The Effect Of Coatings On The Service Life Of Concrete Facades

Erkki Vesikari
VTT Building and Transport VTT Finland

Summary: The effect of coatings on the service life of concrete facades was studied by computer simulation and tests. Computer simulation makes it possible to study the behaviour of a structure as exposed to normal outdoor weather. The effect of coatings on the moisture content, frost damage, carbonation and corrosion of reinforcement in a structural cross-section was examined.

The impact of a coating on the service life of a concrete structure depends on both the original permeability properties and the rate of deterioration of the coating. For durability design a special coating factor of service life was defined both with respect to frost damage and carbonation. The coating factor expresses the relative extension of service life of a coated structure as compared to the service life of an uncoated structure. By some impregnation agents and organic coatings the coating factor with respect to frost damage may be as high as 6-8. With respect to carbonation organic coatings seem to be most effective. The coating factor by some organic coatings may be as high as 10.

Keywords: Service life, coating, concrete facade.

1 INTRODUCTION

Both the aesthetic appearance and durability of concrete facades may be enhanced by coatings. Even if the main purpose of the coating would be aesthetic the effects on durability must also be considered as they may not always be positive.

Coatings act like barriers against moisture and aerial gases. They retard the flow of liquid moisture and gases through the surface of concrete in both directions. Especially the following phenomena depend on the permeability properties of coatings:

- capillary uptake of rain water into concrete,
- evaporation of pore water from concrete to outside air, and
- diffusion of aerial gases, especially CO₂, into concrete.

All degradation factors of concrete structures depend on the moisture content of concrete either directly or indirectly. So the influence of coatings on the moisture content is extremely important when evaluating their effects on the durability of concrete and reinforcement. Usually coatings retard both the wetting and drying processes. The total impact in varying weather conditions is often difficult to predict. In a facade element of a building there is also a moisture flow from the inside of the wall to the outside that has to be considered. The problem becomes still more complicated by the deterioration of coatings themselves because the permeability properties are changed by deterioration. So the final evaluation of coatings is not an easy task and is only possible by either extensive experience or sophisticated moisture physical calculations combined with material tests.

The moisture content of concrete has a direct influence on the internal frost damage of concrete. If the moisture content of concrete can be preserved below the critical content no frost damage is possible. So by preventing or retarding the water uptake into concrete the coatings presumably improve the durability of concrete with respect to frost damage. However, the protective properties of a coating may degrade in the long term when the permeability of the coating is increased by deterioration. Completely impermeable coatings can hardly be used in facades as there is normally a thermal moisture flow through the wall. Also an impermeable coating may prove to be very vulnerable in long term as small defects in the coating may cause a great local increase in the moisture content endangering adhesion of the coating and frost resistance of concrete.

The impact of coatings on carbonation of concrete is both direct and indirect. On one hand the carbonation is retarded as the coating forms a physical barrier to the diffusion of carbon dioxide into concrete. On the other hand the rate of carbonation is accelerated by coatings that keep the structure dryer as compared to the moisture content without coating. That is because the flow of CO₂ through open concrete pores is more rapid than the flow through water filled pores. The total effect is again difficult to predict.
The corrosion of reinforcement is highly dependent on the moisture content of concrete. The rate of corrosion decreases by low and very high moisture contents. The maximum corrosion rate is found to be around 95% RH.

The degradation of concrete facades is a complex function of weather conditions, properties of concrete, structural details, protective impact of other structures and properties of coatings. There are also several degradation processes and these may interact. For instance frost damage may promote both the carbonation and corrosion of reinforcement. These complicated processes can hardly be studied by direct exposure tests. However, they can be studied by computer simulation combined with laboratory tests.

2 COMPUTER SIMULATION AND RECOMMENDATIONS OF SERVICE LIFE DESIGN

2.1 General

The effects of coatings on the degradation of concrete facades was studied with the aid of a computer simulation programme by which the temperature, moisture content, frost damage, carbonation and corrosion of reinforcement can be reproduced in a structural cross section. The structure was exposed to simulated weather from outside. The weather models consider both daily and seasonal changes of temperature, relative humidity, rain, wind and solar radiation. All the degradation processes are studied simultaneously which enables consideration of interaction of degradation factors. The increment of time in the step by step calculation process is one hour, which is small enough to consider also the hourly variation of weather stresses (Vesikari 1999a and b).

