- Technical Paper -

ANALYTICAL STUDY ON FUNCTIONALLY GRADIENT STRAIN-HARDENING CEMENTITIOUS COMPOSITE FOR HIGH DURABILITY

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ABSTRACT

A method to improve the durability is investigated analytically for the case where SHCC is used as a functionally gradient repair material. The SHCC part is divided into multiple layers and the material properties of each layer are set functionally gradient. Then, it has been shown that the time needed for corrosion initiation can become longer depending on the selection of material properties of each layer. Also, the influence of crack width of the SHCC part is clarified.

Keywords: SHCC, functionally gradient material, durability, chloride ingress

1. INTRODUCTION

Strain hardening cementitious composite (SHCC) material used as a repair material on reinforced concrete structures for protection against environment exposure is considered in this study. By layering different SHCC mixtures, one can create functionally gradient material (FGM) to control crack spacing, localization and opening. FGM is characterized by variation in structure gradually over volume, resulting in changes of the material properties. Compared to cracks in ordinary RC, formation of micro-cracks increases resistance to moisture, gas and salt penetration, the key to cement-based material durability. Another benefit of fine crack width in SHCC is its ability for intrinsic self-healing, recovering transport and mechanical properties.

Transport of chloride ions through the cementitious material using the pore liquid as a medium is usually described with Fick's 1st law equation, i.e., the flux of diffusing substance (e.g., chloride ions) is proportional to the gradient of the distribution of the diffusing substance. The proportional coefficient is called diffusion coefficient.

Penetrability and transport properties, i.e., diffusion of chloride ions in the pore liquid and convection of chloride ions in the pore liquid by liquid transport are retarded by the chloride binding to the cement gel. Another significant influence on the binding capacity of the chloride solution has the chemical composition [1]. The use of $CaCl_2$ instead of NaCl increases the amount of bound chlorides [2]. Furthermore, the diffusion coefficient depends on the hydration level and the pore humidity *RH* of the pore system. Presented analysis of FG-SHCC (Functionally Gradient SHCC) uses diffusion coefficients of the unfavorable conditions, where material is subjected to cycling wetting and drying conditions, i.e., full pore saturation or dry material causing negligible diffusion of chloride is not considered. Cycling of wetting and drying is unfavorable, because this cause deeper penetration of salts into the material. Some researchers pointed out, that during test of chloride diffusion into SHCC salts are collected on the other face of specimen [3]. This is a case of thin samples and it is not expected in this analysis, because the concrete slab is thicker and evaporation from unexposed surface is negligible.

Goal of this analysis is to inspect possible durability improvement by layering SHCC of different material properties. Layered material is usually found in nature as the most efficient material distribution. Firstly, this idea should be confirmed by analysis of sound SHCC with constant layer thickness, as the most basic concept and find the ideal material distribution whilst using available SHCC mixtures. When this concept is proven to be working and ideal distribution is found, effect of cracks from mechanical loading must be understood and estimated durability is presented.

2. DIFFUSION OF CHLORIDES IN FG-SHCC WITHOUT CRACK

In the following diffusion analysis, diffusivity of the place with the largest crack is examined. The mesh size and time step size is selected so the result of the analysis is close to the known semi-infinite solution [4]. Time step is set to 0.01year and the element size is 1mm, i.e., 5 elements in a single layer of SHCC. In this analysis, concentration of chloride at the reinforcement is monitored and durability is defined as a time, until which corrosive environment is not initiated, i.e., concentration of chloride at 1.2kg/m^3. Rebar, which is not modelled, is in an unrepaired concrete with a cover thickness 25mm, i.e., located 40mm deep from the surface of repair material. Therefore, critical concentration of chlorides is controlled on the edge of a model. Location of the analyzed detail is schematically represented in Fig.1. The detail is located on the

