Effect of different field exposure conditions and surface treatments on internal relative humidity (RH) and expansion

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Abstract

In 2014, the Norwegian Public Roads Administration initiated a test programme to examine: 1) The effect of surface treatment on the moisture content in outdoor exposed concrete and 2) The relation between moisture content and expansion of ASR-affected concrete. In collaboration with SINTEF, two types of test elements simulating cylindrical bridge columns (ø150 mm x h300 mm and ø400 mm x h800 mm) were produced with alkali reactive concrete. All the cylindrical test elements were pre-exposed under accelerated conditions (~95 % RH and 40°C) for about six months until they reached an expansion of approximately 0.1 %. Subsequently, the cylinders were surface treated (with two hydrophobic impregnations and one coating, respectively) and placed in natural outdoor climate at SINTEF's field exposure site in Trondheim (summer 2015). In addition, parallel untreated reference cylinders were placed in two environments; sheltered and not sheltered for rain. Furthermore, other parallel untreated small cylinders were stored outdoors in containers with 93 % relative humidity (RH). Several parameters including expansion, weight and internal moisture state will be measured over a period of minimum 10 years. This paper describes the initial work including casting, pre-exposure, surface treatment, monitoring and placing at the field exposure site. Results from measurements during the first 4 years of field exposure are also presented.

Keywords: alkali silica reaction (ASR); field exposure; pre-expansion; relative humidity; surface treatment.

1. BACKGROUND

The Norwegian Public Roads Administration (NPRA) develops national guidelines for management of bridges and performs the maintenance of 5,600 bridges, of which a large number are suffering from alkali-silica reaction (ASR). ASR damages were put on the map in Norway in the late 1980's and the main R&D topics since then have been on reaction mechanisms, mapping of occurrence of ASR and classification of reactive rock types by petrography, accelerated aggregate and performance test methods and preventive measures to avoid ASR in new concrete structures. During the last decade, however, increasing effort has been on appraisal, protection and repair of existing structures. For ASR-affected concrete structures exposed in Norwegian outdoor climate, it is not expected that any mitigating measure will totally stop the development of damages. It is, however, assumed that the expansion and degradation may be delayed by reducing water ingress, e.g. by surface treatment. The NPRA has long term experiences with both hydrophobic impregnations and flexible cement-based coatings, mainly applied to reduce chloride ingress into the concrete. Challenges are identified on the following product/substrate properties [1, 2]: 1) Penetration depth of the hydrophobic impregnation – minor penetration depths result in rapid degradation of the impregnation due to UV exposure, 2) Vapour diffusivity of coatings – low diffusivity may cause accumulation of moisture behind the coating with subsequent flaking or frost degradation and 3) Crack-bridging ability of coatings – cracking of coating gives free access of water ingress through cracks, and increased risk of moisture accumulation. For silanes, a deep penetration is aimed. The contact time between silane product and concrete, the degree of water saturation and the porosity of the concrete are earlier reported as the major factors affecting the penetration depths [3].

As part of the NPRA project "Durable structures" (2012-2015), Mannvit performed a literature review on surface treatment of ASR-affected concrete structures. The review report [4] summarizes that hydrophobic impregnations such as silanes may contribute to a reduction in both RH and expansion. The moisture reducing effect is restricted to depths of maximum 100-200 mm from the treated surface and the effect is mostly pronounced for concretes with limited cracking, i.e. in an early phase of degradation. It is reported that the durability of the impregnation is dependent on the penetration depth of the silanes and that the effect of impregnations is reduced if cracking of the concrete continues. Surface treatment by coating is reported to have best effect when applied on slender elements, preferably prior to significant cracking. Coatings may prevent ingress by closing the outer parts of the cracks, but this effect is generally temporarily as continued expansion will cause further cracking. A possible risk when applying coatings is capture of moisture due to reduced vapour permeability through the surface.

Based on the literature review and general experiences, the NPRA initiated a test programme to examine: 1) The effect of surface treatments on the moisture content in outdoor exposed concrete and 2) The relation between moisture content and expansion of ASR-affected concrete.

2.   TEST PROGRAMME

2.1   Introduction

The test programme was initiated in 2014 and is performed in collaboration with SINTEF. Two types of test elements simulating cylindrical bridge columns (ø150 mm x h300 mm and ø400 mm x h800 mm) were produced with alkali reactive concrete. The cylindrical test elements were pre-exposed under accelerated conditions (~95 % RH and 40°C) for about six months until they reached an expansion of approximately 0.1 %. Subsequently, the cylinders were surface treated with three different products, two silanes and one flexible cement-based coating, and placed in natural outdoor climate at SINTEF's field exposure site at Voll in Trondheim. In addition, parallel untreated reference cylinders were placed in two environments; sheltered and not sheltered for rain. Furthermore, other parallel untreated small cylinders were stored outdoors in containers with 93 % relative humidity (RH). Several parameters including expansion, weight, moisture state and internal cracking will be measured over a period of minimum 10 years. The Damage Rating Index analyses are carried out at Laval University in Quebec, Canada.