Design recommendations were given for coating protection against frost damage and carbonation using the factor approach (Vesikari 2000). A special coating factor of service life was defined both with respect to frost damage and carbonation. The coating factor expresses the relative extension of service life of a coated facade as compared to that of an uncoated facade:

$$t_{lc} = A_c \cdot t_{lu}$$

where

- $t_{lc}$ is service life of a structure with coating,
- $t_{lu}$ service life of a structure without coating, and
- $A_c$ coating factor of service life.

The designer can choose the recoating frequency but it affects the coating factor of service life both with respect to frost damage and carbonation.

2.2 Moisture content and frost resistance

2.2.1 Computer simulation of moisture content

Well known moisture physical calculation methods were used in the computer simulation of moisture content. The rate of water uptake was controlled by the capillary index ($k$) and the rate of evaporation from concrete was controlled by the moisture transfer coefficient ($\beta$).

By doing capillary water uptake tests in a laboratory with coated and uncoated concrete specimens the reduction factor for the capillary index was defined and determined as follows:

$$m_{k0} = \frac{k_{c0}}{k_u}$$

where

- $m_{k0}$ is reduction factor of the capillary index (new coating),
- $k_{c0}$ capillary index of coated concrete (new coating), kg/(m$^2$$\sqrt{s}$),
- $k_u$ capillary index of uncoated concrete, kg/(m$^2$$\sqrt{s}$).

Correspondingly by doing drying tests with coated and uncoated concrete specimens the reduction factor for the moisture transfer coefficient was determined as follows:

$$m_{\beta 0} = \frac{\beta_{c0}}{\beta_u}$$

where

- $m_{\beta 0}$ is reduction factor of the moisture transfer coefficient (new coating),
\( \beta_d \)  
moisture transfer coefficient with coated concrete specimen (new coating), kg/(m\(^2\)sPa),

\( \beta_u \)  
moisture transfer coefficient with uncoated concrete specimen, kg/(m\(^2\)sPa).

The rate of deterioration in coatings was studied in a laboratory by aging tests. Concrete specimens with coatings were exposed to both UV radiation and freeze-thaw cycles. After the period of aging exposure the water uptake test was repeated. The deterioration of coatings was defined by the increase of the reduction factor of capillary index as follows:

\[
m_k = \sqrt{m_{k_0}^2 + f(t) \cdot (1 - m_{k_0}^2)}
\]

(4)

where

- \( m_k \) is reduction factor of the capillary index with a deteriorated coating,
- \( f(t) \) is deterioration function (0 < \( f < 1 \)),
- \( t \) is time, years.

Correspondingly the reduction factor of the moisture transfer coefficient was determined as follows:

\[
m_e = m_{e_0} + f(t) \cdot (1 - m_{e_0})
\]

(5)

where

- \( m_e \) is reduction factor of the moisture transfer coefficient with a deteriorated coating.

Assuming a linear degradation rate we can write:

\[
f(t) = v \cdot t
\]

(6)

where

- \( v \) is rate of deterioration of coating, 1/s.

The relationship between the rate of degradation in natural conditions and that in the laboratory exposure test was roughly evaluated by experience.

The moisture content of concrete varies depending on the rate of wetting and drying at each moment. The moisture content varies at hourly, daily and monthly levels. If the structure is sheltered from rain the moisture content varies only a little with the varying relative humidity of air. Normally the relative humidity alone is not able to raise the moisture content high enough to endanger the adhesion of coatings or the frost resistance of concrete.

When the structure is exposed to rain the moisture content of concrete normally stays low as long as the coating has not deteriorated. By increasing deterioration of the coating the moisture content of the concrete rises to approach the critical limit both with respect to adhesion failure of the coating and frost damage of concrete. If frost damage takes place the coating completely loses its protective properties. However, even if no frost damage would occur the service life of the coating is considered to end at a high moisture content because the solar radiation causes high cycling pressures on the coating, normally resulting in an adhesion failure. The critical moisture content with respect to adhesion loss is close to that with respect to frost damage, both representing a state when all the capillary pores are filled with water.

