: Chloride penetration through FS-SHCC1 at 30 (a), 60 (b) and 90 (c) days.

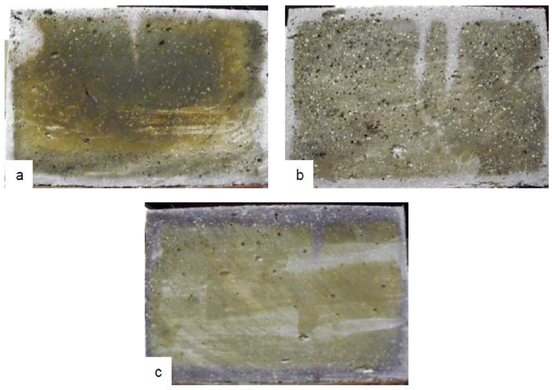

Figure.14: Chloride penetration through CS-SHCC1 at 30 (a), 60 (b) and 90 (c) days.

Table 5: Chloride penetration in SHCC at different days (faces representation are shown in Figure 2b)

SHCC type	Specimens face	Chloride penetration (mm) at different durations (days)		
		30	60	90
FS	Top	4.7	8	13
	Bottom	4.0	7.3	7.5
	Avg of two sides	3.7	4.7	5.0
CS	Top	5.7	9.0	14.5
	Bottom	5.7	6.0	8.0
	Avg of two sides	4.0	5.3	5.0

To determine the concentration of chloride content in the specimen, two layers of SHCC were sliced and tested (see Figure 13c) only from one specimen FS-SHCC1 at 90 days. In layer one and two the concentration of chloride was about 0.1% and 0.004% respectively by weight of cement. It is noted that for the discolouration, a chloride content level of about 0.1 – 0.15% is present at the lower end of the crack, but because of the large portion of material away from the crack tip included in this particular chloride concentration test, the low overall concentration of 0.004% was found. The details about the discolouration for various chloride content level by weitght of cement in the cementitious matrix materials can be found in Otsuki et al [21]. A next step will be to determine whether corrosion initiates in steel reinforcement of finely cracked SHCC, and corrosion rate.

7 CONCLUSIONS

The initial cost of the SHCC is relatively higher than NC but the potential better performance against the long term deterioration processes is of importance. If increased life span and/or reduced repair frequency can be assured by SHCC, it will be possible to save money from the repairs and rehabilitations of structures. The insight gained from this work can be summarised as follows:

Coarse sand including particles of size up to or more than 2 mm can be an alternative source of sand, instead of the usual fine sand used in SHCC. The prominent behaviour typical of fine sand SHCC can be reproduced. The multiple cracks in SHCC are fully depending on its overall mix design.

In both fine and coarse sand SHCC, a reduction in strength and ultimate strain was found for lower fibre volume at 28 days. So, the higher fibre volume leads to improved mechanical behaviour of SHCC.

Both FS-SHCC1 and CS-SHCC1 show reduction in ultimate strain at the age of 28 days compared to that at the age of 14 days. However, before coming to any solid conclusion in this regard, it is necessary to perform more studies to determine whether this is mix dependent.

In the particular mix of FS-SHCC and CS-SHCC with 1% fibre, CS-SHCC shows better performance in terms of number of cracks, average crack width and maximum crack width. So, future studies need to prove the critical fibre volume for both fine and coarse sand at this lower fibre volume. Coarse sand in SHCC leads to an increased crack tip toughness, and probably also a higher bond strength.

Chloride penetration depth in uncracked parts of SHCC is dependent on the number of wetting and drying cycles. A crack width of 0.02 mm in SHCC allowed chloride penetration apparently to its full depth. So future research needs to determine whether chloride penetrating through fine cracks leads to corrosion initiation in reinforcing bars, and if so, the corrosion rates.

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