CHAPTER 8

Environmental deterioration of building materials

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1 Introduction

By the durability of individual building materials and of the structures built of them, it is the time of usability under preservation of their original properties is understood. The words corrosion and deterioration are primarily derived from this term. Corrosion is applicable to metals, reinforcement and polymers. For silicate building materials such as concrete, plasters, mortars, we use the term deterioration. Deterioration of concrete is a gradual and irreversible permanent erosion of its basic properties leading to its disintegration. The study of concrete and building material deterioration and durability and the knowledge of these properties form the fundamental basis for the evaluation of structures. The durability of structures is influenced by many factors. The general defects and failures of building structures can be divided into the following (see Fig. 1):

- deterioration by the environment,
- defects and failures in design and in completion of structures,
- unsuitable design,
- bad quality of material,
- bad execution, and
- failures caused by inappropriate utilisation.

Defects and failures of buildings can be eliminated by proper control of products and execution of construction, and inappropriate utilisation of materials can also be eliminated. Generally, we cannot influence the environment much.
For this reason, it is necessary to select suitable materials for structures with the knowledge of their deterioration processes in a given environment. Different types of environment have been described in the earlier chapters of this book. This chapter provides practical examples of construction deterioration. Buildings were mostly damaged by the atmosphere as a result of CO₂ effect (carbonation), SO₂ effect (sulphation) and by different forms of water effect. The last cause manifests itself during condensation and frost effect and even afterwards as water supply for the necessary chemical reactions. Effects of groundwater in the form of dilatation are mentioned as examples of corrosive liquid media. Finally, biological effects and the influence of stray currents are represented which, besides their corrosive activity on the reinforcement of reinforced concrete, can negatively act in different forms of corrosion, for instance, in reaction with sulphates.

2 Damage to residential and office buildings

The amount of influence of environmental deterioration depends mainly on the kind of building material used. The influence of the building structure is not so significant. The kinds of building materials were significantly determined in the past by local availability and transport limitations. This fact has an influence even at the present time when the selection of building materials is influenced by tradition, especially with regard to residential buildings built by individuals.

Building materials for building of family houses consist mostly of wood, ceramic and bricks materials, concrete (blocks, components), cellular concrete, blocks from alternative materials – sawdust concrete, stone in some regions and other alternative materials, as the case may be. The same types of structures and materials are currently used in such cases for large residential and office buildings too.

This concerns mostly skeleton building systems with a load-bearing structure of reinforced concrete or steel. The internal division and jacketing is made from prefabricated cellular panels, concrete or ceramic products.
2.1 Concrete and reinforced concrete structures

Concrete, which is a material with alkaline reaction, can be attacked by many corrosive factors. The common corrosive medium for all reinforced concrete structures of residential and office buildings are corrosive gases of acidic character. These corrosive gases are contained mainly in pollutants. The corrosive effects of gases from the atmosphere are significant, in particular, if gases can penetrate into concrete.

Among corrosive gases, carbon dioxide \( \text{CO}_2 \), sulphur dioxide \( \text{SO}_2 \), sulphur trioxide \( \text{SO}_3 \) and the nitrogen oxides are important. The \( \text{CO}_2 \) concentration in the atmosphere is on the whole stable; it is about 60 mg in 1 m\(^3\) of air. A great increase of concentration can be observed in \( \text{CO}_2 \) sources, for instance, in large deposits of natural springs. The normal \( \text{SO}_2 \) concentration in the natural environment does not exceed 0.01 mg in 1 m\(^3\) of air. An increased \( \text{SO}_2 \) concentration is identified in large industrial centres. The nitrogen oxides are mostly secondary products of motor traffic, but we can find them in great quantities in atmosphere polluted by chemical industries, and they are mostly not the decisive corrosive factor.

Water vapour from the atmosphere, much like carbon dioxide and other gases, penetrates capillary, porous materials by diffusion. The moisture penetrates into building structures not only in the gaseous state but also in the liquid state (capillary elevation, leaking in, etc.). Diffusion cannot take place in pores filled with water. The course of diffusion determines if corrosive chemical reactions will take place at all and, if so, under what conditions. Diffusion thus has an influence on the results of corrosive reactions.

2.1.1 Carbonation of concrete structures

Carbon dioxide in contact with cement that is formed by basic hydration binder products starts a neutralisation reaction – carbonation. The main products of this reaction are different carbonates.

The carbonates formed by carbonation generate new formations of insoluble \( \text{CaCO}_3 \) sediment in pores and capillary tubes which are filled by them step by step. This process decreases the possibility of new \( \text{CO}_2 \) penetration. In dense concrete it causes an external decrease of the concrete’s permeability. This factor is very important as it explains why the perfectly dense concrete is resistant against the harmful effect of carbonation and why the steel reinforcement in it remains protected against corrosion for many decades.

