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Publication date
2019

Document Version
Final published version

Published in
Proceedings of the Konferencija Savremena Građevinska Praksa 2019

DEPARTMAN ZA GRAĐEVINARSTVO I GEODEZIJU
FAKULTET TEHNIČKIH NAUKA NOVI SAD

KONFERENCIJA
SAVREMENA GRAĐEVINSKA PRAKSA
2019

DRUŠTVO GRAĐEVINSKIH INŽENJERA NOVOG SADA

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STRAIN-HARDENING CEMENTITIOUS COMPOSITE (SHCC) FOR DURABLE CONCRETE REPAIR

Summary (Style SGP Rezime): *Infrastructure is ageing and we are facing a serious challenge on how to deal with it. One possible solution is to repair it, but the life of current concrete repairs, including all types of repairs and application of different materials, is not satisfactory and there is an urgent need for improvement. Understanding the damage development in a repair system, and how to predict, model and prevent its failure is critical to improving performance of concrete repairs. Therefore, the aim of this work was to experimentally and numerically study the interaction between the repair material and existing concrete in two aspects which are so far scarcely understood. Firstly, the dynamics of moisture exchange in repair systems was studied, because this interaction is critical for the development of properties of the repair material and the interface. Secondly, the interaction between the repair material and the substrate, i.e. fracture behaviour of the repair system under different exposure and loading conditions was investigated. The main repair material used in this study is a recently developed fibre reinforced ultra-ductile cement-based material, known as SHCC (Strain Hardening Cementitious Composite). Fine PVA fibres and special material composition ensure that instead of single crack localization, like with conventional concrete, many tiny cracks are generated in SHCC. This is better for durability of repairs and enhances ductility and damage resistant behaviour. Finally, based on acquired knowledge, SHCC and four other repair materials were applied and inspected in a trial repair of the 70-year-old Maastunnel. More details about the presented work can be found in [1].*

Key words: *Concrete Repair, Interface, SHCC, Lattice model*

VLAKNIMA ARMIRANI SHCC ZA DUGOTRAJNE BETONSKE SANACIJE (STIL SGP NASLOV)

Rezime (Stil SGP Rezime): *U građevinskoj praksi, ozbiljan izazov sa kojim se sukobljavamo je starenje infrastrukture. Moguće rešenje je sanacija, ali trajnost saniranih betonskih konstrukcija, uključujući različite reparaturne tehnike i primenu različitih reparaturnih materijala nije zadovoljavajuca. Da bi se uspešnost sanacija poboljšala, bolje se mora razumeti ponašanje saniranog sistema, odnosno kako da se predvidi, modelira i spreči lom. Dakle, cilj ovog istraživanja je eksperimentalno i numeričko ispitivanje interakcije između reparaturnog materijala i postojećeg betona u dva apsekta do sada nedovoljno istražena. Prva interakcija koja je ispitana je transport vode u reparaturnom sistemu jer je distribucija i zastupljenost vode kritična za razvoj čvrstoće reparaturnog materijala i njegovog spoja sa starim betonom. Zatim, interakcija između reparaturnog materijala i postojećeg betona, odnosno lom reparaturnog sistema usled različitih opterećenja i uslova sredine je ispitana. Kao baza za istraživanje i glavni reparaturni materijal, korišćen je nedavno razvijeni vlaknima armiran beton, takozvani SHCC. Fina PVA vlakna i specijalni sastav SHCC-a omogućavanju umesto lokalizovane pukotine, kao u slučaju običnog betona, stvaranje puno malih pukotina sa ograničenim širinama. Ovo poboljšava trajnost saniranih konstrukcija i omogućava duktilno ponašanje sanianog sistema. Na osnovu stečenog znanja, SHCC i druga 4 reparaturna materijala su primenjena i ispitana u probnoj sanaciji Maastunnel-a, starog 70 godina. Detaljne informacije u vezi sa predstavlenim članakom mogu se naći u [1].*

Ključne reči: *Sanacije betonskih konstruckija, Spoj dva betona, SHCC, Numeričko modeliranje*

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1. INTRODUCTION

In the construction industry the demand for repair and maintenance of concrete structures constantly increases. Concrete infrastructure is ageing and we are facing serious challenges on how to deal with it. One possible solution is to repair it. However, the service life of current repairs is too short, around 10 years [2]. As such, the performance of current concrete repairs is not satisfactory and there is an urgent need for improvement.

Most of the past efforts to improve the performance of repair focused on reducing free shrinkage of the repair material, increasing its compressive/tensile strength, or increasing the bond strength between the repair material and the concrete substrate. Still, in spite of continuous development and improvements in the field of repair techniques and materials, the performance of repair systems remains poor. Focus on developing “a perfect” repair material, its bond and technique for application is not sufficient if the interaction between the repair material and the existing substrate is scarcely understood.

There are two main aspects that are not well understood. The first one is the dynamics of moisture exchange in a repair system. The interaction between the repair material and the substrate, combined with interaction with the environment, determines the moisture state in the repair system. Moisture state is critical for the development of material properties in the repair material and the interface between the repair material and the substrate. Once the interface and the repair material are hardened, the second scarcely understood aspect becomes important: interaction between the repair material and the substrate under different exposure and loading conditions. If designed well, the interaction can be referred to as compatibility (or balance in properties) between the two materials (repair material and substrate). One of the main gaps in knowledge here is caused by the fact that the interface, which governs this interaction, cannot be directly tested in currently available meso/macro scale tests. The thickness of the interface is around 30-50 µm and therefore, the proper size scale for its testing should be the microscale. Interface properties further determine the system performance and its possible failure modes. Understanding the damage development and failure modes, and how to predict, model, and prevent these failures in repair systems is critical to improving performance of concrete repairs.

1.1. Aim of the study

The aim of this study was to study damage development and failure modes in repair systems. For this purpose, interaction between the repair material and the existing substrate was investigated. First the dynamics of moisture exchange in repair systems were studied. Furthermore, a method to study interface and repair material properties at the microscale is developed. Finally, the interaction between the repair material and the substrate under different exposure and loading conditions was investigated. The most common causes of repair failure were studied here: flexural effects, drying shrinkage and ongoing corrosion of reinforcing bars in the repair system. Finally, a case study of applying five different types of repair materials for developing a repair strategy for 70-year-old Maastunnel is performed. Laboratory tests were combined with on-site investigations and the performance of the five repair materials is critically examined.

As a main repair material, ultra-ductile fibre-reinforced composite - strain hardening cementitious composite (SHCC) - is used in this study [3]. The main benefit of this material is its high ductility, which is potentially very beneficial for concrete repair applications. Over the years, this type of material was studied and further developed for application in concrete repair and overlay systems. A “green” mixture of ductile fibre-reinforced composite, originally developed at TU Delft, was used [4]. The “green” material is developed by incorporating an industrial waste product - Blast Furnace Slag (BFS) - into the SHCC mix, without compromising the material performance. That being said, an even more significant sustainability improvement would be achieved by increasing the service life of the SHCC repair system compared to conventional repair.

It needs to be emphasised, however, that the goal of this study was not to develop a new and “perfect” repair material. Rather, the focus was on understanding how different repair material types (e.g. commercial repair mortars, concrete, SHCC) interact with the concrete substrate under different exposure and loading conditions. No single repair material could perform well under all circumstances. Understanding the underlying mechanisms and the influence of critical parameters that will lead to more educated selection of repair material in any given situation, was the ultimate goal of this work.

1.2. Methodology and scope

Moisture exchange between the freshly cast repair material and the concrete substrate was studied by X-ray absorption. Nanoindentation tests were proposed to experimentally quantify micromechanical properties of the interface and the repair material. Experiments were carried out to investigate the influence of interface and repair material properties on fracture behaviour of repair systems under different boundary conditions (flexure test, restrained shrinkage test and accelerated corrosion test).

Lattice type modelling was used to explain the experimentally observed behaviour. Two types of models were used and further developed in this research: a mechanical model to simulate mechanical performance of the repair system [5] and a transport model to simulate moisture transport in the system [6]. These models were coupled to investigate damage caused by moisture transport in the repair system.

In the repair system, it would be too complicated to study all parameters that determine the development of interface and repair materials properties and their impact on damage development in the repair system. Therefore, these parameters were limited to the following:

- the influence of different water-to-cement ratio (w/c) of repair material (0.3, 0.4 and 0.5) is considered to be critical for moisture exchange and was, therefore, studied in X-ray absorption tests;
- the influence of substrate (i.e. concrete, mortar) saturation level and drying of the surface of the repair material (after 1 day, 3 days and 5 days of curing) are critical for moisture dynamics and they were studied in X-ray absorption tests;
- the influence of BFS addition to the repair material is considered critical for material and interface properties. Therefore, the influence of different amount of BFS on micromechanical properties of interface and repair material was studied. In this study, interface properties are defined as material properties, while the influence of substrate surface roughness is considered as geometrical effect and is explicitly studied;
- the influence of the substrate surface roughness is considered to be critical for fracture performance of repair systems and was, therefore, studied in fracture tests. Substrate roughness is defined as a meso-level roughness (order of magnitude of several millimetres);
- it is considered that fibres do not affect either the moisture exchange nor the development of repair material and interface properties. However, they affect fracture response and, therefore, the influence of fibre addition is studied in fracture tests.