2.2   Concrete specimens

2.2.1   Concrete mixture

The concrete mixture (Table 2.1) was intended to represent a concrete typically used in Norwegian bridges built in the 1950-1960'ties, i.e. with water/cement (w/c) about 0.50 and no silica fume or fly ash added. It is almost identical with a mixture previously documented in the EU PARTNER project [5], both in accelerated laboratory testing (Norwegian CPT [6] and RILEM AAR-3 and -4 [7]) and in field (Fig. 4 and 10 in [5]). The fine aggregate (Årdal 0/4 mm) is a natural sand mainly consisting of granite/gneiss classified as non-reactive. The coarse aggregate (Ottersbo 4/16 mm) is a highly alkali reactive crushed cataclasite. The concrete mix has an alkali content of 5.6 kg Na_2O_{eq} /m^3. The w/c is 0.48.

Table 2.1: Concrete mixture

Materials	Quantity [kg/m^3]
Norcem Industri, CEM I 42.5R (OPC)	457
Årdal sand 0/4 mm	667
Ottersbo 4/8 mm	172
Ottersbo 8/11 mm	518
Ottersbo 11/16 mm	345
Superplasticizer Sika FB-2	1.4
Water (free)	217

2.2.2 Concrete specimens

Different types of specimens were cast from two concrete batches for testing of different parameters as shown in Table 2.2. The test specimens prepared for long term exposure are intended to represent cylindrical bridge columns.

Table 2.2: Concrete specimens prepared for testing

Type of specimen	No. of specimens	Test method
Small cylinders (ø150 mm x h300 mm)	60	Initial testing (before exposure at site) of internal cracking and penetration depth of silanes
		Long term (yearly) testing of weight, expansion and relative humidity (RH) in field
		Periodically (after 4 and 10 years) laboratory testing of moisture content (DCS/RH), internal cracking and penetration depth of silanes
Large cylinders (ø400 mm x h800 mm)	10	Long term (yearly) testing of expansion and RH in field
Prisms (100 mm x 100 mm x 500 mm)	2	Initial testing of bond strength of coating
Cubes (100 mm x 100 mm x 100 mm)	3	Initial testing of compressive strength
Prisms (100 mm x 100 mm x 450 mm)	3	Accelerated ASR testing - Norwegian CPT [6]
Prisms (70 mm x 70 mm x 280 mm)	6	Accelerated ASR testing - RILEM AAR 4.1 [7] and ASTM C-1293
Cubes (300 mm x 300 mm x 300 mm)	2	Long term field testing of expansion, Trondheim and Lisbon

2.2.3 Curing and installation of measuring studs

The prisms for accelerated ASR testing were cured and treated according to the test methods [6, 7]. The other specimens (except the 100 mm cubes) were de-moulded after 1 week. The specimens were then kept in laboratory environment for three weeks while measuring studs were mounted on 18 of the small cylinders and all the 10 large cylinders. The ø10 mm studs were mounted in drilled holes in the concrete and glued with HBM Scnellklebstoff 1-X60, see Figure 2.1. The placement of the studs is shown in Figure 2.2, resulting in the following possible measurements:

- Small cylinders: Four length measurements (200 mm) on the cylindrical surface, along four evenly distributed generatrices, four diameter measurements and one total length measurement (between end faces).
- Large cylinders: Eight length measurements (200 mm) on the cylindrical surface, along four evenly distributed generatrices (2x3 and 2x1 measurements) and six diameter measurements.

Figure 2.1: Gluing of measuring studs into drilled holes on the cylindrical surface of a large cylinder
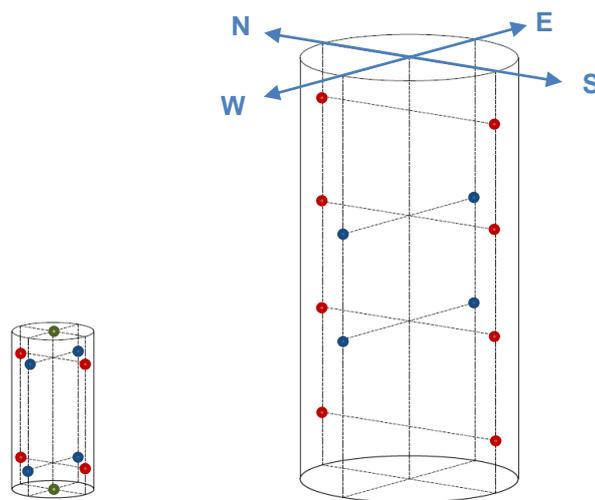
Figure 2.2: Location of the measuring studs on small and large cylinders. The orientation of the cylinders at the field exposure site is also shown.

2.3 Accelerated pre-exposure

To simulate real conditions with ASR-induced expansion prior to application of the surface products, the concrete specimens were pre-exposed to provoke an expansion of approximately 0.1 %. For this purpose, a plastic chamber was raised in a room with air temperature of approximately 40 °C. Humid air was blown into the plastic chamber through a channel to achieve a RH of minimum 95 %. A lot of effort was made to keep a stable humidity level in all parts of the chamber, which demanded close control to avoid both unwanted drying and condensation of water.