The most common kinds of concrete, especially those of lower and medium strength class, have a higher porosity that cannot be substantially lowered by the new carbonate formations and thus results in lower permeability of concrete to gases and vapours. Carbonation progresses into still greater depth, attacks the adjoining cement paste and, due to the decrease of pH, causes a very strong corrosive reaction of the reinforcement. The effects of carbonation on reinforced concrete structures can be expressed by two consequences (see Fig. 2).

When concrete is saturated with water, the micro pores of the concrete are practically completely filled with water and the water film prevents deeper gas penetration into the internal parts of the concrete, even if the gases are dissolved in
Concrete cannot passivate reinforcement against corrosion.

Consequence 2
- pH decreases cement paste from original value 12.4 to roughly 9.0-9.6
- Reaction with hydration products
  - Other products: $C_xA_H_y$, $C_xA_S_H_z$
  - $Ca(OH)_2$
  - Calcium hydroxide $C_xSH_y$
  - $CaCO_3$ in different modifications

Water as in the case of CO$_2$. If the pores are filled with water, concrete carbonation becomes significantly slower. However, the presence of a certain level of moisture in concrete is the condition for the proceeding of carbonation, which is an ionic reaction. Completely dried concrete does not react with CO$_2$ and other gases at all. The dependence of concrete carbonation velocity on the relative air moisture is graphically depicted by Matoušek and Drochytka (Fig. 3).

Figure 2: Scheme shows two different consequences of carbonation. Nomenclature: C – CaO, S – SiO$_2$, A – Al$_2$O$_3$, H – H$_2$O [1].

Figure 3: Dependence of the concrete carbonation on relative air humidity by Matoušek and Drochytka [1].
2.1.2 Four stages of carbonation

The process of carbonation, following long-term knowledge and measurements, has been divided into four correlated stages. The stages of concrete carbonation are very important for a correct evaluation of corrosion and the rehabilitation of the design of concrete structures.

In the first stage of carbonation, Ca(OH)\textsubscript{2} or its water solution in the inter-granular space is transformed into insoluble CaCO\textsubscript{3} which partially fills the pores. The main physical-mechanical parameters of concrete improve.

In the second stage, the rest of the cement hydration products are attacked by carbon dioxide. The products of these reactions are calcium carbonate (CaCO\textsubscript{3}) and the amorphous gel of silicic acid. These substances remain in pseudo-morphologic forms after the products of binder hydration and a part of them creates very fine new crystalline formations of CaCO\textsubscript{3}, respectively. New, coarse crystalline formations occur very rarely. The concrete properties do not change much; the mechanical properties fluctuate in the range of the original values.

The third stage of carbonation is characterised by the recrystallisation of the new carbonate formations previously formed from the inter-granular space. At the same time, many calcite and aragonite crystals that are relatively very large – ten-times and even greater – in comparison with the former systems are formed. The physical-mechanical properties of concrete gradually decrease during the third stage. A significant decrease of the concrete pH also takes place.

The fourth stage is characterised by almost hundred per cent carbonation. The coarse crystals of aragonite, and those of calcite, penetrate the total material structure of the cement mass. This can cause, in the worst case, a loss of the cement mass cohesiveness and strength. In this stage the pH is of course low, and a significant corrosion of the reinforcement takes place. This phenomenon can be graphically represented as seen in Fig. 4 (schema) and Fig. 5 (practical example).

![Diagram of carbonation process]

Figure 4: The picture represents the progress of carbonation into concrete, closer to the rebar, and consequences of the carbonation [2].
2.1.3 Alkaline reaction of aggregates
Further possible defects discovered in office buildings were in the area of alkaline dilatation (see Fig. 6). This was described in detail in Chapter 5.

2.2 Masonry structures
Masonry structure differs according to the material used for bricklaying—bricks, blocks, concrete, cellular concrete, blocks from alternative materials etc.
The surface treatment of masonry structures is the most sensitive part of these building structures. An attack by the surrounding shows itself first on facing walls. The damage caused by water takes place mainly in the following ways:

- Water contained in the pores of the material at temperatures below the freezing point turns to ice, and forces formed during crystallisation damage the masonry structure.
- Water containing soluble substances – crystallisation during the drying of water – creates pressures that damage the plaster and the masonry, which is also referred to as efflorescence.
- Water washing out the binding components, soaking and decreasing the strength of materials, neutralisation reaction of acid rains and lime binder – all lead to the decrease of strength of the masonry (mortars, plasters, masonry from cretaceous marly limestone, limestone and sandstones with lime cement).
- Different types of volume changes – dilatation is determined by the presence of water.

