Hydrophobe IV
4th International Conference on Water Repellent Treatment of Building Materials
Aedificatio Publishers, 3–16 (2005)

Effect of Water Repellent Coatings on the Corrosion Rate of Reinforcement in Carbonated Concrete Facade Panels in a Nordic Climate

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Abstract

Carbonation induced reinforcement corrosion is a widespread and important problem affecting many kinds of outdoor concrete structures which are not exposed to saline environment, for example concrete facades and balconies. In these structures, a water repellent treatment may lower the rate of already initiated corrosion remarkably, which will be favourable from the viewpoint of durability. However, the effect of these treatments can not be easily evaluated theoretically because of the complex moisture behaviour of outdoor concrete structures. In the author's laboratory, an apparatus has been developed which is capable for automated continuous multi-channel field monitoring of corrosion rate of steel reinforcement in concrete. This device is used to evaluate the long-term efficiency of water repellent coating to decrease the corrosion rate of reinforcement in carbonated concrete facades panels. According to the results, the average rates of corrosion decreased roughly by 80 % in the surfaces treated with water repellent coatings compared to "open" surfaces coated with a permeable silicate paint. The corrosion rates in the surfaces treated with water repellent coatings were equal to the one of the surfaces treated with the protective coatings with higher water vapour resistance. From the instantaneous corrosion rates around freezing temperature it can also be concluded that the moisture content of coated concrete has been well below the critical level needed for the development of frost damage.

1 Introduction

Deterioration of concrete structures may lead to extensive need of repair causing large direct and indirect costs. There are many factors leading to repairs, but by far the most part of repair needs is known to result from reinforcement corrosion and disintegration of concrete.

To avoid massive increase of repair costs it is sensible to try to struggle against deterioration mechanisms by protective measures. However, the proven protective treatments, such as cathodic protection and cladding with additional thermal insulation on facade surfaces, are expensive. Therefore, there is a great need for lighter alternatives such as coatings to protect structures from deterioration. The problem is that the performance of many of these light alternatives has not been proven by independent research in representative exposure. They do not usually have a long track record in well-documented conditions either to prove their efficiency.

2 Protection from moisture

Protection of reinforced concrete structures by lowering their moisture content is theoretically an effective alternative because the progress of practically all significant deterioration mechanisms is strongly dependent on the availability of water. Corrosion of steel is most rapid in partially saturated concrete [1] and also the progress of disintegration (frost damage, formation of late ettringite and alkali-aggregate reactions) require that concrete is nearly fully saturated at least from time to time. If the humidity of concrete can be lowered down to 90 % of relative humidity or less, corrosion rate will decrease some 90 % [2] (see also Figure 1). Simultaneously, the disintegration by freeze-thaw exposure halts totally. This simultaneous impact of drying on several degradation mechanisms is useful not only because of this multi-influence, but also because a protection designed to retard one mechanism cannot easily accelerate some other deterioration mechanism. What comes to the acceleration of carbonation due to drying of concrete [3], it is important to realise that protective coatings are not generally intended to be applied to new structures, but as a part of maintenance. In these aged structures it is usual that carbonation has already reached some part of reinforcement. To achieve a durable repair result it is important to make sure that the active corrosion in these spots is slow enough. Another important point is that from experience it is known that corrosion damage due to carbonation has not occurred in those parts of facades where the moisture exposure is low and carbonation quick but just the opposite. In practise, most part of corrosion damage is located in the parts of facades where moisture exposure has been more intense than the average value.

As discussed above, the protection of a reinforced concrete structure by lowering its moisture content is a relatively straightforward and easy method when the viewpoint is in the degradation mechanisms. It turns much more complicated when the different kinds of engineering viewpoints are considered, especially if protective coatings are dealt with.

