Self-healing of concrete with various binders

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Preface

This research work was performed at the division of Building Materials, Lund University, BML, between 2017 and 2019. Magnus Åhs, BML, and Katja Fridh, BML, both worked in this project. Magdalena Rajczakowska, division of Structural and Fire Engineering, Luleå University of Technology, also worked in this project.

Bengt Nilsson, BML, is gratefully acknowledged (in memoriam) for conducting all the laboratory works regarding mould preparations, mixing of concrete, pouring and tri-axial bending tests. Per-Olof Rosenkvist from the division of Structural engineering, Lund University, was also a good support when preparing and performing the tri-axial bending test.

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Lund, 1 June 2020

Magnus Åhs

Summary

This research was conducted at the division of Building Materials, LTH from February 2017 until December 2019. The objectives were to establish if self-healing of concrete depends on binder and exposure climate and to what extent this can be determined using a permeability test developed by the author. The binders used in this study were three binders produced by Cementa, commercially available at the time of the study ("Anläggning Classic", "Bascement" and "Anläggning FA") and four binders mixed in the laboratory. The main binder in the laboratory mixed binder was "Anläggning Classic" which is an ordinary Portland cement.

Self-healing was studied by using cracked beams of concrete. The crack in each beam was induced by an external load, a tri-axial bending test. The beams were subjected to two different exposure climates. The self-healing was determined by means of a permeability test with water flowing through the crack. Self-healing was evaluated by determining the duration of the permeability test. If the duration was less prior to the exposure than after, this indicated that self-healing had occurred. If the duration was similar or longer prior to the exposure than after this indicated that self-healing did not occur.

An indication of self-healing was determined in all binders when submerging the concrete beams in water for the duration of one year. The indication of self-healing was significantly lower when subjecting the concrete beams to an alternate climate exposure of 7 days submersion in water and 7 days of drying conditions during one year.

Contents

1 Introduction

Self-healing in concrete and cement-based materials is an important subject, particularly as it may affect the service-life of concrete structures. As concrete is a widely used building material self-healing may have a large impact of the infrastructural part of society. However, the ability of different binders to self-heal is still not well-known. Such an ability is very important to know to be able to decide if a crack needs to be repaired or not. According to the Swedish transport administration concrete cracks exceeding a crack width of 0.3 mm need to be repaired [1]. The cost of repairs may be reduced if the cracks can self-heal completely and that the properties of the self-healed cracks are equal to the solid un-cracked concrete. The research community has therefore addressed self-healing of concrete in many reports and investigations.

Self-healing in concrete can be divided into two parts; autogenous and engineered self-healing [2]. Autogenous self-healing is exhibited by the binder itself and engineered self-healing is promoted by using an additive in the concrete mixture.

One major advantage of concrete is its compressive strength which is high compared to other building materials. However, a disadvantage of concrete is its tensile strength which is roughly about one tenth of its compressive strength. In addition, concrete is also a brittle material which makes it prone to cracking.

In order to improve structural concrete to withstand tensile forces, and thus to limit cracking, reinforcement bars are used. When a concrete beam is subjected to external forces small cracks will form when the tensile strength is reached. Such cracks are referred to as load-induced cracks. When cracks have formed, tensile forces are transferred to the reinforcement bars. Cracks may also form because of other mechanisms, for example non-uniform shrinkage, non-uniform thermal distribution and restraint forces. The latter crack forming mechanisms were not addressed in this research.

Before cracking appears, the reinforcement bars embedded in the concrete are protected from environmental conditions due to the concrete cover. When a crack is formed it may reach through the concrete cover and thus the reinforcement becomes exposed to environmental conditions. Such cracks can shorten the service life of the structure considerably.

When a crack has formed, the surface of the crack becomes exposed to the environment. It is possible that there is unreacted cement at the surface of the crack which can start to react with moisture supplied by the environment. Such a reaction may bridge the gap of the crack and fill it with new reaction products. These reaction products may partly close the crack and can therefore mitigate the environmental impact on the reinforcement bars. In such a case, self-healing can also contribute to a longer service life of the concrete structure.

In this study the self-healing ability of seven types of binders has been examined. The autogenous self-healing ability has been determined indirectly by using a permeability test on beams with seven types of binders load-induced crack. The crack width on each beam was 0.4 mm as such a crack needs to be repaired according to the Swedish transport administration regulations [1]. The permeability test was performed prior to and after subjecting the cracked concrete beam to two different exposures. Two pairs of beams were PVA-fibre reinforced, which may be categorised as engineered self-healing.

1.1 Aim

The aim of this study was to determine differences in self-healing of concrete with different types of binders. In addition, the study aimed to establish differences in self-healing ratio depending on exposure conditions. The water binder ratio, w/b, of the concrete in this study was mainly 0.4, which is commonly used in large infrastructural structures like bridges and tunnels. These structures are typically subjected to alternate exposure conditions.

2 Materials

A total of 26 reinforced concrete beams were used in this study. Seven types of binders were used in this study. Three of them were commercially available and manufactured by Cementa. These were as follows:

-“Anläggning Classic” which, according to EU and Swedish Standard, is a CEM I 42,5 N – SR 3 MH/LA cement, Blaine fineness 310 m^2/kg,

- “Bascement” which is a CEM II/A – V 52,5 N cement, Blaine fineness 450 m^2/kg, contains about 7-15 weight-% fly ash,

- “Anläggning FA” which is a CEM II/A – V 42,5 N - MH/LA/NSR cement, Blaine fineness 370 m^2/kg.