2. DEVELOPMENT AND QUANTIFICATION OF MATERIAL AND INTERFACE PROPERTIES

This part deals with the development of material and interface properties and their characterisation. The main factor influencing material properties is the moisture exchange between the repair material and the concrete substrate, and the moisture exchange between the repair system and the environment. Monitoring of moisture movement inside the repair system is done by X-ray attenuation and microstructure was investigated by CT-scanning and measuring the degree of hydration of the repair materail. Successively, it is dealt with quantification of interface and repair material fracture properties. Influence of addition of BFS on the interface and the bulk material microstructure is investigated experimentally by nanoindentation. Its influence on fracture properties (tensile strength, E-modulus and fracture energy) is evaluated by numerical study using the lattice model.

2.1. Moisture movement in the repair system

A procedure to study moisture exchange in the repair system by the CT scanner (based on X-ray absorption) is developed. An example of the mortar substrate absorption profiles as a function of time is given in Figure 1. The moisture profile is averaged over the specimen width (16 mm) and specimen thickness (18 mm). Results obtained by X-ray absorption, were successfully verified with gravimetric test measurements. The total (cumulative) amount of absorbed water, as given in Figure 2, is calculated by integrating the moisture profile at a certain time step.

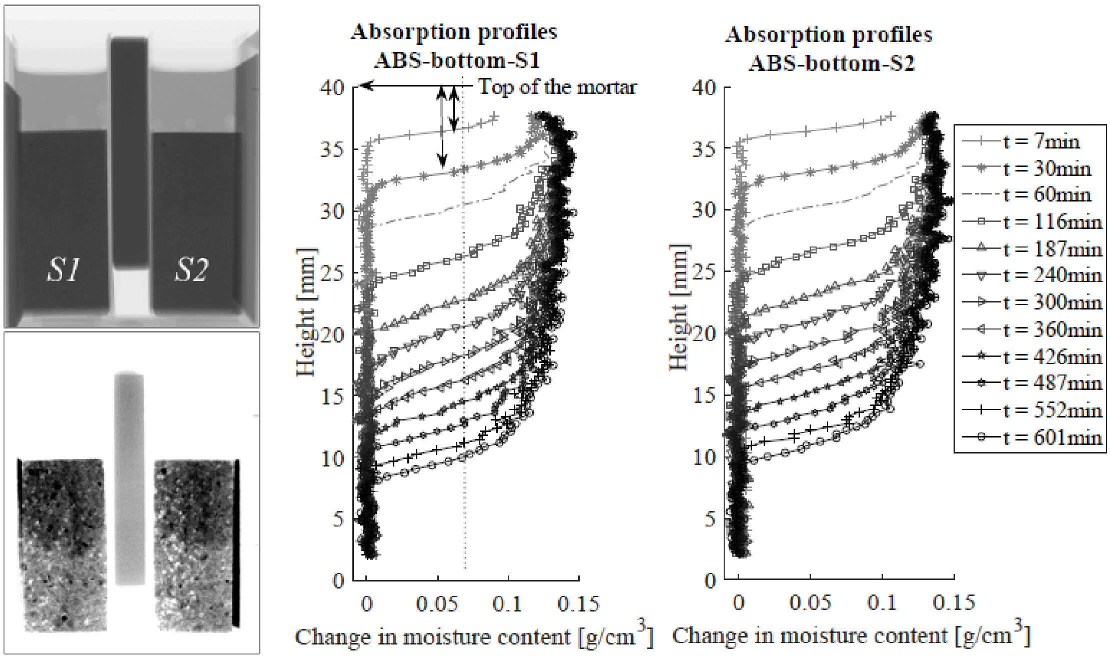


Figure 1: X-ray absorption results when water is absorbed from the top, an example of the original X-ray images of two replicate samples (left) and their moisture profiles over time

Influence of w/c of the repair material, the duration of sealed curing, primer application and the initial moisture content of the substrate on moisture exchange and microstructure formation in the repair system were investigated. Cement pastes with a w/c ratio of 0.3, 0.4 and 0.5 and around 15 mm thickness, were cast on the top of the 40 mm thick dry mortar substrate. Immediately after casting samples were sealed with aluminium self-adhesive tape. Experimental results show that the absorption rate by the dry substrate in the first 5 hours after casting of the repair material (regular Ordinary Portland Cement - OPC - paste without any chemical admixtures, as used in this research) is independent of the w/c of the repair material. Furthermore, water from the repair material is absorbed by the substrate at the same rate as “pure” water is absorbed (Figure 2). In addition, the rate of absorption is the same, irrespective whether water is absorbed from the bottom or from the top of the substrate. This means that the pore structure of the concrete and mortar is such that capillary forces are dominant and gravity can be neglected. Consequently, water from the repair material cast on the wall, floor or ceiling will be lost with the same speed.

Although the initial absorption rate is similar, the final amount of water that is absorbed in the three systems is different. The repair material with w/c=0.3 exhibits fastest reduction in the rate of the absorption. Furthermore, it was observed that water from the substrate migrates back to the repair material to enahce its hardening. The lower the w/c ratio of the repair material, the higher the migration is.

The influence of substrate saturation was also studied. If compared to the saturated substrate, dry substrate caused a reduction in the degree of hydration of the repair material. This is due to the reduction of the effective w/c ratio caused by moisture loss of the repair material. Note that with a thinner layer of repair material, or cracked substrate, the reduction would be probably even higher. As a result, hydration of the repair material and the interface will be hindered or stopped even earlier, emphasizing the need of saturating the concrete substrate prior to the application of the repair material.

Duration of sealed curing has also an effect on development of properties of the repair material and interface. For the repair material thickness of 15 mm it was found that, when the substrate was initially saturated, increasing duration of (sealed) curing both from 1 to 3 days and from 3 to 5 days had a beneficial influence on the hydration of the repair material. The influence is more critical for prolonged curing between 1 and 3 days. However, when the substrate was initially dry, curing samples for 3 instead of 1 day was beneficial, but curing samples for 5, instead of 3 days did not result in significant improvements. Due to the lack of water, hydration probably stopped. Therefore, if too much water is absorbed by the substrate, there are no benefits of prolonged sealed curing. This means that the effect of curing is also affected by the initial saturation state of the substrate.

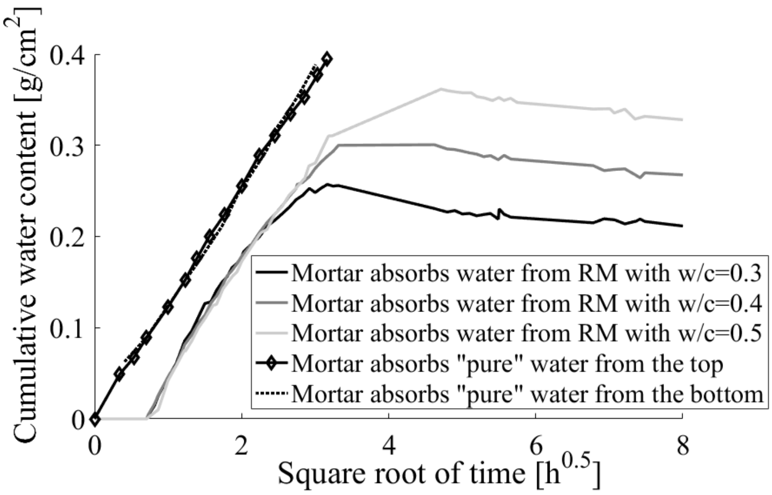


Figure 2: Cumulative moisture absorption by the mortar substrate from Repair Material (RM) with w/c of 0.3, 0.4 and 0.5 in repair systems, compared to cumulative moisture absorption when "pure" water is absorbed from the top or bottom of the mortar.

The saturation level of the substrate and moisture movement showed to have significant influence not only on resulting w/c and uniformity of properties inside the repair system, but also on void content close to the interface. Significantly more voids are observed when the substrate was initially dry (Figure 3) .Dry substrate and higher absorption results in a more porous zone around the interface in a repair material. Pores and voids in the substrate, which are initially air-filled, are releasing this air to get water. Due to the high viscosity of the repair material and difficulties in compacting, air remains entrapped close to the interface. This study proves that the substrate should always be saturated (with the dry surface) prior to repair.

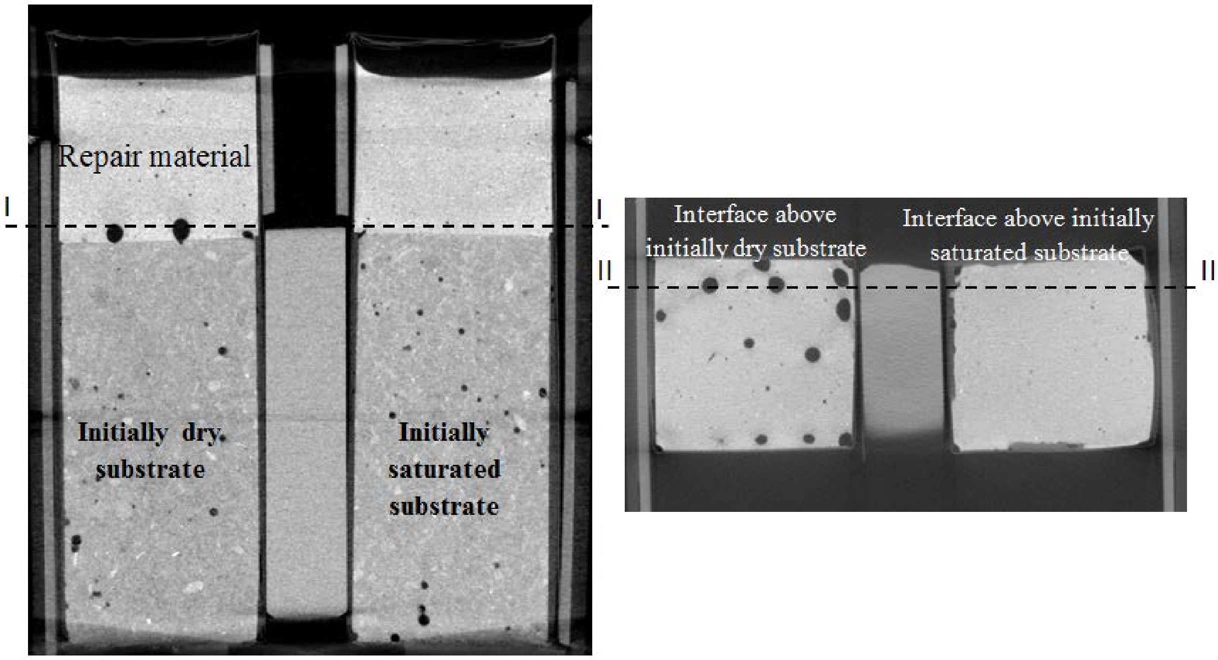


Figure 3: X-ray computed tomography images from repair systems with initially dry and saturated substrate made at the age of 3 days after casting the repair material with w/c of 0.3 (repair material thickness 15 mm, mortar substrate thickness 40 mm).