The evaluation of the efficiency of the coatings to lower the moisture content of concrete structures is a complicated problem. The performance of a coating does not depend on the coating itself alone, but also on the properties of the structure and on the type and level of moisture exposure. The performance of coating in lowering the moisture content of concrete can be evaluated by different kinds of calculations. However, these calculations are in many cases too simple to reflect reality even coarsely. For example,

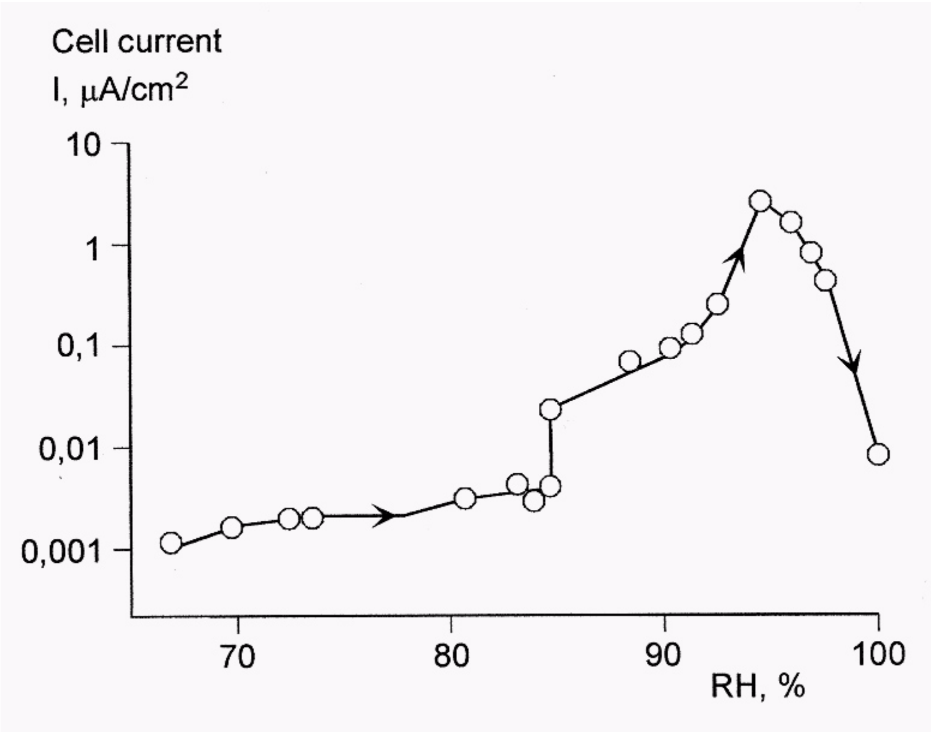

Figure 1: Relationship between cell current and relative humidity in concrete according to [2]

although the majority of the moisture exposure in a sandwich type of concrete panel wall with no ventilation gap results from driving rain, a significant amount of water may find its way behind the coating due to diffusion of indoor humidity or due to leakage of joints or through cracks in concrete. These factors, which might affect the performance seriously, are usually not taken into account in calculations at all.

3 Monitoring of the efficiency of coatings to retard corrosion

The evaluation of the performance of the protective coatings to retard active corrosion is a complex task due to many reasons. The corrosion rate is extremely steeply dependent on moisture content of concrete, as can be noticed from Fig. 1. This means that even a minor beneficial change in moisture content may be sufficient to retard corrosion significantly. Another difficulty is faced in measuring moisture content of concrete. The accuracy of top quality electronic moisture meters is usually not better than ± 3 percentage units relative humidity at high humidity range. Within this range the corrosion rate may vary more than a decade [2]. Another important point is that the maximum reading of relative humidity meters is naturally 100 %, which is, however, not the maximum moisture content of concrete. The super hygroscopic humidity levels should be able to be taken into account as well. Therefore, the performance of coatings to reduce active corrosion cannot be studied reliably by measuring moisture unless the decrease of the moisture content is systematic and large.

Another important point is that the moisture exposure in outdoor concrete structures cannot be simulated accurately enough in laboratory. The reason for this is that all the parameters determining the microclimate inside the structure, which determines the rate of degradation, cannot be predicted accurately enough. This means that the performance of coatings has to be studied in real structures and under real conditions to obtain reliable results.

The moisture conditions of real structures under climatic exposure are known to be in a continuous state of change. Therefore, it is important that the single measurements are taken frequently enough to catch also short-term phenomena. For example, readings taken once a day in the morning might give very different results than the same readings taken in afternoons.

