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SELF-HEALING STRAIN-HARDENING CONCRETE COVER

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Abstract: An experimental study is carried out to investigate the structural behaviour and durability performance of hybrid reinforced concrete beams with U-shaped covers made via mould-casting method and 3D printing method. Structural behaviour, surface crack pattern and crack propagation between the reinforced concrete core and U-shaped SHCC cover are studied. A qualitative assessment of the crack appearance before and after healing was also performed. Findings reveal that mould-casted SH-SHCC covers enhance crack control without compromising beam properties, offering comparable or improved load capacity and ductility under shear and flexure. Although 3D-printed covers are slightly less effective in crack control, they still improve overall performance and offer advantages in manufacturing efficiency. Both cover types effectively prevent delamination and disperse major cracks into finer, healable cracks, facilitating crack healing observed after one-month moist curing.

1 INTRODUCTION

The development of novel high-performance cement-based materials has opened new possibilities in designing more resilient and versatile concrete structures. The new materials can offer improved mechanical properties, such as higher tensile strength [1], better ductility [2,3], and enhanced durability [4], which can improve the structural performance of concrete structures under different loading and environmental conditions. However, while advanced materials offer promising advantages, they typically come at a higher cost and demand specialized production processes. This renders them economically and technically impractical for fully replacing conventional concrete. To address this challenge, researchers have devised hybrid structural elements, merging high-performance concrete with conventional concrete to minimize the use of costly materials in individual structural components [5–8]. An illustrative instance of this innovation is the creation of SHCC/reinforced concrete (RC) hybrid elements [9,10].

The interface between distinct constituents holds paramount importance in designing hybrid elements to guarantee optimal performance. A robust interface ensures effective stress transfer, prevents delamination, and minimizes the risk of premature failure [11]. In the case of hybrid RC elements with SHCC, various methods have been proposed to ensure the integrity of the interface between the layers. Aside from the shear-key pattern proposed in the prior chapter, conventional practices encompass surface preparation to eliminate contaminants, application of bonding agents to bolster adhesion [12], and integration of mechanical interlocking features such as grooving [13] or steel anchorages [14].

However, most of these methods entail multiple procedural steps and the requirement of intricate moulds for production, occasionally proving impractical and inefficient.

The extrusion-based 3D concrete printing (3DCP) technology provides another possibility to tackle the delamination issue. 3D printing of concrete is effective at producing desired surface texture due to its precise layer-by-layer deposition process, allowing for customizable patterns and textures to be easily integrated into the printed structure [15]. Therefore, additional efforts in treating the interface may be avoided when 3D printing technology is used to fabricate permanent

The aim of the current study is to assess the structural response and healing performance of hybrid reinforced concrete beams with 3D-printed U-shaped cover, and to compare the performance with hybrid elements made with precast U-shaped cover. This cover zone is made of self-healing strain-hardening cementitious composite (SH-SHCC), designed to control crack width and promote crack healing. A total of 4 beams were prepared and tested, including 1 reference RC beam, 2 hybrid beams with mould-cast cover, and 1 hybrid beam with 3D-printed cover. These beams subjected to flexural loading. Subsequent to testing, the beams were cut into smaller segments, which were then stored in a humid environment for one month as a short-term healing study. Surface crack patterns before and after healing were then compared to qualitatively assess the healing performance.

2 MATERIAL AND TESTS

The geometry and reinforcement details of all the beams are given in Figure 1. The two mould-cast (MC) hybrid beams differ at the bottom interface between the cover and the core. All interfaces between the cover and the core have been treated with a thin layer of Vaseline. The design principles and geometric details of the Vaseline-treated shear-key pattern have been reported in [9].

As can be seen, the reference beams and the hybrid beams with mould-cast cover have a cross-section of 150 mm × 200 mm. The hybrid beam with 3D-printed cover (Fle-3DP) features a slightly larger cross-sectional area, due to a thicker printed cover layer and the applied nozzle size. Our preliminary trials indicate that, to prevent fibre jamming, the nozzle diameter must exceed 1.5 cm, resulting in an average cover thickness of approximately 2.5 cm. Still, as depicted in Figure 2, the printed cover zone exhibited satisfactory shape retention ability as small variation in the average thickness of the cover along the height of the beam was observed. In addition, the hybrid beam with printed cover maintains identical reinforcement details and consistent cover depth between the longitudinal rebar and the bottom surface (*i.e.*, 38 mm).

