Effect of paint degradation on carbonation protection of concrete

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Extended Abstract

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1. Introduction

Nowadays the carbonation is one of the biggest issues of concrete durability. The carbonation itself doesn’t represent a great influence on the concrete structural behavior, however on reinforced concrete this type of phenomenon could lead to an enormous impact on reducing the durability due to steel corrosion. Over the years has been developed various solutions to diminish this process, the superficial coating is one of those solutions, particularly the paint which has the main goal to protect the concrete against carbonation.

Those paints have a high effectiveness to protect reinforced concrete during early ages, while the superficial coatings are relatively new, although towards the end of paint life service period that effectiveness is probably reduced. This lack of performance is caused by the degradation of the paint coating and, at a certain point, that reduction of effectiveness could represent a not properly protected concrete.

The paint life service is between 2 and 10 years and a good maintenance and conservation could extent it to approximately 12 years, according to Brito [2004]. Chai [2011] determine that the paints life service is approximately 9,75 years. Nevertheless these periods are substantially lower than the other construction materials, mainly because the effects of ultraviolet (UV) radiation on superficial coatings, which accelerate the degradation. The UV radiation has photons with enough energy to dissociate the molecules from the paint [Almeida & Sinêzio, 2005], this process, designated by photolysis, is responsible for changing the material properties and also for a yellowing discoloration phenomenon.

Given the fact of paint susceptibility to deteriorate and consequent loss of function, the main concern is to study how long is the life service period and, more importantly, how effective is the protection of the concrete structures against carbonation during its life service.

Thus, the main objective of this study is to investigate the velocity of carbonation process in concrete specimens protected with paint coating and also to predict the behavior of the carbonation in concrete as the superficial coating is being deteriorated by natural environmental exposure. The paint coating degradation must be fully understood in order to predict the real extent of the carbonation damage in reinforced concrete.
2. Experimental Program

The experimental procedure described below has the main objective to evaluate the durability and the effectiveness of protecting the concrete from the carbonation phenomenon during paints life service.

For this procedure four different paints were applied on several concrete specimens, later these samples were exposed to four different environments particularly chosen to maximize the degradation of the paint coatings. The periods tested for paint degradation were associated to one month, three months, six months and one year of natural environment exposure. At the end of each periods of natural exposure, the samples were subjected to accelerated carbonation in order to evaluate the velocity of carbonation process. This artificial exposure with high level of CO$_2$ was performed using the carbonation chamber, where the concrete specimens were tested for 90 days.

With this experiment the penetration of CO$_2$ in concrete was measured using the phenolphthalein indicator, thereby it was possible to predict the behavior of the carbonation front in concrete specimens painted with paints chosen for this study.

2.1. Concrete Mixture

The concrete mixture produced for this experiment was a very poor quality concrete, with low compressive strength and high porosity. This assumption was made so it was possible to evaluate exclusively the carbonation resistance given by the superficial coating and not by the concrete itself. Thus the concrete sample produced had the following characteristics: C15/25 class strength, 0.65 w/c ratio, 23.3 KN/m$^3$ of density of hardened concrete and a 15.3% of absorption of water by immersion according to LNEC Specification E 394:1993.

Also was produced a reference concrete with the same characteristics so it was possible to expose in the same environments on the same degradation periods, thus could be analyzed the real effectiveness of the paint applied to protect the concrete.
2.2. Concrete Specimens Preparation

The concrete specimens produced were disc-shaped samples with approximately 10 cm diameter and 5 cm height. On the lateral surface was applied two coats of paint selected for the test and on the top and the bottom of the concrete specimen were applied an epoxy resin (Figure 1).

![Figure 1](image.png)

Figure 1 – Dimensions of concrete specimen and surface on each paints were applied.

The objective of applying the epoxy resin on the top and bottom of the concrete samples was to create radial direction of CO\(_2\) penetration within the concrete. Otherwise, if there wasn’t an epoxy resin, the CO\(_2\) penetration would be also from the top and the bottom and, besides that, there could be a conflict of various penetration directions which would difficult the measurement of the carbonation front.