2.2. Micromechanical interface properties in the repair system

Following moisture exchange tests, the interface properties were also tested. Due to its size (around 30 µm), the interface must be studied at the microscale. Well-controlled tension testing at this scale, however, is still not possible. In this thesis, an approach is proposed to quantify interface fracture properties at the microscale. The influence of Blast Furnace Slag (BFS) addition to the repair material is considered as critical for interface and repair material properties. Therefore, three repair material mixtures, with varying the amount of BFS were tested. In each specimen, multiple interface, repair material and substrate locations are chosen and tested by nanoindentation. Each indentation area, consisting of multiple indents distributed in a regular mesh as shown in Figure 4, was randomly selected in a specimen.

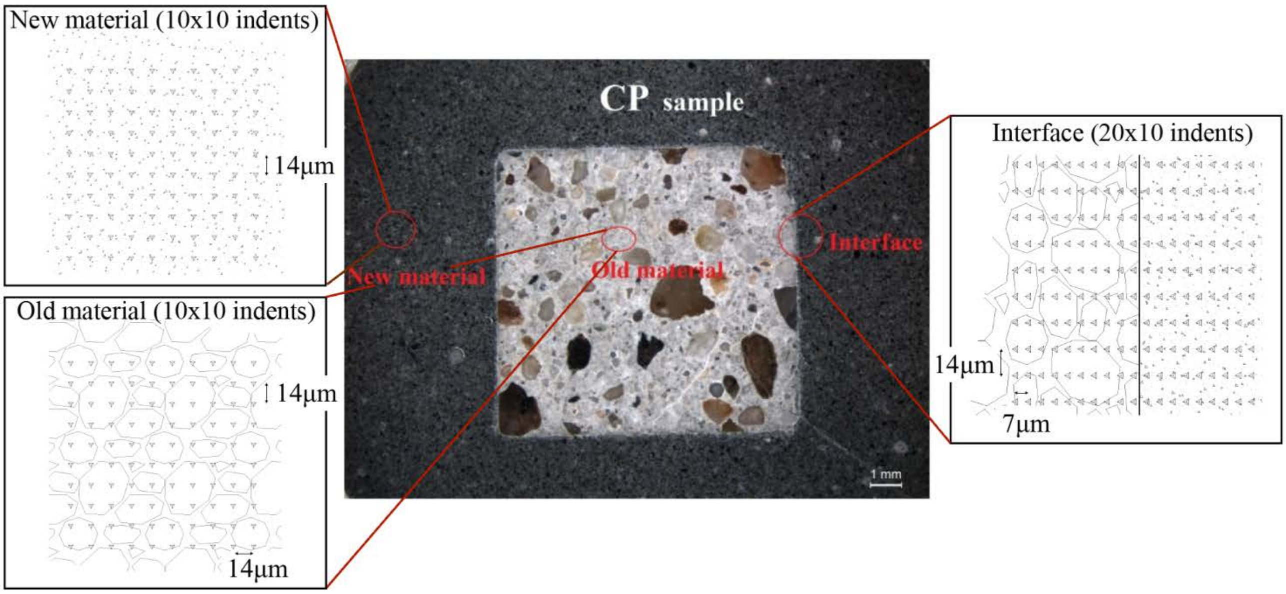
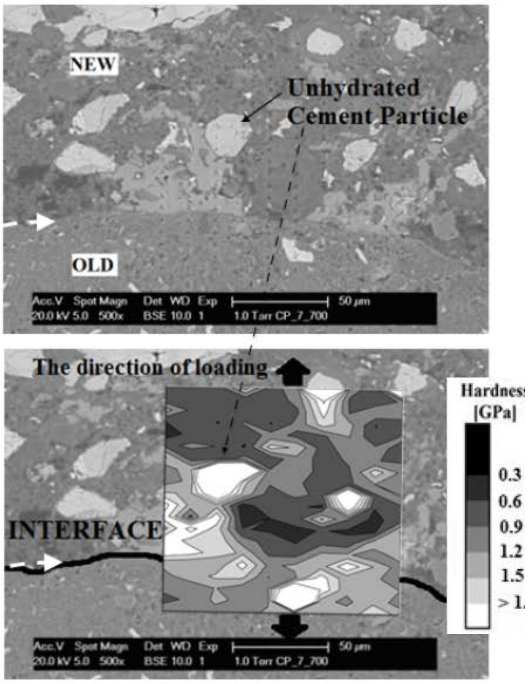
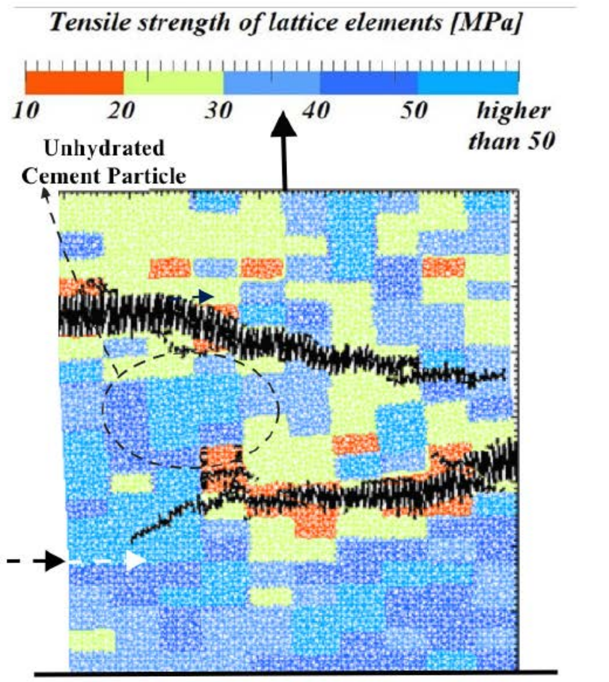


Figure 4: Reflected light photomicrographs of one set of locations for the nanoindentation testing. New material = Cement paste (CP), Old material = Substrate, 5 years old mortar

Experimentally measured modulus of elasticity and hardness are used as input for simulated uniaxial tension test at the microscale (Figure 5). Fracture properties of interface, repair material, and substrate were obtained and compared. It needs to be highlighted that only failures that occurred exactly at the interface are considered as interface failures. The ratio between interface and repair material fracture properties (i.e. tensile strength, elastic modulus and fracture energy) is calculated and it was found that the ratio between the tensile strength of the interface and tensile strength of the bulk repair material at the age of 28 days, is lower than 0.9 when pure OPC paste (OPC 100%, Figure 6) is applied as a repair material. This ratio decreases with the addition of BFS. The study gave an insight in how, with the choice of repair material and its composition, interface strength can be modified. If higher interface strength is needed, less BFS as the replacement of OPC should be used. The same approach can be further used to study interface properties in other types of composite materials and systems, or with different types of substrate preparations.

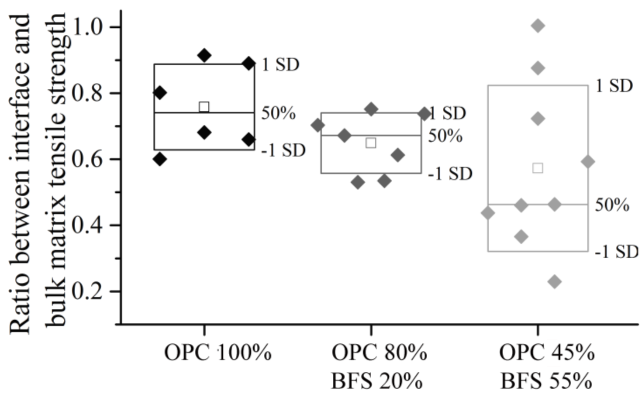


(a) Initial microstructure (top) with the measured hardness (bottom) used as input for lattice modelling

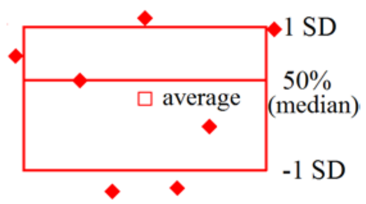


(b) lattice mesh with properties ascribed from nanoindentation measurements, resulting damage pattern is shown in black

Figure 5: Generation of the lattice mesh and ascribing properties from nano indentation measurements, interface is marked with arrows (in all three images, the same unhydrated cement particle is marked).