2.2.2 Evaluation of the service life of coating by the critical moisture content

The moisture content of concrete surfaces exposed to rain was studied by computer simulation. The values of the reduction factors \( m_k \) and \( m_e \) were varied between 0 and 1. From the results the limiting values for \( m_k \) by which the critical moisture content is never exceeded were determined as a function of \( m_e \). The results could be expressed mathematically in the following form:

Vertical surface:

\[
m_k \leq 0.6 \cdot m_e^{0.6}
\]

(7)

Horizontal surface:

\[
m_k \leq 0.35 \cdot m_e^{0.65}
\]

(8)

The critical lines of \( m_k \) as a function of \( m_e \) are presented graphically in Figure 1.

Coatings that do not fulfil the requirements of Equations 7 and 8 are not recommended in use on exposed concrete facades as the service life of them is probably short. Usually the facade coatings meet this requirement when new but as a result of deterioration they later lose their protective property.
The critical lines below which the moisture content of concrete is always low enough to prevent adhesion failure and frost damage on vertical and horizontal exposed surfaces.

The service life of a coating can be evaluated by inserting terms from Equations 4, 5 and 6 to the condition of Equation 7 on a vertical surface and the condition of Equation 8 on a horizontal surface and solving for the time $t$.

2.2.3 Rules for service life design

In the service life design of coatings the service life of coating is evaluated conservatively by assuming that the deterioration of a coating only effects the water uptake and not the drying process. Then we insert only Equations 4 and 6 to the conditions of Equations 7 and 8 and we get:

Vertical surface

$$t_{Le} = \frac{0.36 \cdot m_{e0}^{12} - m_{k0}^{2}}{v_f \cdot (1-m_{k0}^{2})}$$

(9)

Horizontal surface

$$t_{Le} = \frac{0.12 \cdot m_{e0}^{13} - m_{k0}^{2}}{v_f \cdot (1-m_{k0}^{2})}$$

(10)

where

- $t_{Le}$ is the service life of coating, years.
- The coating safety factor is determined from the formula:

$$\gamma_{tc} = \frac{t_{Le}}{t_{Rc}}$$

(11)

where

- $\gamma_{tc}$ is safety factor of the coating and
- $t_{Rc}$ is period of recoating (given by the designer), years.

The coating factor of service life with respect to frost resistance of the structure, $A_{cf}$ (ref. Formula 1), depends on the coating safety factor $\gamma_{tc}$. The factor $A_{cf}$ increases by increasing values of $\gamma_{tc}$ as presented in Table 1. The values apply to both vertical and horizontal surfaces.

<table>
<thead>
<tr>
<th>Coating safety factor, $\gamma_{tc}$</th>
<th>1</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating factor of service life, $A_{cf}$</td>
<td>1.5</td>
<td>4.5</td>
<td>6.9</td>
<td>8.3</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Several coating systems for concrete facades were tested in a laboratory. The quantities $m_{k0}$, $m_{e0}$ and $v_f$ were evaluated for each coating based on tests. The service life and the safety factor of each coating system was determined as presented above and the coating factor for service life was determined from Table 1.
By some impregnation agents and organic coating systems reasonable service lives for coatings ($t_{coating} > 10 - 30$ years) were obtained on vertical surfaces. The coefficient of service life with respect to frost damage could be as high as 6 - 8. The cement based coatings did not prove to be effective in the protection from frost damage.

Very few coating systems can be recommended on exposed horizontal surfaces. For many coatings the calculated service life appeared to be negative, indicating that these coatings may accelerate the rate of frost damage in concrete. However, some impregnation agents and organic coatings may be beneficial.