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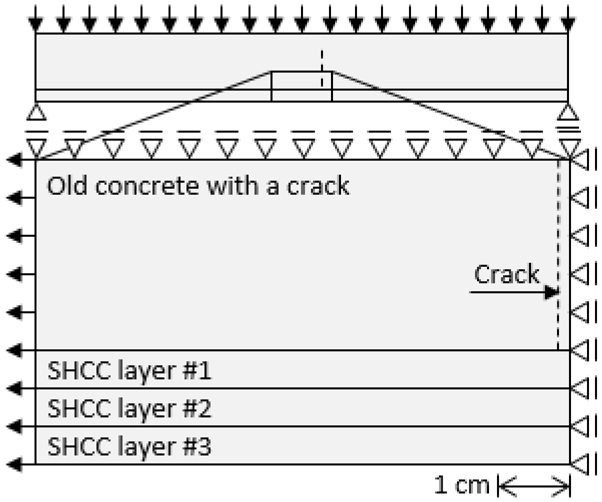

Fig. 1 Location of the detail in the structure

bottom part of a slab repaired with an FG-SHCC material. Old concrete slab contains a crack, in the detail modelled on the right side, area of cracked elements is 62.5mm^2, i.e., 10 elements in crack analysis. Axisymmetric model has size 80x40mm, where SHCC layer is 15mm thick in total.

Diffusion of chloride ions is obtained by modifying the effective diffusivity parameter and monitoring the concentration in the location of the rebar using a known boundary chloride concentration, time and a thickness from experiments [5,6]. It should be understood, that from this analysis, exact chloride profile cannot be obtained.

FGM is created by layering SHCC of different material properties. Different diffusion can be achieved mainly by varying the amount of fibers in a matrix, water to binder ratio or possible admixtures, e.g. water repellent [3]. FGM in this study is understood to be identical to a homogeneous layer when summary of relative material quality is identical, i.e., three identical layers of SHCC have 100% of fracture energy each, compared to FGM, where this ratio can vary (e.g. 50%, 100%, 150%).

Three layers of SHCC with identical constant thickness of 5mm are used for optimization for the best

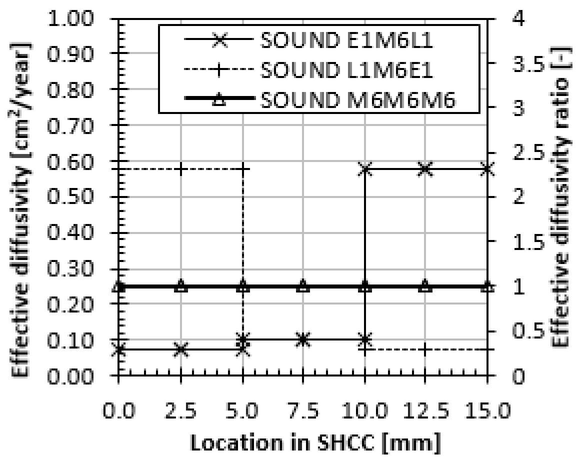

Fig. 2 Distribution of effective diffusivity in sound SHCC

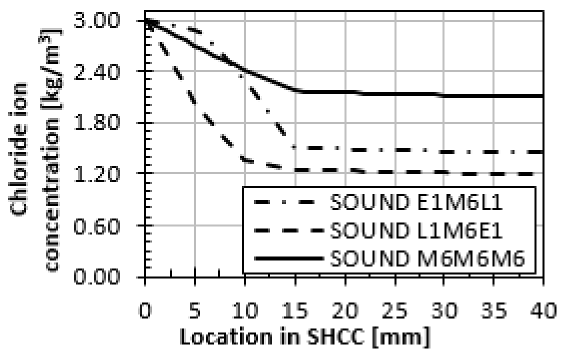

Fig. 3 Diffusion of different sound SHCC layers at t=49.7years

performance of sound FG-SHCC. Four different materials are used. Mechanical performance of adopted mixture M6 [7] is used as a base material for homogeneous SHCC distribution. An average value of chloride diffusivity based on the W/C ratio is assigned to the mixture M6. From this base M6 material, three materials of different effective diffusivity and mechanical performance are assumed by extrapolation of their respective properties. In Table 1, equivalent diffusivity of a material to form FGM is represented as a ratio, e.g., L1 at 2.3 has 230% of diffusivity of M6 and E1 has 30% diffusivity of M6.