The pre-exposure period started 33-35 days after casting. Prior to pre-exposure, the specimens were weighted, and the reference lengths (distances between different studs) were measured with extensometers. During pre-exposure, all the small cylinders were weighted, and the lengths measured after 3 and 5 months (after cooling to 20 °C).

2.4 Surface treatment

Three different products for surface treatment, complying with EN 1504-2, are included:

P1: Hydrophobic impregnation, 85-90 % triethoxy(2,4,4- trimethylpentyl)silane in gel form

P2: Flexible coating, a two-component system with cement/latex binder. The latex is an ammonia free acrylic copolymer in aqueous dispersion.

P3: Hydrophobic impregnation, 80 % triethoxy(2,4,4-trimethylpentyl)silane in cream form

The products were applied by the product suppliers, outside SINTEF's laboratory, at temperatures of 7-12 °C. The application of the products was performed in May 2015, 22-25 days after ending the pre-exposure. In this intermediate period, the cylinders were stored in the laboratory at approximately 20 °C and 40 % RH, partly covered with plastic sheets.

The product P1 was applied with a brush with a measured consumption (including spill) of 434 g/m^2, product P2 was applied with a brush in four steps (priming, pore filling and two layers of coating, intended thickness 2 mm), while product P3 was applied by spraying with an intended amount of approximately 500 g/m^2. The concrete surfaces were rubbed by sand/water jetting prior to application of product P2, whereas product P1 and P3 was applied directly on untreated surfaces.

2.5 Installation of RH sensors

After application, the surface products could "cure" in the laboratory for 24-27 days before the cylinders were exposed outdoors at SINTEF's field site at Voll in Trondheim. During the curing period, holes were drilled, and RH sensors were installed, in selected small and large cylinders. The holes were drilled in different distances from the cylindrical surfaces pointing towards the north-easterly and south-westerly directions on site. The location of drilled holes is illustrated in Figure 2.3.
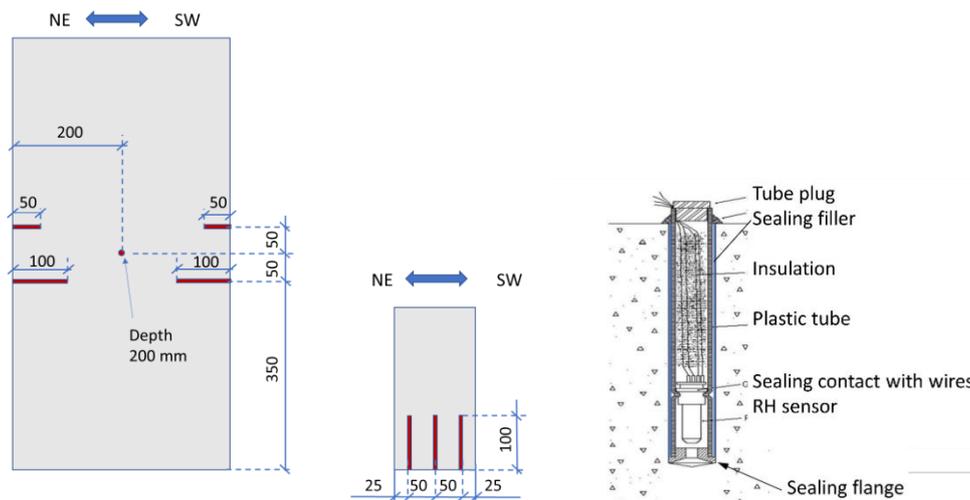
Figure 2.3: Location of holes with RH sensors; cross-sections of large cylinder (left) and small cylinders (middle). To the right; cross-section of a hole with the RH sensor system installed.

The RH measurement system used is the Swedish Humiguard supplied from Industrifysik (www.industrifysik.se). Plastic tubes with a sealing flange/filler were inserted into the holes. An RH sensor was then mounted on a sealing contact with contact wires, which was inserted into the plastic tubes. The humidity inside a tube will be in equilibrium with a small concrete surface at the inner end of the tube, see Figure 2.3.

2.6 Exposure site

After application of surface products and installation of RH sensors, the treated cylinders (P1, P2 and P3) were placed outdoors, not sheltered, at SINTEF's exposure site in Trondheim. Untreated reference cylinders were correspondingly exposed at the field station as follows:

R1: Outdoors, not sheltered
R2: Outdoors, sheltered from precipitation
R3: Outdoors, in buckets maintaining RH 93 % - above saturated KNO_3 (only small cylinders)

All cylinders exposed to precipitation is covered with a rubber "hat" to avoid water ingress from the top face, aiming to simulate the situation in a bridge column. Additionally, an epoxy sealing was applied on the top and bottom faces. The cylinders placed at the exposure site are shown in Figure 2.4. The wooden shelter in the background houses the untreated references R2 and R3. Precipitation is hindered from entering the inside, but air is free to circulate through the walls of the shelter.

