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Assessment of Self-Healing in Pre-Cracked Concrete with Low-Carbon Binder Blends under Cyclic and Submerged Exposure



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ABSTRACT

This study presents an investigation into the self-healing potential of concrete incorporating various binder systems under two exposure conditions. Seven binder types were evaluated, including three factory-blended cements and four laboratory-prepared blends containing fly ash or Ground Granulated Blast Furnace Slag (GGBFS). Load-induced cracks were introduced in concrete beams, which were tested using a custom-designed water permeability method before and after one year of exposure to either continuous water submersion or cyclic wet/dry conditions.

Results indicate that continuous water submersion promotes self-healing in most cases. All factory blended cements demonstrated healing to a varying degree. In contrast, mixtures where slag partially replaced Portland cement showed no indication of self-healing under either condition. Cyclic wet/dry conditions generally resulted in limited self-healing. The inclusion of polyvinyl alcohol (PVA) fibres contributed positively to healing, although the effect was less pronounced than in mixtures with cement-only or fly ash-based binders. Despite the limited number of specimens, the study provides valuable insights into long-term self-healing

behaviour on early-age cracks and different exposure scenarios. The permeability-based test method used proved practical for identifying self-healing trends and may be of use for future studies of self-healing in cementitious systems.

Key words: Concrete, Self-healing, Ordinary Portland Cement, Fly ash, Blast furnace slag, PVA fibres.

1. INTRODUCTION

Self-healing in concrete and cementitious materials has been known for many years and is a subject of growing research interest due to its potential to enhance the durability and service life of concrete structures. Given that concrete is one of the most widely used construction materials globally, self-healing mechanisms may have a significant impact on the longevity and sustainability of civil infrastructure. However, the self-healing capacities of different binder systems are still not fully understood. Other researchers have investigated self-healing in concrete with different binders using different methods [1-6].

A clear understanding of the mechanisms of self-healing is essential for assessing whether observed cracks require active repair. In a review by Mohamed et al., the ability to self-heal was shown to depend on several factors, including pre-cracking age, healing conditions and the crack width itself [7]. In addition, current concrete design codes, such as Eurocode 2, specify requirements for limiting the crack width to < 0.2 mm [8]. Repair costs could potentially be reduced if such cracks are capable of fully self-healing, thereby restoring properties comparable to intact concrete. As a result, self-healing in concrete has been the focus of extensive investigations. Many reviews on the self-healing of concrete have been published such as [9-12], each addressing different aspects of the phenomenon.

Self-healing in concrete may be categorised into two primary mechanisms: autogenous (or autonomic) and engineered self-healing [13]. Autogenous self-healing refers to the natural capacity of the cementitious matrix to close cracks through ongoing hydration and other intrinsic reactions, whereas engineered self-healing involves the deliberate incorporation of additives or design features intended to promote crack closure. This study focuses on autogenous self-healing and different binders' ability to self-heal.

One of the main advantages of concrete is its high compressive strength compared to most other building materials. However, its relatively low tensile strength—about one-tenth of its compressive strength—along with its inherent brittleness, makes it susceptible to cracking.

To mitigate cracking under tensile stresses, structural concrete is commonly reinforced with steel bars. When subjected to external loads, concrete beams initially form microcracks once their tensile strength is exceeded; these are typically referred to as load-induced cracks. After cracking occurs, tensile forces are transferred to the embedded reinforcement. Cracks may also develop due to other factors such as differential shrinkage, thermal gradients, and restraint forces; however, these mechanisms were not addressed within the scope of the present study.

Prior to crack formation, the concrete cover serves to protect embedded reinforcement from environmental exposure. Once a crack propagates through the cover layer, however, the reinforcement may become directly exposed to moisture, oxygen, and aggressive agents. Such

exposure can significantly compromise the long-term performance and durability of the structure.

Following crack formation, the surfaces of the crack are exposed to environmental conditions. Unhydrated parts of the cement particles remaining on these surfaces may react further in the presence of moisture, leading to the precipitation of new hydration products. These products can partially seal the crack, thereby reducing permeability and limiting the ingress of deleterious substances, ultimately contributing to the protection of the reinforcement and extension of the structure's service life. In addition, reduced permeability may arise from the partial obstruction of the crack by small particles detached from the crack surfaces [14].

In this study, the autogenous self-healing capacity of seven binder systems was investigated. Self-healing performance was assessed indirectly by means of water permeability measurements conducted on concrete beams containing load-induced cracks. Such experimental techniques have been used in various set-ups to characterise self-healing of cracks in concrete [13, 15]. All beams were subjected to three-point bending until a crack width of 0.4 mm was induced. The crack width was measured on each side of the specimen using a linear variable displacement transducer (LVDT). Two sets of beams were also reinforced with polyvinyl alcohol (PVA) fibres, representing engineered self-healing systems. Other researchers studying self-healing potential with the addition of fibres have shown that fibres may promote self-healing [16, 17], both by reducing the actual crack width and by serving as a precipitation site for the crystalline products. This study serves as an investigation, aimed at providing insights into the self-healing potential of various binders under two distinct exposure conditions. The experimental details, including crack formation and crack stabilising procedure, permeability test method, are described in the following sections.