To pass the problems mentioned above, a tailor-made device for the monitoring of corrosion rate of steel in concrete was developed in Tampere University of Technology, Laboratory of Structural Engineering in late 1990's. The developed device uses polarisation resistance method [4]. The device

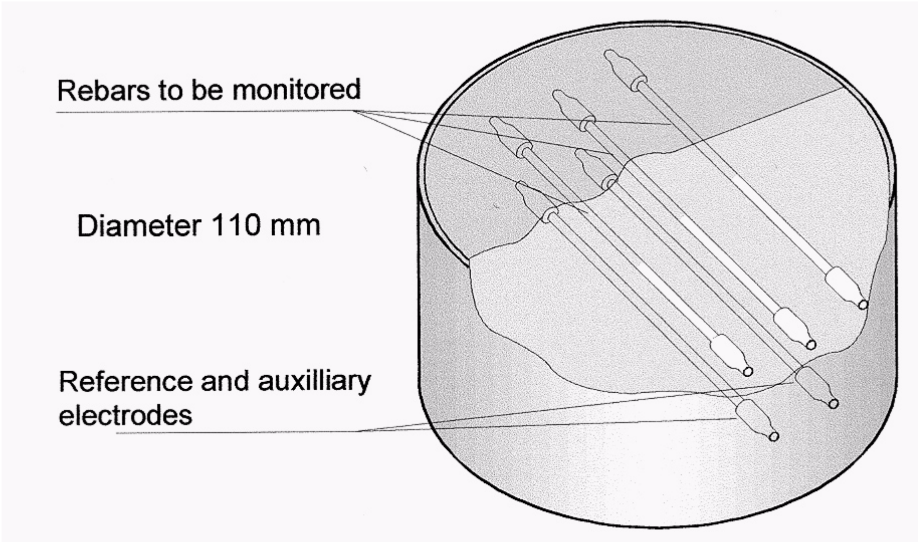

Figure 2: Schematic diagram of the sensor developed

is fully automated to perform continuous monitoring of corrosion rate and equipped with mobile data connection so that no manual operation on site is needed. The device can deal with a maximum of 120 measurement channels. The device is described in more detail in [5].

4 Experimental

4.1 Introduction

The device described shortly in the previous chapter was utilised to monitor the performance of coatings to reduce corrosion rate of steel reinforcement in carbonated concrete facade panels. The practical experimental arrangements are described in this chapter.

4.2 Sensors

For the monitoring of corrosion rate, special sensors to be mounted into structures of existing buildings were prepared (see Fig. 2). The basic idea of the sensors was to simulate reinforced concrete structure where reinforcing steel is corroding in carbonated concrete. The sensor contains reinforcement bars and suitable electrodes for the monitoring of corrosion rate by polarisation resistance method.

Table 1: Mix design and basic properties of the concrete used in the sensors

Quality	Value
Binder	OPC 300 kg/m^3
Water/cement-ratio	0,65
Air content	3,8 %
Compressive strength	25 MPa
Moisture content in capillary saturation	6,2 w-%

The composition of the concrete used in the sensors was selected so that the concrete would be as similar as possible to the concretes used in concrete facades in Finland during 1960’s and 1970’s. The mix design and the basic properties of the concrete used in the sensors are presented in Table 1.

The diameter of sensors was 110 mm and thickness 60 mm, which is the typical thickness of the outer panels of Finnish concrete facades. The steel bars used in the sensors were ordinary cold drawn reinforcement with the diameter of 4 mm and nominal yield strength of 500 MPa. There were three reinforcement bars in each sensor with the cover depths of 5, 10 and 15 mm, respectively.

After casting and 28 days of curing in 40 °C water to achieve high degree of hydration as in old structures, the sensors were exposed to accelerated carbonation in 4 % carbon dioxide according to [6] until carbonation has reached all the studied bars.

4.3 Coatings

Four different coating systems were studied. All the coatings were from the portfolio of Tikkurila Paints Oy. The product description of the coating systems and the basic properties of them measured in this research are presented in Table 2.

The coatings were applied by brush onto carbonated ends of the sensor cylinders according to manufacturer’s instructions.

4.4 Instrumentation arrangements

Coated sensors were mounted in three residential blocks, of which two were located in Tampere (exposed to midland climate) and one in Espoo near to the south coast of Finland (exposed to more severe coastal climate).

Table 2: Product descriptions and basic properties of the coating systems studied

Code	Description	Water vapour permeability *) s_d [m]	Water suctionrate 7 h*) [g/m²s½]
C0	Silicate paint (permeable treatment for a reference)	0.32	0.069
C1	Silicon resin paint	0.57	0.011
C2	Hydrophobic primer and acrylic paint 1	0.89	0.019
C3	Polymer modified finishing mortar 3 mm and acrylic paint 2	1.61	0.014

*)The permeability was measured from the samples, where coating was applied on the concrete discs (mix as in Table 1). The thickness of the discs was 20 mm.

