Assessment of reinforcement corrosion in concrete façades

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ABSTRACT: Outdoor concrete structures are damaged by several different phenomena whose propagation, again, is influenced by many structural, condition and material factors. In Finnish climate disintegration of concrete and corrosion of reinforcement are the most significant mechanisms creating need to repair concrete facades. The aim of facade condition investigations is to provide the property owner and designers information to help them decide on the repair needs and possibilities of facades and to select the repair methods best suited for each facility. The content of the condition investigation must be such that set goals are met. Generally, a condition investigation is made to determine the remaining service life of examined structures, their need of repair and safety. To achieve that, the investigation must reveal any damage to structures and defects in their performance. This requires determining the existence of damage, its extent, location, degree, impacts and future propagation by damage types.

1 INTRODUCTION

1.1 *Background*

A lot of concrete facades, over 30 million square metres, have been built in Finland since the 1960s as well as more than half a million concrete balconies. Thousands of other structures have also been built so far of concrete such as bridges, multi-level car parks, industrial plants, etc.

The maintenance and repair of these concrete structures has presented many problems. They are subject to many different types of degradation whose propagation, again, is affected by many structural, condition and material factors. Consequently, their service lives vary a lot in practice. Unexpected and technically and cost-wise significant repair need has occurred in the structures early on – sometimes only 10 years from completion.

Concrete structures have been repaired extensively in Finland since the early 1990s. Repair methods and materials have also been developed simultaneously as well as instructions for determining repair needs. Besides the correct repair method, it is also important to be able to determine the optimal time of repairs both technically and economically.

1.2 *Condition investigations*

Damage to structures, its degree and extent, due to various degradation phenomena can be determined by a comprehensive systematic condition investigation. A condition investigation involves systematic determination of the condition and performance of a structural element or an aggregate of structural elements (e.g. a facade or balcony) and their repair need with respect to different degradation mechanisms by various research methods such as examining design documents, various field measurements and investigations and sampling and laboratory tests.

The wide variation in the states of degradation of buildings, and the fact that the most significant deterioration is not visible until it has progressed very far, necessitate thorough condition investigation at most concrete-structure repair sites. Evaluation of reinforcement corrosion and the degree of frost damage suffered by concrete are examples of such investigations.

Condition investigation systematics for concrete facades and balconies have been developed in Finland since the mid-1980s. The following is based on the authors' experiences from about 150 condition investigations of concrete structures, long-continued development of condition investigation systematics and national condition investigation instructions (Anon. 2002).

2 GENERAL ASPECTS OF CONDITION INVESTIGATION

Information about the condition of concrete structures needed for the planning and design of repair work can only be acquired by a systematically conducted condition investigation. The main reason for this is that the general degradation mechanisms related to concrete structures normally proceed for relatively long before becoming visible.

The following instructions should be followed in a condition investigation in order to ensure its reliability:

1. The investigator must have sufficient knowledge about the performance and properties of the examined structures. He must also thoroughly understand the degradation mechanisms, defects, deficiencies, and repair methods at issue. Then, he can focus on studying the appropriate problems and collecting information and observations that are relevant to the client's needs.

2. The examined subject must be divided up into structure groups according to performance, type, material and exposure conditions, so that the systematic variation in the state of degradation and properties of structures between the groups can be detected.

3. The investigation must be able to determine the state of all potential degradation mechanisms that endanger the performance and durability of the structure as well as the structural and exposure factors that affect their progress.

4. An effort must be made to examine each issue under scrutiny using several parallel information collection and measurement methods.

5. Observations and measurements describing the state of different degradation mechanisms must be produced in sufficiently representative and large samples, so that the conclusions drawn on the basis of samples are reliable.

6. Sufficiently valid and reliable methods must be used for observations and measurements.

7. The collected information must be analysed carefully, so that the condition and repair need of structure groups can be determined. Conclusions must be clearly based on collected factual information. The existence, extent, degree and reasons for different types of degradation are examined as factors governing the condition of each structure group. Then, the impact of degradation on the structure's performance (e.g. safety), the propagation of degradation, suit**able** repair methods, and recommended timing of repairs can be assessed.

