Controlling ASR in concrete by surface treatment - Field performance investigation

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Abstract

Several concrete structures in Denmark have been built with potentially ASR-reactive aggregates. Most of these concrete structures have been constructed in the 60's and 70's and includes more than 600 large concrete bridges. Unfortunately, during the last 10 to 20 years an increasing number of these concrete structures have become severely deteriorated due to alkali-silica reaction (ASR). Since it can be extremely expensive to replace these concrete structures, it is desirable to develop and implement better economic methods to prolong the service life of these concrete structures. Surface treatment of concrete samples in the laboratory shows promising results by controlling the moisture content. The surface treatment can delay or even prevent the ASR from developing. In this study, it is investigated whether silane-based surface treatment can reduce the relative humidity inside the concrete. Eight concrete cubes (0.3×0.3×0.3m^3) with water/cement-ratios of 0.45 and 0.55 have been casted and exposed to outdoor climate conditions over a period of nearly three years. Half of the concrete cubes contain ASR-reactive aggregates (porous opaline flint) and half of the concrete cubes have been impregnated with a silane-based surface treatment. Moisture and temperature sensors (HumiGuard) measure the relative humidity and the temperature inside the concrete cubes during outdoor exposure (field exposure). The results of this study show that the surface treatment can significantly reduce the relative humidity inside the concrete. Furthermore, it is shown that the ASR expansion was delayed or even prevented by avoiding external moisture contribution to the ASR development. The w/c-ratio has a significant influence on the initiation of cracking in the concrete cubes.

Keywords: *alkali-silica reaction; expansion; field exposure; moisture sensor; silane-based surface treatment*

1. INTRODUCTION

Service-life extension of concrete structures with potential to develop deleterious alkali-silica reaction (ASR) is a major interest for public building owners around the world. A possible extension of service-life results in significant economic savings for the society, due to reduced costs for repair works or avoiding replacement of the structure. In Denmark, the Danish Road Directorate estimated in 2008 that at least 600 larger road concrete bridges have the potential to develop ASR [1]. The 600 concrete bridges do not include municipal bridges, railway bridges or other types of construction elements, such as walls, road barriers and others. Potential means that the bridges are constructed with a critical amount of porous opaline or calcareous opaline, which is known to be very fast reactive aggregate resulting in significant cracks in the structures under the right circumstances. In Denmark, five concrete bridge structures have been demolished due to ASR [2]. Moreover, thousand meters of cantilever beams from several structures have been replaced due to the formation of severe ASR cracks. The estimated cost for replacement of ASR deteriorated edge beam is 1,500 Euros per meter [3].

Therefore, there is a great potential for the Danish Road Directorate and other building owners to implement preventive methods to reduce future economic costs for repairs and replacements of these potential ASR structures. In this context the Technical University of Denmark took the initiative to initiate a project to investigate the durability of field exposed concrete with and without surface treatment in relation to ASR. The purpose of the project is to obtain experimental test results of field exposed ASR-reactive concrete and a greater understanding of the effect of surface treatment on possible prevention of deleterious ASR. The perspective is to apply these results and techniques from the extensive in-situ monitoring program in actual structures. Silane products have become the most important and widely used product for impregnation [4]. Some studies have confirmed that impregnation has a significant influence on reducing the ASR in concrete [5].

The investigation of ASR in concrete in Denmark started in the 1950's [6] and [7]. There were comprehensive research results on ASR in 1961 [8] but no official regulation until 1987 to secure non-reactive aggregates to be used in concrete. The Danish Code of practice was published in 1987 to prevent deleterious ASR [9]. The code provided the acceptance criteria of the potentially ASR-reactive aggregates for the expected environmental exposure of the structure. The lack of regulation meant that many concrete structures were built with a critical amount of reactive aggregates in the 60's and 70's, as a consequence of the fast development of the Danish road infrastructures. The aggregates used to construct these concrete structures were taken from local Danish quarries, where primarily the sand fraction can contain a critical amount of potential ASR particles. Porous opaline flint and porous calcareous flint are the main reactive fine aggregate types in Denmark [8] and both types are characterized as fast reactive [10]. The cement types in Denmark have typically a low or moderate alkali content below 0.6 % and the total alkali content in the concrete is typically below 3 kg/m^3 which also includes external supply of alkalies e.g. deicing salts [9] and [10]. The pessimum behavoir of the reaction of porous opaline flint and porous calcareous flint has been shown in many tests [11]. The pessimum behavior illustrates the importance of the ratio between the alkali content and the amount reactive silica. The maximum expansion occurs when there is a certain amount of alkali present for all reactive material to react. However, if there is less or more reactive material for the same amount of alkalis the expansion will be smaller.