In addition to these commercially available cements four binders were prepared in the laboratory. This was done by replacing 20 weight-% and 40 weight-% of “Anläggning Classic” by either a fly ash, class F according to standard ASTM C618, or a ground granulated blast furnace slag, GGBFS, but with identical total binder content in each of these mixtures.

Despite the fact that the water 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 volume therefore changes at maximum replacement of fly ash of about 5 % compared with the total concrete volume.

In addition to using different binders, two concrete beams were cast with polyvinyl alcohol, PVA, fibres added to the concrete mixture; 0.75 weight-% and 1.5 weight-% of binder content.

Sikament EVO 26 is a super plasticizing admixture for concrete and mortar, this admixture was used in all concrete mixtures.

The concrete mixtures are described in Table 1 and Table 2. Two beams were cast of each concrete mixture.

Table 1. Concrete mixtures used for the concrete beams, each component is expressed in kg/m^3.

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*
Anläggning Classic	430			350	550	430	430
Bascement		430					
Anläggning FA			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
EVO 26	2.56	3.00	2.68	8.00	1.00	6.80	2.00

Table 2. Concrete mixtures used for the concrete beams, each component is expressed in kg/m³.

Material	**H**	**I**	**J**	**K**	**L**	**M**
W/B	*0.40*	*0.40*	*0.40*	*0.40*	*0.40*	*0.40*
Anläggning Classic	344	258	344	258	430	430
Fly ash	86	172				
Slag, 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-fibre					3.23	6.45
EVO 26	4.20	2.00	4.80	3.20	3.08	3.08

3 Methods

The method descriptions are divided into casting and curing, crack forming procedure, permeability test and wet/dry exposure. They are described in sections 3.1-3.4.

3.1 Casting and curing

All concrete beams were made according to a method designed and tested in earlier previous studies performed by Fagerlund and Hassanzadeh [3-5].

The concrete beams were 200 mm high, 150 mm wide and 300 mm long. Two 12 mm reinforcement bars, quality K 500 C-T, were embedded in the concrete beams. The concrete cover was set to 55 mm, see Figure 1. Note the notch at the bottom of the beam. This notch is there in order to initiate the crack at the centre of the beam.

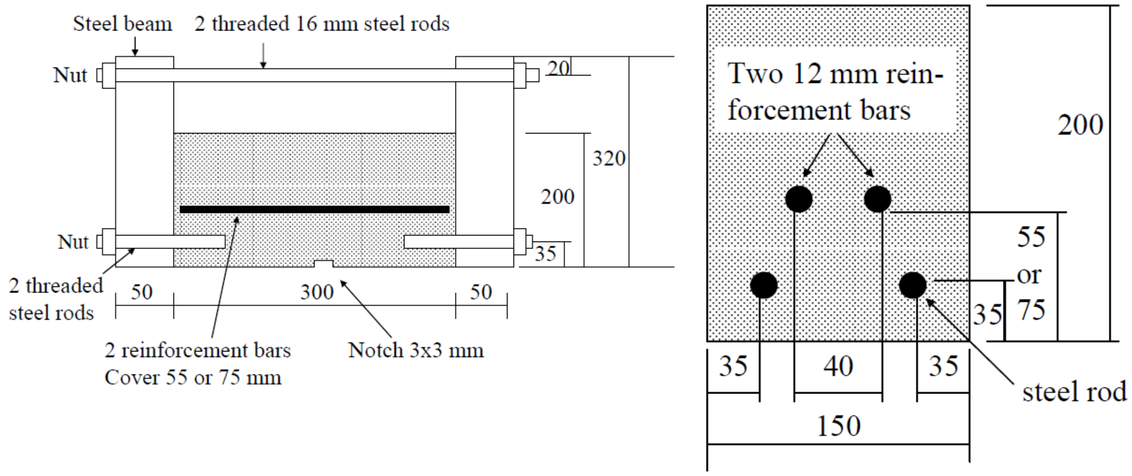

Figure 1 The concrete beam as seen from the side (left) and a cross-section (right), illustration from [3].

The formwork of the concrete beam is shown in Figure 2.

Figure 2. The formwork for the concrete beams.

The inside of the formwork is shown in Figure 3 and Figure 4.

Figure 3. Top view of the formwork used to pour the concrete beams.

Figure 4. Top view, close-up of the bottom of the formwork, note the white plastic ruler perpendicular to the reinforcement bars to create the notch.

All beams were cured at 20°C and a relative humidity of about 60 % RH, covered with a plastic sheet. The plastic sheet was removed and the concrete was cured for another 144 hours prior to initiating the crack forming procedure.

3.2 Crack forming procedure

After curing for in total 7 days the beams were subjected to a tri-axial bending test in order to form a crack at the centre of the beam. Two linear variable displacement transformers, LVDT gauges were placed over the notch in order to monitor the growth of the crack. When the crack was 0.4 mm wide, the nuts of the 16 mm steel rods at the top were firmly tightened with a wrench. This was done in order to keep the beam in a bent state and therefore keeping the crack width constant throughout the exposure procedure. After forming the crack and tightening the nuts the LVDT-gauges were removed.

In Figure 5, the tri-axial bending test setup is shown.

Figure 5. Picture of a tri-axial bending test to form a crack in the notched concrete beam.