2.2.1 Brickwork

As mentioned earlier, the most frequent damage of brick masonry is caused by water and by moisture in general. The brick body is relatively resistant against other corrosive environmental factors (CO₂, SO₂ solid and liquid materials such as oil products, etc.). A detailed description of the frost effect is given in Section 3.2 in Chapter 7 and the damage caused by crystallisation pressure of salts is described in Section 3.3 in Chapter 7.

The problem of mortars, and masonry mortar durability, is discussed in detail in Section 4 and especially in the Section 4.1.1 of Chapter 7.

2.2.2 Cellular concrete structures

Cellular concrete is a progressive, light building material that considerably surpasses the utilization of cellular aggregates and of concrete manufactured with these aggregates. The building systems YTONG and HEBEL are the most well-known producers of cellular concrete at the present time. They are used especially for their excellent heat-insulation properties, the favourable relationship between mechanical strength and volume mass, superior workability and more particularly for the completeness of individual building elements and the subsequent high productivity of construction. Cellular concrete has found a way into residential, agricultural and even industrial construction, especially as blocks, insulation plates or as wall components for the outer jacket of buildings. Cellular concrete represents worldwide 10% of the market of bricklaying materials, whereas in the Czech Republic it claims 25–27%.

On the other hand, there are many constructions using cellular concrete showing a typical system of failures. The failures of structures made from cellular concrete blocks are mostly caused by:

- chemical aggression of the environment,
- efflorescence,
2.2.2.1 Chemical corrosion of the environment

The durability of cellular concrete, in the strict sense of the word, is chiefly understood as the frost resistance of cellular concrete and its resistance to atmospheric effects (acid rain, gases CO₂, SO₂ and H₂S). The influence of corrosive substances is increased by the macroporosity of cellular concrete, making the deep penetration of the above-mentioned substances into the material easily possible. On the other hand, this macro-porosity improves resistance against new formations of carbonation or sulphation because it enables the growth of new crystals in the pores. The velocity of atmospheric corrosion in the case of both gases is significantly influenced by the moisture of the building material (see Fig. 3 and the description of carbonation in Section 1 in Chapter 1).

Moisture, and the frequent addition nowadays of gypsum in cellular concrete production can lead to the formation of thaumasite 3CaO·SiO₂·CO₂·SO₃·15H₂O, which by its volume pressure in the first phase, can cause the formation of micro-cracks in the masonry. The formation of thaumasite was observed mostly at the places of loading joints, i.e. in mortars with the Portland clinker.

Another chemical factor influencing cellular concrete durability is the formation of efflorescence. We know cases during the reaction with the cellular concrete mass in the autoclave when feldspar with high alkali content formed easily soluble compounds, which were subsequently leached. By the influence of the diffusion gradient these compounds gradually appeared on the surface, in spite of the properly applied surface treatment, forming crystals with dimensions up to 20 mm.

2.2.2.2 Volume changes

In silicate building products we observe two types of volume changes: hydration-change and post-hydration change. In the case of cellular concrete, only post-hydration changes take place. The most frequent volume changes are connected with drying and moistening. These are chiefly reversible changes of drying from the state containing the production of moisture of 30% to the constant moisture of about 6%. These changes, following valid standards, can be the cause of shrinkage of 0.15–0.20 mm/m. Owing to the influence of these changes in the so-called ‘unripe buildings’, i.e. buildings with high moisture content, destruction can take place that manifests itself mainly externally on the facing. Typical examples of plaster damage can be found in Fig. 7. The failures were caused at first by the formation of thaumasite in the loading joint between blocks, and successively by moisture problems with diffusion-proof painting, which was implemented in November. The enclosed moisture after the first frosts damaged the whole structure.
Figure 7: On the left can be seen a typical defect of cellular concrete. As the result of volume changes wall-cracking took place and cracks appeared even on the façade – typical drawing of individual wall blocks. The defect on the right is caused by volume changes resulting from wall drying. The next set of problems are defects of the wall-surface layer by frost because of the high diffusion resistance of this layer and the prevention of drying which caused the freezing of surface layers.

2.2.3 Concrete structures
Concrete structures from plain concrete are not a common material for building structures. Plain concrete is used for the manufacture of blocks with thermal insulation for outer building jackets, without thermal insulation, different slope components and grassing blocks, interlocking pavements, and profiled pavements (Figs 8 and 9). This type of material is more resistant, due to the absence of reinforcement, which is more sensitive to corrosion; carbonation for instance is not such a serious problem as in the case of reinforced concrete. The greatest problem becomes frost resistance and resistance against defrosting salts of tiles and of horizontal surfaces (Figs 10 and 11). Sufficient density of the concrete and the application of aerating admixtures provide protection against these most frequent factors.

Figure 8: Concrete block.
Figure 9: Slope block.