Three criteria must be fulfilled for developing ASR - reactive aggregates, high pH and moisture. Considering moisture, deleterious ASR typically develop in concrete when the relative humidity (RH) is above 80-85 %. Below 80 % RH the ASR-induced expansion is significantly reduced or suppressed [12]. The present investigation utilizes the knowledge about the influence of the moisture to reduce or even prevent ASR.

This paper presents an in-situ investigation on controlling ASR in concrete by surface treatment. Eight concrete cubes with two different w/c-ratios have been casted where some concretes contain ASR-reactive aggregates and cement with high alkali content, and some have been impregnated. The cubes with non-reactive materials represents the control samples. The RH and expansion results have been obtained with HumiGuard sensors and a DEMEC gauge, respectively, during nearly two years of investigation.

2. MATERIALS AND METHODS

2.1 Mix design

Table 2.1 summarizes the concrete mixes and the classification of the cubes. In the spring 2018, eight concrete cubes (0.3 x 0.3 x 0.3 m^3) were casted from four concrete mixes. Half of the concrete mixes has a w/c-ratio of 0.45 and the other half has a w/c-ratio of 0.55.

Two cement types are, a Danish CEM I Portland cement with an equivalent alkali content of 0.6 % and a Swedish CEM I Portland cement with an equivalent alkali content of 1.0 %. Consequently, the total alkali content on half of the mixes is calculated to 5.0 kg pr. m^3 of concrete and on the other half calculated to 2.7 kg pr. m^3 of concrete.

A non-reactive coarse aggregate is used in all mixes, and a Danish reactive fine aggregate, Hastrup sand, is used on half of the concrete mixes, see Table 2.1. Control mixes consist of non-reactive coarse aggregate and non-reactive fine aggregate, Great Belt sand.

2.2 Preparation of concrete surface and surface treatment

After the cubes were cast, they were sealed in plastic foil for one day. Afterwards, the plastic foil was removed, and the cubes were prepared for the surface treatment by degreasing all surfaces. An alkaline cleaning product was used to degrease the concrete surfaces. After cleaning, the concrete cubes were thoroughly washed with water and ventilated for two days. The concrete cubes were impregnated 9 days after casting. A silane-based surface treatment product, SILRES BS Creme C, was applied to one of the two concrete cubes made from the actual concrete mix. The silane-based product was applied in amount of 300 g/m^2 with brushes in even layers. All the surfaces were impregnated except for the bottom of the concrete which was impregnated the day after. After application, the concrete cubes were stored in a basement until they were moved to the field exposure area at the Technical University of Denmark, see Figure 2.1. To avoid the cubes absorbing water from the soil, each concrete cube rests on a membrane and on four cobble stones. Measurements have been conducted outside the exposure area for approximately two years.

The surface treatment is designed to penetrate deeply into the concrete to afford optimum protection against ingress of water. The silane-based product contains alkoxysilane, siloxane, water, and minor parts of chlormethylisothiazolinon and methylisothiazolinone (3:1). The product penetrates the concrete within 30 minutes to several hours depending on the porosity of the concrete. When silanes penetrate the concrete, they will react with the cementitious material at the sides of the pores forming a hydrophobic “layer” in the pores. Hydrophobic treatments change the surface tension of concrete to keep water and aggressive water-soluble salts out.

Table 2.1: Materials and mix designs

Block [300mm × 300mm × 300mm]	Mix 1	Mix 2	Mix 3	Mix 4
Date of casting	05-03-2018	12-03-2018	19-03-2018	09-04-2018
w/c ratio	0.45	0.45	0.55	0.55
Cement type	CEMI - High alkali Portland cement	CEMI - Low alkali Portland cement	CEMI - High alkali Portland cement	CEMI - Low alkali Portland cement
Cement [kg/m^3]	500	500	500	500
Total Na_2O [kg/m^3] content of concrete	5	2.7	5	2.7
Fine aggregate type	Potential reactive sand	Potential non-reactive sand	Potential reactive sand	Potential non-reactive sand
Fine aggregates [kg/m^3]	620.2	634.2	577.2	581.9
Coarse aggregates 1 (Rønne Granite 4-8 mm) [kg/m^3]	326.8	327.8	299.8	300.8
Coarse aggregates 2 (Rønne Granite 11-16 mm) [kg/m^3]	632.0	633.9	579.8	581.6
Water [kg/m^3]	225.0	225.0	275.0	275.0
Air content [%]	1.5	1.5	1.5	1.5