3.3 Permeability test

The permeability tests were performed 7 days after casting. A glass cup was used as a water container for the permeability test. The glass cup was made from an ordinary Ø100 mm glass beaker and a Ø12 mm test tube attached at the centre of the glass beaker, see Figure 6.

Figure 6. Glass cup designed to be used for the permeability test.

The glass cup was fixed on the side of the concrete beam, using an adhesive, SikaBond®-500. The glass cup covered the major part of the crack opening, other parts of the crack were covered with adhesive.

Prior to the permeability test, the crack opening was sealed by filling the notch with the same adhesive as used for fixing the glass cup, see Figure 7.

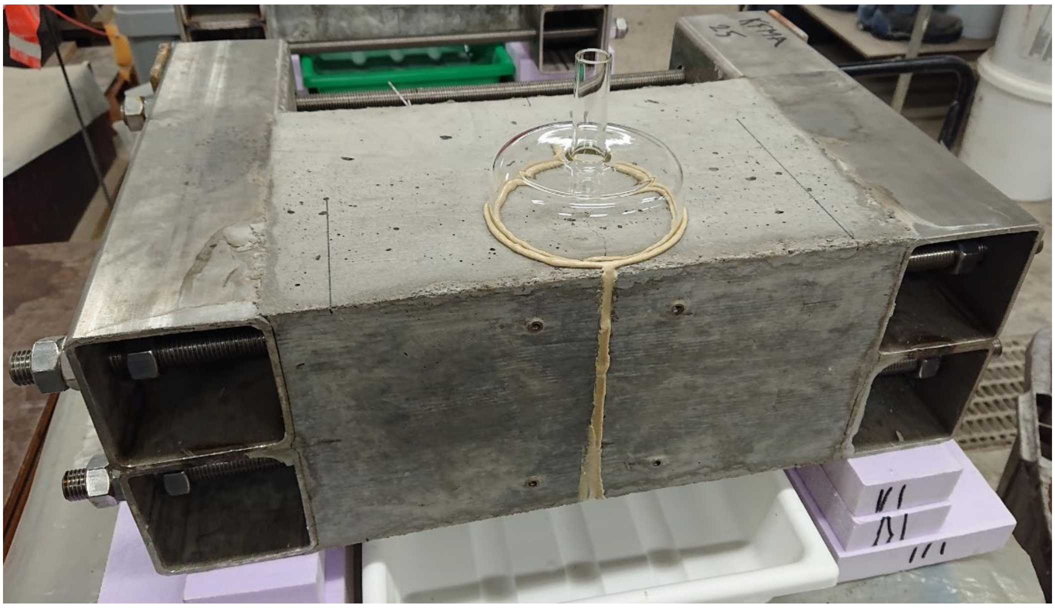

Figure 7. Picture of the cracked beam prepared for the permeability test.

Figure 8 shows an illustration of the cracked concrete beam prior to the permeability test.

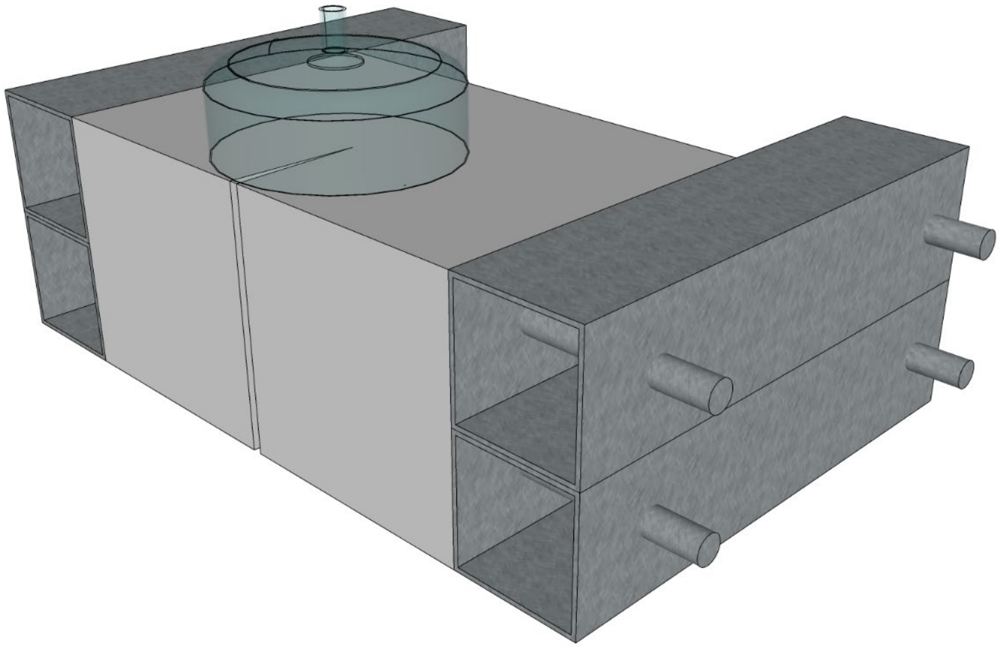

Figure 8. Illustration of the notched beam with a crack and a glass cup fixed on the side of the beam, prior to sealing the crack.

The adhesive was allowed to harden for approximately 24 hours. Two lines were drawn on the smaller tube of the cup in order to create two precise and constant reference levels. The glass cup attached onto the side of the beam was then filled with de-ionized water up to the top reference line, see Figure 9.