Compared to a homogeneous layer of SHCC, FG-SHCC shows better performance of up to 214% increase in durability in sound SHCC, see durability years in Table 1. Ratios of effective diffusivity of such FGM are 2.3, 0.4 and 0.3, i.e., negative gradient, see the layering L1M1E1 in Fig.2. The resulting respective chloride ion concentration for each layering order is presented in Fig.3. Best used material layer for this analysis has equivalent diffusivity of 0.067cm^2/year, which is a diffusivity of the UHP-SHCC (Ultra-High Performance SHCC) material [8]. This analysis uses the effective diffusivity of UHP-SHCC as the best material, but with progress in research of SHCC mixtures, formed function can be even more effective.

Table 1 Durability of sound SHCC repair material

Layers	Ratio order from interface to surface [-]			Durability [years]
E1M1L1	0.3	0.4	2.3	39.6
L1M1E1	2.3	0.4	0.3	49.7
M6M6M6	1	1	1	23.2

3. DIFFUSION OF CHLORIDES IN FG-SHCC WITH A CRACK

This part of the analysis studies the effect on diffusion of cracked FG-SHCC, because material parameters are changing due to applied mechanical load. Effect of creep and other sources of cracks are not modelled, because the beneficial effect of FGM can be shown on an average width crack distribution from live load. One must understand, that not only the material properties are changed because of formed cracks, but also because of chemical changes due to chloride ion penetration.

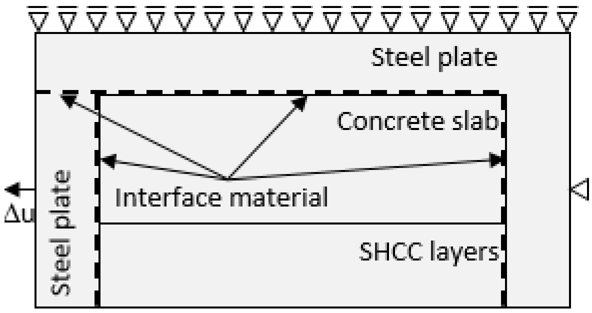

Fig. 4 Plain tensile test, (Δu=4.0x10^{-5}m)

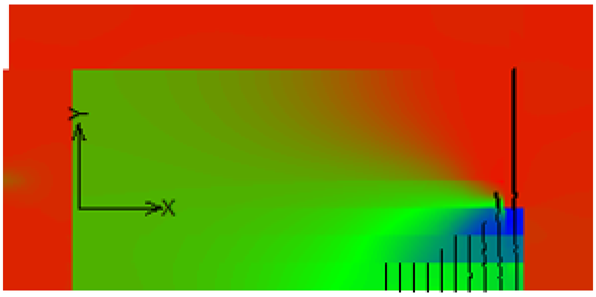

Fig. 5 Crack distribution from crack analysis and stress distribution, (red=min, blue=max)

SHCC under chloride exposure suffers from a decreased chemical bond strength between fibers and a matrix, with reduction of up to 40% [9]. On the other hand, mechanical bond strength is increased up to 125%, [8]. It is presumed, that this is caused by salt crystals growing on the interface and providing better contact. Such changes in the interfacial transition zone (ITZ) cause reduced fracture energy, therefore formation of smaller number of cracks, but with a larger average crack width resulting in reduced durability.

Prepared FEM model is firstly pre-loaded using the crack analysis to obtain the crack width at the stage after repair and application of first live load. Material's equivalent diffusivity is then updated due to newly formed cracks.