Figure 2.4: Small and large cylinders at SINTEF's outdoors exposure site at Voll in Trondheim. The wooden shelter in the background houses the untreated references R2 and R3.

2.7   Testing

2.7.1   General

Testing was planned both as accelerated ASR testing of the concrete, initial behaviour of the surface products (penetration depths of hydrophobic impregnation and bond strength of coating), yearly in situ measurements of expansion, RH and weight and periodically destructive testing of small cylinders to determine moisture content (DCS and RH) and extent of internal cracking (see also Table 2.2).

2.7.2   Accelerated ASR testing

To further document the concrete mixture, accelerated ASR testing was performed according to three concrete prism test (CPT) methods; the Norwegian CPT [6], ASTM C-1293 and RILEM AAR-4.1 [7]. The main differences between the test methods are the exposure temperature (38°C vs. 60°C) and the volume of the prisms (100 x 100 x 450 mm^3 vs. 70 x 70 x 280 mm^3). For all test procedures the prisms were kept unwrapped and stored vertically on grids above water, aiming for a humid environment close to 100 % RH.

2.7.3   Penetration depth of hydrophobic impregnation

The penetration depths of the hydrophobic impregnations were measured periodically according to EN 1504-2 by longitudinal splitting of small cylinders and adding water to the split faces. Non-impregnated zones of the concrete will absorb water and turn dark grey, while impregnated concrete will stay light grey, see Figure 3.2. The distance between the surface and the level of colour change was measured in several points and the mean value reported as the depth of penetration.

2.7.4   Initial bond strength of coating

The initial bond strength was measured by pull-off testing according to EN 1542, on two coated prisms, 3 months after application of the coating. The test was performed by drilling circular cuts to a depth of 5 mm into the concrete, gluing ø 60 mm steel dollies to the surface and applying a load perpendicular to the surface (0.1 MPa/s) until failure occurred. The type of failure was determined for each specimen.

2.7.5   Internal moisture state (DCS and RH) measured in the laboratory

The Degree of Capillary Saturation (DCS) was determined on slices of thickness approx. 50 mm, split from small cylinders. The slices were weighed immediately after splitting (w1), then after submersion in water for 7 days (w2) and drying at 105 °C for 7 days (w3). DCS was calculated as DCS=(w1-w3)/(w2-w3) [8]. Measurements of relative humidity (RH) in the laboratory was performed by use of calibrated Vaisala RH sensors [8]; parts of the concrete slices were crushed, and minor mortar parts were put on sealed glass tubes together with the RH sensors. During the entire process, actions were taken to avoid loss of moisture, i.e. DCS and RH should reflect the in-situ moisture state of the concrete.

2.7.6   Internal moisture state (RH) measured on site

SINTEF has almost 20 years of experience using the Swedish Humiguard system supplied for field measurements of RH [8, 15]. Based on the instruction manual prepared by the supplier and experience gained at SINTEF, a SINTEF test procedure has been prepared. Readings are taken by connecting a voltmeter to the contact wires. The readings are converted into temperature and RH values based on readings performed on parallel RH sensors (from the same pre-calibrated lot) placed in a fixed environment (RH 85 %, temperature 20°C) in the laboratory. The sensors are replaced yearly, prior to measuring.

2.7.7   Expansion on site

Expansion of the field exposed specimens is determined regularly based on length measurements on studs (see Figure 2.2). Length measurements on cylindrical surfaces are performed with a 200 mm Digital DEMEC Mechanical Strain Gauge instrument, while diameter and total length measurements are performed with bow shaped Mitutoyo Digimatic Micrometers with measuring ranges 0-150 mm and 300-400 mm, respectively. The expansion is expressed as increased length/diameter divided with the initial (reference) distance, in % ($\Delta l*100/l_{ref}$). Reference readings were performed prior to pre-exposure (l_{ref}).

2.7.8   Internal damage assessment

The internal damage of the small cylinders was periodically determined by the Damage Rating Index method, on plane polished sections prepared from half cylinders (cut lengthways). A grid was drawn on the sections, with squares of 1 cm^2, as recommended by Villeneuve et al. [9]. The test specimens were

examined under a stereomicroscope at ±15x magnification and damage features associated with ASR were counted by an operator. The petrographic features and their related weighing factors proposed by Villeneuve et al. [9] were applied for the determination of the DRI number (Table 2.3). The DRI numbers obtained with these weighing factors can reliably assess damage of concrete due to ASR in terms of expansion [10] and loss in mechanical properties [11]. The cracks were counted in the coarse aggregate and sand particles larger than 1 mm in diameter to consider also the reactivity of the sand (if any), as recommended by Sanchez et al. [12]. The operator's experimental precision proposed by Champagne [13] was used to compare the obtained values with a 95 % confidence level (further details in [14]).

Table 2.3: Petrographic features and relating weighing factors [9] used to determine the DRI number.