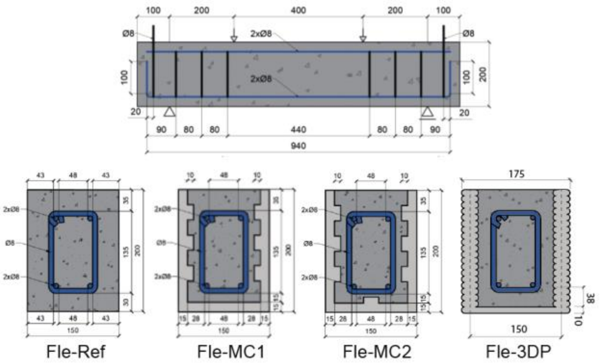


Figure 1: Design details of the beams [unit in mm].

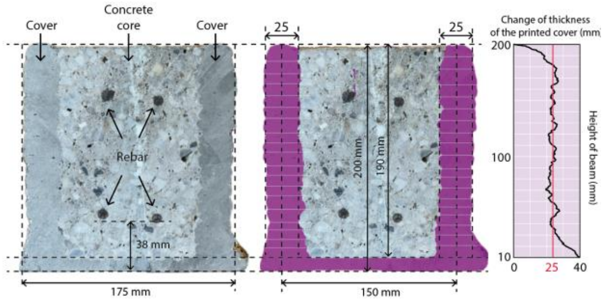


Figure 2: Cross-section of hybrid beam with 3D-printed cover zone with highlighted area of the cover zone.

Table 1 shows the mixture compositions of SH-SHCC and concrete used in the current study. The SH-SHCC adopts an ultra-high-molecular-weight polyethylene (PE) fibre as reinforcement. The the SH-SHCC matrix has Blast furnace slag (BFS) cement CEM III/B 42.5 N and silica fume as binder. Silica fume was added to enhance the bond strength between PE fibre and cement-based matrix and to improve the fresh properties of the mix.

Finely grinded limestone powder was used as filler. Two different SH-SHCCs were used to prepare mould-cast cover (SHCC-MC) and 3D-printed cover (SHCC-3DP), as can be seen in Table 1. The main difference between the mixes is the amount of silica fume used, as silica fume controls the workability of the fresh materials.

Table 1: Mixture compositions of SH-SHCC and concrete [unit in kg/m3].

Material	SHCC-MC	SHCC-3DP	Concrete
CEM I 52.5 R	-	-	260
CEM III/B 42.5 N	842	807	-
Silica fume	94	115	-
Limestone powder	468	448	-
Sand (0.125-4 mm)	-	-	847
Gravel (4-16 mm)	-	-	1123
PE fibre (vol.%)	10 (1%)	10 (1%)	-
Healing agent	20	20	-
Water	374	359	156
Superplasticizer	3	3	0.3

All the hybrid beams in the current study were casted in two steps. In the first step, SH-SHCC covers were prepared either by mould-casting or by 3D-printing. In the second step, reinforcement cages were placed in, and conventional concrete was poured. The mould casting process and 3D-printing process were illustrated in Figure 3 and Figure 4.

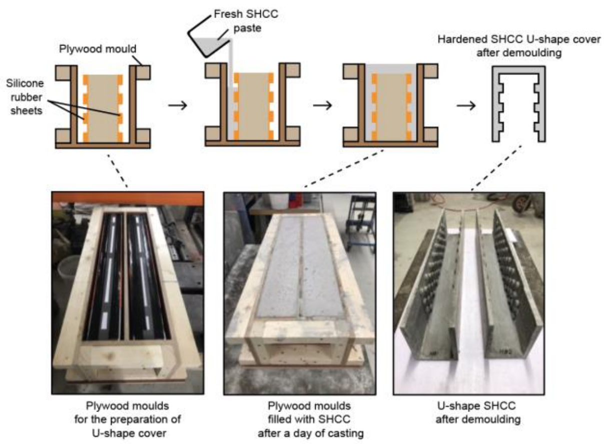


Figure 3: Preparation procedure of the SH-SHCC cover.