2.3. Paint Coating

The paints tested for this experiment were from four different manufactures and the criterion for the selection was, first of all, the companies which have a high reputation particularly on constructor sector. After choosing the manufactures, the paints selected were the ones recommended from each manufacturer. Therefore, the paints for this experiment were: from EURONAVY (acrylic paint HA01), from MAPEI (acrylic paint ELASTOCOLOR PINTURA), from ROBBIALAC (acrylic paint SERIE 553), and finally, from SIKA (acrylic paint SIKAGARD 680 S). Henceforth those paints are going to be designated by the following abbreviations: EN; MP; RB and SK, respectively and for reference concrete specimen will be designated as S/T.
2.4. Environment Exposure

Having in consideration the main factors of paint coating degradation, it was determined that to maximize the paint degradation best location would be place with:

a) a great exposure to sunlight for several hours during the day so the concrete specimen would be exposed directly to solar radiation;
b) the concrete samples would have an exposure to a great number of atmospheric pollutants;
c) High relative humidity so the paint couldn’t protect properly the concrete;
d) Relatively high emissions of CO$_2$ environment, where the concrete specimens could be exposed.

For those environments characteristics, the following were chosen:

a) For high solar exposure it was selected the terrace of the Department of Civil Engineering and Architecture Department, Instituto Superior Técnico (IST), Technical University of Lisbon;
b) For high levels of pollutants were selected a balcony on the first floor of a building located in Almirante Reis Avenue, in Lisbon. This avenue is one of the city’s main roads and also is one of the most polluted areas;
c) For high levels of relative humidity exposure was selected the humidity chamber located on the laboratory of construction in the Department of Civil Engineering and Architecture, IST;
d) For a high levels of CO$_2$ exposure was selected the underground parking garage from the same department.

From now on these environments are going to be designated by the following abbreviations: COB, AAR; CH, GAR, respectively.

Figure 2 – Locations of natural degradation exposure of the concrete specimens. From left to right are COB, AAR, CH and GAR.
2.5. Calendarization for Measurement

Despite the concrete specimens located on natural environments which theoretically represent the maximum degradation for paint coating, that fact alone, doesn’t guarantee that the carbonation front would be measurable. The paint degradation is more significant on medium and long term but, due to temporal limitation for this investigation, the procedure taken for this study had to be the following: in every testing environment there were 4 groups of 5 concrete specimens (four painted and one reference concrete) on each group was associated a different period of environmental exposure (30, 90, 180 and 360 days). At the end of each exposure the concrete specimens were tested to determine the natural carbonation front, according to the LNEC Specification E 391:1993. After that procedure the concrete tested samples were subjected to 30 days of accelerated carbonation and then it was collected the accelerated carbonation front. This last procedure were executed two more times ate the carbonation chamber and represented the exposure to 30, 60 and 90 days of artificial environment, respectively (Figure 3).

![Figure 3 – Scheme of calendarization for measurement.](image)

For each concrete specimen 4 measurements of carbonation front were collected, one measure was the natural carbonation front, proceeded at the end of the natural environmental exposure and three measures of accelerated carbonation front collected during the 90 days on the carbonation camber. With these measurements was possible to determine the carbonation coefficient for the natural and accelerated exposure, respectively.
3. Results and Discussion

The results obtained from this experiment were analyzed to determine the accelerated carbonation coefficient from the equation (1). With different periods of natural degradation exposure it was possible to establish the evolution of accelerated carbonation coefficient. The evolution of accelerated carbonation coefficient is probably caused by the degradation of paint coating.

\[ x[\text{mm}] = k[\text{mm.years}^{-0.5}] \times t^{0.5}[\text{years}] \]  

After calculating the accelerated carbonation coefficient obtain for the different periods of paint degradation, the progression of the coefficient was adjusted with an exponential curve with the following expression:

\[ K_{\text{accelerated}}(t) = a \times e^{b \times t} + c \]  

This expression was chosen for two main reasons, due to be a model which the growth rate of the accelerated carbonation coefficient attenuates as the degradation period increases, till the point that coefficient is constant (value c, of the equation (2)). And secondly, due to be the adjusted model which presented the best coefficient of determination ($R^2$).