### 2.3 Carbonation

#### 2.3.1 Computer simulation of carbonation

The progress of carbonation was determined stepwise by computer simulation. For each time increment the corresponding increment of carbonation depth was determined using relevant parameter values. The parameters of carbonation were the temperature and relative humidity of concrete, depth of carbonation (at the beginning of the time increment), coating parameters, etc. Mathematically the increment of carbonation depth on an uncoated surface can be expressed as follows:

$$\Delta x_{0i} = \frac{k_{ca;i}^2 \cdot \Delta t_i}{2 \cdot x_i}$$  \hspace{1cm} (12)

where

- $\Delta x_{0i}$ is increment of carbonation depth of concrete without coating within the $i^{th}$ time increment, m,
- $k_{ca;i}$ coefficient of carbonation of concrete at $i^{th}$ time increment (depending on moisture content of concrete), m/s$^{0.5}$
- $x_i$ carbonation depth of concrete without coating at the $i^{th}$ time increment, and
- $\Delta t_i$ $i^{th}$ time increment, s.

The increment of carbonation depth of concrete with a non-deteriorated coating is determined as follows:

$$\Delta x_{1i} = \Delta x_i \cdot m_{ca;i}$$  \hspace{1cm} (13)

where

- $\Delta x_{1i}$ is increment of carbonation depth of concrete with a non-deteriorated coating within the $i^{th}$ time increment, m,
- $\Delta x_i$ increment of carbonation depth of concrete without coating within the $i^{th}$ time increment, m (ref. Formula 12) and
- $m_{ca;i}$ the reduction factor of carbonation depth at the $i^{th}$ time increment.

The reduction factor of carbonation depth is determined from the following formula:

$$m_{ca;i} = \sqrt{\frac{1 + 2 \cdot \frac{R_b}{x_{1j-1}}}{1 + \frac{R_b}{x_{1j-1}}}}$$  \hspace{1cm} (14)

where

- $R_b$ is the equivalent concrete thickness of the coating with respect to diffusion of carbon dioxide, m.

The value of $R_b$ is determined by simple carbonation tests with coated and uncoated concrete specimens. As the value of $x_1$ is still unknown, the value of factor $m_{ca}$ is determined using the known value of $x_1$ at the earlier time interval. If the increment of time is one hour the error is insignificantly small.

The increment of carbonation depth of concrete with a deteriorated coating is determined as follows:

$$\Delta x_{2i} = \Delta x_i \cdot \left( m_{ca;i} \cdot f_i \cdot (1 - m_{ca;i}) \right)$$  \hspace{1cm} (15)

where

- $\Delta x_{2i}$ is the increment of carbonation depth of concrete with a deteriorated coating within the $i^{th}$ time increment, m and
- $f_i$ value of the deterioration function at the $i^{th}$ time increment.

In the case of constant degradation rate the value of the deterioration function is determined as follows:

$$f_i = v_j \cdot t_i$$  \hspace{1cm} (16)

where
t_i is total time in the beginning of the i$^{th}$ time increment.

The total carbonation depths $x_0$, $x_1$ and $x_2$ are then determined as follows:

$$x_{ni} = \sum_i \Delta x_{ni} \quad n = 0, 1 \text{ or } 2$$  \hspace{1cm} (17)

where

$x_{ni}$ is carbonation depth on concrete after the i$^{th}$ time increment, m, and

$\Delta x_{ni}$ increment of carbonation depth during the i$^{th}$ time increment, m.

In practice all the three carbonation depths, $x_0$, $x_1$ and $x_2$, are determined simultaneously. As an example the carbonation depths have been determined on a concrete facade as sheltered from rain in Figure 2. In Figure 3 the carbonation depths have been determined when exposed to rain on a vertical concrete facade.

Fig. 2. Progress of carbonation depth on a concrete facade as sheltered from rain:

- $x_0$ at holes of the coating, $x_0$,
- $x_1$ under a non-deteriorated coating, and
- $x_2$ under a deteriorated coating on an average.

Fig. 3. Progress of carbonation on an exposed vertical concrete facade:

- $x_0$ at holes of the coating, $x_0$,
- $x_1$ under a non-deteriorated coating, and
- $x_2$ under a deteriorated coating, as an average.
2.3.2 Rules for service life design

The coating factor of service life with respect to carbonation (ref. Formula 1), can be presented in the following form:

\[ A_{cc} = (1 + \frac{2 \cdot R_b}{c_c} a_f) \] \hspace{1cm} (18)

where

- \( A_{cc} \) is coating factor of service life with respect to carbonation,
- \( c_c \) concrete cover, m and
- \( a_f \) deterioration factor of coating with respect to carbonation.

