

# Performance evaluation of a coating protection system for concrete structures affected by internal expansive reactions

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**Abstract.** In the last decades, a significant number of large concrete structures with deterioration problems, related to internal expansive chemical reactions, have been detected in Portugal. This type of degradation is associated with the formation of expansive products in concrete causing its disruption, leading to the decrease of the structure's service life and, ultimately, to the decommissioning or demolition of the structure. In Portugal, structures affected by this pathology are very important in economic and strategic terms, since these reactions are usually encountered in large dams, bridges and viaducts. Two separate material-based mechanisms have been identified to cause the concrete swelling: Alkali-Silica Reaction (ASR) and Delayed Ettringite Formation (DEF). Both reactions result in the formation of expansive products and a common requirement for their occurrence is the presence of a sufficient moisture content inside concrete. By controlling the humidity level in concrete, coatings applied onto the concrete surface should contribute to mitigate ASR or DEF by acting as a barrier against ingress of water and allowing the concrete to dry, as long as they have adequate water permeability characteristics. This paper presents the general criteria that may be followed to select a surface protection system, based on coating materials (hereinafter designated by coating system), for the rehabilitation of concrete structures affected by expansive reactions, in order to mitigate them and, thus, contribute to improve durability and service life of affected structures. In addition, a laboratory study is presented concerning the performance evaluation of a surface protection system, composed of two coating materials, in terms of its capacity to bridge cracks, its permeability to liquid and to water vapour, and on its effectiveness on controlling humidity inside concrete.

## 1 Introduction

Internal expansive reactions affect several large concrete infrastructures all over the World. In Portugal, Alkali-Silica Reaction (ASR) and Delayed Ettringite Formation (DEF, a term normally used in the literature to designate the phenomenon of heat-induced internal sulfate attack) are the most common swelling reactions identified in structures such as dams, bridges and viaducts [1].

Since their discovery (ASR in the early 1940s and DEF more recently in the early 1980s [2]) several studies have led to the development of guidance documents and specifications to prevent these reactions in newly constructed structures. However, there are many structures, constructed before the publication of such regulations, presenting premature concrete deterioration as a result of expansion and cracking of the concrete induced by ASR and DEF, which in turn accelerates the ingress of moisture and other aggressive agents into the concrete, leading to further degradation of the structure.

Furthermore, due to the complexity and multiplicity of factors involved in ASR and DEF, together with the variability of the materials used in concrete, deterioration of concrete structures due to these reactions continues to be a serious problem and it is predicted that will continue to worsen in the future. ASR reasoning being: distress signs appear decades after construction; numerous structures were built with aggregates which are now

known to be reactive; concrete formulation considered that the only alkali source was the cement, this is now known not to be true; structures can now be built free from deleterious ASR, but several are being constructed with aggregates for which reactivity tests produce unreliable results; large structures require vast amounts of aggregates so, in some cases, local rocks are preferred, despite being potentially reactive; there are now concerns on the reliability of current laboratory tests used to assess the very long-term efficacy of supplementary cementitious materials (SCM) on ASR and DEF mitigation. Today, concrete may be formulated free from deleterious DEF, yet many new structures exhibit DEF, this is because preventive measures, such as those described in [3], are not always feasible or applied in practice, and consequently temperatures above 65 °C are obtained during concrete cure. For instance, to reduce construction costs, concrete structures must be built in a very short period, implying that often concrete has a cement content higher than necessary just to obtain the design strength; concrete might have to be placed during hot periods; concreting large structural elements using thick layers; etc. Therefore, it is extremely important to study effective methods of mitigating these phenomena in affected structures.

ASR is a chemical reaction that occurs when alkalis in the concrete react with some forms of silica found in certain aggregates. The essential factors for ASR

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development are the following: the presence of alkali-reactive aggregates; sufficient moisture in the concrete; and sufficient alkalinity of the pore solution. Eliminating one of these factors prevents ASR [4].

DEF is a reaction between sulfate ions in the pore solution and calcium aluminates present in the hardened cement paste. The essential factors for its occurrence are the following: temperature higher than 65 °C during concrete cure, high relative humidity in concrete, sufficient amount of alkalis, sulphate and C<sub>3</sub>A in cement and calcium hydroxide in the concrete pore solution [4]. As in the previous reaction, the elimination of one of these factors prevents the occurrence of DEF.