Figure 2.1: Exposure area

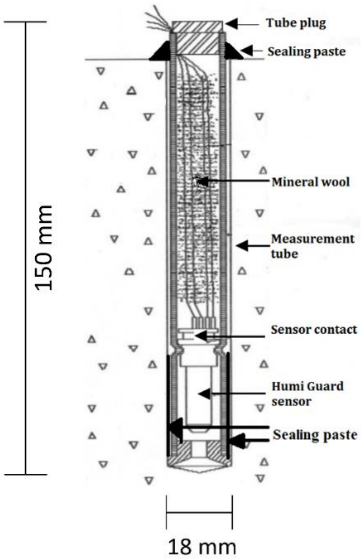

Figure 2.2: Implementation of the HumiGuard sensors – edited image from http://www.rbk.nu/.

2.3 Installation of measurement studs

For monitoring the surface expansion of the concrete cubes, measurement studs were installed into the surface of the concrete cubes. The location of the measurement studs on the cube surfaces are shown in Figure 2.3 and 2.4.

The holes for the measurement studs were drilled, and the concrete dust was removed with compressed air. The holes were filled with X60 glue [13], and the measurement studs were placed immediately into the holes. A reference bar was placed on the top of the two measurement studs in order to keep them at a fixed length until the glue had hardened. This length was used as reference length for the expansion measurements. The measurement studs were implemented at room temperature at approximately 20°C before moving the concrete cubes outside to the exposure area. A Demec gauge was used to measure the length between the measurement studs for expansion calculations.

Four cubes (mix 1 and mix 2) have four measurements studs placed on the top side, on the south-west side, on the north-west side, and on the north-east side. This gives eight surface expansion measurement results on each cube. The four other cubes (mix 3 and mix 4) have four measurement studs placed on the top side, on the south-west side, and on the north-west side. This gives six expansion measurement results on each cube. For more information see Figure 2.3 and 2.4.

2.4 HumiGuard sensors - Relative humidity and temperature sensors

As a part of the casting process, three sensors (product name Hygro-I, capacitive sensor), which measured the RH and the temperature, were installed into the concrete. The results from these sensors were unreliable and not used. In October 2018 new RH-sensors (product name HumiGuard, electrical conductance in a hygroscopic electrolyte) were installed in the concrete cubes.

HumiGuard sensors are used to measure the RH and the temperature inside the concrete cubes. Two sensors in each cube were installed as illustrated in Figure 2.3 and 2.4. The principle of the sensor installation can be seen in Figure 2.2. The distance from the sensors to the concrete surface can be seen in Figure 2.3. First, the hole for the sensor was drilled, then the concrete dust was removed with compressed air and a plastic tube was inserted into the hole.

Sealing paste was placed at the bottom and at the top of the tube in order to make it airtight due to the manual implementation of HumiGuard sensors [14]. The airtightness was tested by use of a rubber ball. The sensors were implemented into the tube and the tube was filled with mineral wool. Then the tube was closed off with a tube plug.

Each HumiGuard sensor has a sensor contact with four wires. Two of them are used to measure the RH and the two others are used for measuring the temperature. The RH and temperature measurements were obtained by measuring the conductivity between the two wires with a conductance meter where the units were in micro Siemens [µS].

Alongside with the measurements inside the concrete cubes, two HumiGuard reference sensors were continuously used to account for the possible deviation over time. They were sealed inside a reference aluminium block and placed over a certified salt solution at 85 % RH in a metal block stabilizing the temperature [14]. The measurement results from the sensors inside the concrete cubes and inside the reference aluminium block were registered into the program for the HumiGuard system [14], and the correct value for the RH and temperature inside the concrete were calculated.

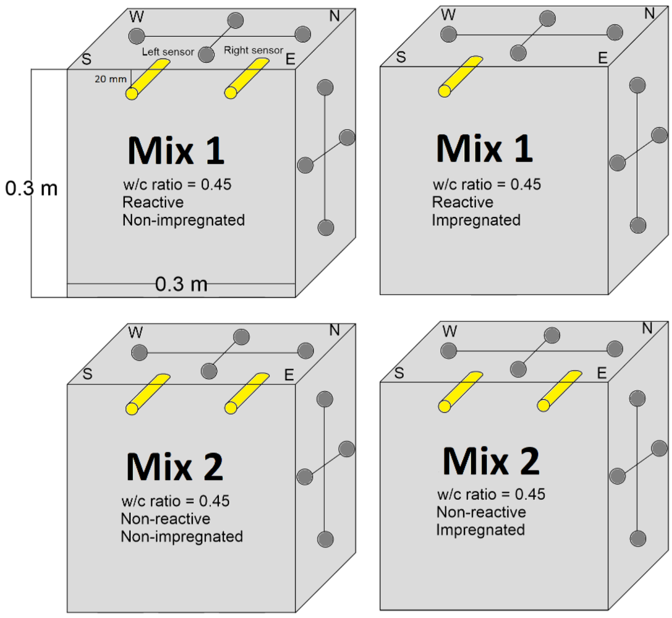

Figure 2.3: The concrete cubes for mix 1 and 2 with a w/c-ratio at 0.45 equipped with measurement studs (the grey dots) at all sides of the cubes except of the south/east side and the bottom, where southwest side and northwest side are not shown.