Petrographic features		Acronyms	Weighing factor [9]
Crack in the particles (> 1 mm)	Closed (without reaction products)	CCA	0.25
	Opened or in a fine network (without reaction products)	OCA	2
	Opened or in a fine network (with reaction products)	CA + RP	2
Crack in the cement paste	Without reaction products	CCP	3
	With reaction products	CCP + RP	3
Debonded aggregate (> 1 mm)		Debon	3
Reacted aggregate particle (> 1 mm)		RAP	2
Reaction rim (> 1 mm)		RR	---
Reaction products in voids of the cement paste		RPV	---

3. RESULTS

3.1 Accelerated ASR testing

The results from the measurements of expansion and mass increase according to the three CPT methods are presented in Figure 3.1. The following abbreviations are used: Norwegian CPT ("VK-0.48 N.2"), ASTM C-1293 ("VK-0.48 ASTM") and RILEM AAR-4.1 ("VK-0.48 4.2"). Additionally, dynamic Young's Modulus of elasticity and alkali leaching were measured (not included in this paper).
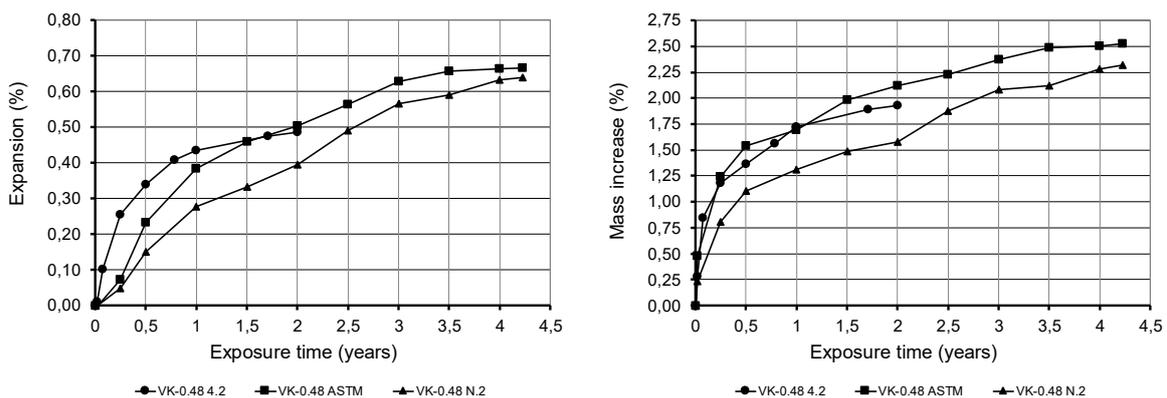

Figure 3.1: Accelerated ASR testing - expansion and mass increase over 2 to 4 years.

3.2 Initial testing (before exposure at site)

3.2.1 Penetration depth and bond strength

The following results were obtained in the documentation of the application and the initial conditions of the surface products:

- Penetration depth of the hydrophobic impregnations (see Fig. 3.2): P1 = 21 mm; P3 = 11 mm.

- The measured bond strength of the coating (P2) was 1.3 MPa (mean of 2x5 single tests). The dominating type of failure was cohesion failure in the coating (63% of the total area). Failure between concrete substrate and coating occurred for 37 % of the total test area.

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Figure 3.2: Penetration depth of P1 (left) and P3 (right).

3.2.2 Internal moisture state

The moisture state, Degree of Capillary Saturation (DCS) and Relative Humidity (RH), was measured after the humid pre-exposure period and one week after application of the surface products (see 2.7.5). One small cylinder was picked at each time and divided in two halves. One half was split into slices with thickness approx. 50 mm, the other into slices of thickness 30-40 mm. DCS was determined on all six 50 mm slices, while RH was determined on the internal part of three of the 30-40 mm slices. Mean values for the two different methods at the two points in time are presented in Table 3.1.

Table 3.1: Internal moisture state in small cylinders, at 20°C.

Point in time	DCS, %	RH, %
After pre-exposure	90	93
One week after application of the surface products	81	87