Altogether 14 sensors were installed in each building, five sensors coated with totally open reference paint (C0) and three sensors coated with each water repellent coating. All the sensors were mounted in a horizontal row in the middle of the uppermost wall panels facing to south.

The sensors were mounted into holes drilled through outer leafs of concrete panels (see Fig. 3). The gap between the sensors and the panel were sealed with elastic polyurethane sealant to prevent the leakage of water into the structure. In addition, the envelope surfaces of the sensor cylinders were sealed with aluminium adhesive tape to prevent the moisture transfer between the sensor and the concrete of the outer panel so that the performance of the old coating on the concrete surface surrounding the sensor would not have an influence on the moisture stress of the sensors.

The installation of the sensor took place in the summer 2000 and the monitoring system was installed during the autumn 2000. The collection of the corrosion rate data was started from the beginning of December 2000 and it was stopped at the end of year 2002.

5 Results and discussion

The efficiency of the protective coatings was measured by continuous monitoring of the corrosion rate of reinforcing steel in carbonated and coated concrete. The quantity measured by the monitoring system is the corrosion

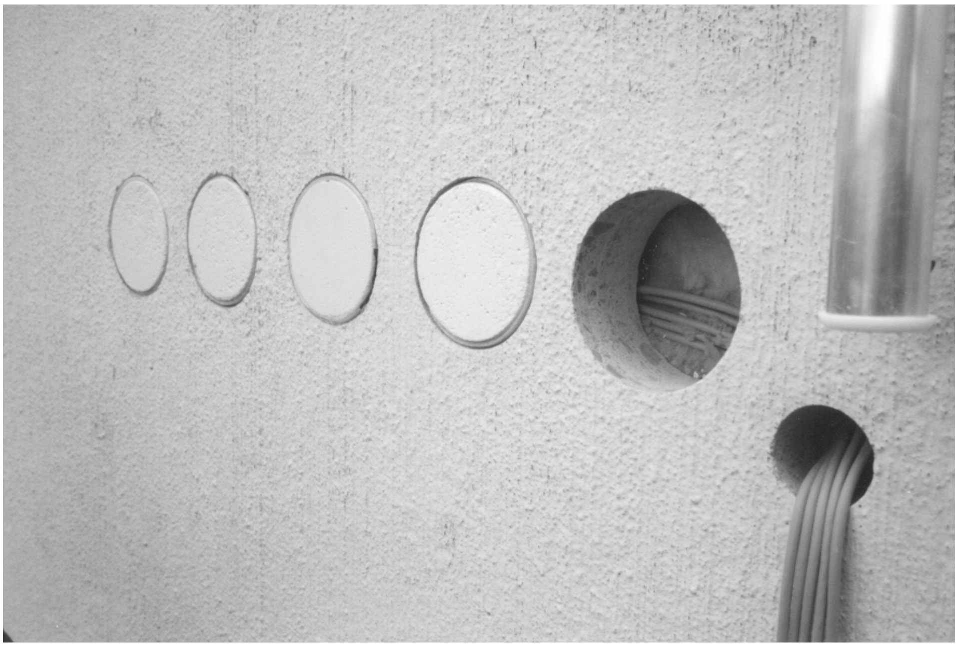

Figure 3: Principle of the installation of sensors into existing structures

current [µA/cm^2]. This was converted to cumulative radius loss of steel section in µm (corrosion depth) by integrating the corrosion currents over time and applying the Faraday's law. This was made to make it easier to get a quantitative picture and significance of the results.

The cumulative radius losses calculated from the monitoring results from the 25 month monitoring period are presented in Fig. 4. The sections of each bar in the figure represent the monthly values of radius loss so that the bottom section of each bar represents the radius loss measured in the first monitored month, i.e. Dec. 2000 and the uppermost section represents the last monitored month, i.e. Dec. 2002. All the sections are not distinguishable in all the bars because of the exiguity of the monthly corrosion especially in the sensors with protective coatings.

From Fig. 4 it can be observed that all water repellent treatments reducing the amount of liquid water intake of concrete (C1, C2 and C3) decreased the corrosion rate of steel in concrete clearly and systematically. The reduction over the monitoring period varied between 68 and 84 % compared to a permeable reference coating (C0) depending on the treatment and building. The reductions in the corrosion rate due to each coating in the three buildings in average are presented in Table 3.