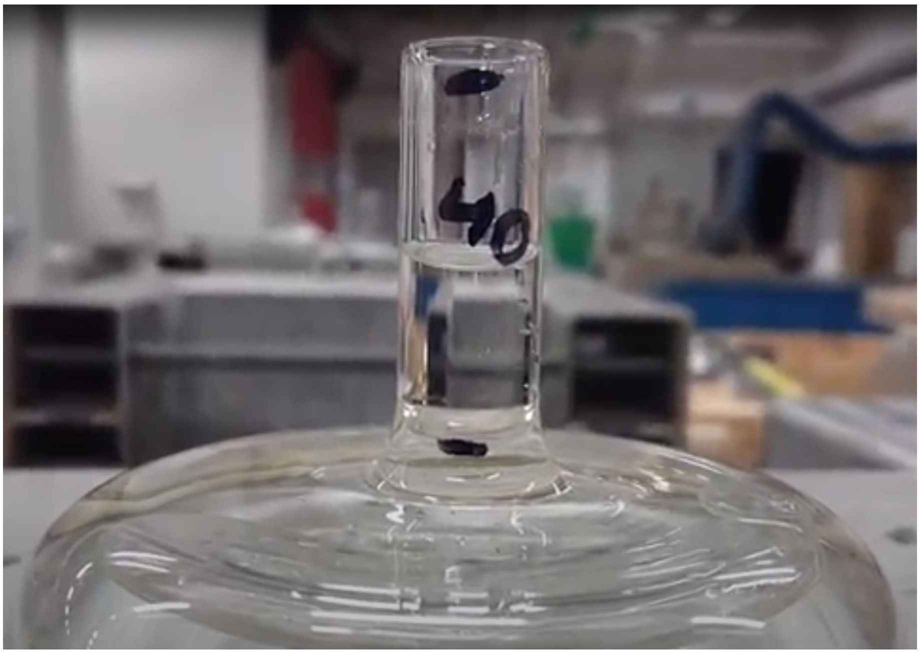

Figure 9. Picture from the water permeability test, showing the top and the bottom reference levels.

The permeability test was performed by letting water flow through the length of the crack. The time during which the water level passed between the top line and the bottom line was determined. After this permeability test, the cracked concrete beams were subjected one of the two exposure climates. Note that the crack surface was dry at the start of the first permeability test.

3.4 Wet/dry exposure

After performing the permeability test, the beams were submerged in de-ionized water. One beam of each pair was then kept submerged during one year, exposure climate 1, in a large polymer container, see Figure 10. The beams subjected to this exposure were labelled with a capital letter + 1, i.e. A1, B1, C1.

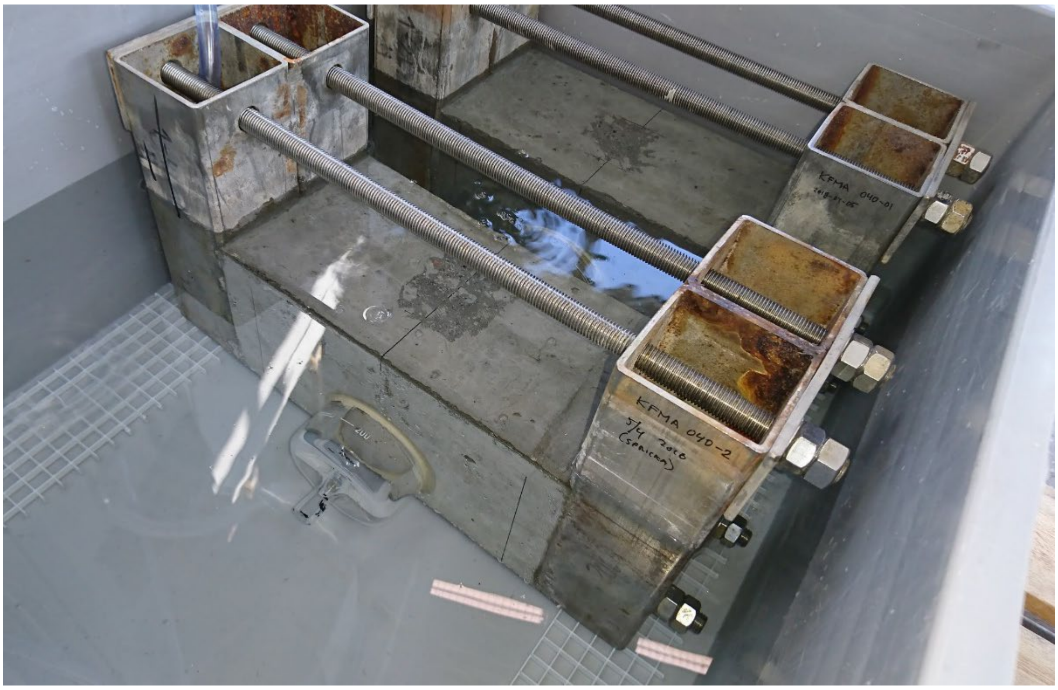

Figure 10. Two cracked beams stored submerged in (de-ionized) water in a large polymer container.

The other beam of each pair was submerged in water (wet exposure) for 7 days and then stored at 20 °C and approximately 60% RH for 7 days (dry exposure), exposure climate 2. These beams were labelled with a capital letter + 2, e.g. A2, B2, C2. This wet/dry exposure was repeated during one year.

After one year, a second permeability test was performed on each cracked beam.