3.1 Average Crack Width

Using the FEM analysis, 2D nonlinear model of an SHCC repair material on a concrete slab was created. Analyzed model represents a small part of a repaired structure Fig.1, where a 25mm layer is representing an old concrete with a crack and 15mm layer is representing the SHCC repair material. Layers of SHCC of various mechanical and physical properties forms an FGM. Thickness of the 2D model is 40mm, except FEM elements that represents a crack, where thickness is set to 15mm. Stress in the thinner area is reaching the material strength earlier than in other elements, and the early formed crack can simulate the pre-cracked specimen. As it is recommended [10], boundary conditions are applied on the model through steel plates, Fig.4. Special interface material must be modelled in between the plate and the cementitious material to remove a tangential displacement restriction causing incorrect crack propagation. In the model with the rigid connection in between the steel plate and the

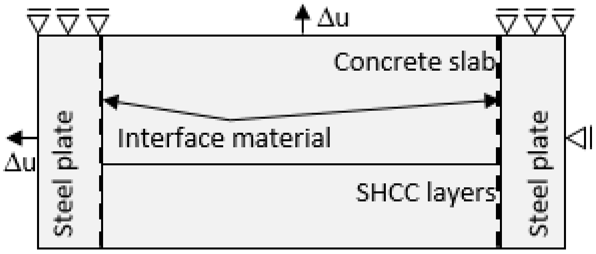

Fig. 6 Interface test model, (Δu=5.0x10^{-6}m)

Table 2 SHCC material parameters in FEM vs test data

Test Data	E [GPa]	f_t [MPa]	f_c [MPa]
M6 Matrix	20	3.5	$-10f_t$
Fiber material	40	1640	$-f_t$
FEM input data			
Model M6 tensile test	20	3.5	$-10f_t$
Model E1 derived from M6	25	4.5	$-10f_t$
Model L1 derived from M6	20	2.5	$-10f_t$

cementitious material, the plate is confining the model against a lateral contraction, causing incorrect cracking. Cracked model with layering E1M1L1 is presented in Fig. 5, where red is a minimal stress and blue is the highest with graphical representation of formed cracks by vertical lines, where 1D diffusion analysis is carried at the place of the widest crack, i.e. under the single crack in concrete. Material input data are summarized in Table 2, where E is the Young's modulus of elasticity, f_t is the ultimate tensile stress and f_c is the ultimate compressive stress.

The interface material has high stiffness in a normal direction, so the model has an identical stiffness when loaded. This was tested on a modified model presented in Fig.6, where model with an interface and a model with a rigid connection were compared. Material properties of the interface set so the stiffness of both rigid and interface model have identical normal stiffness are summarized in Table 3. Tangential stiffness must satisfy two main conditions, former the reaction from displacement up to a value of transversal compression must be negligible and latter condition is a numerical stability of the analysis.

One meshing size was selected with respect to computational efficiency and possible representing of number of cracks on the element body. In open cracks, stress is transmitted only by fibers. Stress is gradually redistributed to the matrix, with zero value at the crack edge, increasing with the distance from the crack. The condition for a matrix cracking may not be fulfilled in a certain distance from a crack, therefore cracks must maintain certain minimum spacing x. To ensure that the crack spacing does not become less than x, presented analysis utilizes regular meshes with finite element size equal to approximately $2x$, noting that the 4-noded quadrilateral element employed may accommodate a maximum of two semi-parallel cracks. In this model, mesh size is 2.5x2.5 millimeters.