Figure 10: On the left, general view of concrete paving damaged by dilatation of the concrete base – bulging and crushing of individual tiles. On the right, a detail of concrete base-damage of the pavement.

Figure 11: Damage of the concrete pavement surface by the effect of frost and of defrosting salts causing dilatation.
Concrete blocks are to a great extent used for building of retaining walls and sloping abutment walls. The material of these structures is exposed to both rainwater and underground water. Furthermore, the influence of biological disturbances of concrete by roots of plants is not negligible.

3 Environmental damage to industrial buildings

Besides the imperfections originating in production/construction, the most frequent causes of damage and failure of industrial buildings and structures in industrial zones arise from atmospheric deterioration. In the environment around industrial agglomerations, sulphur dioxide SO₂ and other corrosive gases especially cause the deterioration of concrete.

The process of concrete deterioration by sulphur dioxide is called sulphation [3]. Sulphur dioxide (SO₂) is a markedly more corrosive gas than CO₂, but owing to its lower concentration in the normal atmosphere, the manifestation of sulphation is less frequent than that of carbonation (see Fig. 12). In general, at a lower concentration of SO₂, just as during carbonation, the effect of the relative humidity of the environment is dominant, whereas at a higher concentration of SO₂, the value of relative humidity is not as decisive. The effect of sulphur dioxide on concrete structures in mutual synergism may be seen in Fig. 12.

The process of sulphation may be clearly seen in the pictures of SEM (electron microscope) (Fig. 13).

Figure 12: Simplified schema of final products of concrete carbonation and sulphation. Nomenclature: C – CaO, S – SiO₂, A – Al₂O₃, H – H₂O [1].
Figure 13: Figure (1) shows the original structure of hydration products in the form of fine crystals and gel structures. By the action of SO$_2$, first a coating is formed on the concrete surface (2), and gradually small fine crystals of new forms are created (3). Then, almost coarse crystals of gypsum CaSO$_4$·2H$_2$O (5 and 6) are gradually formed from small crystals of hemihydrates (5 and 6) (Photo: author).

3.1 Reinforced concrete framing and concrete halls

The durability of industrial reinforced concrete beams is usually highly influenced by the environment and character of production in concrete halls (see Fig. 14).

Figure 14: View of the horizontal elements of concrete skeleton monolithic hall in the chromium section of the production plant (Photo: J. Bydovský).
Figure 15: Details of a strongly damaged concrete layer through the action of a high concentration of sulphur dioxide and liquid moisture (Photo: J. Bydzovský).

The most frequent type of damage of the concrete beams, of both pillars and girders, is caused by gaseous pollutants, especially by sulphur dioxide. Besides the above-mentioned effects of these gases, the pH in the given environment is also decisive in the increase of deterioration. A typical example of damage is one in which the surface of load-bearing elements of the framework monolithic hall is strongly deteriorated by sulphur dioxide, and wherein samples of the concrete surface layer minerals such as gypsum and ettringite were identified. The formation of ettringite was triggered by the access of liquid water from the process of production by the wetting itself and also by the condensation on the structure surface (Fig. 15).

3.1.1 Structures of alumina cement

From the year 1930 to the 1960s, alumina cement was abundantly used for structural concrete. Alumina cement was especially used where a rapid increase of concrete strength was required, or where winter concrete placing connected with the excessive development of hydration heat was carried out [4]. A rapid increase of initial strength is often achieved at the level of ordinary Portland cement of the same class after 28 days. However, it is generally known that through the course of time, concrete containing alumina cement gradually loses its physical-mechanical parameters to such an extent that destruction of structures very often occurs. In its composition, alumina cement markedly differs from Portland cement. Compared with calcium silicates contained in Portland cement, alumina cement most noticeably contains calcium aluminates, while the silicate components are harmful here.
The decrease of alumina cement concrete strength is usually caused by its spontaneous conversion, and it is explained by a gradual conversion of hexagonal hydroaluminates CAH$_{10}$ and C$_2$AH$_8$ formed by cement hydration to cubic hydroaluminates, C$_3$AH$_6$ which, however, take only 47.1% of the original volume (see Fig. 16). This circumstance, just as water separation, causes increase of porosity, creation of cracks and a considerable decrease of concrete strength. The increased porosity of concrete results in a more distinctive deterioration by corrosive gases and vapours from the atmosphere. Alumina cement is not used today as a material for structural purposes, but due to its specific properties it is used with an advantage as, for example, a binder for lining resistant to the action of high temperatures.

One of the greatest disasters in recent years was charted in a single aisle hall in the Czech Republic. Two of the concrete columns of 500-mm diameter were made of concrete containing alumina cement. The gradual spontaneous conversion and subsequent secondary carbonation caused an enormous decrease of compressive strength from the original 25 MPa to the value of 3 MPa (see Fig. 17).