This model permitted to estimate, for each paint, the life service and also the equivalent period needed to present a degradation as the same as the unprotected concrete. Thereby it was possible to determine the equivalent natural carbonation coefficient. This coefficient was calculated by knowing the value of the natural penetration of CO$_2$ in the concrete and the respective time needed for the equivalent degradation.

Collecting the natural carbonation coefficient for each paint by the methodology described above, a second model was adjusted to predict the evolution of the coefficient over the life service period of the paint. On this adjustment it was used a Weibull curve with the following expression:

\[ K_{\text{natural}}(t) = c \times \left(1 - e^{-\left(b t^{b}\right)}\right) \]  

This model was chosen due to represent the degradation of the superficial coating with a great coefficient of determination and also according to Garrido, Paulo & Branco [2012] and Meeker & Escobar [1998] the Weibull curve is particularly relevant in this field.

After the adjustment of each paint, it was estimated the behavior of the CO$_2$ penetration on the unprotected concrete. It was also estimated on the concrete with one intervention of protective
paint application at the beginning of the concrete exploration phase and a third option was predicted which consisted on the application of a new paint coating always at the end of the live service of the old one.

3.1. Concrete Specimens Located on AAR

For the concrete specimen exposed on AAR the life service period of each paint can be seen on Table 1.

<table>
<thead>
<tr>
<th>Life Service Period [years]</th>
<th>EN</th>
<th>MP</th>
<th>RB</th>
<th>SK</th>
</tr>
</thead>
</table>

The Figure 4 shows the progression of the carbonation depth on the concrete exposed on AAR during the exploration phase of the concrete structure. The blue line designated by S/T is the progression of the carbonation front on the unprotected concrete. The progression of the carbonation front shown by continuous lines is the concrete protected with a paint coating applied just at the beginning of the concrete life service. The progression shown as a dashed line represents the concrete with a new paint coating applied every time that the old coat is almost at the end of its own life service.

![Estimation the Carbonation Depth - AAR](image)

Figure 4 - Estimation the carbonation depth for the concrete exposed on AAR.
Table 2 – Estimation of carbonation depth on AAR, at the end of 100 years of concrete exploration phase.

<table>
<thead>
<tr>
<th></th>
<th>Carbonation Depth [mm]</th>
<th>Carbonation Depth with 1 Paint [mm]</th>
<th>Reduction</th>
<th>Carbonation Depth with Re-Paint [mm]</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/T</td>
<td>30,1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EN</td>
<td>-</td>
<td>24,6</td>
<td>-18,4%</td>
<td>15,5</td>
<td>-48,5%</td>
</tr>
<tr>
<td>MP</td>
<td>-</td>
<td>24,5</td>
<td>-18,8%</td>
<td>15,5</td>
<td>-48,5%</td>
</tr>
<tr>
<td>RB</td>
<td>-</td>
<td>26,3</td>
<td>-12,8%</td>
<td>17,9</td>
<td>-40,6%</td>
</tr>
<tr>
<td>SK</td>
<td>-</td>
<td>24,8</td>
<td>-17,9%</td>
<td>15,8</td>
<td>-47,7%</td>
</tr>
</tbody>
</table>

The concrete specimens exposed on AAR shown a significant reduction of carbonation depth when applied the superficial coating. The reduction is more noticeable if the paint has a good maintenance and is renewed every time that the old coating end its life service period.

3.2. Concrete Specimens Located on COB

Table 3 shows the life service of the paints exposed on COB.

Table 3 - Life service periods for each tested paint exposed on COB.