The presence of moisture in concrete plays a key role in the development of the above expansive reactions. Water works as a transport medium of ions but also participates in the expansive processes [5]. In ASR, the sorption of water by the alkali-silica gel causes the swelling, which can lead to the damage of concrete. In DEF, the water participates in the reactions to form ettringite [6]. Reported threshold values of relative humidity in concrete for the deleterious development of the reactions are about 80-85 % for ASR and 90-92 % for DEF [5].

Surface protection systems like water repellents, impregnation products and coating materials can act as a physical barrier against aggressive agents, such as, water, carbon dioxide and chlorides. By controlling the humidity level inside concrete, coatings may mitigate ASR and DEF by acting as a barrier against ingress of water and allowing the drying of concrete, as long as they have adequate characteristics of water permeability. The control of water ingress in the concrete by the use of coatings is reported in the literature as a preventive and remedial measure to mitigate ASR and DEF [7-9]. However, there is a wide range of coating products available in the market, with very different properties, which may or may not make them suitable to mitigate the abovementioned phenomena; thus, appropriate selection of a coating system, considering factors like barrier properties, is critical to ensure that it will effectively mitigate the reactions in a structure. Especially, as, currently, there are no standards providing specific guidance on the selection and acceptance of appropriate surface protection systems for preventing or mitigating these phenomena in structures.

Hence, this paper presents the general criteria that may be followed for the selection of coating systems for rehabilitating concrete structures affected by expansive reactions, and thus increase of their durability and service life. Furthermore, a laboratory study is presented concerning the performance evaluation of a coating system in terms of its resistance to water penetration and permeability to water vapour, its capacity to bridge cracks, and also on its effectiveness to control the humidity level inside concrete.

## 2 Coating system performance and evaluation

The selection of an appropriate coating system to mitigate internal expansive reactions in concrete can be made following the principles set out in European standard EN 1504-2 [10], which specifies requirements for the identification, performance, safety and evaluation of conformity of products and systems to be used for surface protection of concrete. This is because, even though the standard does not consider these specific swelling phenomena, it enumerates several performance characteristics that may be used by the specifier to select a product for this exact intended use.

EN 1504-2 [10] defines performance characteristics of the coating system, according to the following protection principles: ingress protection, moisture control, physical resistance, chemical resistance and increasing resistivity. These principles are directly related to the actions that are intended to protect the concrete. Therefore, the selection of the coating system is conditioned by the specificity of the environmental exposure or physical/chemical actions to which the concrete structure is subject.

In the case of internal expansive reactions, the coating system must prevent water absorption, but it should be also permeable to water-vapour (to allow concrete drying).

Thus, according to the Principle P1 – protection against ingress (in this case against the ingress of water), and to the Principle P2 – moisture control, the mandatory characteristics and the respective requirements that should be evaluated are summarized in Table 1. Although, this work focuses only on barrier properties, such as liquid and water-vapour permeability, and crack bridging ability, for a coating system to effectively mitigate ASR and DEF it must be also evaluated for other characteristics, e.g., bond strength, and durability. The objective of this study is mainly to correlate barrier properties with the effectiveness of coating systems in controlling humidity inside concrete.

**Table 1.** Mandatory performance requirements of coatings for all intended uses (for Principles P1 and P2 in EN 1504-2).

Performance characteristic	Test method	Requirement/Class	
Carbon dioxide permeability	EN 1062-6	$s_D > 50 \text{ m}$	
Water-vapour permeability	EN ISO 7783	Class I: $s_D < 5 \text{ m}$ (permeable to water vapour)	
		Class II: $5 \text{ m} \leq s_D \leq 50 \text{ m}$ Class III: $s_D > 50 \text{ m}$ (dense against water vapour)	
Liquid water permeability	EN 1062-3	$w < 0.1 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-0.5}$	
Bond strength by pull-off	EN 1542	Trafficking	Rigid systems
		Without trafficking	Crack-bridging or flexible systems $\geq 0.8 \text{ N} \cdot \text{mm}^{-2}$ (Individual values $\geq 0.5$ )
		With trafficking	$\geq 1.5 \text{ N} \cdot \text{mm}^{-2}$ (Individual values $\geq 1.0$ )
			$\geq 1.0 \text{ N} \cdot \text{mm}^{-2}$ (Individual values $\geq 0.7$ )
			$\geq 1.5 \text{ N} \cdot \text{mm}^{-2}$ (Individual values $\geq 1.5$ )

### 3 Laboratory study

The experimental program carried out to evaluate the coating system is divided into two parts. In the first part, permeability to liquid water and to water-vapour (barrier properties of coating), as well as the coating system's crack bridging ability, were appraised. In the second part, the effectiveness of the coating system on controlling humidity inside concrete is assessed; in addition, the feasibility of using superabsorbent polymers (SAP) to decrease the relative humidity inside concrete is also evaluated. In the next sections, the coating system is presented and the methodology used in the assessments is described.