3.1.2 Floors of concrete halls
Another potential cause of floor failures in industrial halls may arise from the effect of the alkali reaction of the aggregate and from the increased humidity. A case was discovered in which the aggregate in concrete was at adequate level, but owing to the condensation of moisture on the ceiling structure coated with paint with a high
alkali content, the alkali dissolved and dripped down to the fresh concrete floor. Then, the increased concentration of alkali caused a subsequent destruction of the concrete surface where a pool containing this solution was formed.

3.2 Cooling towers

Cooling towers represent special industrial structures from the viewpoint of service life and durability of concrete. There are two main types of cooling towers: those with a natural draught of Iterson type and towers with a forced draught (see Fig. 18). The problems of durability of both types of towers are almost identical. The structure of the cooling tower is a very thin concrete shell structure (only 100 mm in the narrowest place of the jacket thickness) exposed to extreme deterioration factors owing to its function. In lessons dealing with concrete durability, this type of structure is given as an example from the viewpoint of the comprehensiveness of action of particular factors.

In the following sections, we shall try to give a brief explanation of factors that may be encountered within cooling towers (henceforth CT), and which, especially by synergic action, cause significant failures of these towers. These factors may be classified as follows:

- the orientation of CT to cardinal points – effects of temperature and wind,
- the operational routine of CT in view of the time and especially the frequency of shutdowns in the winter period,
- the concentration of acid-forming gases in the atmosphere,
- the effect of the structure itself,
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Figure 18: General view of four typically repaired draft cooling towers of the Itterson type; the structures and the interior equipment of the towers are supported by concrete columns (Photo: J. Bydžovský).

- the poor quality of the existing concrete of the cooling tower cladding,
- insufficient cover layer of the reinforcement or the insufficient amount of the reinforcement,
- geometrical shape imperfections, and
- the absence or the low quality of secondary protection.

3.2.1 Orientation to cardinal points
Damage to the shell structure of the cooling tower is affected by the orientation to cardinal points. These factors include the effect of the prevailing wind; especially in winter months freezing and thawing of CT cladding occur. Insolation has another negative effect in which the CT cladding is time-variably heated from one side, which may cause the motion of the freezing zone (see Fig. 19). In the normal operational routine, temperatures in winter may significantly fluctuate due to different temperatures in the night and the insolated surface in the daytime. Insolation also results in the thermal expansion of the shell as a whole, during which cracks are formed that have dire consequences.

3.2.2 CT operational routine
Within the framework of operating CT in the winter season, cooling towers are shut down at very low temperatures. This causes total freezing of the wetted cladding of the cooling tower within several hours, and the structure is considerably frost-loaded because the temperature in the inner space of the tower is 16°C and the relative
humidity is almost 100%. On the other hand, the temperature of the surrounding environment drops below the freezing point (under winter climatic conditions of Central Europe, commonly to −10 to −15°C). Therefore, at the moment of the shutdown, marked volume changes occur as a result of the creation of ice in the mass of the thin cladding of CT. This phenomenon may cause the formation of freezing zones (see Fig. 19).

3.2.3 The action of acid-forming gases from the atmosphere

The phenomena of carbonation and sulphation together with the co-action of frost and humidity effects considerably decrease the service life of the cladding of cooling towers in power plants of any type. The durability of concrete structures is markedly influenced by the action of atmospheric carbon dioxide, and in some localities also by sulphur dioxide.

The extent of concrete deterioration increases with the rise in humidity. The degree of relative humidity influences the velocity of chemical reactions between corrosive gases and products of hydration of cement, i.e. the rate of carbonation and sulphation (see Fig. 3). In a tower that was not repaired, a relatively high degree of carbonation was detected (see Fig. 20). Together with the extraction of the cement matrix, both factors contribute to the reduction of pH. Concrete with a pH value less than 9.6 loses its alkali passivation capability [5, 6].
3.2.4 The effect of structure quality

These effects are especially characterised by their dangerousness in synergic action with other effects. The poor quality of the existing concrete of the CT cladding may be caused by a number of factors such as:

- high porosity of concrete,
- high absorption of concrete (sometimes as much as 10–12%),
- low resistance to frost (‘freeze-thaw resistant’ concrete exhibits absorption below 6.5%),
- insufficient quality of concrete from the viewpoint of strength characteristics,
- a higher capacity to diffuse water vapour and acid-forming gases (CO₂, SO₂, etc.),
- the influence of the technology used on the cooling tower durability,
- incorrectly executed or cured construction joints,
- insufficient covering of reinforcement with concrete affecting the service life of the reinforcement,
- washing out of concrete, and
- too stringent reinforcement in the CT cladding.