3 DEGRADATION MECHANISMS

The degradation of concrete structures with age is due primarily to weathering action which deteriorates material properties. Degradation may be unexpectedly quick if used materials or the work performance have been of poor quality or the structural solutions erroneous or non-performing. Weathering action may launch several parallel deterioration phenomena whereby a facade is degraded by the combined impact of several adverse phenomena. Degradation phenomena proceed slowly initially, but as the damage propagates, the rate of degradation generally increases.

The most common degradation mechanisms causing the need to repair concrete facades, and concrete structures in general, are corrosion of reinforcement due to carbonation or chlorides as well as insufficient frost resistance of concrete which leads to, for instance, frost damage (Pentti et al. 1998).

These degradation mechanisms may result in, for instance, reduced bearing capacity or bonding reliability of structures. Experience tells that defective performance of structural joints and connection details generally causes localised damage thereby accelerating local propagation of deterioration.

3.1 *Corrosion of steel*

Reinforcing bars in concrete are normally well protected from corrosion due to the high alkalinity of the concrete pore water. Corrosion may start when the passivity is destroyed, either by chloride penetration or due to the lowering of the pH in the carbonated concrete.

3.2 *Carbonation*

Carbonation of concrete is a chemical reaction where atmospheric carbon dioxide diffuses into the pore system of concrete and reacts with the alkaline hydroxides of concrete. Due to carbonation, the pH of the concrete decreases from the level of 13 to the level of 8.5 and the passivity of reinforcing steel is lost. This initiates the active corrosion if there is enough moisture and oxygen available in the concrete.

Carbonation begins at the surface of a structure and propagates as a front at a decelerating rate deeper into the structure. The speed of propagation is influenced foremost by the quality of concrete (proportion of cement and density) as well as rain stress. Heavy rain stress slows down carbonation.

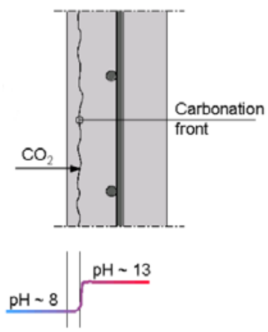

Figure 1. Carbonation propagates as a front into the structure (Varjonen et al. 2006).

The high alkalinity of concrete protects the reinforcement within from corrosion. When the carbonation front advances in concrete to the depth of the reinforcement, the surrounding concrete neutralises and corrosion of reinforcement can begin. The rate of corrosion clearly depends on the moisture content of concrete and advances significantly only at over 80 % RH (Tuutti 1982). Corrosion lowers the tensile and bond strength of reinforcement while the pressure from corrosion products causes the concrete cover around the reinforcement to crack.

3.3 *Chloride contamination*

It is possible that chlorides have been added to the concrete mix during preparation to accelerate hardening. Chlorides were used mainly in the 1960s in connection with on-site concreting and in prefabrication plants during the cold season when concrete hardens slowly. The amount of salt used as accelerator was generally manyfold compared to steel's corrosion threshold.

Chlorides may also penetrate into hardened concrete if the concrete surface is subjected to external chloride stress, for instance, on bridges in the form of de-icing salts. Strong spotty corrosion is characteristic of chloride corrosion of reinforcement, and it may propagate also in relatively dry conditions. Chloride-induced corrosion becomes highly accelerated when carbonation reaches reinforcement depth whereby the extent of visible damage may increase strongly in a short time.

3.4 *Active corrosion*

Once the passivity is destroyed either by carbonation or by chloride contamination, active corrosion may start in the presence of moisture and oxygen (Parrott 1987). Corrosion may run for a long time before it can be noticed on the surface of the structure. Because corrosion products are not water soluble, they accumulate on the surface of steel nearby he anodic area (Mattila 1995). This generates an internal pressure, because the volume of the corrosion products induced by carbonation is four to six times bigger than original steelbars (Tuutti 1982).