4 Results and discussion

The duration of the permeability test was noted before and after the exposure. All duration times of the permeability tests are presented in the appendix. As each crack is unique it is not possible to evaluate self-healing just by comparing the duration of the permeability test before and after exposure. Therefore, 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 and t_b are equal to the duration of the permeability test after (*a*) and before (*b*) the exposure respectively. This ratio could then be used to quantify the self-healing ratio. If this ratio is a negative value it means that the permeability test duration was shorter after the exposure climate than before i.e. the water flowed through the crack more easily. This indicated that self-healing of the crack had not occurred. It is possible that the dry surface of the concrete initially absorbed some water during the first permeability test. However, this effect was considered to be minor.

A positive ratio on the other hand meant that the duration of the permeability test was longer after the exposure climate compared to prior to the exposure. This indicated that self-healing had occurred. The results of the permeability tests are shown in bar plots Figure 11 through Figure 14. Blue bars represent exposure climate 1 (continuously wet for one year) and red bars represent exposure climate 2 (7 days wet and 7 days dry, cycled for one year).

4.1 Commercially available cements

In Figure 11, the results from the evaluation of the permeability test of the three commercially available cements are shown.

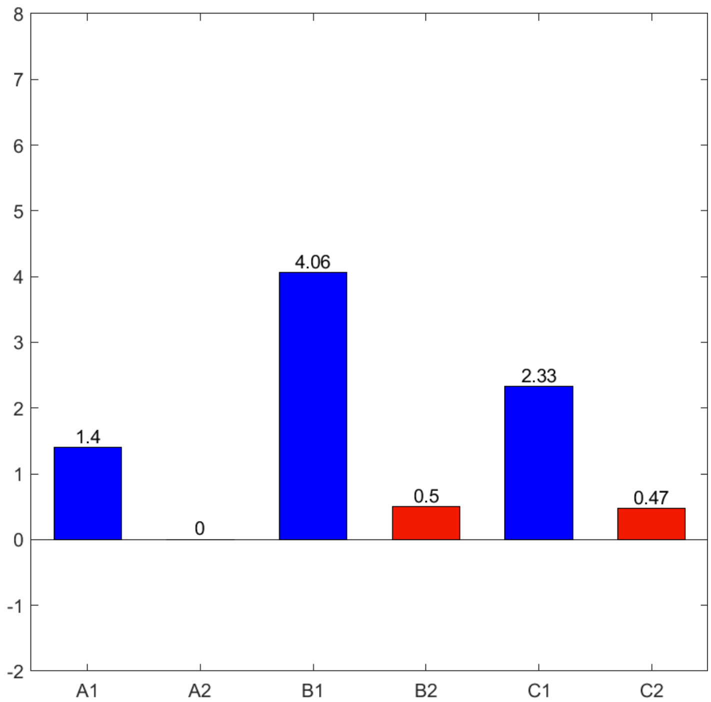

*Figure 11. R_{sh}, achieved in the two exposure conditions by using three different commercial cement types, "Anläggning Classic", **A**, "Bascement", **B**, and "Anläggning FA", **C**.*

The R_{sh} is clearly positive showing that the permeability test duration is longer for concrete mixture A, B and C after being subjected to exposure climate 1. This may be interpreted as an indication of self-healing. This increase in permeability test duration is not equally clear regarding exposure climate 2, thereby indicating a lower self-healing potential. There is a clear difference between the two exposure climates regardless of the three different commercial cements. Binder B and C both contain FA and they both showed a small increase in self-healing ratio in climate 2, whereas binder A with no FA showed no increase at all.

4.2 Influence of binder content

The results of three different concrete mixtures with different binder content but equal w/b, are presented in Figure 12.

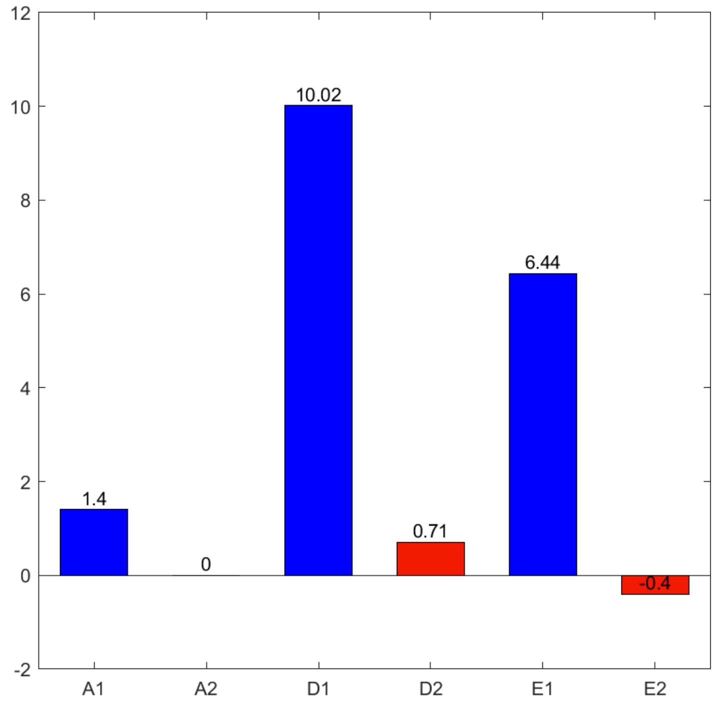

*Figure 12. R_{sh}, achieved in the two exposure conditions by using the same binder "Anläggning Classic", but three different binder contents, 430 kg/m^3, **A**, 350 kg/m^3, **D**, and 550 kg/m^3, **E**, with w/b 0.4.*

There is a clear increase of the permeability test duration, $R_{sh}>0$, in all the concrete mixtures shown in Figure 12, in exposure climate 1. There is no clear correlation between the binder content and the R_{sh} value 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. Exposure climate 2 does not seem to facilitate self-healing and there is no clear correlation between the binder content and the R_{sh}. There is even a negative impact on the R_{sh} when the binder content is 550 kg/m^3.