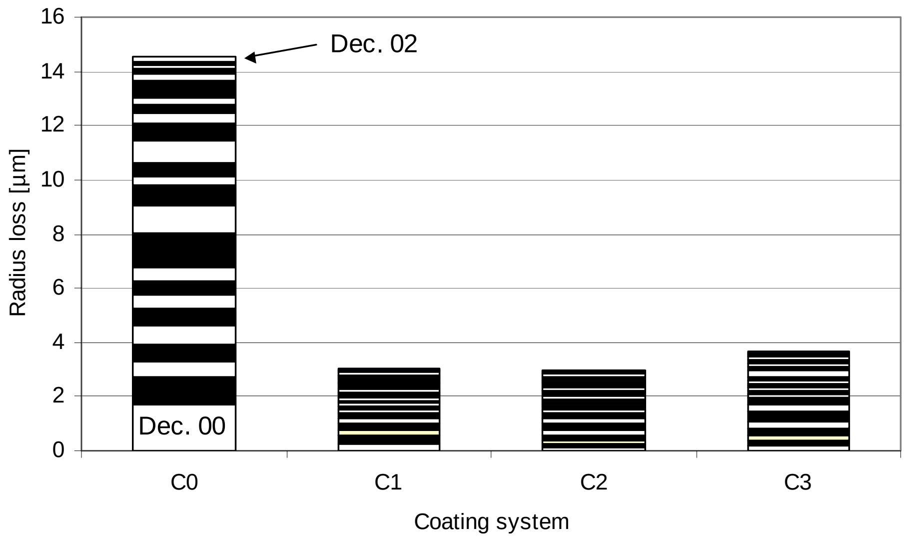

Figure 4: Average cumulative radius losses of steel sections in three buildings in the 25 month monitoring period

Table 3: Average reductions of corrosion rates of steel in the sensors treated with different water repellent coatings compared to the reference sensors treated with a permeable coating

Coating system	C1	C2	C3
Proportional average reduction of corrosion rate compared to reference coating C0	-79%	-79%	-75 %

To evaluate the measured quantities (radius losses), results from [7] and [8] can be used as a guideline. According to these, an average radius loss of 50 µm is required to cause the first visible crack (0.05 - 0.1 mm) in the cover concrete when the cover depth is relatively small. On the basis of this it can be calculated coarsely, what will be the duration of the active corrosion phase before cracking in studied structures. The results from this calculation are presented in Table 4. In the calculation, the limit radius loss is considered to be lower in the case of water repellent coatings because the initiation of crack may weaken the efficiency of the protection even significantly. Therefore, the limit radius loss of 30 µm has been applied in the case of protective coatings.

Table 4: Average yearly corrosion depths and calculated durations of the active corrosion in the structure treated with different coating systems

Coating system	C0	C1	C2	C3
Average yearly corrosion depth during the monitoring period [µm]	7	1.5	1.4	1.7
Duration of the active corrosion [a]	7	21	21	17

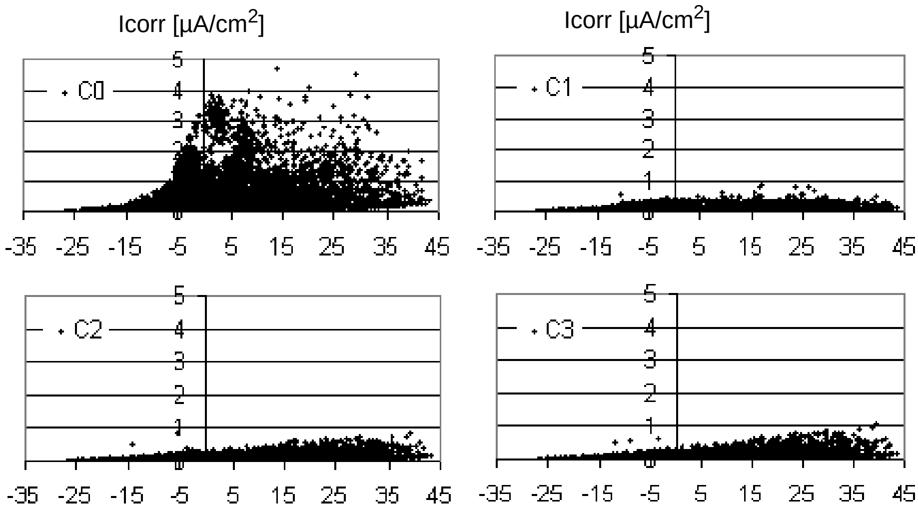

Figure 5: Instantaneous corrosion currents plotted against the temperature of the concrete at the moment of measurement. The horizontal axes represent temperature in °C and vertical axes corrosion current in µA/cm^2