#### 3.1 Coating system

The selected surface protection system is composed of two layers of a polymer modified cementitious coating and an acrylate water-based finishing coating. Products were applied as per the manufacturer's instructions.

#### 3.2 Coating system properties

##### 3.2.1 Test methods

###### Liquid water permeability

The permeability to water was determined using a gravimetric method described in EN 1062-3 [11]. The coating system was applied in an appropriate substrate according to the manufacturer technical data sheets. After drying in a controlled environment for one month, the water permeability coefficient ( $w$ ,  $\text{kg}\cdot\text{m}^{-2}\cdot\text{h}^{-0.5}$ ) was determined according to the standard. The test temperature was 23 °C.

###### Water-vapour permeability

The water-vapour permeability test was carried out in accordance with the cup method described in EN ISO 7783 [12]. Water-vapour diffuses through the coating system driven by the partial vapour pressure gradient established between the surfaces of the coating. After the steady state has been reached (constant change of weight per unit of time), the water-vapour transmission rate ( $V$ ,  $\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ) and the water-vapour diffusion equivalent air layer thickness ( $s_D$ , m) were determined.

###### Crack-bridging

The crack-bridging properties were assessed according to Method A defined in EN 1062-7 [13], i.e., in which the crack width is continuously enlarged at a defined speed, and then the measurement is taken when either failure occurs in the coating system or when the required crack width is reached.

##### 3.2.2 Results and discussion

Table 2 shows the results of the evaluation of the coating system barrier properties. Regarding liquid-water permeability, the results obtained show that the coating

system complies the requirement set in the standard EN 1504-2 [10] ( $w < 0.1 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-0.5}$ ). Thus, it is expected that this system can effectively protect concrete from liquid water ingress. This will be confirmed with the tests in the second part of this study.

In relation to water-vapour permeability, the system is classified as Class II - the coating system is not dense against water-vapour nor permeable to water vapour. Since the value obtained is closer to the lower limit of the class, it is likelier to be somewhat permeable; in any case, the second part of the study will be essential to assess whether this system allows the drying of the concrete or not.

**Table 2.** Water permeability and water-vapour permeability of the coating system.

Characteristic	Result
Water-vapour permeability (EN ISO 7783)	$V = 2 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ $s_D = 9 \text{ m}$ (EN 1504-2: Class II; $5 \text{ m} \leq s_D \leq 50 \text{ m}$ ; not dense against water-vapour and not permeable to water vapour)
Liquid-water permeability (EN 1062-3)	$w = 0.01 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-0.5}$ (EN 1062-1: $< 0.1 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-0.5}$ ; Low. EN 1504-2: $< 0.1 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-0.5}$ )

Table 3 shows the results of the evaluation of the crack bridging properties of the coating system, obtained at 23 °C. The results of the tests classifies it as A3 (according to classes described in the standard EN 1062-7 [13] – see table 4). The coating system has crack bridging abilities and can maintain its integrity even if the concrete substrate cracks, at the level of the referred class.

**Table 3.** Crack-bridging properties of the coating system (at 23 °C).

Width of the crack bridged ( $\mu\text{m}$ )	Class
1180 *	A3 ( $> 500 \mu\text{m}$ at 0.05 mm/min)

NOTE: \* Average of three test pieces.

**Table 4.** Crack-bridging properties classification according to EN 1062-7 (method A) [13].

Class	Width of the crack bridged ( $\mu\text{m}$ )	Speed (mm/min)
A1	$> 100$	Static tensile test
A2	$> 250$	0.05
A3	$> 500$	0.05
A4	$> 1250$	0.5
A5	$> 2500$	0.5

NOTE: \* Average of three test pieces.

#### 3.3 Coating system effectiveness

##### 3.3.1 Test methods

###### Effectiveness of the coating system to control humidity inside concrete

The effect that the coating system has on the moisture level in concrete was assessed by making periodic measurements of relative humidity (R.H.) in 12 concrete cubic specimens ( $100 \times 100 \times 100 \text{ mm}^3$ ) coated with the surface protection system described in section 3.1.