(a)



(b)

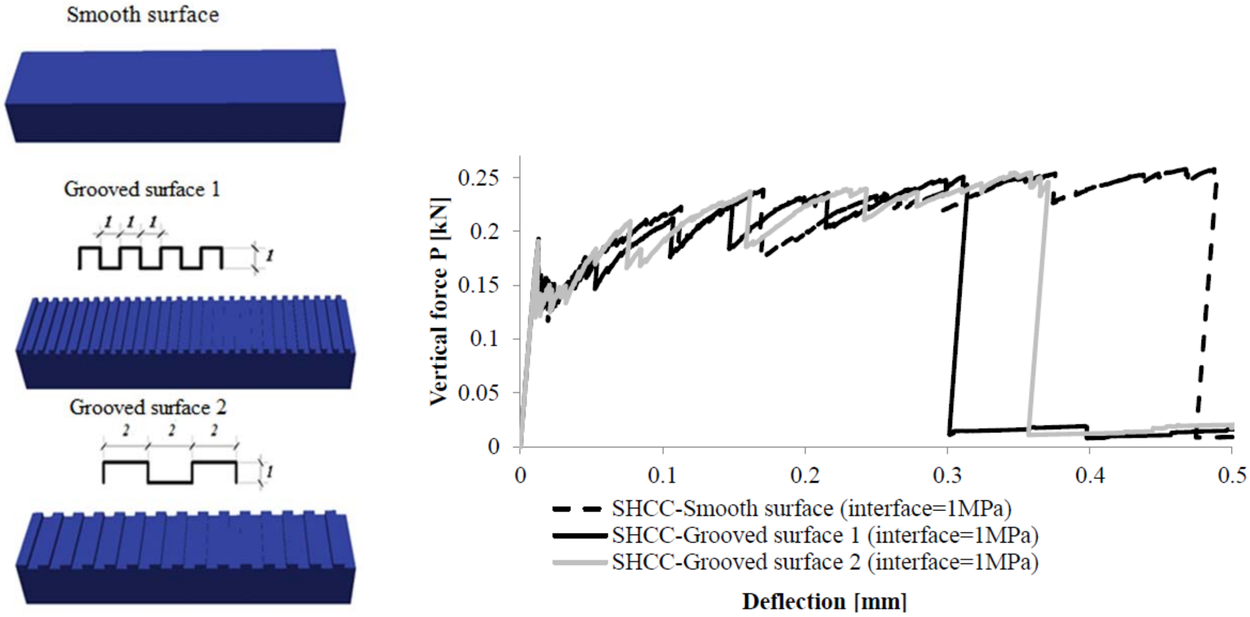
Figure 6: a) Calculated ratio between the tensile strength of interface and tensile strength of repair material for different types of repair materials (percentage given by total binder content), b) legend, SD is standard deviation.

3. FRACTURE BEHAVIOUR OF THE REPAIR SYSTEM UNDER DIFFERENT LOADING AND EXPOSURE CONDITIONS

Once the material properties are quantified, the interaction between the repair material, the substrate, and the interface under different exposure and boundary conditions is further studied. The most common causes of repair failure were studied here: flexural effects, drying shrinkage and ongoing corrosion of reinforcing bars in the repair system. Experiments and numerical analyses are performed. The interface strength and its influence on fracture behaviour at the mesoscale is investigated. In addition, influence of different parameters such as the substrate surface roughness, substrate strength, thickness of the repair material, the fibre addition in the repair material, etc. are studied.

3.1. Mechanical loading – flexural tests

First, analyses were performed to investigate the influence of the interface and SHCC material properties on the fracture behaviour of repair systems due to mechanical loading. Three different types of interfaces were simulated (Figure 7a).



(a) (b)

Figure 7: a) Simulated surface profiles b) Force-deflection diagram in three-point bending tests for different roughness profiles for SHCC repair system

Three-point bending test, DIC (Digital Image Correlation) and epoxy impregnation were used experimentally, while the lattice fracture model was used as a numerical tool. The influence of surface roughness on the tensile and shear bond strength was also investigated. It was observed that higher surface roughness does not increase the tensile strength significantly (6%). It does, however, increase the fracture energy in a uniaxial tensile test and increase significantly the shear bond strength (up to 25 %). Furthermore, the surface roughness of the substrate does not affect the load-bearing capacity in flexural tests (Figure 7b), but there is a substantial difference in crack pattern and debonding tendency in the repair system (Figure 8).

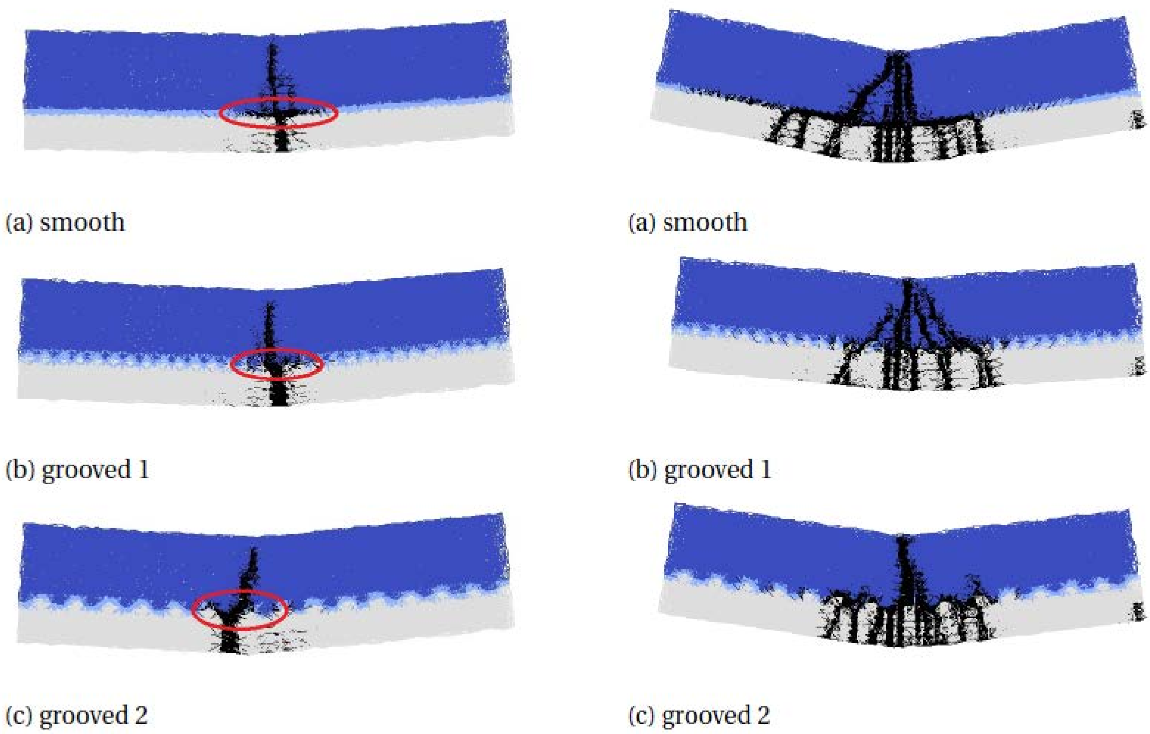


Figure 8: Simulated final fracture pattern in non-fibre reinforced (left) and SHCC (right) repair system

When the substrate surface is rough, cracks from the repair material are interlocked by grooves and directed to the substrate. In flexural and reflective cracking tests low interface toughness (low interface strength and smooth surface of the substrate) are beneficial: with less restraint at the interface, there is more local debonding around the cracks, resulting in more microcracking in the SHCC and higher ductility of the repair system (Figure 9). This is different from what we find in standard recommendations for surface preparation, which advises strong bond and roughening of the substrate surface prior to application of the repair material.

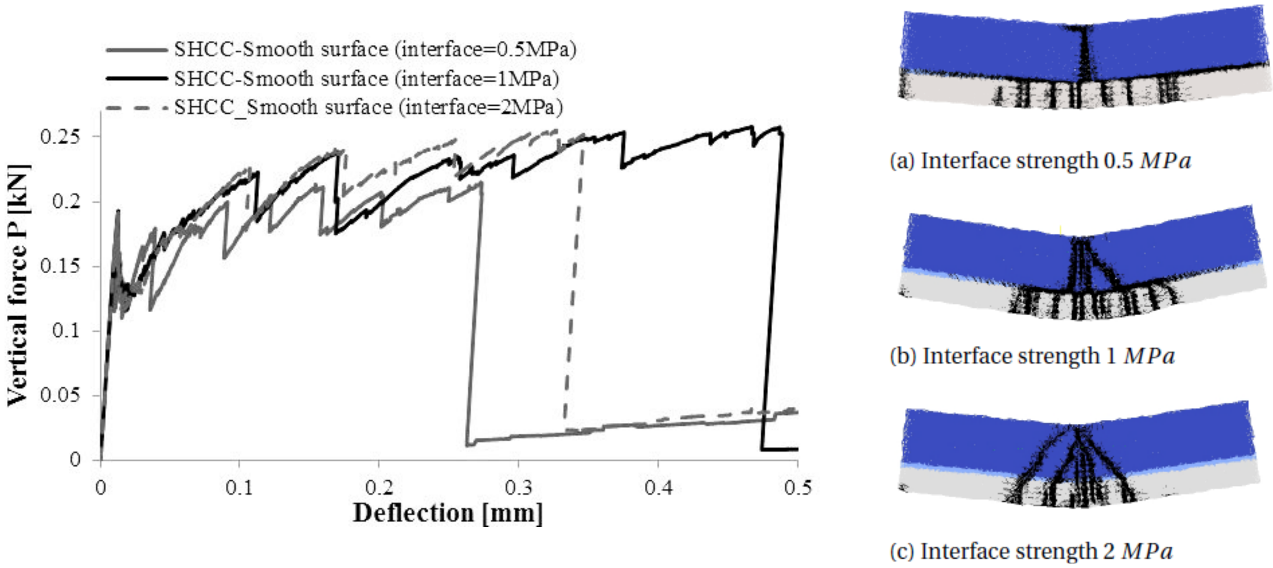
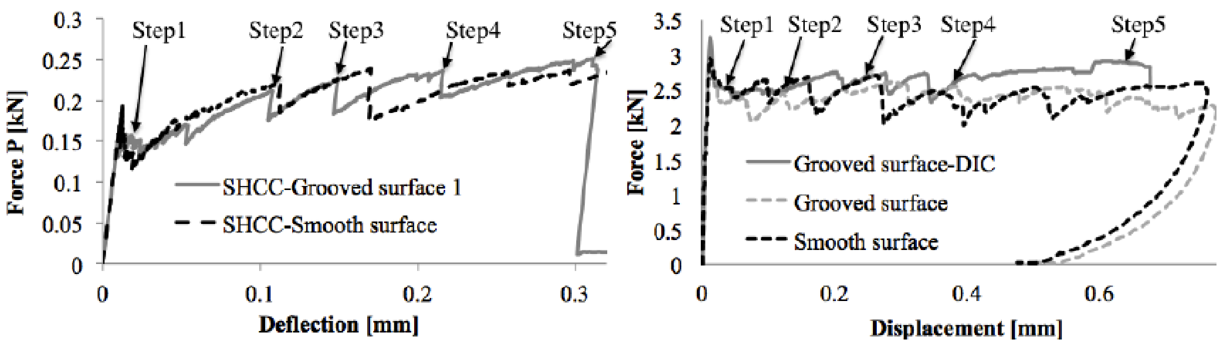