2. MATERIALS

Three different cement binders were used in this study CEM I 42,5 N SR3 MA/LA (C1), CEM II/A-V 52,5 N (C2), and CEM II/A-V 42,5 N MH/LA/NSR (C3), from Cementa (now Heidelberg Materials Cement Sverige). In addition, four binders were prepared in the laboratory by replacing 20 mass-% and 40 mass-% of C1 with either fly ash (FA), class F ASTM C618, or ground granulated blast furnace slag (GGBFS). The chemical composition of the binders and supplementary cementitious materials, SCMs, are shown in Table 1.

Table 1 – Chemical composition of binders and SCMs.

Chemical Composition (%)	C1	C2	C3	FA*	GGBFS*
CaO	63.3	57.1	55.4	1.37	38.5
SiO ₂	21.2	22.2	24.7	60.2	37.9
Al ₂ O ₃	3.4	6.2	5.6	17.7	13.2
Fe ₂ O ₃	4.1	3.4	4.3	2.78	0.37
MgO	2.2	2.9	2.5	0.43	7.78
Na ₂ O	0.18	0.31	0.3	0.62	0.45
K ₂ O	0.56	1.2	0.82	0.58	0.64
SO ₃	2.7	3.5	2.8		
Cl ⁻	<0.01	0.06	<0.01		

* SO₃ and Cl⁻ content were not included in the elemental analysis of FA and GGBFS.

Thirteen concrete mixtures were used in this study and two beams were cast for each mixture. The water-to-binder ratio (w/b) was 0.4, except in two mixes where the w/b ratios were 0.35 and 0.45, respectively. The mix proportions of the materials are listed in Tables 2 and 3, (materials A–M) all quantities are given in kg/m^3 .

Table 2 – Mixing proportions for materials A to G.

Material	A	B	C	D	E	F	G
w/b ratio	0.40	0.40	0.40	0.40	0.40	0.35	0.45
C1	430			350	550	430	430
C2		430					
C3			430				
Water	172	172	172	140	220	150.5	193.5
Sand 0-2 mm	893	881	881	968	779	921	864
Gravel 8-12 mm	893	881	881	968	779	921	864
Superplasticizer	2.56	3.00	2.68	8.00	1.00	6.80	2.00

Table 3 – Mixing proportions for materials H to M.

Material	H	I	J	K	L	M
w/b ratio	0.40	0.40	0.40	0.40	0.40	0.40
C1	344	258	344	258	430	430
FA	86	172				
GGBFS			86	172		
Water	172	172	172	172	172	172
Sand 0-2 mm	878	864	889	886	893	893
Gravel 8-12 mm	879	865	889	887	893	893
PVA fibres					3.23	6.45
Superplasticizer	4.20	2.00	4.80	3.20	3.08	3.08

Even though the water-to-binder ratio was held constant, the total volume of water and binder was not constant. This depends on the different densities of the binders, e.g. cement, slag and fly ash. The water and binder volumes therefore change about 5% at maximum replacement of fly ash, compared with the total concrete volume. In addition to the use of different binders, polyvinyl alcohol (PVA) fibres were incorporated into two concrete mixtures at mass fractions of 0.75 % and 1.5 % relative to the binder content. The PVA fibres had an approximate length of 5 mm and a diameter of 0.025 mm. The PVA fibres were straight and had a smooth surface morphology, with no visible crimping, embossing, or surface deformation. A superplasticizing admixture, Sikament EVO26, was used in all concrete mixtures to improve workability. It was not possible to cast materials D and F without exceeding the maximum recommended dosage of EVO26 (1.5% by mass of cement). This excess dosage was necessary to achieve a reasonable workability and to facilitate proper flow during casting.

3. METHODS

The method descriptions are divided into casting and curing, crack formation, permeability test, exposure conditions, and evaluation of self-healing. They are described in Sections 3.1 to 3.5.

3.1 Casting and curing

All concrete beams were cast and cured according to a method designed in earlier studies performed by Fagerlund and Hassanzadeh [18-20]. The concrete beams measured 200 mm in height, 150 mm in width, and 300 mm in length. The formwork for the sides and bottom was made of plywood, with two rectangular stainless-steel tubes positioned at each end of the beam. Holes were drilled near the lower flange of each steel tube to accommodate two threaded stainless-steel rods, which were subsequently cast into the concrete. These rods enabled the transfer of tensile forces from the steel to the concrete during bending of the specimen, which was used to induce the load-induced crack.

Two holes were drilled at the top of each steel beam to fasten two threaded stainless-steel rods, which were used to maintain the crack width during testing. Two ribbed reinforcement bars with a diameter of 12 mm were positioned within the formwork with a specified concrete cover of 55 mm from the bottom surface. A plastic strip measuring 150 mm in length, 3 mm in width, and 3 mm in height was positioned at the mid-span, spanning the full width of the concrete beam. This strip created a notch in the specimen, thereby localising crack initiation during bending. A drawing of the formwork and specimen is shown in Figure 1.