3.3 Testing up to 4 years of field exposure

3.3.1 Expansion

The longitudinal expansion of the small cylinders (mean of three cylinders of one length and four generatrices, respectively), from the start of the exposure at site in June 2015 until October 2019, is shown in Figure 3.3. The reference (zero readings) were performed before starting the pre-exposure.
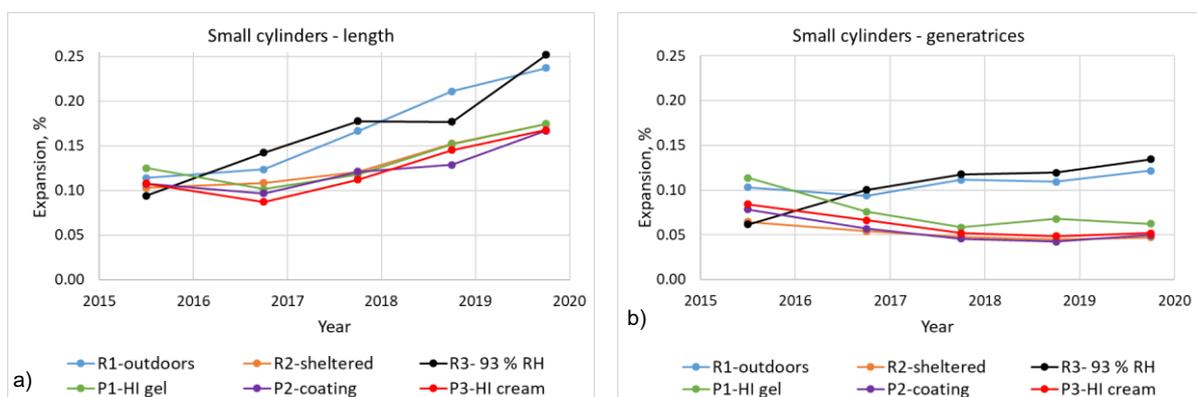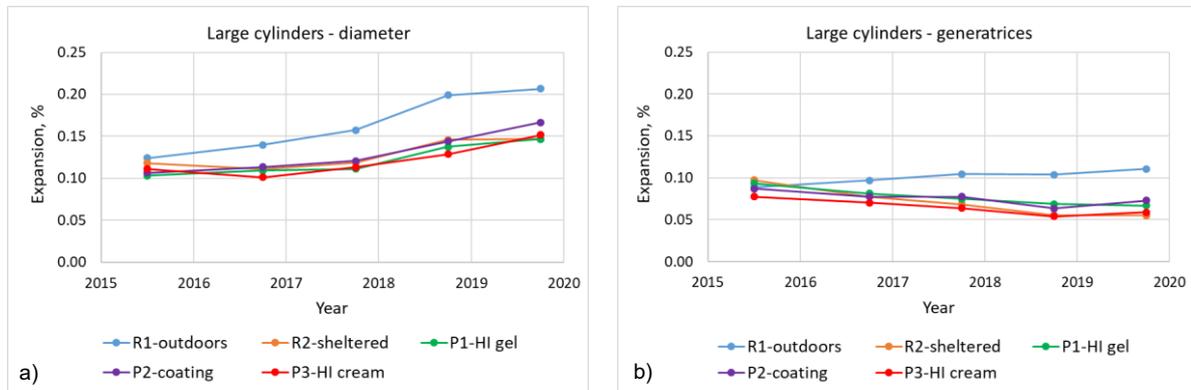

Figure 3.3: Expansion of small cylinders over a four year period, from the start of the exposure at site in June 2015 – mean of three cylinders of a) one length and b) four generatrices.

The longitudinal and diametral expansion of the large cylinders (mean of two cylinders of eight generatrices and six diameters, respectively), from the start of the exposure at site in June 2015 until October 2019, is shown in Figure 3.4. The reference (zero readings) were performed before starting the pre-exposure.

Figure 3.4: Expansion of large cylinders over a four year period, from the start of the exposure at site in June 2015 – mean values of two cylinders of a) six diameters and b) eight generatrices.

3.3.2 Relative humidity in the field

Relative humidity (RH) is measured by the Humiguard system in different depths from the cylindrical surfaces (see Figure 2.3 and section 2.7.6), starting from the time when exposed at site in June 2015. The results are corrected for temperature and related to 20°C. Mean RH values of each small cylinder measured in three depths and mean RH in five depths for two parallel large cylinders are presented in Figure 3.5. Due to problems with several of the RH sensors in the large cylinders from 2018, these results are omitted.
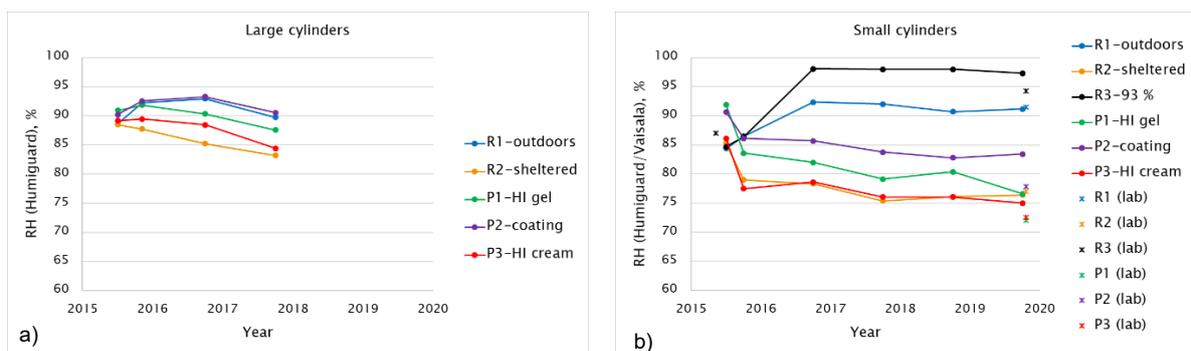