In older times, the design of the construction of the majority of towers used concrete of C 16/20 type – the required strength of concrete is 20 MPa – without further requirements regarding water tightness or the durability of concrete. Neither any type of water tightness nor the number of freezing cycles or resistance of surfaces to the action of water and frost was required [6]. The concrete for use in a given environment of extremely loaded structures of cooling towers (temperature...
Figure 21: View of a cooling tower wall where, owing to the marked effects of carbonation, humidity and less compactness, the concrete crumbled and the so-called ‘windows’ originated.

changes and also the action of external forces by the action of wind) should be designed with special consideration of structure durability (Fig. 21).

3.2.5 Geometrical shape imperfections
Geometrical imperfections of the cooling tower’s cladding in the shape of local bulging, a ring or in other shapes represent a very interesting failure. Large geometrical imperfections of cooling tower cladding are especially typical in older towers. These shape imperfections are often apparent with the naked eye; however, only in a few cases they were precisely measured. In some towers, local deviations from the correct geometry reach up to almost 500 mm. Nevertheless, these large deviations, these imperfections, do not substantially affect the total load-carrying capacity and dynamic behaviour of the cooling tower. However, the danger of shape imperfections lies in the fact that in the place of imperfections, peak local bending moments originate for which the cladding was not designed. In these places, cracks in concrete occur before the tower is put into operation. These cracks, moreover, extremely accelerate the process of permanent deterioration of the concrete’s condition. Shape imperfections are also connected with the fluctuating and generally insufficient cover layer.

3.2.6 Protective surface finish of concrete
In the majority of cooling towers, a protective surface finish was not applied during their construction. This fact is still apparent only on the cooling towers that have
Figure 22: Frost damage of the concrete cover of stanchions (columns) supporting the whole structure of a cooling tower. The stanchions are fixed-ended in a foundation plate flooded with water.

not been repaired. Surface protective systems form an additional barrier against the penetration of undesirable media on the surface of the rehabilitated concrete structure and in this way prolong its durability, and especially, help the passivation of the steel reinforcement (Fig. 22).

The secondary surface protection of the concrete structure is not carried out using only one coat of paint, but a comprehensive surface protective barrier composed of several layers where each of these layers may secure different properties (e.g. penetration guarantees water tightness, the cover layer the diffusion capabilities, etc.). As far as the corrosive media are concerned, these especially refer to the penetration of CO₂, SO₂ and H₂O, either as vapours or as liquids.
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Figure 23: Completely damaged and non-functional paint of the interior part of the tower (Photo: R. Kepáč).

In cooling towers, the interior surface finish (see Fig. 23), which should prevent the penetration of water vapour and water from the tower’s interior environment (100% humidity) into the structure, is of greatest importance. And conversely, the exterior surface finish should allow water vapour to escape from the structure (fully vapour-permeable paint), but at the same time, not allow water (rainwater) into the structure. Then, the whole surface finish should simultaneously limit the access of carbon dioxide or other corrosive media into the concrete structure from both sides.

3.3 Wastewater treatment plant, sewerage system and pits

In the field of water management structures we may come across water treatment plants that usually either comprise water reservoirs, drinking water tanks, etc. or have facilities for wastewater. The main feature of water treatment facilities is that they are mostly designed for the addition of various chemicals that are of low concentrations, so that their harmful activity is not too distinctive. Structures for this purpose utilise impermeable concrete, which is a guarantee for the trouble-free operation of the whole treatment plant. Only certain cases were detected when during the repair of the treatment plant the silicate paints based on water glass reacted due to chemical additives in water, especially with the addition of chlorine.

Far more distinctive corrosion activity may be seen in wastewater. In general, wastewater is divided into the following four main groups:

1. municipal wastewater,
2. industrial wastewater,
3. rain water (storm water), and
4. infiltration subsurface water.
3.3.1 Municipal water

Urine and faeces make the principal part of polluted municipal water, almost 80% of organic substances. Faeces dry matter is formed by the residua of intestinal bacteria, lipids, proteins, polysaccharides and products formed in their decomposition. The largest proportion of organic substances form nitrogenous substances is mostly represented by urea amino acids and ammonium nitrogen. However, in municipal water, biological hydrolysis of urea and biological decomposition of amino acids occur very quickly. In inorganic substances, sodium and chlorides are dominant. The concentration of chlorides is especially very high. Then follow the sulphates (forming as much as 80% of the entire sulphur content) and phosphates (phosphorus – predominantly present in the inorganic bonded form, of which 60% is in soluble form) (see Fig. 24).

The temperature of the municipal water in the sewerage depends on the season. In winter the temperature ranges from 8 to 12°C. In summer it approaches 20°C. Biochemical processes are accelerated with the temperature increase, so the dissolved oxygen is depleted more easily. The reaction of municipal wastewater (see Fig. 25) is normally slightly alkaline; pH is usually within the range 6.5–8.5 [7].