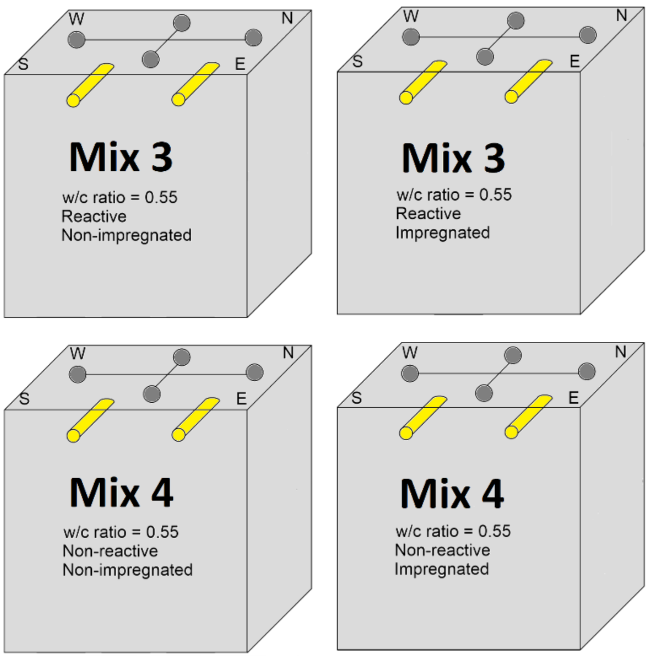

Figure 2.4: The concrete cubes for mix 3 and 4 with a w/c-ratio at 0.55 equipped with measurement studs (the grey dots) at the top, the south/west side and west/north side of the cubes, where southwest side and northwest side are not shown.

2.6 Measurements of the relative humidity in concrete with HumiGuard

The website (www.industrifysik.se) of the manufacturer of the RH-sensor HumiGuard states in summary: "The HumiGuard measurement system is intended for measurement at a certain depth in a concrete or floor screed slab. Sensors are installed in a drillhole inside a measurement tube. The RH-sensor contains a hygroscopic electrolyte in a non-hygroscopic fibrous body with imbedded pins. The electrolyte will be in humidity balance with material at the tube bottom and this happens with exchange of an extremely small amount of water vapor. Electrical conductance, unit μS, of the RH-sensor varies strongly with ambient air for RH within the measurement range. Two RH sensors per sensor lot, factory selected in order to represent the lot sensors well, are called reference sensors. They are installed and stay in a reference block together with reference cells (humidity standards), which are calibrated by a recognized laboratory. As the sensors in the drill holes are read, so are the reference sensors of the lot. Readings from the reference sensors enable measurement with the drill hole sensors, because all sensors of a lot are equivalent to each other in every respect (with a statistical deviation from exact equivalence). Temperature is measured with a sensor in the RH-sensor contact. The website calculates concrete RH and temperature, and also RH measurement uncertainty. Measurement ranges are 75 - 95 (98) % RH and 0 - 40 °C". The HumiGuard system is approved as one of three system by The Advisory Council for Building Competence, RBK, Sweden.

3. RESULTS

In this paragraph the relative humidity and expansion results are presented.

3.1 Relative humidity results

As part of the investigation, the RH inside the concrete cubes has been measured. The average RH results are shown in Figure 3.1. The dotted lines illustrate the results from the impregnated cubes, and the straight lines illustrate the results from the non-impregnated cubes. The non-impregnated cubes are control samples. In Figure 3.1 it has been observed that the non-impregnated cubes have a higher RH than the impregnated ones. Furthermore, the reactive material cubes have a higher RH than the non-reactive material cubes. The concrete with higher w/c-ratio has a higher RH compared with the concrete with lower w/c-ratio.