Internal pressure caused by corrosion products leads to cracking or spalling of the concrete cover. Visible damage appears first on the spots where the concrete cover is smallest.

Due to corrosion, the diameter of steel bars becomes smaller and their tensile capacity is weakened. Thus, besides the aesthetic problems the corrosion may also cause a safety hazard.

3.5 *Disintegration of concrete*

Concrete is a very brittle material. It can stand only extremely limited tensile strains without cracking. Internal tensile stresses due to expansion processes inside concrete may result in internal cracking and, therefore, disintegration of concrete. Disintegration of concrete accelerates carbonation and this way also steel corrosion. Concrete may disintegrate as a result several phenomenon causing internal expansion, such as frost weathering, formation of late ettringite or alkali-aggregate reaction.

3.6 *Frost resistance of concrete*

Concrete is a porous material whose pore system may, depending on the conditions, hold varying amounts of water. As the water in the pore system freezes, it expands about 9 % by volume which creates hydraulic pressure in the system (Tuutti 1982). If the level of water saturation of the system is high, the overpressure cannot escape into air-filled pores and thus damages the internal structure of the concrete resulting in its degradation. Far advanced frost damage leads to total loss of concrete strength.

The frost resistance of concrete can be ensured by air-entraining which creates a sufficient amount of permanently air-filled so-called protective pores where the pressure from the freezing dilation of water can escape. Finnish guidelines for the air-entraining of facade concrete mixes were issued in 1976 (Anon. 2002).

Moisture behaviour and environmental stress conditions have an impact on frost stress. For instance, the stress on balcony structures depends on the existence of proper waterproofing.

3.7 *Formation of ettringite*

In certain conditions crystalline substances may form in concrete pores and take up pore space. In the initial stages this is not generally detrimental to the concrete structure. It becomes problematic if the protective pores start to fill up which lowers the frost resistance of concrete. It is also possible that the crystallising substance itself creates tensions within the concrete that damage it. One substance of this type is ettringite that forms in concrete, for instance, as a result of excessive thermal treatment.

The ettringite reaction is a chemical reaction caused by sulphate minerals that occurs in hydrated cement. It involves strong volume expansion of reaction products, or swelling, since the volume of ettringite is 300-fold compared to the volume of the reactants (Anon. 1989). The forming ettringite mineral crystallises onto the walls of the air-filled pores whereby the volume of protective pores and the frost resistance of concrete decrease. An ettringite reaction may lead to concrete degradation either as a result of frost weathering or as the pressure created by the filling of pores produces cracks in the concrete.

3.8 *Alkali reactivity of aggregate*

An alkali-aggregate reaction is an expansion reaction in the concrete aggregate due to the alkalinity of hydrated cement, which may degrade concrete. The reaction requires that the cement contains an abundance of alkalis (Na, K), the aggregate includes minerals with low alkali resistance, and the moisture content of the concrete is sufficiently high (Punkki & Suominen 1994).

Alkali-aggregate reactions are generally divided into alkali-silicon, alkali-carbonate and alkali-silicate reactions depending on the reacting aggregate (Punkki & Suominen 1994). Finnish dense deep-seated rocks generally have high chemical resistance which makes the phenomenon rare in Finland.

A concrete structure affected by an alkali-aggregate reaction is typically stained by surface moisture, exhibits irregular pattern cracking and swelling and has a gel-like reaction product oozing out of the cracks (Pentti et al. 1998). The damage caused by the alkali-aggregate reaction resembles the cracking due to frost weathering and both often appear simultaneously.

4 FIELD AND LABORATORY INVESTIGATIONS

The cause and exact extent of corrosion damage can be determined by laboratory and field tests. Initial data for the study of corrosion of reinforcing steel is gathered from the documents and by visual inspection. By visual inspection it is possible to estimate:

- the amount and location of visible damages (spalls, cracks, rust stains or spots)
- the depth of covering concrete in damaged spots
- the moisture behaviour that affects the rate of active corrosion.