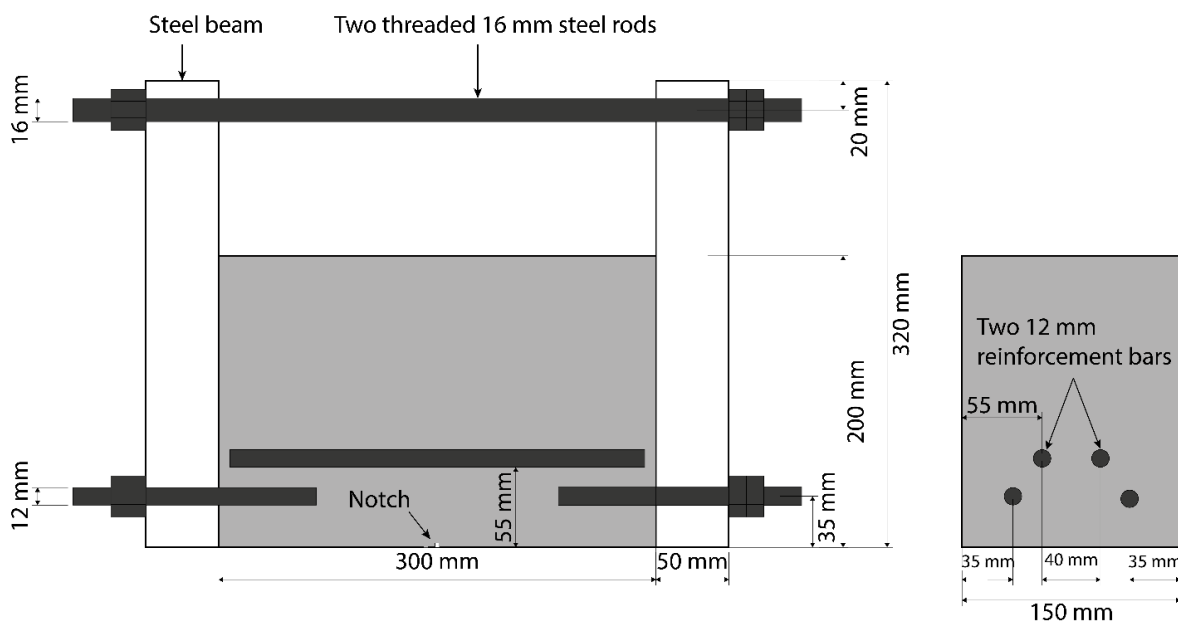


Figure 1 – The concrete beam as seen from the side (left) and a cross-section (right), redrawn from [18].

All beams were cured at 20 °C and a relative humidity (*RH*) of about 60 %, covered with a plastic sheet. The plastic sheet was removed after 24 hours, and the concrete was cured for another 144 hours prior to crack formation.

3.2 Crack formation and restraint through mechanical loading

After a total curing period of seven days, the beams were subjected to a three-point bending procedure to induce a crack at mid-span, see Figure 2 (left). An LVDT was positioned across the notch on each side of the beam to monitor the crack width, as shown in Figure 2 (right). When the crack width reached 0.4 mm, the nuts on the 16 mm diameter steel rods located at the top of the beam were securely tightened using a wrench. This step was undertaken to maintain the beam in a bent configuration, thereby stabilising the crack width throughout the subsequent exposure phase. The applied load was then removed, and the crack width was remeasured after unloading to ensure that it remained stable. Finally, the LVDTs were removed.



Figure 2 – Experimental setup for the three-point bending test on a notched concrete beam (left). The LVDT mounted across the crack initiated at the notch, enabling measurement of the crack opening displacement during loading (right).

3.3 Permeability test

The permeability tests were performed 1-4 days after crack formation. A custom-made glass cup was used as a water container for the tests. The glass cup consisted of a standard Ø100 mm glass beaker with a Ø12 mm test tube attached centrally to its base, as shown in Figure 3.

Prior to testing, the beam was rotated so that the bottom face was oriented vertically. This repositioning resulted in one side of the crack facing upwards and the other downwards, creating a wedge-shaped cavity. The crack opening on the bottom face of the beam was then sealed by filling the notch with the adhesive SikaBond-500. Subsequently, the glass cup was affixed to the upward-facing side of the beam using the same adhesive. It was positioned to cover a major part of the crack opening, while any remaining exposed sections were also sealed with adhesive, as illustrated in Figure 3. The adhesive was then allowed to cure for approximately 24 hours.

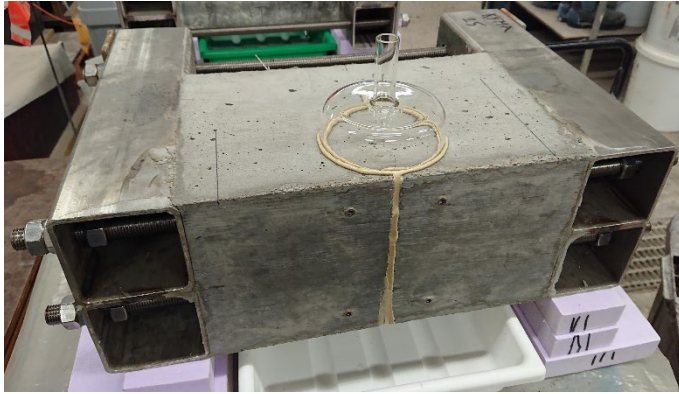


Figure 3 – The cracked beam with the attached glass cup prepared for the permeability test.