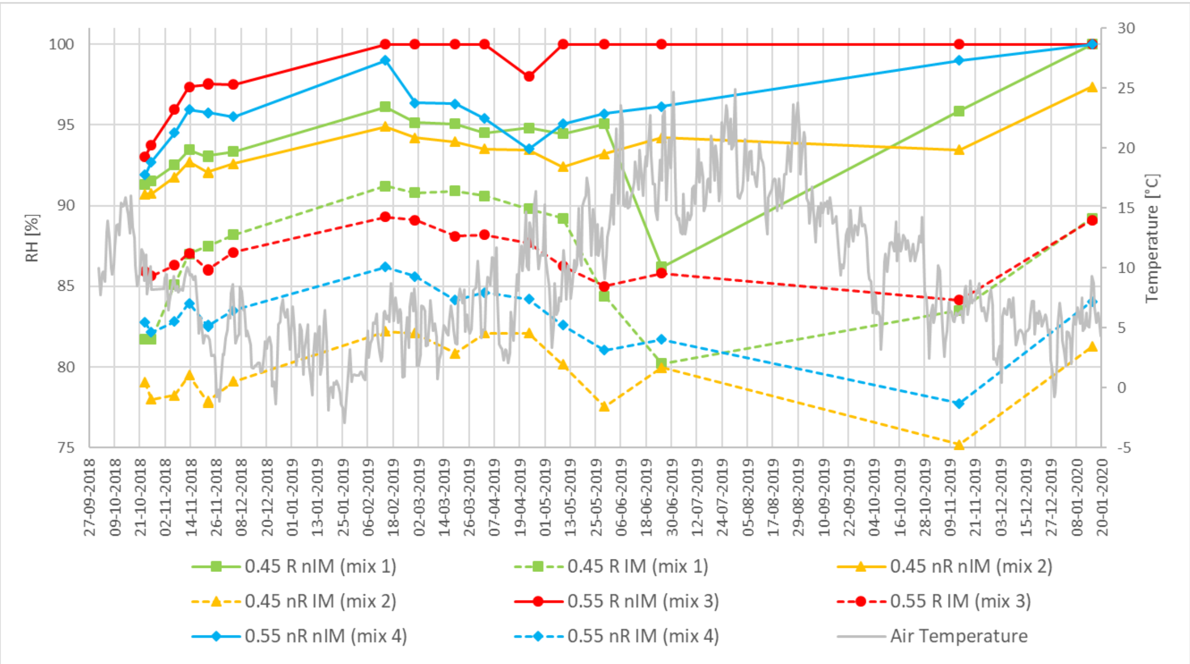

Figure 3.1: The average relative humidity results for the 8 cubes (R = reactive, nR = non-reactive, IM = impregnated and nIM = non-impregnated) and the outdoor air temperature.

3.2 Expansion results

The expansion results have been collected from multiple surfaces of the concrete cubes. The specific location of the measurement studs has been clarified in section 2.3. The average expansion results for all surfaces for each cube can be seen in Figure 3.2. The dotted lines illustrate the expansion/shrinkage measurement results from the impregnated cubes, and the straight lines illustrate the expansion/shrinkage measurement results from the non-impregnated cubes. The expansion results for each surface for the non-impregnated material cube (mix 3) are shown in Figure 3.3. The expansion results for each surface for the impregnated material cube (mix 3) are shown in Figure 3.4.

Considering Figure 3.2, two non-impregnated reactive material cubes (mix 1 and mix 3) with a w/c-ratio at 0.45 and 0.55, respectively has expanded. This corresponds with the crack pattern for the cubes seen in the Figures 4.1 and 4.3. The non-impregnated reactive material cube (mix 1) with a w/c-ratio at 0.45 has started to expand much later than the non-impregnated reactive material cube (mix 3). The impregnated reactive material cubes (mix 1 and mix 3) with a w/c-ratio at 0.45 and 0.55, respectively has not expanded. The Figures 4.2 and 4.4 illustrates the appearance of this cubes since there are almost no cracks.