<table>
<thead>
<tr>
<th>Life Service Period [years]</th>
<th>EN</th>
<th>MP</th>
<th>RB</th>
<th>SK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9,1</td>
<td>9,8</td>
<td>6,3</td>
<td>8,6</td>
</tr>
</tbody>
</table>

On Figure 5, the blue line designated by S/T is the progression of the carbonation front on the unprotected concrete. In continuous lines is the progression of the carbonation front in concrete protected with a paint coating applied just at the beginning of the concrete structure life service. The progression shown as a dashed line represents the concrete with a new paint coating applied every time that the old coat is about the end of its own life service.
On the concrete specimens exposed on COB the carbonation depth for protected concrete had a significant reduction. And that reduction has more impact if the paint is kept with good maintenance and if the concrete is painted every time that the life service period of the paint coating is exceeded.

### 3.3. Concrete Specimens Located on GAR

Table 5 shows the life service of the paints exposed on GAR.

<table>
<thead>
<tr>
<th>Life Service Period [years]</th>
<th>EN</th>
<th>MP</th>
<th>RB</th>
<th>SK</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13,9</td>
<td>16,5</td>
<td>11,7</td>
<td>12,7</td>
</tr>
</tbody>
</table>
On the next figure shows the progression of the carbonation depth on an unprotected concrete (line designated by S/T), the progression of the once painted concrete (continuous line) and the repainted concrete (dashed line).

![Estimation the Carbonation Depth - GAR](image)

**Figure 6 - Estimation the carbonation depth for the concrete exposed on GAR.**

**Table 6 - Estimation of carbonation depth on GAR, at the end of 100 years of concrete exploration phase.**

<table>
<thead>
<tr>
<th></th>
<th>Carbonation Depth [mm]</th>
<th>Carbonation Depth with 1 Paint [mm]</th>
<th>Reduction</th>
<th>Carbonation Depth with Repaint [mm]</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/T</td>
<td>41,0</td>
<td>-</td>
<td>-</td>
<td>21,0</td>
<td>-48,9%</td>
</tr>
<tr>
<td>EN</td>
<td>-</td>
<td>31,7</td>
<td>-22,7%</td>
<td>21,0</td>
<td>-51,3%</td>
</tr>
<tr>
<td>MP</td>
<td>-</td>
<td>30,5</td>
<td>-25,5%</td>
<td>20,0</td>
<td>-46,0%</td>
</tr>
<tr>
<td>RB</td>
<td>-</td>
<td>32,8</td>
<td>-20,0%</td>
<td>22,2</td>
<td>-47,3%</td>
</tr>
<tr>
<td>SK</td>
<td>-</td>
<td>32,3</td>
<td>-21,3%</td>
<td>21,6</td>
<td>-47,3%</td>
</tr>
</tbody>
</table>

As the cases before presented, the application of paint coating to protect the concrete against carbonation has a significant reduction, but for the concrete specimens located in GAR that reduction was even higher.

At the end of 100 years of the exploration phase, the paints effectiveness on protecting the concrete against carbonation has shown the best results. These results was obtained due to a reduce numbers of degradation agents present on this environment. This underground garage has a low incidence of solar radiation, meteorological conditions and polluting agents, therefore the paints are able to protect more effectively the concrete.
3.4. Concrete Specimens Located on CH

The concrete specimens located on CH presented almost opposite results from the cases before. On this environment, the accelerated carbonation coefficient was decreasing as the paint degradation period was higher. This fact occurred due to the concrete saturation and not because of the paint coating protection. The longer the concrete was exposed to high levels of relative humidity more saturate it became and, therefore, more difficult was to the CO$_2$ to penetrate into the concrete. According to Bekker [1988] the CO$_2$ diffusion coefficient in water is approximately 10,000 times lower than in the air. Thus explain the improvement of the accelerated carbonation coefficient and this is probably the main reason why carbonation does not manifest on saturated concretes.

The estimation of paint effectiveness, with this methodology, during its life service, reveals to be insufficient due to saturated concrete itself, which motivate the reduction of the accelerated carbonation coefficient. It was not possible to estimate the life service of the paint exposed on this environmental, and that represents one of the inconvenient of this methodology, the impossibility of predicting the behavior of paints located on high levels of relative humidity.