The assessment of the amount of steel in active corrosion state at various depths is based on samples of carbonation depths and cover depths of reinforcement. In the field, the distribution of cover depths is measured by covermeter separately from each group of structures. In laboratory it is possible to determine the penetration of carbonation from core samples by using phenolphthalein indicator.

The progress of chloride corrosion can be estimated on the basis of depth of chloride penetration. The critical content is usually considered to be between 0,03 – 0,07 % by weight of concrete (Varjonen et al. 2006). When this content is exceeded at the level of reinforcement, corrosion is initiated. The chloride contamination is measured from drilled powder samples for example by titration.

In condition investigation it is not possible to investigate every facade panel or balcony element one by one, but field examination and taking of samples for laboratory tests must be carried out by sampling. Investigation methods must be cost-effective. Cheaper methods, like visual inspection, can be used for extensive investigation, which are confirmed by more expensive methods like sampling and laboratory tests.

5 ESTIMATION OF SERVICE LIFE CONCERNING STEEL CORROSION

The remaining service life of a concrete structure is estimated on the basis of the expected impact of damage on reinforcement corrosion and related safety of the structure as well as the future rate of damage propagation.

The extent of corroding reinforcement can be estimated by comparing the carbonation or chloride depth distribution of concrete to the cover depth distribution of reinforcement.

5.1 *Propagation of reinforcement corrosion*

The corrosion state of reinforcement can be estimated by comparing the carbonation distribution of concrete to the cover depth distribution of rebars according to Figure 2.

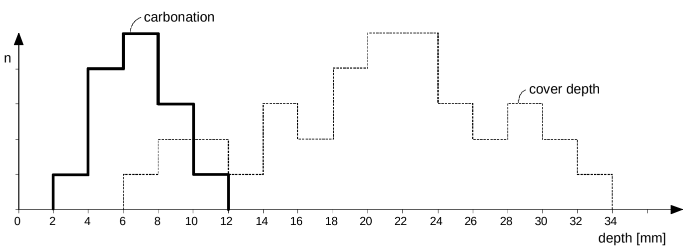

Figure 2. An example of histograms of measured carbonation and cover depth distributions (Pentti 1999).

Future propagation of concrete carbonation can be estimated by the so-called square-root model (Tuutti 1982), according to which carbonation in concrete advances at a decelerating rate as a function of time:

$$x = k\,t^{0.5} \qquad (1)$$

where,

x is carbonation depth [mm]

k is carbonation coefficient [mm/$a^{0.5}$]

t is time [a].

This model allows calculating the time when the carbonation front reaches the reinforcement or the share of rebars in corrosion state at each moment in time.

The advancement of chloride corrosion can be estimated by the so-called critical chloride content. Literature considers the critical content to be around 0.03–0.07 % of concrete by weight, and in Finnish guideline (Anon. 2002) 0.05 % is usually used critical chloride content. When the critical chloride content is exceeded at the level of reinforcement, it starts to corrode.

The amount of chlorides added during mixing of concrete does not increase as a function of time which means that if the chloride threshold is not exceeded, there is no chloride corrosion. In the case of concrete structures exposed to chloride solutions, such as road bridges, the penetration depth of chlorides must be monitored regularly.

5.2 *Safety of structures*

The estimation of the overall service life of a building or structure requires combining the effects on various structures by different degradation mechanisms. The continued safety of each structure must be assessed and a decision made whether to use the structure to the end of its service life or repair it – appearance of the building must also be a consideration.

The safety of a structure is essentially affected by, for instance, frost damage to reinforcement, various embedded fixtures and anchorage zones of connecting trusses as well as corrosion of reinforcement. Far advanced degradation may also cause spalling of the concrete cover and breaking off of pieces of concrete.

6 CONCLUSIONS

A condition investigation allows evaluating the remaining service life of structures. This involves assessing the service life of a damaged structure which the generally used service-life models normally do not do. Based on the results of the condition investigation, the impacts of degradation can be estimated and the occurrence of future damage predicted when no visible damage yet exists.

Properly timed maintenance measures can often arrest propagation of degradation effectively thereby increasing the service life of a structure.

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