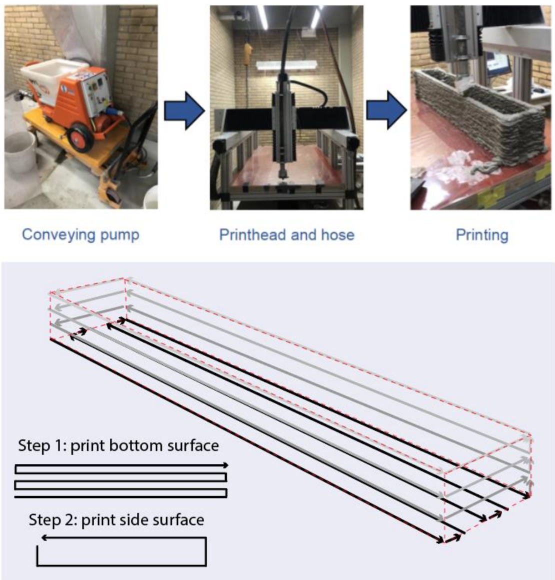


Figure 4: Set-up for the fabrication of the 3D-printed cover as well as the printing path map.

Figure 5 shows the appearance of the casted and printed covers as well as a close shot of the vertical surface. The resulting texture of printed cover (Figure 5d) is poised to improve interface integrity, akin to the shear-key pattern in mould-cast covers (Figure 5c).

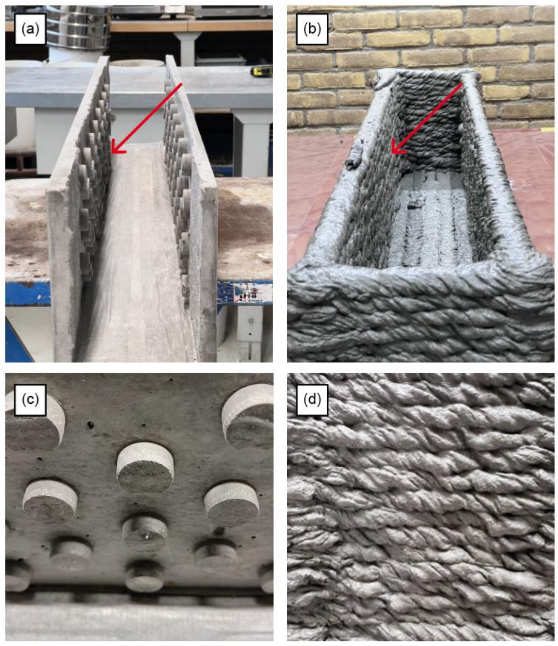


Figure 5: Pictures of (a) mould-cast cover and (b) 3D-printed cover, as well as (c) and (d) their detailed surface textures.

The beams underwent testing in a four-point-bending configuration, as depicted in Figure 6. The tests were conducted under displacement control at a rate of 0.01 mm/s. The relative vertical mid-point deflection of the beams with respect to the supports was measured using a LVDT while deformation of the beams was tracked using DIC on both sides.

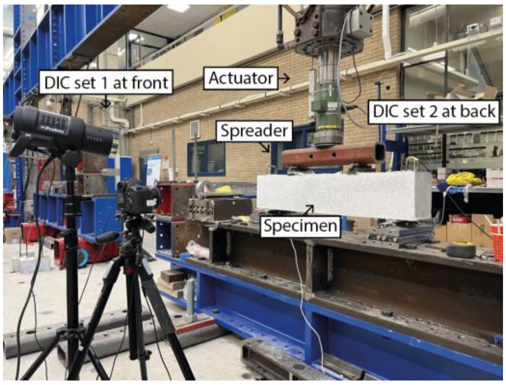
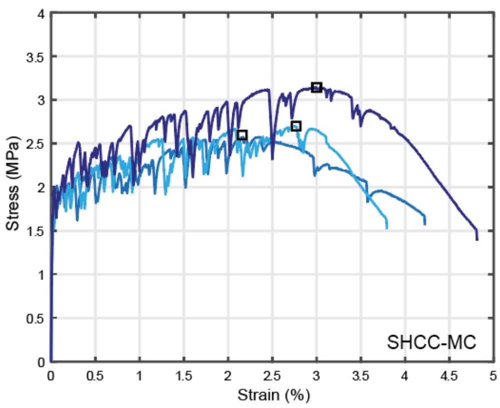


Figure 6: Experimental set-up for beam specimens with DIC measurement on both sides