The concrete specimens were produced at the laboratory following EN 1766 [14], but using limestone

as coarse aggregate instead of silica-based coarse aggregate, in April 2019, and were of the Type C (0,45) (Table 5). After the standard curing regime (20 °C and  $\geq 95$  % R.H. for 28 days), the specimens were moved into a room at  $21 \pm 2$  °C and  $60 \pm 10$  % R.H. In May 2021, the specimens were instrumented with a relative humidity measurement system and moved to a climatic chamber at 20 °C and 90 % R.H., where they remained until the relative humidity in the centre of the concrete cubes became constant, and the coating was applied (specimens 1 to 8) or the actual testing begun (specimens 9 to 12). Specimens no. 1 to 8 were coated with the surface protection system in the period comprised between 2021/10/25 and 2021/11/05, and according to the manufacturer instructions. After another period, for moisture redistribution in the concrete specimens, the internal relative humidity was measured (2021/11/23-26) and the cubes were placed into two different environments (2021/11/29): a room conditioned at  $21 \pm 2$  °C and  $60 \pm 10$  % R.H. (specimens 1 to 4, all coated; and specimens 9 and 11, both uncoated, serving as reference); and a room conditioned at  $20 \pm 2$  °C and with a R.H. close to 100 % (specimens 5 to 8, all coated; and specimens 10 and 12, both uncoated, serving as reference).

**Table 5.** Concrete composition used in the specimens made to study the effect of the coating system on R.H. in concrete.

Constituent	Amount (kg·m <sup>-3</sup> )
Coarse aggregate, 4/20 mm (limestone)	1000
Fine aggregate, 0/4 mm (siliceous)	900
Cement, CEM I 42,5 R [15]	360
Water	162

Afterwards, the specimens' mass and relative humidity were measured periodically to assess eventual variations in the internal relative humidity. These tests are still ongoing.

#### Effectiveness of superabsorbent polymers to control humidity inside concrete

The effect that SAP has on the moisture level in concrete was assessed by making periodic measurements of relative humidity in 12 concrete cubic specimens (150×150×150 mm<sup>3</sup>).

The concrete specimens were produced at the laboratory in October 2020. The concrete used was a self-compacting concrete (C30/37 SF2 XC3 C1 0,40 BAC [16]; compressive strength at 28 days - 44 MPa [17]) (Table 6). After the standard curing regime (20 °C and  $\geq 95$  % R.H. for 28 days) (EN 1766 [14]), the specimens were kept in that same room until February 2021. In March 2021, the specimens were instrumented with a relative humidity measurement system (to measure R.H. in the centre of the cube), and 4 holes were drilled into them ( $\varnothing 15 \times 50$  mm). After that all the cubes' top side, where the holes are located, and the top part of the sides were sealed with an epoxy resin. The specimens were then completely isolated with several layers of cling film and moved to a climatic chamber at 20 °C and 90 % R.H., where they remained until the relative humidity in the centre of the concrete cubes

became constant. In May 2021, the SAP's [18] were introduced (specimens 5 to 7 with SAP 1 placed in the four holes; specimens 8-10 with SAP 2 placed in the four holes) or the actual testing begun (specimens 1 to 4; control specimens).

**Table 6.** Concrete composition used in the specimens made to study the effect of SAP on R.H. in concrete.

Constituent	Amount (kg·m <sup>-3</sup> )
Coarse aggregate, 4/16 (limestone)	815
Fine aggregate, 0/4 (siliceous)	565
Fine aggregate, 0/2 (siliceous)	330
Filler	100
Cement, CEM II/A-L [15]	380
Admixture, MasterGlenium SKY 617	7.68
Water	145

Afterwards, the specimens' mass and relative humidity were measured periodically to assess eventual variations in the internal relative humidity. These tests are still ongoing.

### 3.3.2 Results and discussion

#### Effectiveness of the coating system to control humidity inside concrete

The results obtained so far in the test campaign carried out to assess the effectiveness of the coating to control the humidity inside concrete are presented in Table 7. The results show that the coating system is allowing the concrete to dry, as the relative humidity values decrease once the specimens were placed at an environment with 60 % R.H. However, it appears that the coating does not prevent moisture ingress, as the specimens that were placed in a humid chamber ( $\geq 95$  % R.H., i.e., in which the surfaces of the specimens are continuously wet), show a continuous increase in relative humidity.