Figure 9: Force-deflection diagram in three-point bending test for different interface strength in smooth surface for SHCC specimens with corresponding final fracture patterns on right

The same global facture behaviour and crack initiation and propagation were also found in the experimental study. The sequence of crack development and final crack pattern (Figure 11), with corresponding point in the load – deflection diagram (Figure 10) in simulated and experimentally tested samples is compared.

Both from experiments and simulation, it is observed that, due to the inherent brittleness of the concrete/mortar substrate, the crack in the substrate formed immediately with the first crack in the repair material (Figure 11). Therefore, the achieved microcracking capacity of the SHCC overlay is limited, and cracks will not be uniformly distributed over the tested area in SHCC. On the contrary, the microcracking capacity in the repair material will be determined by local boundary conditions (interface strength and surface roughness) around the crack in the substrate. Similar observations are obtained for the reflective cracking test (i.e. when the crack in the repair material initiates from the existing crack in the substrate). Smooth surface and low bond showed more distributed cracking and larger ductility of the system since it allowed for more debonding and better arresting of the existing defect in the substrate.



(a) (b)

Figure 10: a) Simulated samples and b) Experimentally tested samples (Grooved surface – DIC I the specimen which was processed by DIC technique)

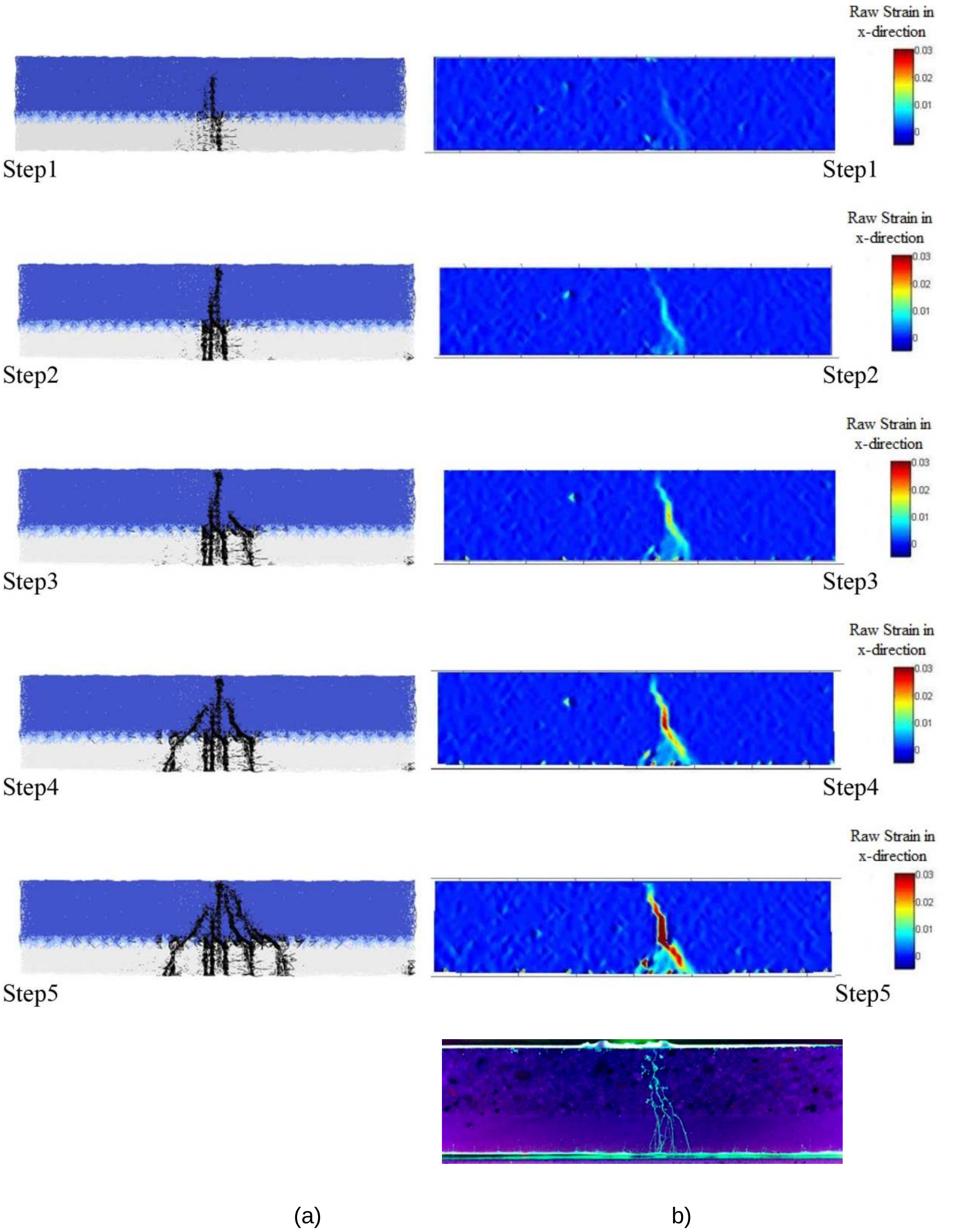


Figure 11: Crack development in different stages of loading in a) simulated and b) tested repair system with the final crack pattern (after testing sample was impregnated with fluorescent epoxy and cut in the middle), top - mortar substrate, bottom - SHCC.

3.2. Differential shrinkage

Experimental and numerical studies were also performed to investigate the influence of interface and SHCC material properties on the fracture performance of repair systems due to drying shrinkage. A model for simulating moisture transport within the lattice modelling framework is developed (Figure 12), and the lattice fracture model is extended to simulate damage development in repair systems due to restrained shrinkage (Figure 13). Influence of substrate surface roughness, repair material thickness, interface strength and type of repair material were tested (Figure 14).

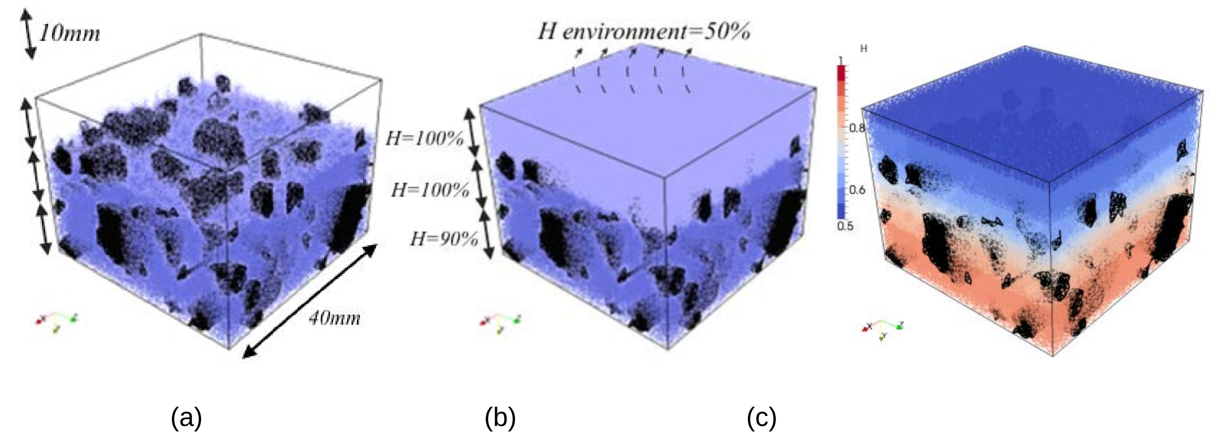


Figure 12: Restrained shrinkage induced damage in the repair system simulated by the lattice moisture model and lattice fracture model a) imitating "sandblasted" surface roughness of the substrate, b) "Casting" repair material and "exposing" it to drying, c) moisture profile after 110 days of drying.