4.3 Influence of w/b ratio

In Figure 13, the R_{sh} of three different w/b ratios, 0.35, 0.4 and 0.45, with "Anläggning Classic" subjected to the two exposure climates are shown, note the scale of the y-axis.

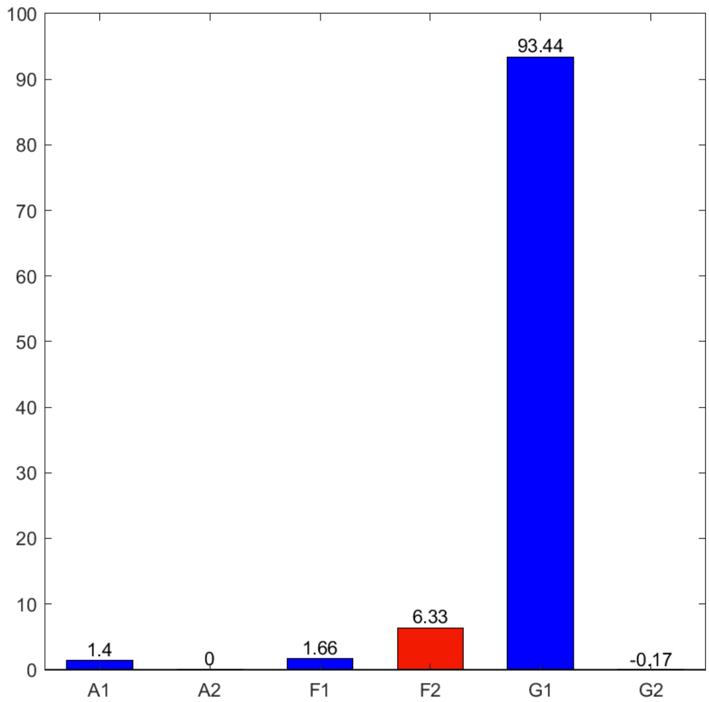

*Figure 13. R_{sh}, achieved in the two exposure conditions by using "Anläggning Classic" as a binder and three different w/b, w/b=0.4, **A**, w/b=0.35, **F**, and w/b 0.45, **G**.*

The R_{sh} in the three different concrete mixtures when subjected to exposure climate 1 are all >0, which could be an indication of self-healing. The R_{sh} for w/b 0.45 seems to be too high compared with the R_{sh} for all other concrete mixtures and it is by far the highest achieved result regarding exposure climate 1. The concrete with w/b 0.35, F, shows a rather high R_{sh} when subjected to climate exposure 2, which is the highest result achieved in this study. This fact does not seem to agree with the rest of the results. If these results are accurate and if the R_{sh} is indeed a suitable indicator for self-healing it shows that self-healing is better in wet/dry conditions compared with wet conditions regarding w/b 0.35. There is no clear correlation between w/b and magnitude of R_{sh}. Also in this context, other factors seem to be more decisive for the self-healing ratio.

The results in this study show that self-healing was correlated to the water/binder ratio. The largest indication of self-healing was shown by concrete G with w/b 0.45 and there was a minor increase of self-healing when the w/b was 0.35. However, a study performed by Reinhardt et al. [6] showed that w/b had an insignificant effect on self-healing. The conclusion that w/b is not correlated to self-healing is supported by another study performed by Gagné and Argouges [7], see quote below.

> *"For a given category of initial crack opening, the evolution of W_{ef} with time is approximately the same for all the W/C considered. Overall, these results suggest that the W/C ratio (0.35–0.60) is not a key factor controlling the kinetics and self-healing of mortars stored in a humid environment (100 % R.H.)."*

However, this source was cited by Rajczakowska in [8] where the author states that a lower water to binder ration leads to a higher self-healing efficiency, see quote below.

> *"A lower water-to-binder ratio and the presence of higher amounts of unhydrated cement particles lead to a higher self-healing efficiency (Gagné & Argouges, 2012)."*

It seems as if Rajczakowska have misunderstood the results in the paper by Gagné and Argouges.

4.4 Influence of fly ash content

Figure 14 shows the R_{sh} of all beams containing fly ash either added by the cement producer, "Bascement", C, or added to the Portland cement at the laboratory "Anläggning Classic", H and I.