**Table 7.** Relative humidity measurements performed for studying the effect of the coating system on concrete.

Specimen no.	2021/11/15 <sup>†</sup>	2021/11/22 <sup>†</sup>	2022/01/24 <sup>‡</sup>	2022/03/21 <sup>‡</sup>
9 (ref. 20°C&65%H.R.)	95	96	81	71
11 (ref. 20°C&65%H.R.)	99	99	80	68
1 (20°C&65%H.R.)	93	93	86	79
2 (20°C&65%H.R.)	93	92	84	78
3 (20°C&65%H.R.)	93	93	85	80
4 (20°C&65%H.R.)	94	93	86	80
10 (ref. 20°C&95%H.R.)	95	95	97	99
12 (ref. 20°C&95%H.R.)	99	99	99	99
5 (20°C&95%H.R.)	94	94	95	96
6 (20°C&95%H.R.)	93	93	94	95
7 (20°C&95%H.R.)	93	92	93	95
8 (20°C&95%H.R.)	93	93	93	95

NOTES: <sup>†</sup> R.H. values, in the centre of the concrete specimens, before they were placed in the test environment; <sup>‡</sup> R.H. values, in the centre of the concrete specimens, after they were placed in the test environment in 2021/11/29.

#### Effectiveness of superabsorbent polymers to control humidity inside concrete

The results obtained so far in the test campaign carried out to assess the effectiveness of superabsorbent polymers to control humidity inside concrete are presented in Table 8. The results obtained thus far

suggest that SAP may be used to lower the relative humidity inside concrete. The moisture level attained inside concrete would be sufficient to hinder the deleterious development of DEF in concrete.

**Table 8.** Relative humidity measurements performed for studying the effect of SAP on concrete.

Specimen no. †	2021/06/18‡	2021/08/09‡	2022/01/31‡	2022/03/28‡
1 (ref.)	99	99	99	99
2 (ref.)	99	99	98	98
3 (ref.)	99	99	98	98
4 (ref.)	99	99	99	99
5 (SAP1)	98	94	90	88
6 (SAP1)	98	96	91	90
7 (SAP1)	98	93	90	89
8 (SAP2)	99	95	90	90
9 (SAP2)	98	95	90	89
10 (SAP2)	99	94	90	89

NOTES: † The R.H. values, in the centre of the concrete specimens before test start, i.e., before the SAP were introduced in specimens 5 to 10, was 99 % for all specimens; ‡ R.H. values, in the centre of the concrete specimens after commencing the test, i.e., after the SAP were introduced in specimens 5 to 10 in 2021/02/23.

### 3 Summary and outlook

This paper succinctly presented the general criteria that may be used to select coating systems for the mitigation of ASR and DEF in concrete structures. In addition, the paper presented the preliminary laboratory results of a study concerning the performance evaluation of a coating system in terms of its capacity to bridge the cracks, its resistance to water penetration and permeability to water vapour, and on its effectiveness on controlling humidity in concrete. The main findings can be summarized as follows:

- Liquid-water permeability – the results of the tests performed to the coating system show that it has a water permeability coefficient 10 times lower than the requirement set in the standard EN 1504-2 ( $0.1 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-0.5}$ ). Tests on concrete cubes, similar to those described in section 3.3.1, but in which the coated specimens are kept immersed in water, are envisaged in the present study. This will allow us to determine if the coating system is adequate for structural elements that are either permanently submerged in water or subject to long-term water contact.
- Water-vapour permeability – the results of the tests performed to the coating system allow categorising it as Class II ( $s_D = 9 \text{ m}$ ), i.e., the coating system is not dense against water-vapour ( $s_D \geq 50 \text{ m}$ ) nor permeable to water vapour ( $s_D \leq 5 \text{ m}$ ) and demonstrates that it has a medium water vapour transmission rate ( $V = 2 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ). The tests performed to the coated concrete cube specimens showed that these properties permit the concrete to dry; however, the results obtained so far suggest that this coating system might not be adequate in situations where the concrete is exposed continuously or for very extended periods to high air humidity.
- Crack-bridging – the results of the tests performed to the coating system, at 23 °C, allow categorising it as

A3 (the width of the crack bridged was above 500 µm and below 1250 µm). Thus, the coating system would be able to maintain protective/barrier properties in the concrete of an affected structure, since it has the capacity to bridge cracks in the concrete substrate, provided that these do not exceed the aforementioned level.

- SAP – the results obtained, in the tests carried out to assess the effect that the SAP have on the relative humidity inside small concrete cubes, show that the relative humidity in concrete may be reduced by the use of SAP. However, more research is needed to assess the feasibility of such use in large concrete specimens and in the field. Such tests are envisaged and will commence very soon.

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