Two reference lines were marked on the smaller test tube section of the glass cup, indicating a vertical distance of 40 mm. These reference lines served as fixed measurement points for determining water flow. The cup was then filled with de-ionised water up to the upper reference line. The Water Table Drop Time (WTDT), defined as the time required for the water table to drop from the upper to the lower reference line, was recorded in seconds, see Tables 4 and 5.

Prior to commencing the permeability measurements, water was allowed to flow through each pre-cracked specimen until it emerged from the opposite face. This ensured that the crack faces were fully wetted before the start of testing. After the test, the cracked beams were subjected to one of two controlled exposure conditions. The cups remained on the beams throughout the exposure period and after the second permeability test.

3.4 Exposure conditions

After the initial permeability test, each pair of beams was exposed to one of two conditions for a duration of one year. In the first exposure condition (EC1), one beam from each pair was continuously submerged in de-ionised water in a large polymer container. The water was not replaced during the test, so de-ionised conditions were only present at the start of the experiment.

In the second exposure condition (EC2), the other beam underwent weekly wet/dry cycles, alternating between seven days of water submersion and seven days of storage at 20 °C and approximately 60% RH. Beams were labelled with a capital letter followed by '1' or '2' to indicate the respective exposure condition (e.g., A1 for continuous submersion, A2 for cyclic exposure). After completing the exposure, the beams were stored seven days at 20 °C and approximately 60% RH, a second permeability test was performed on each beam. The seven-day storage period allowed partial drying of the cracks. However, because the permeability test commenced only after water had emerged from the opposite face, the crack surfaces were likely as wet as at the start of testing.

3.5 Evaluation of self-healing

The WTDT was measured for each beam both before and after the exposure period. Since the cracks in each pair of beams were not identical — due to natural variability in crack formation

— direct comparison of WTDT was insufficient to evaluate self-healing. To account for this, a self-healing ratio, R_{sh} , was calculated by using equation (1)

$$R_{sh} = \frac{t_a - t_b}{t_b} \quad (1)$$

where, t_a (s) and t_b (s) represent the WTDT measured after and before exposure, respectively. A positive R_{sh} indicates an increase in WTDT after exposure, suggesting a reduction in crack width and evidence of self-healing. In contrast, a negative R_{sh} indicates decreased WTDT, and thus a greater water flow after exposure – implying that the crack remained open or had widened. Therefore, a negative R_{sh} does not provide evidence of self-healing.

4. RESULTS AND DISCUSSION

The t_a , t_b , and R_{sh} of each material exposed to climate EC1 and EC2 are shown in Tables 4 and 5, respectively. The last column in Tables 4 and 5 shows the arithmetic mean of all results. All materials exhibit a positive R_{sh} following EC1 exposure, with the exception of materials J and K, see Table 4. The observation that t_a exceeds t_b suggests the occurrence of self-healing. Conversely, the two materials containing 20% and 40% GGBFS replacement demonstrate negative R_{sh} , indicating limited or absent self-healing. Material G presents an unexpected result compared with A and F, with a t_a of 2550 s resulting in an R_{sh} of 93.4. Given the comparatively high w/b ratio of 0.45 for material G, a reduced self-healing capacity would normally be expected, since concretes with higher w/b ratios typically contain a smaller fraction of unreacted cement grain cores that can contribute to self-healing. However, this w/b ratio is not sufficiently high to preclude the presence of unhydrated cement grains after crack formation, particularly considering the short hydration time prior to EC1. Material D also deviates from expectation, showing a t_a of 507 s. In this case, the cement content is 100 kg/m³ lower than in Material A, which would theoretically also reduce the amount of hydration products formed during re-exposure and thus result in reduced self-healing rather than enhanced self-healing. A possible explanation for the unexpectedly high self-healing ratios observed for Materials G and D is a specimen-specific change in crack geometry during exposure. Although the experimental setup was designed to limit crack closure and maintain a stable crack width, the initial crack geometry may not have been fully preserved in all specimens. Even a partial reduction in crack opening would decrease the effective hydraulic crack width and could therefore markedly reduce water penetration during the permeability test. The observed response for Materials G and D may consequently reflect a combined effect of autogenous healing and partial mechanical crack closure. However, there were no obvious signs of malfunction in the crack-closure prevention system for these materials. These results should therefore be interpreted with caution.

Table 4 – WTDT pre and post EC1 exposure.