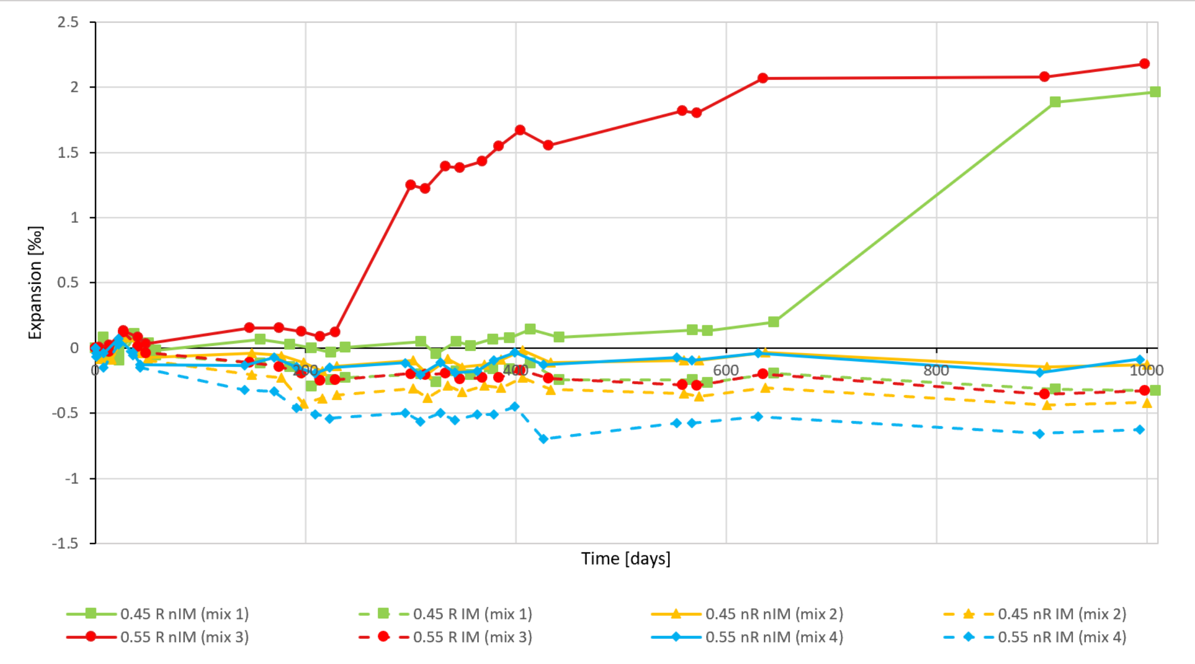

Figure 3.2: The average expansion results for the 8 cubes (R = reactive, nR = non-reactive, IM = impregnated and nIM = non-impregnated).

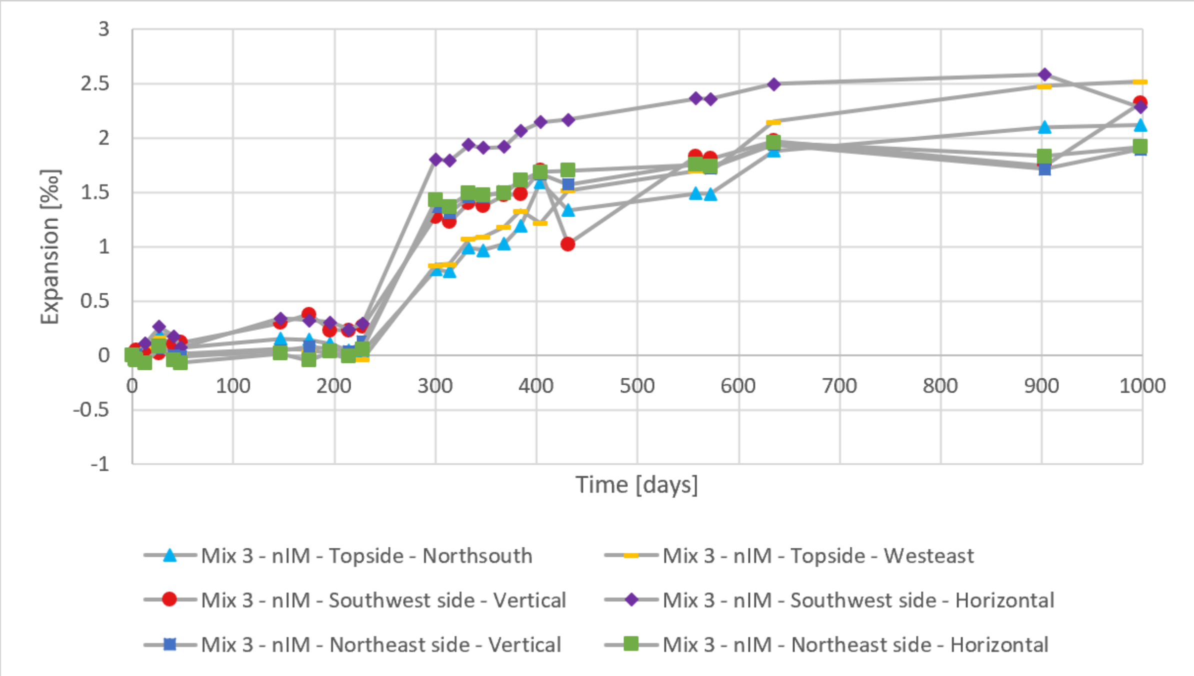

Figure 3.3: The expansion measurements for non-impregnated cube with mix 3 (nIM = non-impregnated).