Without any deterioration the deterioration factor of the coating is 1. If deterioration takes place an approximate function was derived for \( a_f \). The parameters of this approximate function were \( R_b/c_c \) and \( f \). The value of the deterioration function \( f \) is determined at the end of the recoating period:

\[ f = v_f \cdot t_{rc} \] \hspace{1cm} (19)

The coating factors of service life with respect to carbonation can be read from Table 2 as a function of parameters \( f \) and \( R_b/c_c \). The recoating period is chosen by the designer.

Table 2. Coating factors of service life with respect to carbonation.

<table>
<thead>
<tr>
<th>Deterioration function after the recoating period</th>
<th>Coating factor ( A_{cc} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f )</td>
<td>( \frac{R_b}{c_c} )</td>
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<tr>
<td>0.1</td>
<td>0.25</td>
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<td>---</td>
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<tr>
<td>0.00</td>
<td>1.20</td>
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<tr>
<td>0.05</td>
<td>1.20</td>
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<tr>
<td>0.10</td>
<td>1.20</td>
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<tr>
<td>0.15</td>
<td>1.20</td>
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<tr>
<td>0.20</td>
<td>1.20</td>
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<tr>
<td>0.25</td>
<td>1.20</td>
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<tr>
<td>0.30</td>
<td>1.20</td>
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<tr>
<td>0.35</td>
<td>1.20</td>
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<td>0.40</td>
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<td>0.45</td>
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<td>0.50</td>
<td>1.20</td>
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<tr>
<td>0.55</td>
<td>1.20</td>
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<tr>
<td>0.60</td>
<td>1.19</td>
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<tr>
<td>0.65</td>
<td>1.19</td>
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<tr>
<td>0.70</td>
<td>1.19</td>
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<tr>
<td>0.75</td>
<td>1.19</td>
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<tr>
<td>0.80</td>
<td>1.19</td>
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<tr>
<td>0.85</td>
<td>1.19</td>
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<tr>
<td>0.90</td>
<td>1.19</td>
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<tr>
<td>0.95</td>
<td>1.19</td>
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<td>1.00</td>
<td>1.19</td>
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</table>
Carbonation tests were carried out in a laboratory by which the equivalent concrete thickness R_b was determined for each coating system. The rate of deterioration of the coatings was evaluated by test results and experience.

According to the results of calculations the organic coatings proved to be most effective with respect to carbonation resistance. The coefficient of service life by some organic coatings was as high as 10.

3 SUMMARY AND CONCLUSION

The effects of coatings on the service life of concrete facades were studied by computer simulation. The parameters of moisture transfer properties of concrete were modified by reduction factors which were determined by simple laboratory tests with coated and uncoated concrete specimens. The rate of degradation was also evaluated based on tests and experience.

From the results of computer simulation, recommendations for the service life design were given. The coating factors of service life were determined both with respect to frost damage and carbonation. The coating factor expresses the relative extension of service life of a coated facade as compared to the service life of an uncoated facade. The designer can choose the recoating frequency but it affects the coating factor of service life. The recommendations for service life design are general and are based only on functional properties of coatings.

Organic coatings that separate the active capillary pores of concrete from the exposed surface may protect the structure effectively against frost damage. However, they still must be permeable to water vapour. According to calculations the most effective protection against frost damage was provided by water repellent impregnation agents. They set an effective barrier to the rain water but only slightly retard the evaporation of water from the structure.

All coatings deteriorate with time. So frost damage will appear inevitably in concrete if the concrete is not frost resistant and not recoated in time. The recoating period must be shorter than the service life of the coating. The safety margin, which is defined as the relation of the evaluated service life and the recoating period, is the factor by which the effect on the service life with respect to frost damage of the structure is evaluated. By impregnation agents and some organic coatings the coating factor may be as high as 6 - 8.

Almost all coatings lengthen the service life of a concrete facade with respect to carbonation. However, much variation is found in the effectiveness of protection. Cement based materials with a low polymer content and impregnation agents were least effective. By such coatings the service life factor with respect to carbonation was between 1 and 2 while by some organic coatings it was more than 10.

4 REFERENCES