Table 3 Interface material parameters

Parameter type	Value	Units
Normal stiffness, K_{NN}	1.00E+17	[MN/m^3]
Tangential stiffness, K_{TT}	1.00E-05	[MN/m^3]
Tensile strength, F_t	4.50E+00	[MPa]
Cohesion, C	5.00E+00	[MPa]
Friction coefficient	8.50E+00	[-]
Thickness	1.00E-03	[m]

Table 4 Effect of cracks in SHCC

Ref.	D_d [cm^2/year]	D_k [cm^2/year]	ε [%]	w [μm]	D_0 [-]
[2]	0.259	0.37	0.6	21	0.03
[8]	0.26	0.57	0.2	40	0.12

Table 5 Durability of cracked FG-SHCC material

Layers	Ratio order from interface to surface [-]			Durability [years]
E1M6L1	0.3	0.4	2.3	19.0
L1M6E1	2.3	0.4	0.3	30.6
M6M6M6	1	1	1	15.4

Based on a repair method, repair material is generally subjected only to stress from a live load. Stress increase form a live load in a reinforcement is generally around 100MPa, i.e., with Young's modulus of a steel at 200GPa expected strain from a live load is $5x10^{-4}$. Model is pre-loaded up to the specified strain, and then the strain is kept constant, while diffusion of chloride takes place. Cracks width formed in SHCC of different material layers caused by live load strain $\varepsilon = 5x10^{-4}$ are presented in Fig.7.

3.2 Diffusivity of Cracked SHCC

Cracked versus sound material has in general higher diffusivity. The difference in diffusivity between a cracked and a sound SHCC foremost depends on average width of cracks, number of cracks and maximum crack width. That is, two SHCC materials can have identical average crack width, but diffusivity of the one with higher number of cracks is larger.

One way of measuring chloride penetration depth is to use silver-nitrate sprayed solution for a non-direct testing [6]. Area with a changed color after application of a silver-nitrate solution is understood as to be prone for steel corrosion, and a measured penetration depth can be used in the diffusion analysis. Silver-nitrate applied on a cementitious material reacts by changing a color, when concentration of chlorides is in a range of 0.28% to 1.41% by binder mass [11].

Other way is measuring direct concentration profiles by method of X-ray fluorescence (XRF) [3]. For each result was calculated equivalent diffusivity parameter using known boundary concentration, depth of chloride penetration and time of a corrosion initiation.

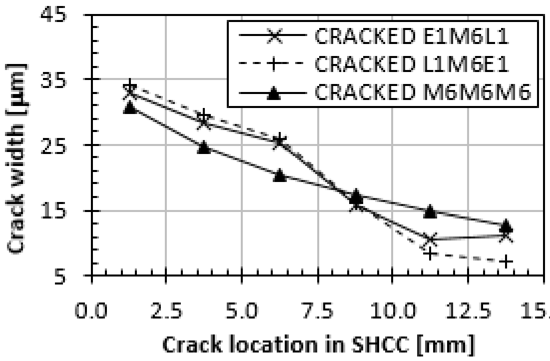

Fig. 7 Crack width profile in SHCC from live load, (Plain tensile test avr. strain: ε=5x10^{-4})

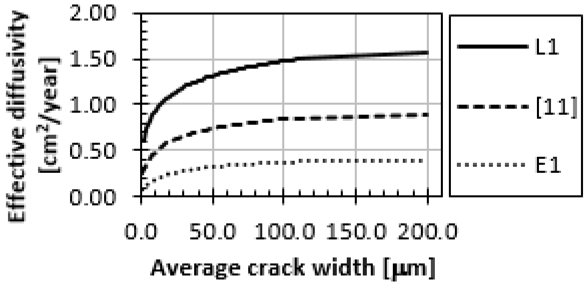

Fig. 8 Effective diffusion as a function of crack width of SHCC

Calculated equivalent diffusivity parameters for diffusion analysis are presented in Table 4 with ε as strain and *w* as crack width values of the respective test data. Using the test data, a parameter D_0 describing the effect of cracks in SHCC can be obtained using following equation for diffusivity defined in Eq. (1), [11] as

$$D_d = D_k + D_0 \log_{10}(\varepsilon \cdot w^2) \qquad (1)$$

where,
D_k : diffusivity of sound SHCC [cm^2/year]
D_0 : parameter for cracks in SHCC [cm^2/year]
ε : strain [%]
w : crack width [μm]