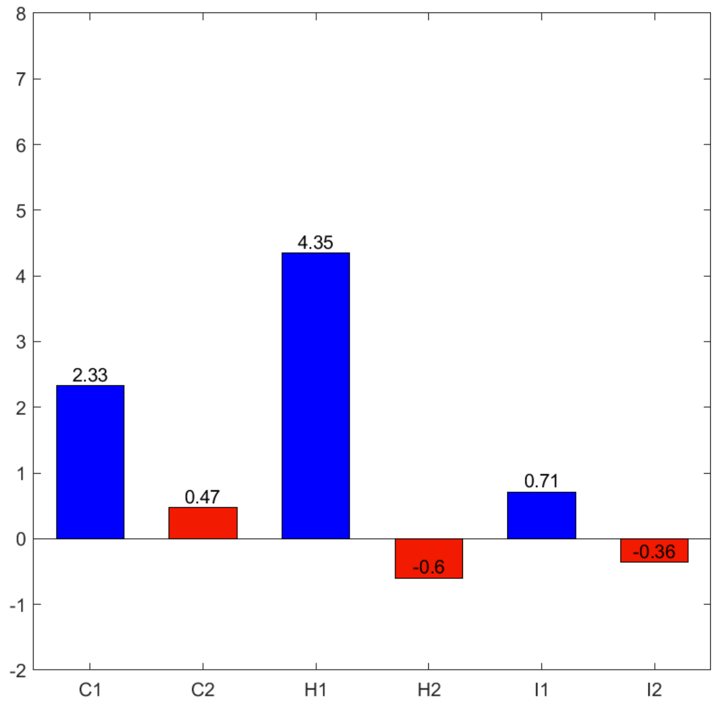

Figure 14. R_{sh}, achieved in the two exposure conditions by using three different binders, "Anläggning FA", ***C****, "Anläggning Classic" 20 weight-% binder replacement with FA,* ***H****, "Anläggning Classic" 40 weight-% binder replacement with FA,* ***I****.*

The results show that all these concrete mixtures had an $R_{sh}>0$ and the largest R_{sh} is shown by "Anläggning Classic" with 20 weight-% FA replacement when subjected to exposure climate 1. This is an indication that self-healing may be improved if a part of a Portland cement binder is replaced with fly ash when exposed to submerged conditions. When exposed to climate 2, the R_{sh} is either slightly positive or negative. This indicates that there is no significant self-healing when exposed to 7 days wet/7 days dry conditions. There are differences in the cement Blaine fineness as fineness of "Anläggning FA" is about 370 m^2/kg and that of "Anläggning Classic" is about 310 m^2/kg. The overall Blaine fineness of the laboratory mixed binder was not determined. But there is no clear correlation to the level of R_{sh} that could be attributed to the Blaine fineness.

Concrete with cement and fly ash as a binder has been found to improve the self-healing of cracks in earlier research. This was shown by Şahmaran et al. [9].

The potential to self-heal is dependent on the amount of unhydrated binder grains at the cracked surface. About 7 days after casting there should be plenty of non-reacted binder components on the cracked surface able to react in presence of moisture. The permeability test should therefore not be executed too long after casting in order to ensure that there are binder constituents that are still unhydrated. This is especially vital when pure Portland cement is used as a binder. When there are other constituents in the binder like fly or slag, the first permeability test may be conducted at a somewhat longer time after casting, since these additives react slower compared with ordinary Portland cement.

4.5 Influence of slag content

Figure 15 shows the results from the permeability test performed on the binders "Anläggning Classic", A, 80 weight-% "Anläggning Classic" and 20 weight-% slag, J, and 60 weight-% "Anläggning Classic" and 40 weight-% slag, K.

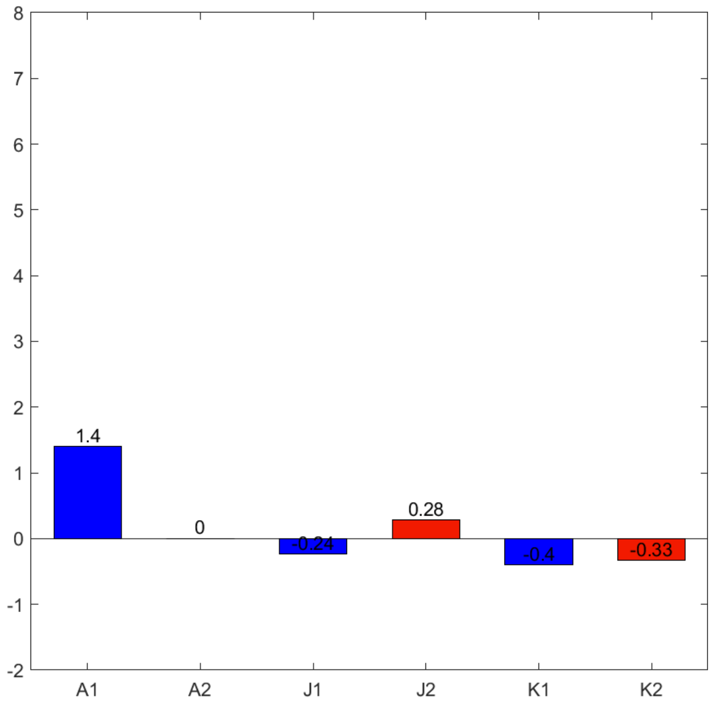

*Figure 15. R_{sh}, achieved in the two exposure conditions by using three different binders, "Anläggning Classic", **A**, "Anläggning Classic" 20 weigth-% binder replacement with slag, **J**, "Anläggning Classic" 40 weigth-% binder replacement with slag, **K**.*

The results shown in Figure 15, indicate that slag had a low effect on the R_{sh} value, therefore the evidence of self-healing was not significant. R_{sh} values were both negative and positive which would imply that water flow through the crack after the climate exposure was more or less equal to the flow prior to the exposure. It therefore indicated a low self-healing ability of cements with slag additives.