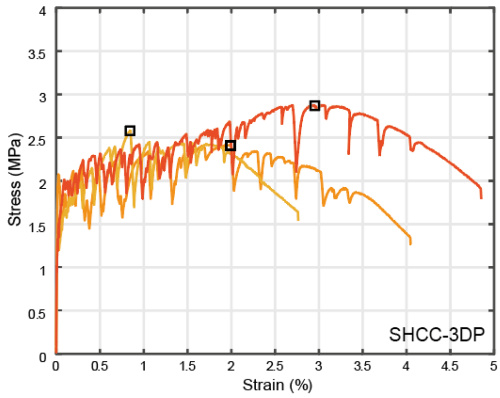
3 RESULTS AND DISCUSSION

3.1 Material properties

Figure 7 presents the stress-strain curves for the two types of SH-SHCC materials. Notably, both mixtures exhibit significant tensile strain hardening behaviour. Although the 3D-printed mixture contains a slightly higher content of silica fume aimed at enhancing buildability, no noticeable changes in tensile behaviour are observed. Therefore, both mixtures can be considered to possess similar mechanical properties.



(a)



(b)

Figure 7: Stress-strain curves of SHCC under direction tension for (a) mould-cast cover and (b) 3D-printed cover.

3.2 Structural performance

Figure 8 illustrates the comparison of load versus mid-span deflection responses for the beams. As can be seen, the load-deflection relationship of the hybrid beams (*i.e.*, Fle-MC1, Fle-MC2 and Fle-3DP) differed significantly from that of the reference beam (Fle-Ref). The hybrid beams exhibited a higher tension stiffening in the stabilized cracking stage, and a higher load-bearing capacity compared to the reference beam. Strain hardening capacity of the cover played a significant role in contributing to the bending moment resistance of the beam. Moreover, it is found that the interface properties between the cover and the core influenced the structural response of the hybrid beams with mould-casting cover. The presence of a line of shear-keys at the bottom interface provided additional mechanical resistance, resulting in 10% (14kN) increase in load-carrying capacity. This enhancement probably stemmed from a more synchronized behaviour between the cover and the core, leading to the activation of more SH-SHCC to bear the tensile load. Besides, despite the larger cross-section and thicker cover of the Fle-3DP beam, its load capacity remained lower than that of the hybrid beam with bottom shear-key. This underscores the critical significance of the interface condition to the load bearing capacity of the hybrid elements.

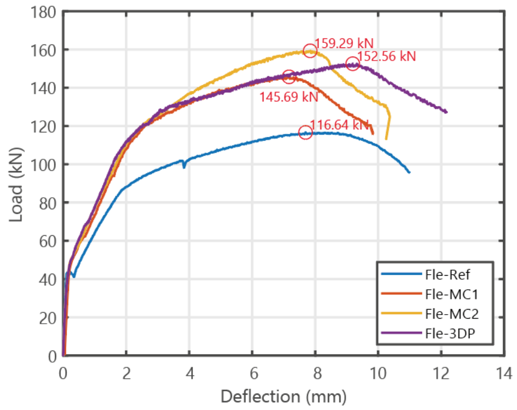


Figure 8: Load-deflection response of the tested beams under flexural loading

Figure 9 (displayed at the last page) depicts the crack patterns based on DIC principal strain analysis in the constant bending moment region for four key stages. These stages correspond to 1) crack formation stage, 2) stabilized cracking stage, 3) reinforcement yielding stage, and 4) ultimate stage of the reference beams. As can be seen, all beams failed as per design, exhibiting flexural tension failure characterized by flexural cracks on the tension side and concrete crushing on the compression side. The crack patterns reveal that all hybrid beams developed significantly more cracks compared to the reference beam. Unlike the reference beam, which exhibited only a few large cracks, the hybrid beams, equipped with either mould-cast or 3D-printed covers, displayed closely spaced fine cracks across the constant bending moment region. Moreover, the hybrid beam with bottom shear-keys displayed an increased occurrence of cracks, which were also more evenly distributed across all deflection levels. This phenomenon helps to elucidate its previously observed higher peak load capacity.

All hybrid beams demonstrated enhanced control over crack widths as a result of forming more cracks. In Figure 10, the development of the maximum crack widths along the bottom edge of the beams, as a function of deflection, is depicted. The maximum values correspond to the maximum crack width observed from the two side of beams by DIC. It is clear that the maximum crack width of the reference beam increased linearly with deflection. In contrast, for the hybrid beams, a distinct pattern of delayed crack width development was observed due to the generation of more cracks rather than the widening of existing ones. Consequently, the hybrid beams achieved higher load capacities while maintaining smaller crack widths. If a surface crack width limit of 0.3 mm is adopted as a benchmark, in line with the prescribed threshold in Eurocode 2 for reinforced concrete under quasi-permanent load across most exposure classes (excluding X0 and XC1), the reference beam exhibited maximum crack widths surpassing 0.3 mm at a load of 59.8 kN. The hybrid beams with mould-cast cover managed to confine crack widths below 0.3 mm until reaching loads of 124.7 kN and 137.3 kN, which is after reinforcement already yielded. The hybrid beam with 3D-printed cover exhibited 100.05 kN when its maximum crack width reached 0.3 mm. Despite overall enhancements, hybrid beams with mould-cast covers surpassed those with printed covers in terms of their ability to control crack width.