Figure 3.5: Relative humidity (RH) measured in cylinders at site (Humiguard system) – starting from the time of field exposure in June 2015. a) Large cylinders, mean of two cylinders in five depths b) Small cylinders, mean of one cylinder in three depths. *RH measured in laboratory (Vaisala system), immediately prior to exposure (June 2015) and in September 2019, is indicated with single spots.*

3.3.3 Moisture state measured in the laboratory

The moisture state was measured on split slices/pieces from one small cylinder from each exposure type after 4 years of exposure (see also 2.7.5 and 3.2.2). The degree of capillary saturation (DCS) was determined on slices in distances 0-75, 125-175 and 225-300 mm from the bottom of the cylinders, while the relative humidity (RH) was measured om crushed pieces from the centre of the cylinder in distances 75-125 and 175-225 mm (two separate samples per level). Mean values are shown in Figure 3.6, together with corresponding values measured after ending the humid pre-exposure and one week after

application of surface products (Table 3.1). The RH measured immediately prior to exposure at site and after four years of exposure is indicated in Figure 3.5 b) as well.
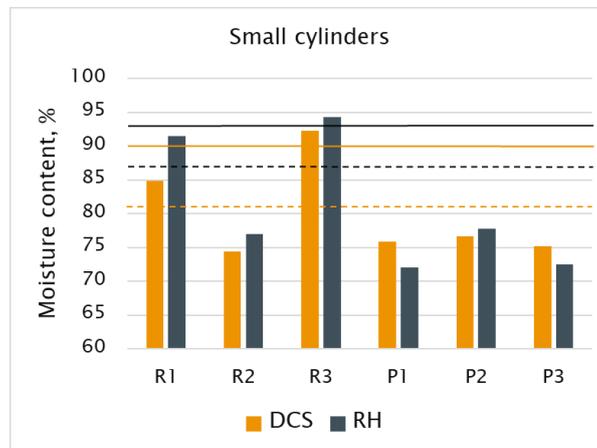

Figure 3.6: DCS and RH measured on split pieces from small cylinders after 4 years of exposure. Solid lines show moisture state immediately after the humid pre-exposure, whereas dotted lines represent the moisture state one week after application of surface products.

3.3.4 Internal damage measured in the laboratory

The Damage Rating Index (DRI) method was carried out on one half small cylinder from each exposure type after 4 years of exposure at site. The first 30 mm from each side (i.e. top and bottom face in the field) were omitted from the area examined, as they were expected to be influenced by end effects. The results are shown in Figure 3.7.
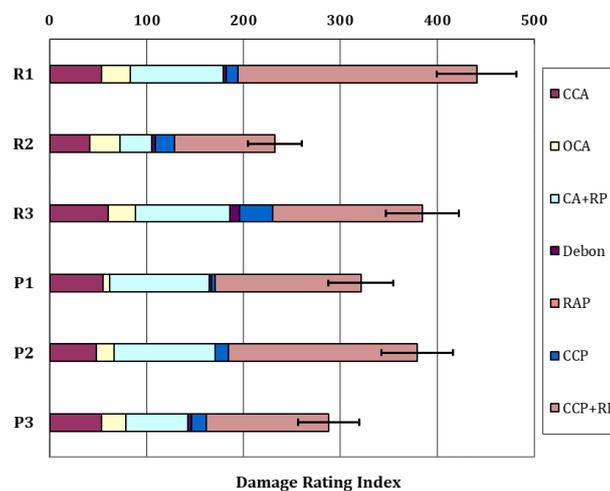

Figure 3.7: Bar chart showing DRI numbers for each small cylinder, with the contribution of each petrographic feature. The error bar is the experimental precision given as a 95% confidence interval using the equation of Champagne [13].

4. EVALUATION

The results from the measurements during 4 years of field exposure can be summarised as follows:

- The 2019 moisture state in the small cylinders is highest in the reference $R3_{93\% RH}$, followed by the reference $R1_{outdoors}$. The moisture state in all surface-treated small cylinders is reduced, practically to the same level as the $R2_{shelterd}$, below 80 % RH (except the coated P2 when measured with Humiguard in field). There is a good correlation between the different moisture measuring methods (DCS, $RH_{Vaisala}$ and $RH_{Humiguard}$), see Figure 4.1.

- The relative humidity (RH) in the large cylinders (latest readings in 2017, after 2 years) are generally higher than in the small cylinders and with less differences between the different specimens, see Figure 3.5 and Figure 4.2. For the large cylinders, the highest RH was measured in the reference $R1_{outdoors}$ and the coated P2, while the impregnated ones have lower RH, P3 close to the reference $R2_{sheltered}$. The generally higher internal RH and lower spread between these large specimens, is compatible with the higher volume of the specimens. Water exchange (drying and suction) will happen in the outer layer of the specimens and higher volume will lead to less influence (on the total volume) from surface-near interaction with the external environment. Two years exposure time is too short to observe a significant effect of the treatments. Moreover, during the intermediate period from the humid pre-exposure until surface treatment and subsequently placing of the samples at the field exposure site, the small cylinders were most likely able to dry out more than the larger cylinders.