EC1	A	B	C	D	E	F	G	H	I	J	K	L	M	Mean
t_b	40	32	30	46	18	32	27	46	42	88	50	26	40	39.8
t_a	96	162	100	507	134	85	2550	246	72	67	30	76	110	325.8
R_{sh}	1.4	4.1	2.3	10.0	6.4	1.7	93.4	4.3	0.7	-0.2	-0.4	1.9	1.7	9.8

The results from EC2, cyclic exposure, show that all but two R_{sh} values range between +0.7 and -0.6, see Table 5. In particular, the R_{sh} of material F is approximately nine times higher than that typically observed in this study, reaching 6.3. Material F has a w/b ratio of 0.35, which indicates that a portion of the cement grains remains unhydrated owing to the shortage of water

at ratios below 0.40 [21]. However, the self-healing performance of material F in EC2 – expected to be less favourable – is greater than that observed in EC1, an outcome that appears unlikely. As in the case of Materials G and D under EC1, it cannot be excluded that the crack-closure prevention system did not fully maintain the initial crack geometry, resulting in partial mechanical crack closure and reduced water penetration during the permeability test. Overall, the finding that EC2 (cyclic submersion) exhibits a lower self-healing capacity is consistent with the results reported by Roig-Flores et al. [22, 23].

Table 5 – WTDT pre and post EC2 exposure

EC2	A	B	C	D	E	F	G	H	I	J	K	L	M	Mean
t_b	32	24	38	56	42	33	18	47	33	29	127	38	41	42.9
t_a	32	36	56	96	25	242	15	19	21	37	85	33	95	60.9
R_{sh}	0.0	0.5	0.5	0.7	-0.4	6.3	-0.2	-0.6	-0.4	0.3	-0.3	-0.1	1.3	0.6

Self-healing is governed not only by the amount of reactive binder available, but also by the relationship between the size of the reaction products, the crack morphology and the crack width. Products formed through continued hydration, such as C-S-H, portlandite and ettringite, as well as secondary precipitation products such as calcium carbonate, develop on the crack surfaces and within local irregularities along the crack path. Since these products are generally small compared with the imposed crack width, a reduction in water permeability does not necessarily require complete filling of the entire crack volume. Instead, even partial deposition, local bridging, or narrowing of the effective hydraulic flow path may significantly increase the WTDT. Therefore, the observed increase in WTDT indicates reduced hydraulic connectivity within the crack system and can thus be regarded as evidence of self-healing.

It should also be noted that several uncertainties may have influenced the test results, including the initial moisture condition of the crack surfaces, small particles partially obstructing the crack during testing [14], and natural variability in crack geometry. These factors were observed during testing, but their influence on the overall interpretation of self-healing is considered to be limited.

In sections 4.1- 4.6 the results are presented as bar charts (EC1 in light grey, EC2 in dark grey), with the discussion focusing on comparisons between the reference and modified mixtures.

4.1 Factory blended cements

Figure 4 shows the results from the permeability test of the three factory blended cements.

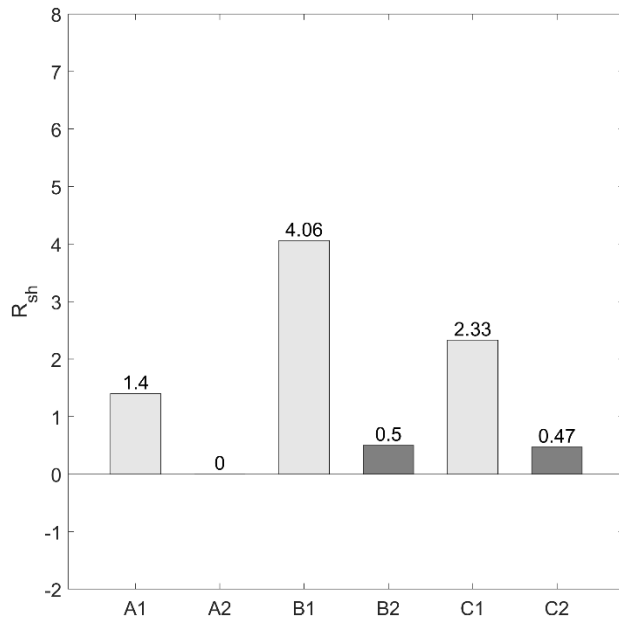


Figure 4 – R_{sh} observed under the two exposure conditions for concrete materials A, B, and C.

The R_{sh} following EC1 is clearly positive, indicating that the WTDT increased after exposure for concrete mixtures A, B and C. This may be interpreted as evidence of self-healing. In contrast, the increase in WTDT under EC2 is less pronounced, suggesting a lower self-healing potential under this exposure condition. A clear distinction between the two exposure conditions was observed across all three factory blended cement types. Materials B and C, both containing binders with fly ash, exhibited a modest increase in self-healing ratio under EC2, whereas material A, which did not contain fly ash, showed no change.

4.2 Influence of binder content

The results from the permeability test of three different concrete mixtures with different binder content but equal w/b , are presented in Figure 5.