3.5. Global Analysis of the Painted Concrete Specimens

In every construction the paints coating are chosen by the technical performance and also by their cost. The second factor is as important as the first, thereby, the results obtain with this procedure have to be globally analyzed with the respective cost of the paint. For that reason it was created an equation (4), designated by Final Appreciation ($AF$) and it represents the paint performance with both factors associated.

$$AF = \frac{C_{\text{unit}} \cdot P_{\text{carb}}}{\nu_u}$$

Where,

- $C_{\text{unit}}$ - Unitary cost, [€/m$^2$];
- $P_{\text{carb}}$ - Carbonation Depth at the end of 100 years of concrete exploration phase, [mm];
- $\nu_u$ - Life service period, [years].

The equation was made so it could benefit the paint which has the best technical performance as well as the lowest cost, thus, the lower the value of the equation the better is the paint. With this criterion the paints have the following results:
Table 7 – The results of the Final Appreciation criteria for each paint in each environment.

<table>
<thead>
<tr>
<th></th>
<th>AAR</th>
<th>COB</th>
<th>GAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURONAVY</td>
<td>1.6</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>MAPEI</td>
<td>3.4</td>
<td>3.3</td>
<td>2.4</td>
</tr>
<tr>
<td>ROBBIALAC</td>
<td>2.9</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>SIKA</td>
<td>2.6</td>
<td>2.7</td>
<td>2.3</td>
</tr>
</tbody>
</table>

As Table 7 shows, the EURONAVY paint presented the best results, as well as ROBBIALAC which became the second best paint. Those paints presented such good results due to be the cheapest materials. In the other hand, the MAPEI presented the worst result mainly because the price of the paint. For the SIKA paint, it shown very regular results demonstrating it has a good performance in any environment.
4. Conclusions

The main goal of this investigation was to estimate the life service of paints to protect the concrete against carbonation and also to determinate the evolution of the protection effectiveness during their own life service. Thus it would be evaluated the real protection not only in early ages but also when the paint is almost at the end of life service period.

The methodology used to predict the behavior of the paint, shows that there was a clear evidence of increasing accelerated carbonation coefficient as the natural degradation period was rising. Nevertheless, this procedure revealed a limitation of not being capable of predicting the paint behavior on saturated environments.

With this experimental procedure was estimated a life service between 8 and 16 years for all paints, except for the ROBBIALAC paint, which presented a life service between 5 and 12 years. This last paint showed a premature degradation relative to the other tested superficial coatings.

The option of applying the protective paint just at the beginning of exploration phase of the concrete structure presented a carbonation depth reduction between 15 and 25% in comparison with an unprotected concrete. Although if the paint has a good maintenance and is repainted every time that the life service of the old one is almost at the end, that reduction can be reached between 45 and 50%.

The EURONAVY, MAPEI and SIKA presented good results of protection effectiveness and also the longest life service estimation, with a slightly advantage for the MAPEI which shown the best results of the three paints. On the other hand, the ROBBIALAC paint showed inferior results.

The results obtained in the garage of the Department of Civil Engineering and Architecture in IST, shows that the paint degradation has a strong influence on protecting the concrete against carbonation. The GAR was considered the most adverse environment, in terms of carbonation depth, despite that, the paints have achieved the most effective results. This effectiveness was due to the presence of a small number of degradation agents at this location.

Creating a new criterion which evaluates the technical performance as well as the economical factor, the paints changed their relative positions. In this criterion the EURONAVY showed to be the best paint and the ROBBIALAC climbed to be the second best. But despite MAPEI great technical performance, it appeared at the last position on this criterion.
The ideal situation would be to have a superficial coating that guarantees it would not degrade and also prevents from carbonation, chloride phenomenon and other types of degradation. Theoretically, if that paint were applied there would be an opportunity to diminish the concrete cover to the strictly necessary, so the concrete elements would have the dimension needed only for mechanical strength reasons.
5. References


CHAI, C. V. *Previsão da vida útil de revestimentos de superfícies pintadas em paredes exteriores*. Instituto Superior Técnico, Departamento de Engenharia Civil e Arquitectura, Lisboa, 2011.