Figure 24: View of completely damaged spillway wall of the pit through which the sludge from municipal water overflows (Photo: J. Hromádko).
3.3.2 Industrial wastewater

This kind of wastewater refers to water discharged into the sewerage from industrial plants, agricultural wastewater or water pre-treated in the plant. Industrial wastewater, unlike municipal water, is of varied character. In inorganically polluted wastewater, the substance present may either be in un-dissolved or dissolved form, and may rank among toxic or non-toxic substances. Industrial wastewater may be divided into the groups:

- wastewater predominantly polluted inorganically by un-dissolved substances (wastewater from coal washing, ceramic and glass industry),
- wastewater predominantly polluted inorganically by non-toxic dissolved substances (see Fig. 26) (wastewater from plants producing potash, phosphate and nitrogenous fertilisers, an iron preparation plant, soda production, agriculture industry), and
- wastewater predominantly polluted inorganically by toxic dissolved substances (surface metal treatment, radioactive water, etc.).

Organic substances contained in industrial wastewater may also be either un-dissolved or dissolved when divided into four groups:
Figure 26: Concrete deterioration of the catch basin in a chemical plant.

- non-toxic and biologically decomposable substances,
- non-toxic and with difficulty biologically degradable substances,
- toxic and biologically decomposable substances, and
- toxic and with difficulty biologically decomposable substances.

### 3.3.3 Rainwater

This kind of wastewater is discharged from the municipality area through the public sewerage. The quality of precipitation water (rainwater, melting snow) is very unsteady and depends on many circumstances. The concentration of organic pollution in this water is like that in municipal wastewater. In winter, the precipitation water from melting snow absorbs a large amount of salts from road maintenance, which demonstrates itself in a large increase of concentration of chlorides. Rainwater can transport large amounts of inorganic material which can cause mechanical abrasive wear (see Fig. 27).

### 3.3.4 Infiltration underground water

Infiltration underground water, the so-called ballast water, is infiltrating into the sewerage system from the surrounding soil. This kind of water is usually not much polluted by corrosive ions, which depends on the surrounding soil. It is a bigger problem for wastewater treatment plants due to the thinning of wastewater.
4 Environmental damage to transportation infrastructure

Transportation infrastructure, i.e. bridges, roads, retaining walls, tunnels, etc. are exposed to the action of a number of specific effects (e.g. de-icing substances), which may cause significant failures.

4.1 Bridges and pavements

Besides other corrosive phenomena affecting all reinforced concrete structures, the deterioration caused by chlorides (see Section 2.3.3 in Chapter 5), alkali expansion (see Section 3.1 in Chapter 5) and stray current are especially dangerous for bridge structures, particularly due to the use of pre-stressed reinforcement.

4.1.1 Stray current

The Pourbaix diagram of conditions of electrochemical corrosion shows the dependence of the potential on pH for the iron-water system. However, these processes and conditions substantially differ with the presence of foreign ions and an exterior electric field. The corrosion rate may increase many times if electric current is introduced. This electric current may be represented by stray earth current that penetrates into the structure from a foreign source. Stray earth current may pass through railway sleepers and structures in the vicinity of places where direct current is used. Structures that face the greatest threat represented by stray earth current are in the vicinity of electrified railway lines using direct-current traction voltage 1.5 and 3.5 kV. So as to limit stray earth current, the rails are welded or provided with
welded current-carrying inter-connections that ensure their proper and permanent current connection (see Fig. 28).

In the case of structural failure where one of the following conditions is satisfied, an exploration must be carried out to discover stray earth current occurrence:

- the direct-current traction railway line is at a distance of 5 km;
- up to a distance of 500 m from the structure there are structures which are potential sources of stray current – the transformation station, facilities of gas pipelines and water piping and cables;
- geological subsoil with the potential of becoming sources of spontaneous polarisation, deposits of ores, graphite or tectonic zones.

The exploration of the occurrence of the stray current should include the following:

- the determination of the direction and intensity of the electric field, the measurement of the reinforcement-soil potential,
- the measurement of the earth resistance of supports and the load-carrying structure,
- the measurement of the potential gradient, and
- the measurement of the insulation resistance – if enabled by the structural design and the scope of the repair.

The situation of existing structures is worse owing to the contamination by conductive ions; the reinforcement is usually not bonded, and the electric resistance between the load-carrying structure and the substructure is low.

The increase of the electric resistance of the reinforced concrete structure to earth ranks among the basic protective measures. In existing structures, only secondary protection by coatings, paints, sprays, foils, insulation strips and the structural design (the separation of particular parts electrically) is possible.