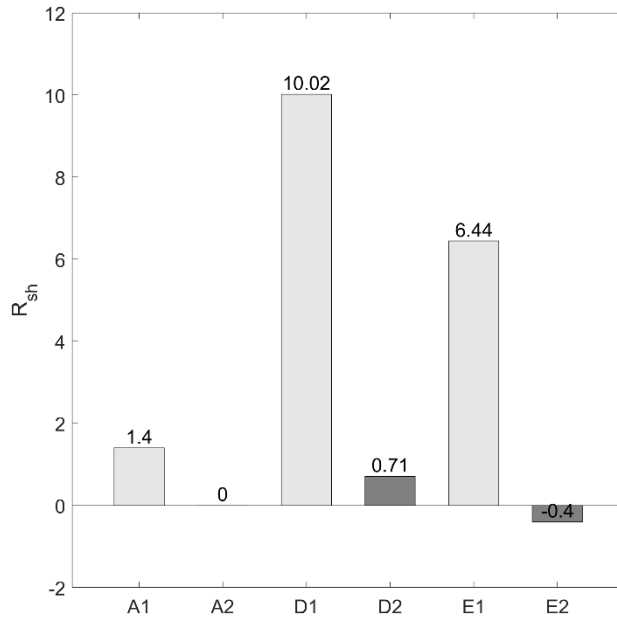


Figure 5 – R_{sh} observed under the two exposure conditions for materials made with binder C1 and three different binder contents: 430 kg/m³ (A), 350 kg/m³ (D), and 550 kg/m³ (E), with w/b 0.4.

There is a clear increase in WTDT, $R_{sh} > 0$, for all concrete mixtures shown in Figure 5 after EC1 exposure. However, the increase in R_{sh} is not proportional to the binder content, as the R_{sh} values are 10, 1.4 and 6.44 for binder contents of 350 (D), 430 (A), and 550 kg/m³ (E), respectively. There is no clear correlation between the binder content and the R_{sh} as the lowest binder content showed the largest R_{sh} . This may imply that there are other factors that are more decisive for affecting the self-healing ratio than the binder content. EC2 does not appear to facilitate self-healing, and no clear correlation between the binder content and the R_{sh} is observed. In fact, a negative impact on the R_{sh} is observed when the binder content is increased from 350 to 550 kg/m³.

4.3 Influence of w/b ratio

Figure 6 shows the results from the permeability test for three different w/b ratios (0.35, 0.4, and 0.45), under both exposure climates. Attention should be paid to the scale of the y-axis.

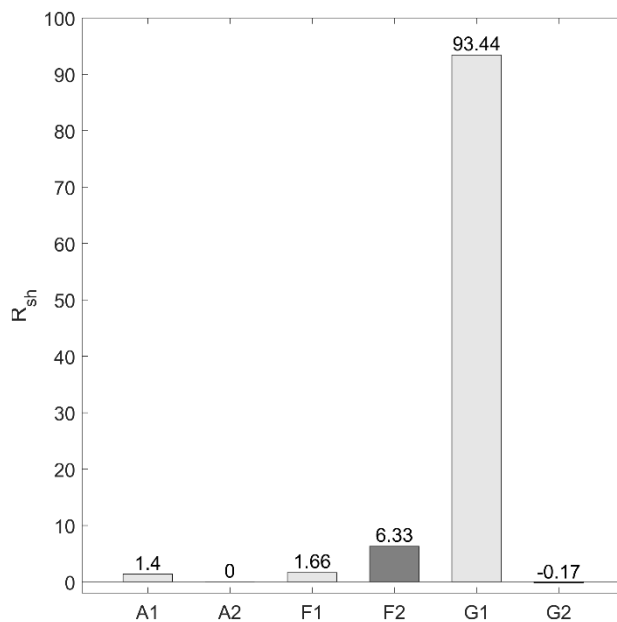


Figure 6 – R_{sh} observed under the two exposure conditions for mixtures made with different water-to-binder ratios: 0.40 (A), 0.35 (F), and 0.45 (G).

All three concrete mixtures (A, F, and G) subjected to EC1 exhibit R_{sh} greater than zero, which may indicate self-healing. However, the R_{sh} for concrete G appears disproportionately high compared to the other mixtures and represents the highest observed under EC1. Notably, the concrete with a w/b ratio of 0.35 (F) also demonstrates a relatively high R_{sh} under EC2 — the highest result obtained in the entire study for EC2. This finding contradicts the overall trend as the cyclic conditions specified in EC2 result in reduced periods of submersion, which are otherwise favourable for healing. If R_{sh} is a reliable indicator of self-healing, these results suggest that self-healing may be more effective under EC2 than under EC1 for a w/b ratio of 0.35 (F). Further investigation is needed to better understand the mechanisms influencing self-healing under different exposure conditions.

The results of this study suggest there is no clear correlation between w/b ratio and self-healing. The highest self-healing performance was observed in concrete with a w/b ratio of 0.45, followed by the second highest at a w/b ratio of 0.35, and the lowest at a w/b ratio of 0.4. However, this finding aligns with the study by Reinhardt et al. [24], which reported that the w/b ratio had an insignificant effect on self-healing. A similar conclusion was reached by Gagné and Argouges [25], who also found no clear relationship between the w/b ratio and self-healing behaviour.

4.4 Influence of fly ash content

Figure 7 shows the results from the permeability test of all beams containing concrete with fly ash, either added by the cement producer (C) or added to the Portland cement in the laboratory (H and I).