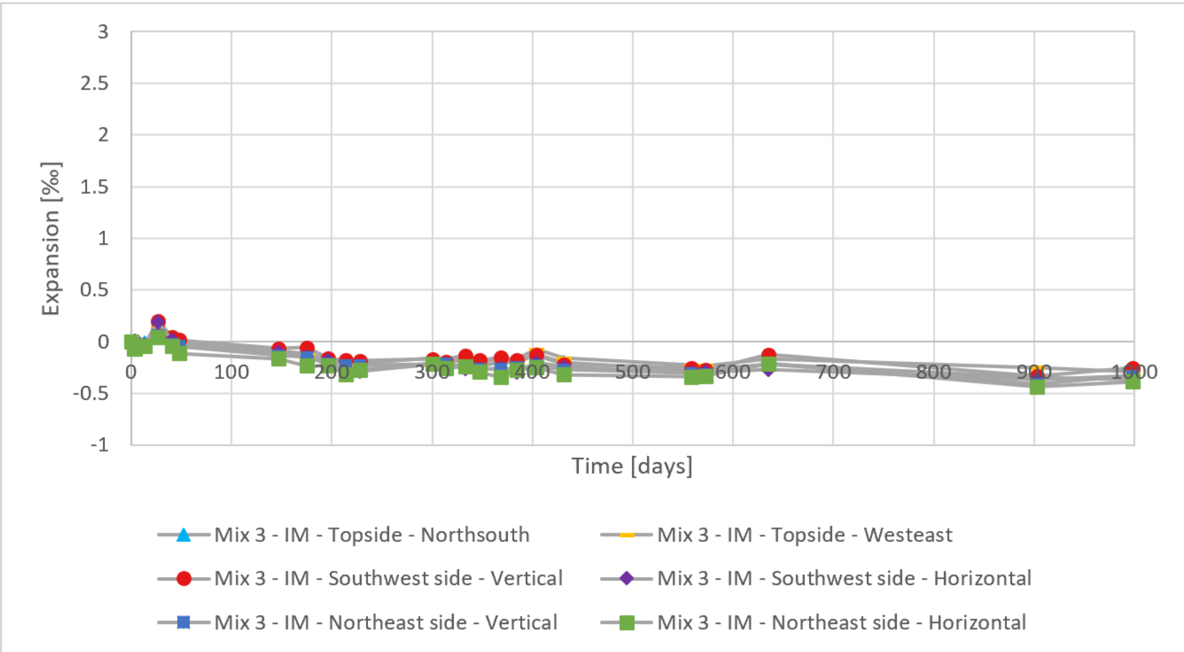

Figure 3.4: The expansion measurements for impregnated cube with mix 3 (IM = impregnated).

4. DISCUSSION

In this paragraph the relative humidity and expansion results will be discussed.

4.1 Relative humidity in ASR-reactive concrete with impregnation

The non-impregnated concrete cubes have approximately 10 % higher RH than the impregnated concrete cubes as shown in Figure 3.1. These results demonstrate that impregnation can reduce the moisture ingress and hereby reduce the RH inside the cubes. It also indicates that the impregnation can reduce the development of potential ASR, since the development of ASR is dependent on a certain high level of RH inside the concrete. A net evaporation is present in the impregnated concrete, since the RH is lowered, and the cube has been exposed to shrinkage.

It is shown in the literature that the ASR development is reduced when the RH is reduced and that it is stopped at around 80 % RH [12]. The ASR gel expands when it absorbs water, which can cause the concrete to crack. In Figure 3.1 it is seen that the reactive impregnated cubes have a RH around 89% in January 2020, whereas the reactive non-impregnated cubes have a RH around 100%. Thus, it is possible to delay the development of ASR even though the RH for the impregnated cube exceeds the limit at 80 % RH. Throughout the year, the RH will naturally oscillate inside the concrete. In the winter season, the RH increases compared to the summertime where more water evaporates from the surface of the concrete.

The results in Figure 3.1 demonstrates that the RH increases with the w/c ratio. The reactive concrete has a high RH compared to the non-reactive concrete. It is known that ASR produces a gel which binds water resulting an increase in the RH. The results in Figure 3.1 indicates that the concrete with reactive aggregates has absorbed more water than the non-reactive concrete which implies the potential development of ASR.