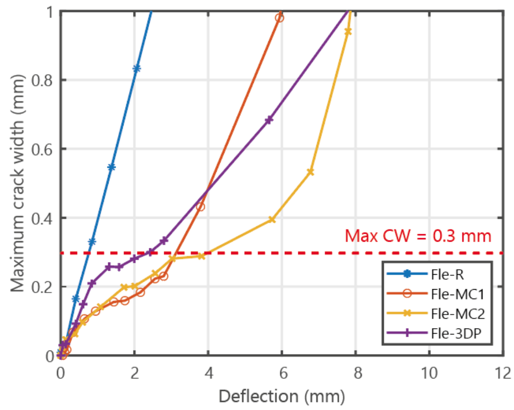


Figure 10: Interface opening expressed as development of maximum crack width versus mid-point deflection

3.3 Healing performance

Since the primary purpose of the U-shaped SH-SHCC cover is to facilitate self-healing, the healing effectiveness of the hybrid beams was evaluated. This involved examining a cracked beam segment before and after a one-month healing period under 95% relative humidity at a constant temperature of 20 ℃. Figure 11 (displayed at the last page) presents a comparative analysis of the bottom surface of a beam segment before and after the healing process. Binary images, highlighting the crack patterns, accompany the original photos. To ensure fairness in comparison, identical thresholds were applied to generate the binary images. As can be seen, the results reveal significant healing of most cracks after a one-month period, indicating the effectiveness of the self-healing mechanism. However, it is evident that not all cracks fully healed within this timeframe. Larger cracks may require more time for complete recovery. Also, the random distribution of healing agents within the matrix may result in areas lacking sufficient amount of agents to facilitate healing. Consequently, healing in these regions relies on autogenous healing of SHCC and bacterial migration from other parts of the cracks, leading to prolonged healing durations. Nevertheless, since the diffusion rate of most ions depends on the crack width [16], even partially healed cracks are expected to contribute to an increase of durability. Furthermore, our previous research characterizing healing along the crack depth revealed that healing products not only form at the crack mouth but also propagate deeper into the cracks over time [17]. This further suggests that a self-healing cover has the potential to enhance the durability of structural elements by reducing the risk of deterioration over time.

4 CONCLUSIONS

An experimental study was carried out to investigate the structural behaviour of hybrid reinforced concrete beams with U-shaped covers made via mould-casting method and 3D printing method. Structural behaviour, crack pattern and crack propagation between the reinforced concrete core and U-shaped SHCC cover were studied. A qualitative assessment of the crack appearance before and after healing was also presented. The main findings of the current study are:

1. Hybrid beams with mould-casted SH-SHCC covers displayed an improved crack control capability compared to the control beam. This improvement in crack control was achieved without compromising other beam properties.
2. The hybrid beams with 3D-printed covers demonstrate improved crack control abilities compared to the reference beam. The mould-cast cover, with its intricately designed interface profile, necessitates multiple steps and the use of sophisticated moulds for production. In comparison, 3D printing offers a more efficient alternative for creating the U-shaped cover.
3. Evident crack healing was observed after a period of 1-month moist curing. Despite that not all cracks had fully closed within this timeframe, those that remained were visibly shorter and smaller, indicating positive progression of healing.