The self-healing of concrete with slag, GGBFS, has been studied by Park and Cheol Choi[10]. This study found a potential improvement of self-healing by using GGBFS that is able to supply Al ions. However, the amount of GGBFS in the binder was 60 weight-% with an addition of 5 weight-% of either $CaSO_4$ or Na_2SO_4. This means that the binder composition in the current study was different from the binder composition used by Park and Cheol Choi [10] and it is not possible to make a direct comparison between the results.

4.6 Influence of PVA-fibre content

Figure 16 shows the results from concrete mixtures with "Anläggning Classic", A, and two mixtures containing 0.75 weight-%, L, and 1.5 weight-%, M, of PVA fibres.

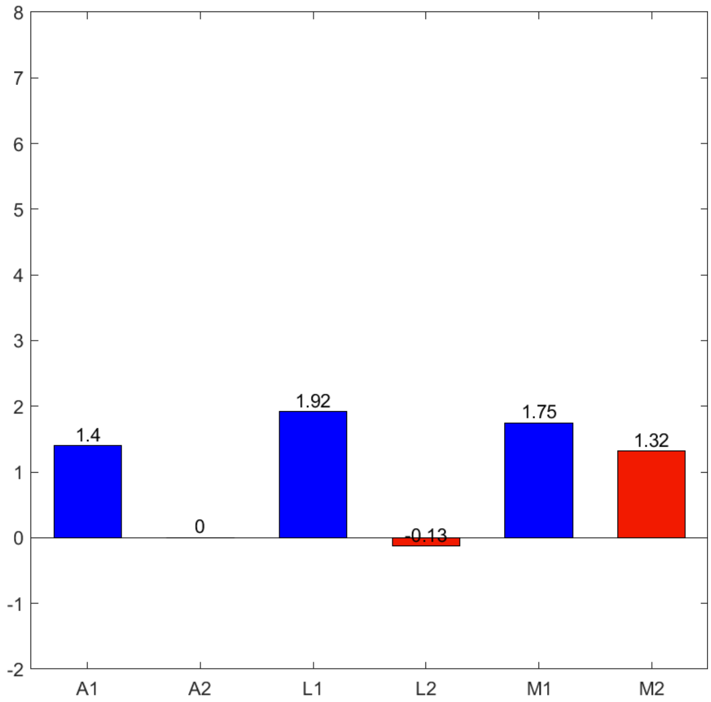

*Figure 16. R_{sh}, achieved in the two exposure conditions by using binder, "Anläggning Classic", **A**, "Anläggning Classic" with added PVA fibres (0.75 weight-% of binder), **L**, "Anläggning Classic" with added PVA fibres (1.5 weight-% of binder), **M**.*

Both concrete mixtures containing PVA fibres showed a significant increase in R_{sh} after being subjected to exposure climate 1. The difference between the mixtures with and without PVA fibres was about 0.5 which was not considered significant for exposure climate 1. The R_{sh} values when subjecting the different concrete beams to exposure climate 2 were not significant in the case of the lower level of added PVA fibres but this difference was significant in the case of the higher level of added PVA fibres.

Other researchers studying self-healing potential with the addition of fibres have shown that fibres may promote self-healing, both by reducing the actual crack width and by serving as a precipitation site for the crystalline products [11, 12].

5 Conclusion

Based on the results in this study self-healing was indicated in exposure climate 1 in which the concrete beams were submerged in de-ionized water during one year. Replacing Portland cement with moderate amounts of fly ash seems to promote self-healing. The only binder that did not show any self-healing in exposure climate 1 was the binder composition/mix with “Anläggning Classic”, both with 20 and 40 weight-% slag.

Exposure climate 1 had a greater impact on the permeability test compared with exposure climate 2 in which the concrete beams were exposed to 7 days wet/7 days dry conditions during one year. Self-healing in the cracks was low or even insignificant when subjecting the beams to exposure climate 2 in/for almost all concrete mixtures. The only exception was the beam with w/b 0.35 and Anläggning Classic as a binder where exposure to climate 2 resulted in more self-healing than when exposed to climate 1.

The permeability method used in this study needs verification by using other methods in parallel to determine self-healing. The conclusions are based on results achieved with a limited number of specimens. Given a larger number of specimens for each binder would increase the possibility to validate the permeability test and even perform a statistical evaluation.

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Appendix

The duration time of both permeability tests and evaluated R_{sh} for each beam are shown in Appendix table 1.

Appendix table 1. Duration time, t_b and t_a, for permeability test before the exposure, PTb, and permeability test after the exposure, PTa, respectively and the evaluated self-healing ratio, R_{sh}.

	PTb	PTa	
	t_b [s]	t_a [s]	R_{sh}
A1	40	96	1,40
A2	32	32	0,00
B1	32	162	4,06
B2	24	36	0,50
C1	30	100	2,33
C2	38	56	0,47
D1	46	507	10,02
D2	56	96	0,71
E1	18	134	6,44
E2	42	25	-0,40
F1	32	85	1,66
F2	33	242	6,33
G1	27	2550	93,44
G2	18	15	-0,17
H1	46	246	4,35
H2	47	19	-0,60
I1	42	72	0,71
I2	33	21	-0,36
J1	88	67	-0,24
J2	29	37	0,28
K1	50	30	-0,40
K2	127	85	-0,33
L1	26	76	1,92
L2	38	33	-0,13
M1	40	110	1,75
M2	41	95	1,32

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