Calculated parameter D_0 (Table 4) is used for prediction of crack width effect on SHCC, Fig.8. Data from [12] are used for scaling the equivalent diffusivity to create two SHCC materials L1 and E1, where L1 has at zero crack width 230% larger diffusivity and E1 30% of equivalent diffusivity, see Fig. 8. As can be seen in Fig.8, equivalent diffusivity became almost constant with average cracks larger than 100μm. Similar behavior was found by Suvash C. P. [6] and Seung Y. J. [13] on a cracked concrete specimen, where for cracks 80-100μm chloride diffusion is constant and independent of crack width. Difference is observed in crack range 0-30μm, where chloride diffusion of concrete is almost unchanged, but SHCC has a logistic growth. In crack range from 30μm up to 100μm, the diffusion in concrete has linear increase, somewhat like SHCC. It must be noted, that even though shape of functions is similar, diffusivity of concrete is much larger.

3.3 Influence of Crack Width on Durability

For the given strain at 5.0×10^{-4} causing crack width up to 35μm, diffusivity of cracked SHCC layer E1 increases up to 243%. Resulting distribution modified by the effect of cracks on effective diffusivity is shown in Fig.9 with respective chloride ion concentration in Fig.10 at the time of the best layer durability performance, i.e., L1M6E1. Durability of the layer with a negative gradient performs almost twice as better as the homogeneous layering. This is due to good quality surface layer, that is not affected by cracking as much as the layer at the interface with concrete substrate and combination of low effective diffusivity.

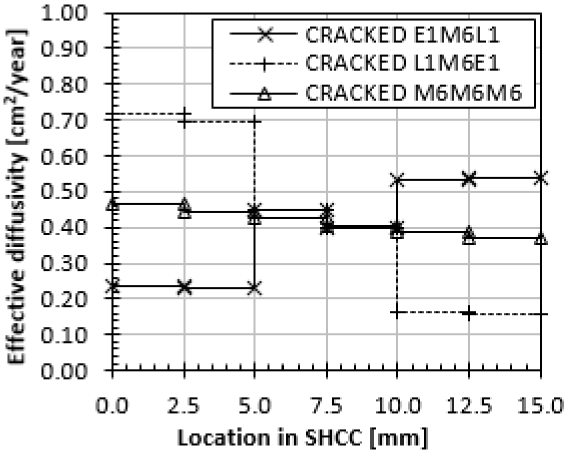

Fig. 9 Distribution of effective diffusivity in cracked SHCC

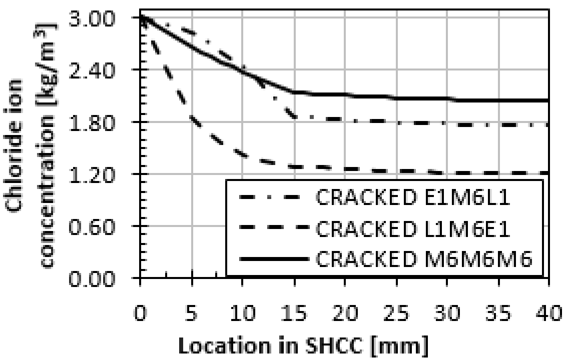

Fig. 10 Diffusion of different cracked SHCC layers at t=30.6years

4. CONCLUSIONS

(1) FG-SHCC shows better durability compared to homogeneous, with up to 214% increase. With further optimizing, one can possibly achieve further better results.

(2) FG-SHCC with the lowest diffusivity on the exterior surface shows better (57%) performance than FG-SHCC of identical layers but inverse order, Table 5.

(3) The above facts in diffusion and crack analysis implies the possibility of material use optimization to get improvement of durability of concrete structures.

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