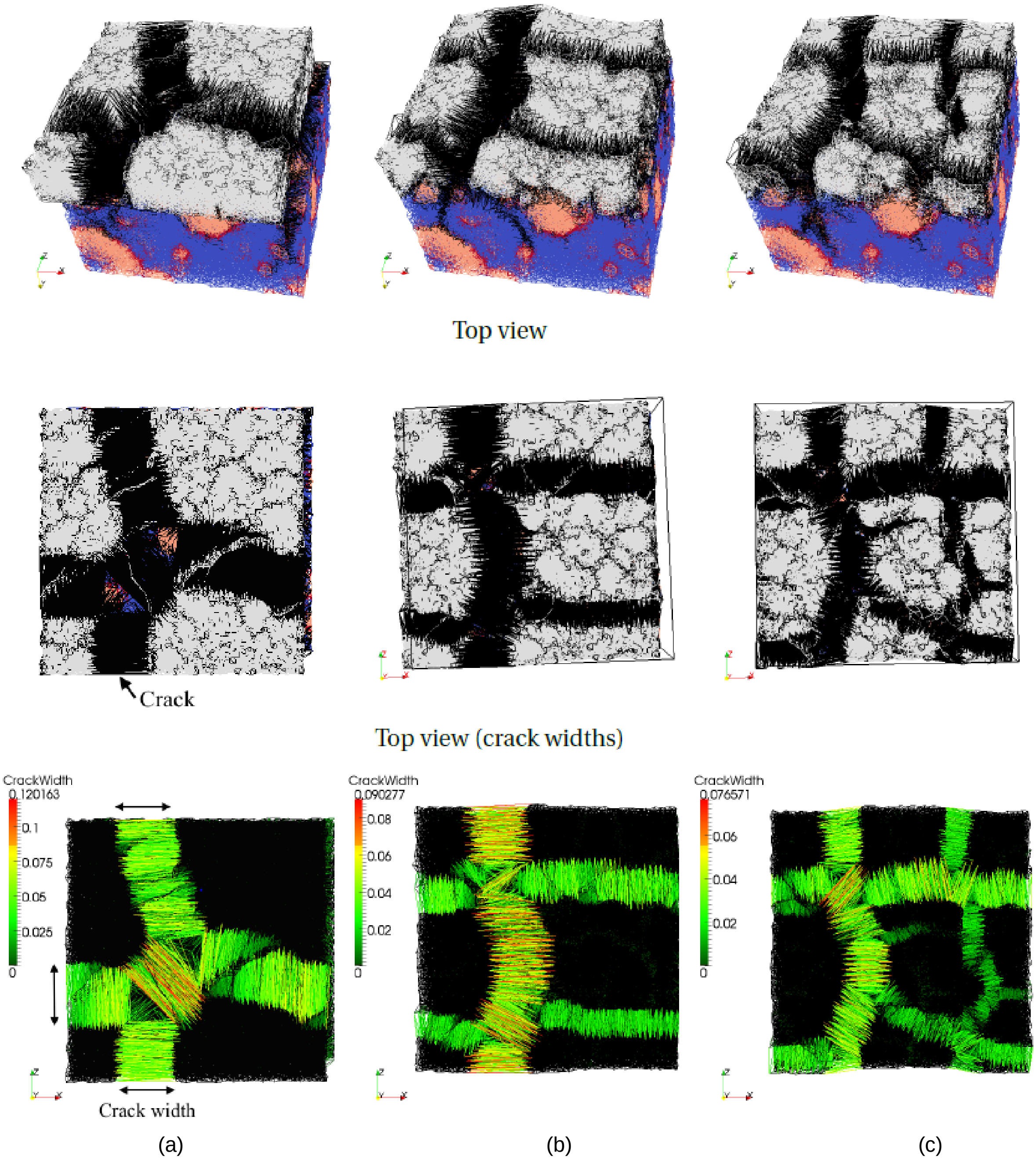


Figure 13 Resulting damage pattern due to restrained shrinkage deformation, influence of bond strength and substrate roughness on cracking after 110 days of drying in a) smooth surface, interface strength 1 MPa, b) rough surface, interface strength 1 MPa and c) rough surface, interface strength 3 MPa.

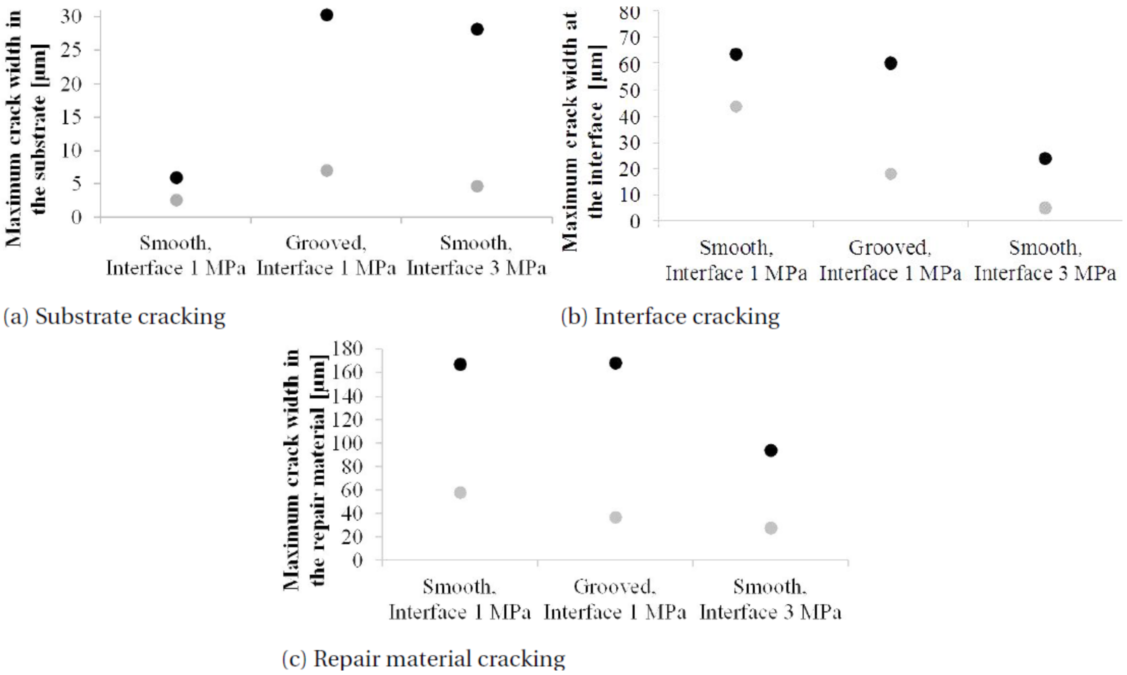


Figure 14: Influence of the substrate roughness and bond strength on the damage in the repair system, black - repair mortar, grey – SHCC.

Free drying shrinkage of repair materials and the effects of restrained drying shrinkage (cracking and delamination) on repair system beams were investigated also experimentally (Figure 15). It was shown that interface strength and surface roughness are more important for performance of thinner overlays compared to the thicker ones due to the higher moisture gradient. With weak bond and thinner repair material, the system is susceptible to large debonding and large crack widths. In contrast to the recommendations from flexural tests, high interface strength and high surface roughness are necessary in order to preserve small crack widths and avoid delamination in the SHCC repair system under restrained shrinkage conditions. With high surface roughness and proper bond SHCC shows superior behaviour over commercial repair material (more cracks with smaller crack widths, Figure 15).

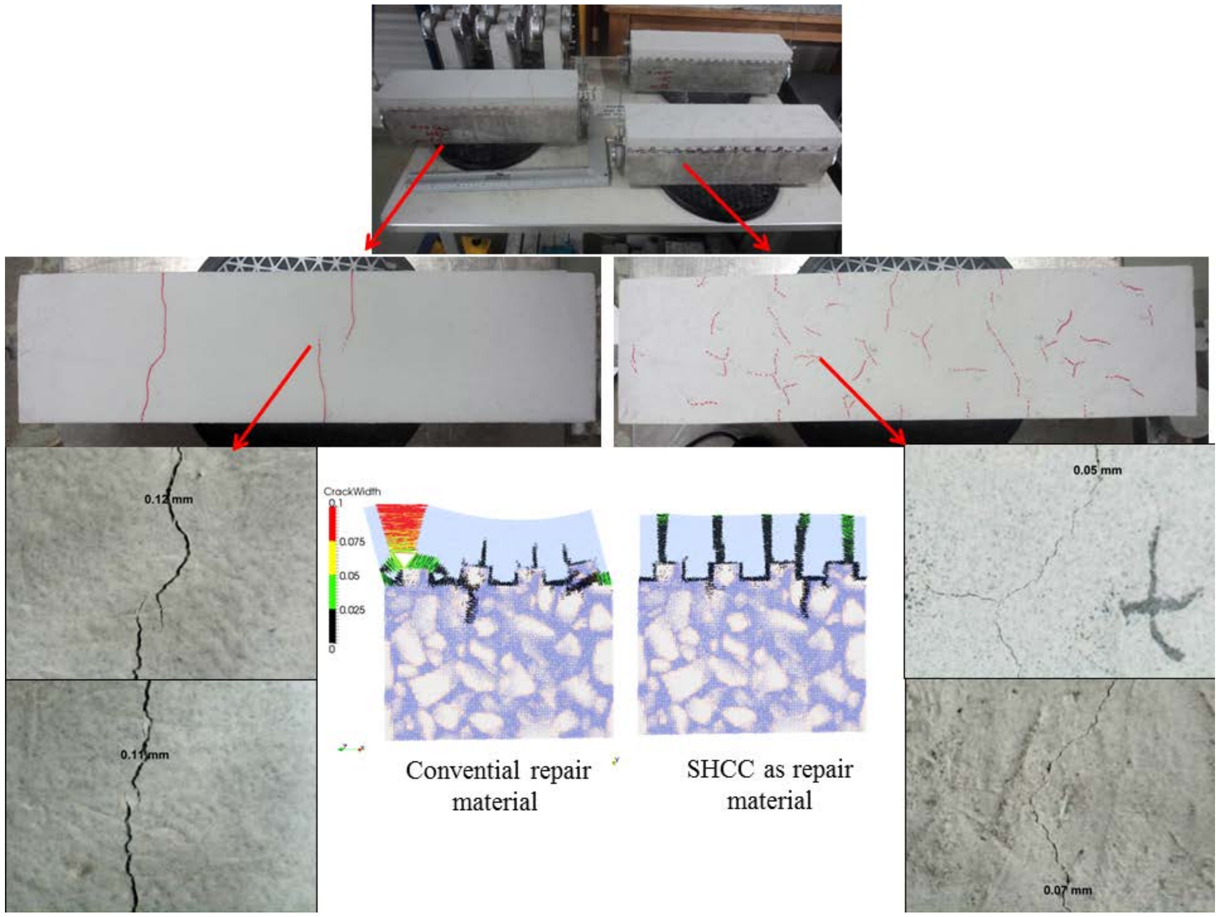


Figure 15: Experimentally obtained damage behaviour compared to numerically simulated in commercial repair material (left) and SHCC (right) with the grooved surface of the substrate.