- The reference specimens $R1_{outdoors}$ and $R3_{93\% RH}$ show continuous expansion from the very beginning of the field exposure period, both the small and the large cylinders and in all directions (length, generatrices and diameter). The surface treated specimens (P1, P2 and P3) and the reference $R2_{sheltered}$ show continuous expansion as well, but at lower rates and "starting" 1-2 years after placement in field – however, only noticeable over the total length of the small cylinders and in the diametral direction of the large cylinders. There is a good correlation between the moisture state and the increase in expansion, both for the small and the large cylinders, see Figures 4.1a) and 4.2.

- The Damage Rating Index numbers, determined on small cylinders, indicate the highest damage in the reference $R1_{outdoors}$, thereafter almost equal DRI's for the reference $R3_{93\% RH}$ and the coated P2. The reference $R2_{sheltered}$ has the lowest damage number, while the impregnated ones (P1 and P3) are counted some higher than the $R2_{sheltered}$. The relation between DRI and the moisture state in 2019 is shown in Figure 4.1b). It should be noted that while the moisture values are 2019 values, the DRIs include the moisture and temperature history of the specimens, i.e. higher moisture state in the earlier years and periodically higher temperatures in the outdoor specimens when exposed to sun. No clear correlation is found, neither between the DRI and the moisture state nor between the DRI and the expansion up to date (except for the "moist" and "dry" stored references).
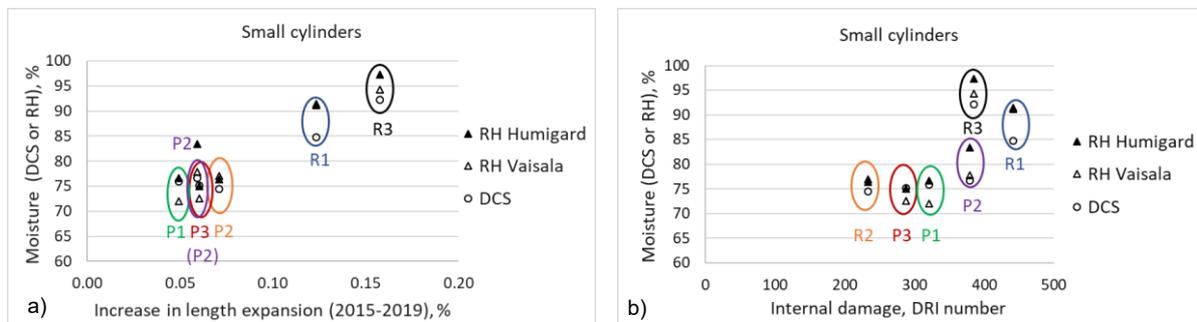

Figure 4.1: Relation between the 2019 moisture state (all methods) and a) the increase in length expansion (from 2015 to 2019) and b) DRI. Small cylinders. The various specimen types are indicated.
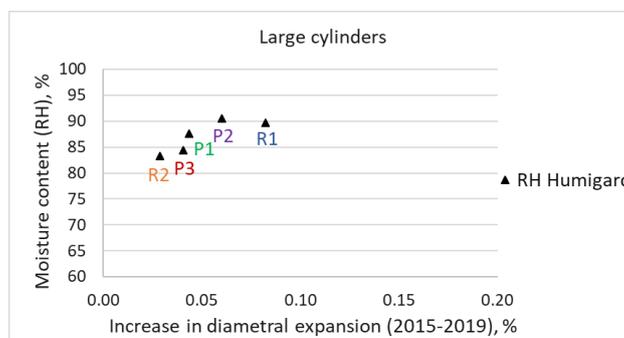

Figure 4.2: Relation between the relative humidity (Humiguard, 2017) and the increase in diametral expansion from 2015 to 2019, large cylinders. The different specimen types are indicated.

5.   CONCLUSIONS

The preliminary results from the field test programme after 4 years of field exposure indicate that the hydrophobic impregnation products have helped reducing the moisture content, the expansion and the internal degradation of the concrete. So far, the flexible coating shows less effect on these parameters, especially on the large cylinders. Although the expansion is reduced for the surface treated cylinders compared to the moist exposed references, they all gain additional expansion at site, as does also the sheltered reference. The internal damage (DRI) of the small cylinders corresponds well with the humidity and the expansion results for the untreated reference specimens stored under humid and dry conditions, but the correlation is so far not consistent for the treated specimens. The penetration of the hydrophobic impregnations is very deep, although the P3 is quite unevenly penetrated. It is assumed that the deep ingress of impregnation is due to low water content in the outer parts of the cylinders at impregnation – which indicates favourable conditions that may be difficult to repeat if applying the silanes in field under real conditions. The results from the small cylinders give early indications of a potential for reducing the degradation rate of concrete elements suffering from ASR. Longer exposure periods and significant results from the large cylinders are, however, needed to draw firm conclusions about the long-term effects of the different exposure conditions and surface treatments.

6.   ACKNOWLEDGEMENT

7.   REFERENCES

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