4.2 Expansion of ASR-reactive concrete with impregnation

For the non-impregnated, reactive material cube it is seen that the concrete with the high w/c-ratio at 0.55 has expanded 2.2 ‰ in January 2021 whereas the corresponding concrete with a low w/c-ratio has expanded 2.0 ‰ - later in the process but more explosive. The w/c-ratio affects the rate of the ASR development. The concrete with w/c-ratio at 0.55 expanded after around 250 days, whereas the reactive material cube with a w/c-ratio at 0.45 expanded after around 650 days. The expansion curve has become steeper for the concrete with w/c-ratio at 0.45 than at 0.55 because the tension has developed over a longer period. Since the cube with w/c-ratio at 0.45 has less porous paste and therefore less room for the ASR-gel to develop then higher expansion levels may occur. According to [15] the more porous paste the more room for the ASR-gel in the paste and less expansion will occur. However, the rate of reaction increases because the transportation of ions to the reactive aggregate increases. Additionally, the physical properties and strength will change due to the decrease in porosity which among other is influenced by the w/c-ratio.

Overall, it is seen in Figure 3.2 that the non-impregnated concrete cubes have a higher expansion compared to the impregnated cubes. The increase in expansion of the non-impregnated reactive material cubes (mix 1 and mix 3) continues during the winter season even though it may be expected that the rate of the expansion would be lower. During the winter season in 2019/2020 there has been almost no freezing temperatures which could explain the continuing expansion rate. Among the cubes that have been subjected to shrinkage, it is the impregnated concrete cube (mix 4) with w/c ratio at 0.55 that have the largest shrinkage. This could not be explained. The reactive impregnated concretes (mix 1 and 3) have not expanded which indicates that impregnation has reduced the development of ASR. A study on concrete pavement [16] confirms that silane-based impregnation reduces the development of ASR.

The crack pattern of the concrete surfaces has also been investigated. The crack development on the surface of the concrete cubes shows that the non-impregnated reactive material cube with the highest expansion also has developed cracks whereas the impregnated cubes have no cracks. For expansions at 1 ‰, it is possible to see the cracks with the naked eye. In Figure 4.1 and 4.2 it is the reactive material cubes with w/c-ratio at 0.45 that are shown. The non-impregnated concrete cube has developed significantly visible cracks, see Figure 4.1, whereas the impregnated concrete cube has developed no cracks, see Figure 4.2. In Figure 4.3 and Figure 4.4 it is the reactive material cubes with w/c-ratio at 0.55 that are shown. The non-impregnated concrete cube has developed significantly visible cracks, see Figure 4.3, whereas the impregnated concrete cube has developed no cracks, see Figure 4.4. In general, the crack pattern which can be seen in Figures 4.1 and 4.3 are typical signs of the development of ASR.

Figure 4.1: Crackmapping picture of concrete cube - mix 1 - non-impregnated - 1008 days after casting.

Figure 4.2: Crackmapping picture of concrete cube – mix 1 – impregnated - 1008 days after casting.

Figure 4.3: Crackmapping picture of concrete cube – mix 3 – non-impregnated - 998 days after casting.

Figure 4.4: Crackmapping picture of concrete cube – mix 3 – impregnated - 998 days after casting.

4.3 Perspective

The expansion results as well as the RH results show that the impregnation lowers the water ingress into the concrete which results in a larger net evaporation of water. This study has been investigating concrete with high alkali content, however in Denmark, the alkali content in new concrete structures is relatively low. Even though the internal alkali content is not harmful then the external supply of alkali will affect the concrete. A study concerning impregnation [17], with the same type of impregnation and concrete quality, found that the impregnation can reduce the influence of chloride ingress and external alkalies e.g. deicing salts. Furthermore, many concrete structures from the 60'ies and 70'ies contains high alkali content. Considering the concrete cubes, the surface treatment has been applied before any potential ASR development and before any expansion and development of cracking. The effect of the surface treatment on old age deteriorated concrete has not been investigated in this project but according to another study, silane-based impregnation can slow or stop further expansions of these structures [18]. An elastic surface treatment could be used as well as a layer of impregnation to investigate if the amount of moisture ingress will be reduced and stop further expansion and cracking. Impregnation could be one of the options to prolong the service life of existing concrete structures with potentially ASR. This could reduce the cost of repairing cracked cantilever beams since the beams would not have to be replaced as often.

5. CONCLUSION

The main preliminary conclusions obtained from the studies on the influence of the ASR-reactive concrete with and without surface treatment on the relative humidity and expansion are:

1. The relative humidity is significantly lower in the ASR-reactive concrete with impregnation compared to the ASR-reactive concrete without impregnation.
2. The expansion is significantly smaller in the ASR-reactive concrete with impregnation compared to the ASR-reactive concrete without impregnation.

This study indicates that the surface treatment can lower the relative humidity inside the concrete and reduce the development of ASR for water/cement-ratios at 0.45 and 0.55.

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