3.3. Ongoing corrosion of the reinforcement

After chloride contaminated concrete is removed and repair material is cast, it is quite common that corrosion of the reinforcement continues at a certain moment. This makes it an important cause of repair material failure. Further experimental and numerical studies were performed to investigate the influence of interface and SHCC material properties on the fracture performance of repair systems subjected to ongoing corrosion of rebars in the repair material. An experimental setup was developed where rebars in the repair material were exposed to accelerated corrosion. Influence of type of repair material, interface strength, substrate strength and substrate surface roughness on damage development is studied. It was shown that in case of continuing rebar corrosion, the ductility and damage resistant behaviour of SHCC is very beneficial because it prevents cracks from opening wide and reduces the probability of spalling (Figure 16b). Surface roughness had a similar influence as in drying shrinkage conditions: grooves directed cracks to propagate to the substrate and a high interface strength and a rough surface are needed to exploit the ductility of the repair material. On the contrary, a smooth substrate surface and a low interface strength cause uncontrolled failure through delamination (Figure 16c).

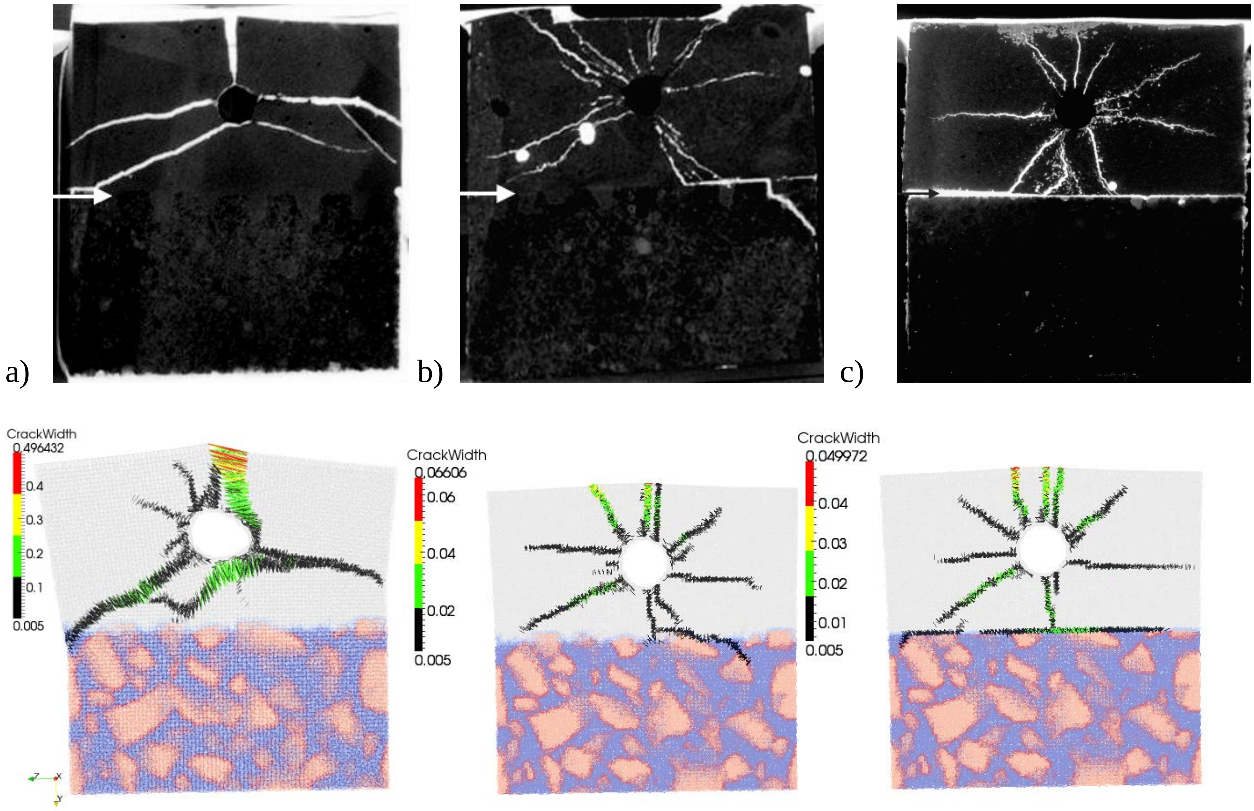


Figure 16: Experimentally (top) and numerically (bottom) obtained crack pattern and maximum crack widths in [mm] due to the pressure imposed by expanding bar in the repair material. a) convention repair material with the rough surface of the substrate; SHCC as a repair material with the b) rough surface and c) smooth surface of the substrate.

3.4. Influence of interface on the fracture behaviour of the repair system

From the fracture tests it was shown that the interface strength and substrate surface roughness have different influence under various exposure conditions that are critical for the SHCC repair performance. For flexure behaviour and reflective cracking low interface strength and smooth surface of the substrate are beneficial as they provide less restraint at the interface, lower stress concentration around the existing cracks in the substrate finally resulting in higher ductility of the repair system. However, under drying shrinkage and ongoing corrosion, high interface strength and rough surface are crucial in order to prevent delamination. Therefore, a balance has to be found. A possible solution is to roughen the surface of the substrate and coat the existing cracks with the hydrophobic agent or vaseline prior to application of the repair material. In this way, complete delamination is avoided but local debonding zone will be induced in the vicinity of existing cracks in the substrate such that it will allow for high ductility of the repair material to be used. Although this might not be a very practical solution, only then all the benefits of SHCC as repair materials can be optimally used. In addition, hydrophobic or vaseline coating will protect cracks from water ingress that could further affect the durability of the repaired concrete structure.

4. A CASE STUDY

Finally, findings from previous chapters are put to practical use. A trial repair section was prepared in the Maastunnel in Rotterdam. This is the oldest submerged concrete tunnel with the rectangular cross section in the world, and is heavily deteriorated due to chloride induced corrosion that caused concrete spalling of large sections in the ventilation tubes (Figure 17). Due to its damage resistant behaviour and high probability that corrosion might continue after repair, SHCC was considered to be a promising solution for the tunnel repair.

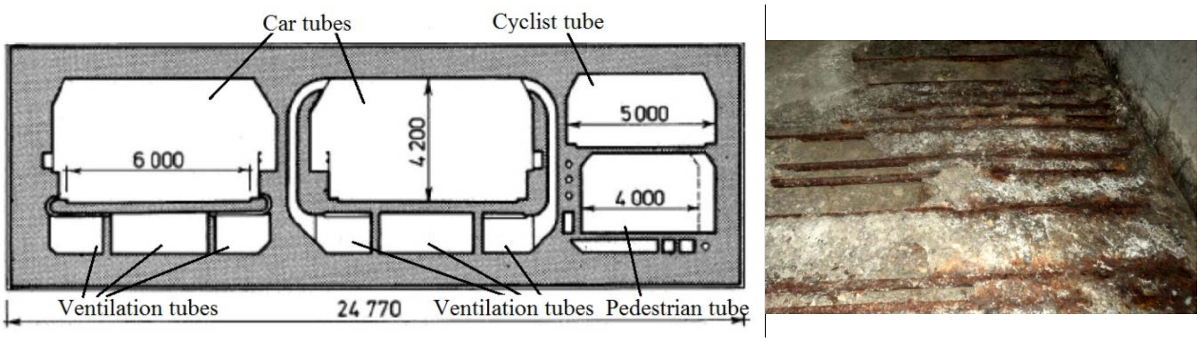
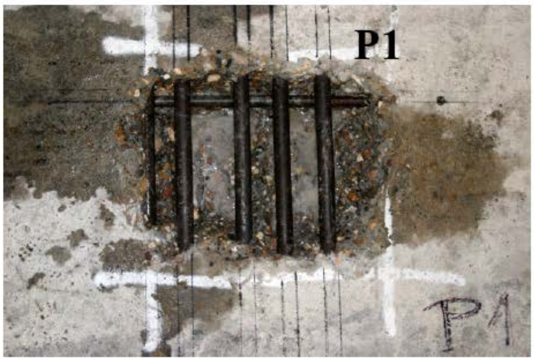
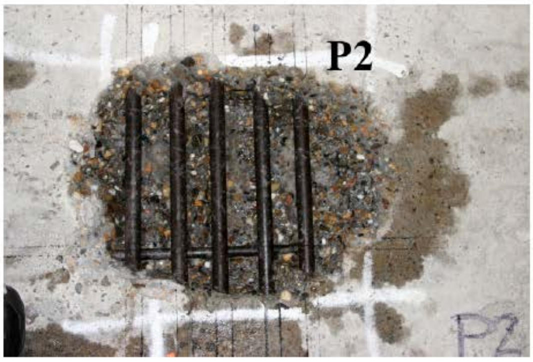


Figure 17: The Maastunnel a) Cross section of the tunnel b) chloride induced corrosion damage in ventilation tubes.