From Table 4 it can be noticed that increase of the service life of the structures can be significant although more strict cracking criteria (30 µm instead of 50 µm) has been applied to water repellent coatings. From the viewpoint of lifespan of a building one or two decades are not a significant period, but from financial point of view it is a remarkable prolongation.

It is worthwhile to notice that also the water repellent coating with very high water vapour permeability (C1) proved as efficient as the more impermeable coatings even during the periods when the air humidity is nearly permanently very high (autumn and winter). Some signs from the permeability can be seen in Fig. 5 where the instantaneous corrosion currents are plotted against the concrete temperature at the moment of measurement. In this figure it can be seen, that the maximum corrosion currents at cold temperatures are only a little bit higher in the case of vapour permeable water repellent coating C1 compared to other protective coatings having greater water vapour resistance. This is probably due to moisture intake in vapour phase when the air humidity is high. On the other hand, in high temperatures the corrosion currents are slightly lower in the case of this coating (C1) than in the case of other protective coatings. This is probably due to fast drying through an open coating in favourable conditions.

The “heavy” coating system (C3) containing polymer modified dense finishing mortar did not show any better than the other protective coatings. One reason for was the good quality of the concrete surfaces in the sensors enabling good quality coating films even without a finishing mortar. The results could have been different if the concrete surfaces would have been uneven like usually after sand blasting of concrete surfaces. In this case the coating system including the finishing mortar might have stood out from the rest of the coatings.

From Fig. 5 it can be also seen that the corrosion rates are in all the conditions remarkably lower in the sensors coated with water repellent coatings than in the sensors coated with a permeable coating (C0). This indicated that the moisture content of concrete is far from the saturation state at the moment of freezing meaning that structures will be efficiently protected by the coatings from frost damage as well.

When considering the reliability of the results it is important to notice that the results depend strongly on the climatic conditions, especially on the number of rainfalls during the monitoring period. Because the period is only a little longer than two years, the conditions might not necessarily fully represent the long-term average conditions. However, on the basis of examination of the meteorological data from the monitoring period, it can be stated, that the weather during the monitoring period was fairly close to the long term average in Tampere (two test buildings) and a little bit drier than normal in Espoo (one test building). This means that the results seem not to be significantly distorted due to abnormal weather conditions.

6 Conclusions

The objective of the work was to study the efficiency of water repellent coatings to retard active reinforcement corrosion in carbonated concrete facades. The results are based on 25 months corrosion rate monitoring of reinforcing steel in coated facades of three existing buildings. Altogether three different types of water repellent coating systems were studied. An inorganic permeable coating was included representing a non-protective reference coating.

On the basis of the results it can be clearly concluded that all the studied water repellent coatings reduced the corrosion of steel significantly. The reduction in the corrosion rate was in average 75 – 80 %. This means that the formation of visual corrosion cracks can be postponed typically for about 10 to 20 years by applying a water repellent coating. Naturally, the prolongation of the service life depends on how much corrosion has been occurred before the application of a protective coating. Another important point is that the coating has to be kept in good shape by sufficient maintenance to get the full-scale protection. This is extremely important especially if the water vapour resistance of the coating is not very low. In this case local defects in coating film may cause accumulation of water behind coating, which means that an originally protective coating may turn to be detrimental for the structure.

Another important finding was that also a water repellent coating with a high water vapour permeability performed as well as the coatings with higher water vapour resistance. The efficiency of this type of coatings is an important finding because these coatings can be considered as most safe alternative, because they do not hinder the drying in potential defected points.

The coating system containing a polymer modified finishing mortar did not prove any more efficient than the other protective coatings. This is probably due to the good quality of the concrete surface which enabled good quality coating films without a finishing mortar.

From the corrosion rates at freezing temperatures it can be concluded that moisture content in concrete was low enough to prevent also propagation of frost damage. This is an important observation especially in Nordic climates where frost damages are common in ageing concrete facades.

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