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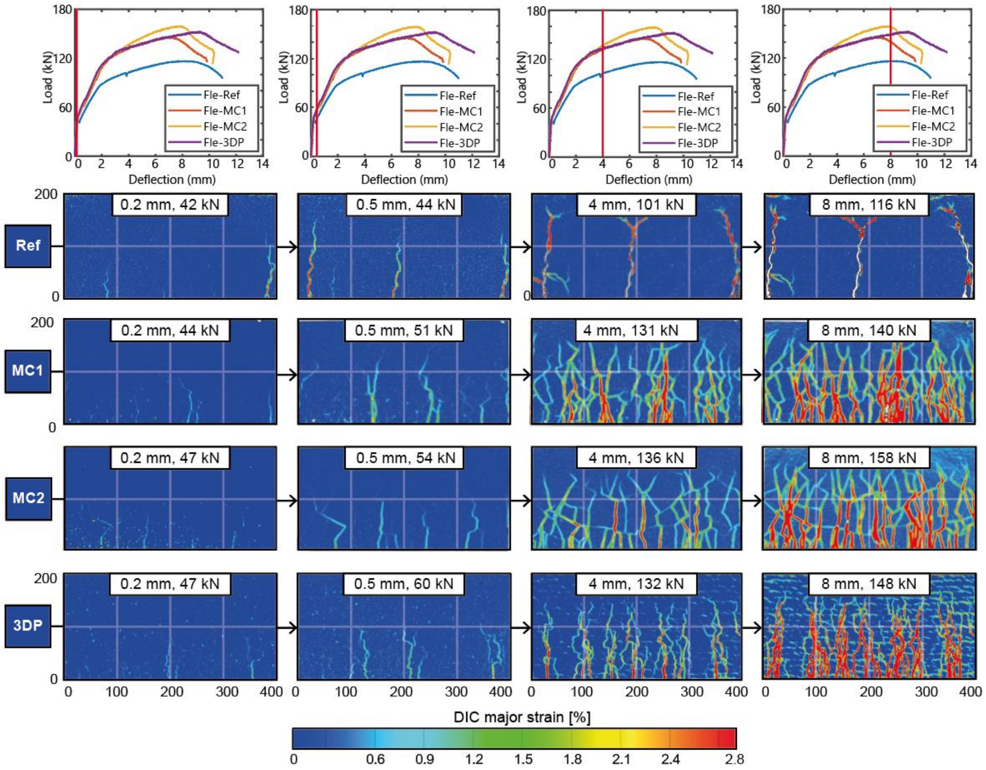

Figure 9: Crack pattern development at critical stages (i.e., crack formation stage, stabilized cracking stage, reinforcement yielding stage, and ultimate stage of the reference beams)

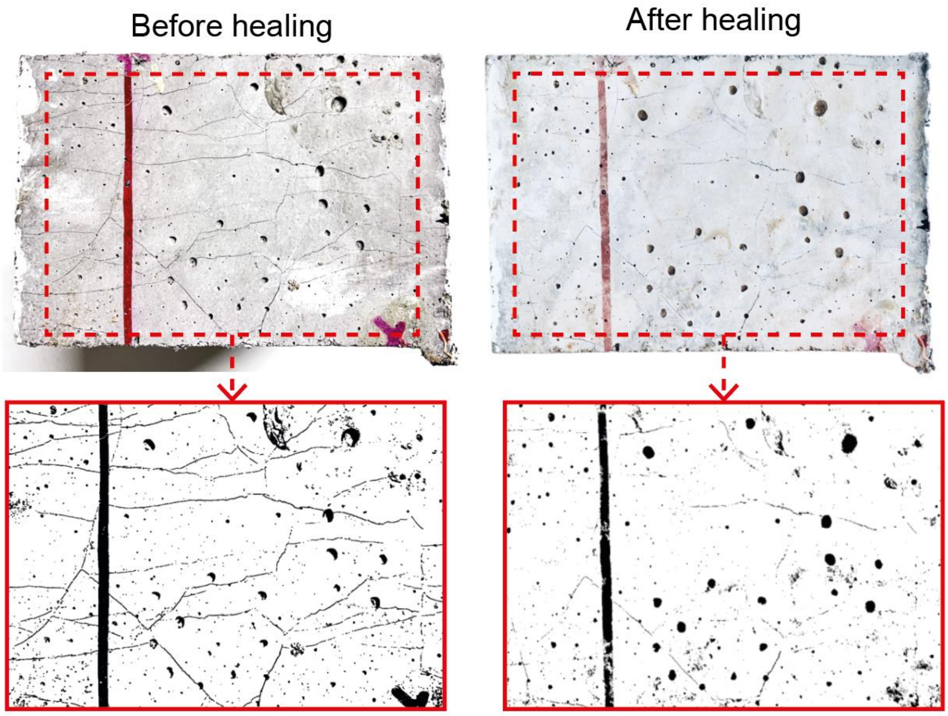

Figure 11: Visual comparison of crack patterns on the bottom surface of tested beams before and after healing.