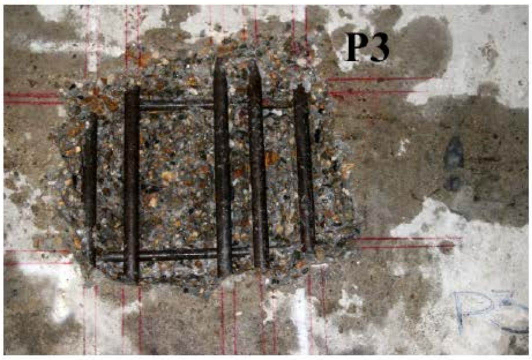
Before the application of the repair material, patches with dimensions of 500 x 500 mm2 and the depth of around 110 mm were prepared in the tunnel (Figure 18).



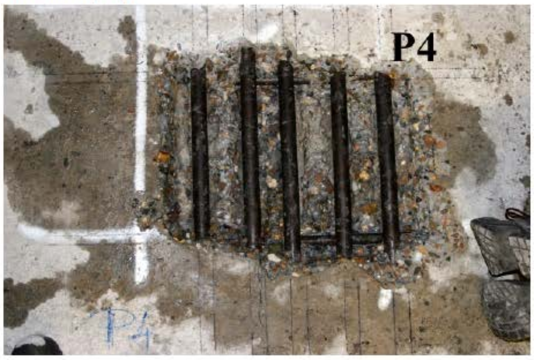
(a) Patch 1 (P1)



(b) Patch 2 (P2)



(c) Patch 3 (P3)



(d) Patch 4 (P4)

Figure 18: Four patches prior to casting of the repair material.

Hydro-jetting was applied for roughening of the concrete substrate. The substrate was water saturated (with a dried surface) in all patches. Besides SHCC (Figure 19), four other repair materials were applied as repair materials. One of these mixtures was regular concrete. As one of the main factors limiting the use of SHCC in practice is its high cost due to high cement content, two new mixtures incorporating coarse aggregates (up to 16 mm size) within the regular SHCC mixture are developed. This resulted in the design of cheaper and commercially more attractive fibre reinforced mixtures. Flexural tests on notched samples showed that both mixtures exhibited deflection hardening behaviour.

In all the patches no delamination occurred, and small shrinkage cracks (smaller than 100 µm) are observed in the mixes with fibres. It was shown that when concrete was used as a repair material, the repair system exhibited the best performance (no cracking nor delamination). However, if, as expected in this case, corrosion of the reinforcing bars continues, use of SHCC is beneficial as it will result in smallest crack widths and more ductility of the repair system. Within the inspected time frame (1 year after casing patches) no continued corrosion was detected in the tunnel.

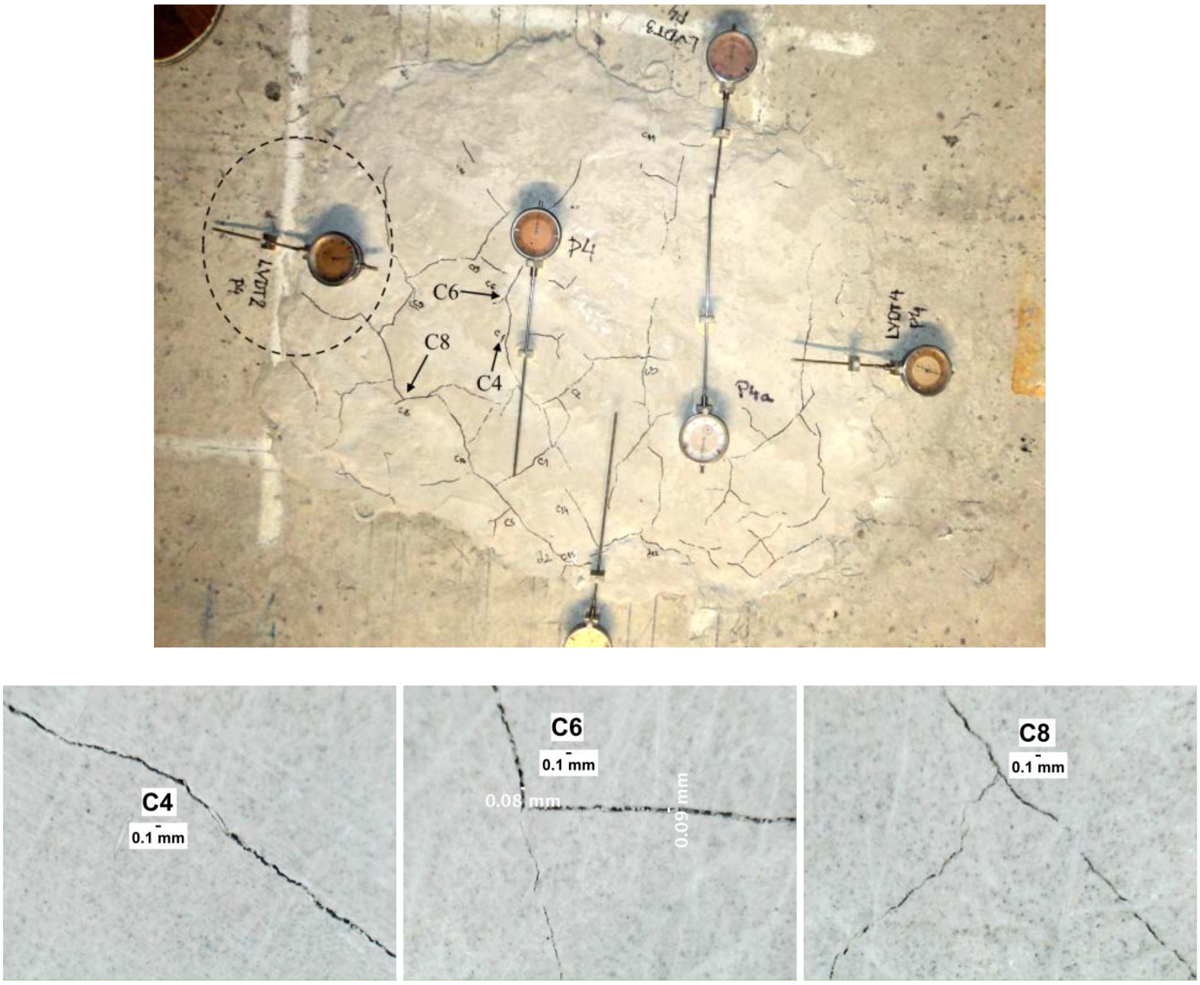


Figure 19: Shrinkage induced cracks in SHCC patch repair and magnified cracks (bottom).

Pull-off tests (Figure 20) indicated that, in general, good bond is achieved between the tested repair materials and the concrete substrate, and that in most of the tests, the concrete substrate was the weakest link in the system.

Figure 20: a) Pull- off test set-up and b) Typical failure mode in the substrate

The case study indicates that findings from this thesis have important practical implications. If properly designed, SHCC offers promising solution for repair applications due to its controlled microcracking behaviour. Considering the fact that most concrete patch repairs fail within the first 10 years, the gained knowledge and practical recommendations might result in financial savings and an improved service life of concrete patch repairs and, therefore, of reinforced concrete infrastructure.

4. CONCLUSIONS

The study provides practical recommendations for substrate preparation and repair material properties in order to enable more reliable repair system performance. The first step is a good preparation of the concrete substrate. Substrate should be always saturated (surface dry) with a rough surface. Dry substrate absorbs water from the repair material with the same speed as free water is absorbed. Pores and voids in the substrate, which are initially air-filled, are realising this air to get water. As a result, void content close to the interface increased significantly. Rough surface provides more heterogeneity and restraint at the interface (similar to aggregates in concrete), enabling more ductility and crack interlocking during failure.

Beside by moisture state, it was shown that material and interface properties are also affected by the material composition. With the addition of BFS in the repair material, the interface strength at the age of 28 days decreases compared to repair material with OPC.

Steps can be made toward improving certain properties (i.e. increasing interface strength, repair material strength, etc.) only when the fracture behaviour of the repair system can be predicted reliably. Fracture behaviour of the repair system was studied by combined experimental and numerical study. It was shown that low interface strength and smooth surface in mechanical and reflective cracking tests can be beneficial, as they enable higher ductility of the repair system. This is, however, in contradiction with requirements for drying shrinkage and ongoing corrosion conditions, where these properties lead to the brittle failure of the system. Therefore, strong interface and high surface roughness of the substrate are not beneficial for all loading and exposure conditions. This is especially the case when SHCC is used as a repair material. Contrary to common belief, it was shown that aiming at higher strength is not always beneficial and it does not guarantee a crack free repair system. Because some damage in repair systems is practically inevitable, behaviour (cracks and debonding) that leads to more ductility and gives more warning signs before failure should be tailored.

The used modelling approach can realistically predict the fracture behaviour of SHCC and non-reinforced repair systems under different loading and exposure conditions. Small changes in material properties lead to substantial differences in maximum crack widths and debonding, or even to a complete change of the failure mode. Modelling and experimental studies helped explaining the interplay between debonding and cracking, and the influence of substrate surface roughness, interface strength, substrate strength and moisture gradients in the repair system.

5. REFERENCES

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