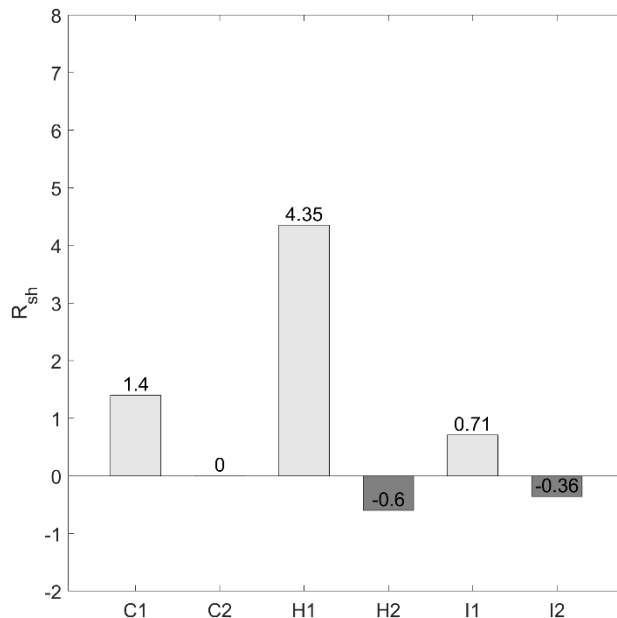


Figure 7 – R_{sh} observed under the two exposure conditions for different binders with identical w/b ratios and varying levels of fly ash replacement: 10–18% (C), 20% (H) and 40% (I) by mass of binder.

The results indicate that all concrete mixtures subjected to EC1 exhibited R_{sh} greater than zero. Materials C and H, which contained 10–18% and 20% fly ash replacement by mass, respectively, showed a larger self-healing effect compared to the mixture with 40% fly ash replacement by mass. This suggests that partial replacement of Portland cement with fly ash may enhance self-healing under submerged conditions. However, when the fly ash replacement was increased to 40%, the R_{sh} decreased, indicating that higher levels of fly ash replacement may reduce the self-healing potential under the conditions investigated. One possible explanation is that the higher fly ash content reduced the proportion of Portland cement clinker in the binder and thereby lowered the availability of calcium-rich hydration products at early age. Since calcium-bearing phases are essential for the formation of C-S-H gel and other healing products that may contribute to crack sealing, a reduced calcium availability may have limited the autogenous healing response.

When exposed to EC2, the R_{sh} are either slightly positive or negative, indicating that the 7-day wet/7-day dry cycle does not significantly promote self-healing.

The self-healing potential largely depends on the presence of unhydrated parts of binder particles at the crack surface. Approximately seven days after casting, a significant amount of unreacted binder is likely to remain, which can contribute to continued hydration in the presence of moisture. Therefore, the initial permeability test should not be conducted too long after casting to ensure that reactive binder constituents are still available. This consideration is particularly important when using pure Portland cement as the binder. In contrast, when

supplementary cementitious materials such as fly ash or slag are incorporated, the first permeability test may be carried out at a later age, as these materials hydrate more slowly than Portland cement. These findings underscore the importance of binder composition and hydration dynamics in enabling self-healing, as supported by previous research. For instance, Şahmaran et al. [26] demonstrated that concrete incorporating fly ash in the binder enhanced self-healing of cracks.

In addition to the binder type, the size of clinker particles may also influence the self-healing potential. Larger cement particles typically have a higher amount of unreacted material, which may be beneficial for self-healing. This aligns with the study by Wang and Wu [27], who demonstrated that the incorporation of coarse clinker particles into cement (CEM II/A-LL 52.5 N) with Blaine fineness between 2 and 40 m²/kg affected both compressive strength and self-healing behaviour of the concrete. Their results indicated that coarse clinker particles with a particle size of 40–60 µm substantially improved self-healing after 28 days. In the present study, however, the differences in Blaine fineness between the binders were relatively small — approximately 370 m²/kg for C3 and 310 m²/kg for C1 — and the particle size distribution was not determined. No clear correlation was observed between Blaine fineness and R_{sh} . Furthermore, the overall fineness of the two laboratory-prepared blended binders was not determined, which may contribute to the lack of observed correlation.

4.5 Influence of slag content

Figure 8 shows the results from the permeability test performed on material A (100 mass-% C1), material J (80 mass-% C1 + 20 mass-% GGBFS), and material K (60 mass-% C1 + 40 mass-% GGBFS).

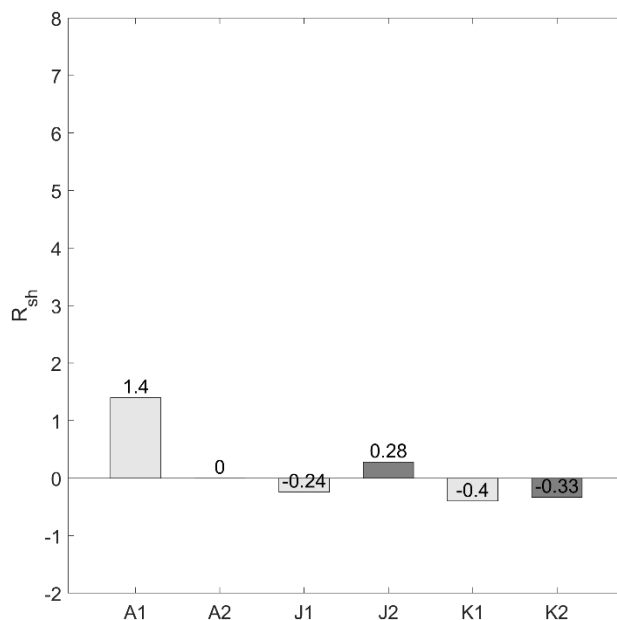


Figure 8 – R_{sh} observed under the two exposure conditions for materials with three different binders A, J and K.

The results show that the R_{sh} for binders with slag replacement was lower than that of the binder without slag replacement, indicating limited self-healing regardless of exposure

conditions. The R_{sh} was both negative and positive, suggesting that the water flow through the crack after climate exposure was approximately the same as the flow before exposure. This indicates a low self-healing potential for cements with slag additives.

The self-healing potential of concrete with GGBFS has previously been investigated by Park and Choi [28, 29]. In one study improved self-healing performance was reported for a binder system containing 60 mass-% GGBFS together with an additional 5 mass-% of either CaSO_4 or Na_2SO_4 [29]. Since this binder composition differs from that used in the present study, a direct comparison is not straightforward. In another study, Park and Choi [28] observed that the use of GGBFS reduced the formation of self-healing products, which is consistent with the findings in this study. This may be explained by the fact that cracking was induced when the specimens were only seven days old. At this age, the OPC still contained a substantial amount of unreacted binder, while the reaction of GGBFS had not progressed sufficiently. Consequently, the amount of $\text{Ca}(\text{OH})_2$ formed through OPC hydration is limited, which may have restricted the activation and subsequent reaction of GGBFS.

4.6 Influence of PVA fibre content

Figure 9 shows the results from the permeability tests performed on material A (without PVA fibres) and materials L and M, containing 0.75 and 1.5 mass-% PVA fibres (by binder mass), respectively.

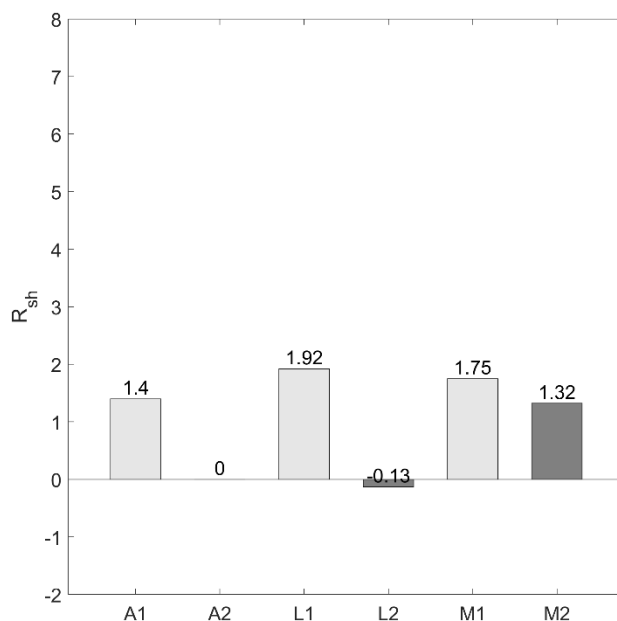


Figure 9 – R_{sh} observed under the two exposure conditions for material without PVA fibre content (material A) and with PVA fibre content: material L (0.75 mass-% of binder) and material M (1.5 mass-% of binder).

Both concrete mixtures containing PVA fibres exhibited a marked increase in R_{sh} after exposure to EC1 compared with EC2. Under EC1, the difference in R_{sh} between the materials with PVA fibres (L and M) and the materials without fibres (A) was approximately 0.3, which

was not considered significant. When exposed to EC2, the material with a lower level of PVA fibre addition showed no significant change in R_{sh} . In contrast, the difference in R_{sh} between material without fibres (A) and that with a high addition of PVA fibres (M) was significant showing a difference of 1.32, which may indicate enhanced self-healing. However, this result is somewhat questionable, as EC2 (cyclic wet/dry conditions) generally produced only moderate self-healing in most other tests conducted in this study.

Due to the complex experimental setup required to produce cracks of uniform width, the restraint setup to maintain constant crack openings, and the relatively large specimen size, only a limited number of specimens could be produced and tested, precluding formal statistical analysis. Each specimen was nevertheless manufactured and tested under rigorously controlled conditions to ensure representativeness.

5 CONCLUSIONS

Based on the results of this study, the concrete beams exhibited the most pronounced self-healing under continuous submersion (EC1) for one year. Replacing Portland cement with moderate amounts of fly ash appeared to enhance self-healing capacity. In contrast, the binders containing C1 combined with 20 and 40 mass-% GGBFS showed no measurable self-healing under EC1.

Crack self-healing under cyclic submersion (EC2) was generally low or negligible for most concrete mixtures. While a lower water-to-binder ratio is expected to enhance self-healing, the overall trend indicates that continuous water exposure promotes more consistent healing than cyclic wet/dry conditions.

The permeability-based method applied in this study shows potential for detecting self-healing, but further validation is necessary. Complementary testing methods should be employed to confirm the findings. Additionally, the conclusions are drawn from a limited number of specimens. Increasing the number of specimens per binder type would improve the statistical reliability of the results and help validate the applicability of the permeability method.

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