Figure 28: One way of possible protection of reinforced concrete structures – correct wiring of stray current circuit.
4.1.2 Volume changes – alkali reaction of aggregate and frost failure
Failure due to the alkali expansion of the aggregate is another serious failure of concrete structures (see Section 3.1 in Chapter 5). This kind of structural failure has been known since the 1930s, and it was first observed and precisely described for highways in California, USA. Based upon the existing knowledge, it may, however, be stated that the phenomenon of the alkali expansion was somewhat neglected in the past. The occurrence of this type of failure highlights the fact that the threat of alkali expansion cannot be minimised (see Figs 29–31).

4.1.3 Carbonation, effects of chlorides and humidity
The combined effect of carbonation resulting in the decrease of concrete pH and the subsequent corrosion of the reinforcement represents a significant source of damage. Extremely high corrosion activity in co-action with chemical de-icing salts – chlorides – occurs especially in bridges within a short period of time. The corrosion products of the reinforcement are of larger volume than the original reinforcement, which induces tensile stress in the concrete cover layer. This tensile

Figure 29: View of a road where concrete failure by alkali expansion was detected.

Figure 30: To the left – a detail of the airport concrete runway, and to the right – the crash barrier, indicating the same cause of failure.
Figure 31: For comparison, an example of concrete frost damage of a crash barrier with the co-action of de-icing salts.

Figure 32: View from below of one of the longitudinal girders of a bridge. An example of the extensive reinforcement corrosion caused by the synergic action of moisture and chlorides (Photo: Jiří Bydžovský).

stress is larger than what the concrete is able to stand in tension, and consequently, cracking and even the total spalling of the cover occur (see Figs 32–34).

4.2 Tunnels

From the viewpoint of durability, concrete structures of tunnels, like other concrete structures, are endangered. The following factors especially act here to a large extent:

- liquids that react with the cement matrix in the following ways:
  - extraction of cement matrix,
  - creation of easily soluble compounds and their washing,
  - creation of compounds of larger volume.
Figure 33: Detailed view from below of the bridge arch where corrosion is caused by the synergic action of: water leaking, carbonation and chloride attack (Photo: Jiří Bydžovský).

Figure 34: View of the bridge pillar corner. The damage was caused by precipitation and re-crystallisation of the calcium constituents of concrete. The high content of chlorides in water leakage into the concrete also contributed to the extract.

- oils and petroleum products,
- increased content of corrosive gases in the atmosphere, and
- high temperatures.

With respect to the closed space and the action of the chimney effect in case of fire, the risk of damage to concrete by high temperatures is higher in tunnels, especially in reference to road tunnels (Fig. 35).
During a fire, the temperature may rapidly increase within a short period of time. In such cases, concrete is damaged by the explosive spalling due to the increase of water vapour pressure in the surface layers of concrete as illustrated in Fig. 36. The situation is accentuated in high-performance concrete used in most cases for the construction of tunnels.

The pictures (Figs 37 and 38) show the damage to concrete in tunnels. Following a series of fires in road tunnels in the Alps, the problem of increasing concrete durability at high temperatures is currently being solved in Austria [8]. Researchers are endeavouring to eliminate the destruction of concrete caused by the action of high temperatures, particularly to prevent the spalling of the cover layer of concrete above the reinforcement. The warped parts of the concrete structure make access more difficult and increase problems during the rescue work and removal of the fire’s ill effects.

5 Farm buildings deterioration

The deterioration of farm buildings may be major, especially in facilities where manure is handled and where fertilisers or other chemical agents are stored. It also occurs in buildings serving as animal housing due to the effect of indoor pollution and the interior climate. Another potential damage to structures may be the deterioration of their properties by biological corrosion (see also Section 2.2 in Chapter 5).

Figure 35: During a fire in a tunnel, the tunnel is completely disintegrated owing to high temperatures that may reach a maximum of 1400°C. The picture shows a warped reinforced vault made of shotcrete (Photo: J. Horvath).
Figure 36: Diagram of the origin of damage to concrete surface layers during fire [8].

Figure 37: General view of a tunnel vault without concrete surface layers damaged by fire (Photo: J. Horvath).
5.1 Corrosion effects during storage of fertilisers

Nitrogenous, phosphate and magnesium-phosphate fertilisers rank among the most commonly used fertilisers. These are generally powdery or crystalline substances that, when applied or handled, strongly raise dust and stick to the concrete surface. This particularly refers to the hygroscopic substances that with atmospheric moisture create strongly corrosive substances such as NaCl, NH₄Cl, and (NH₄)₂SO₄ (see Section 1 in Chapter 7). The consequences of corrosion caused in this way are observable as early as after 2–3 years. It is a case of different type of deterioration, especially the extraction of the binding matrix as a result of the chemical reaction, or cover layer spalling and uncovering of the reinforcement, which afterwards is quickly subject to further corrosion (Fig. 39).

5.2 Micro-climate and indoor pollution of stables and corrosive solutions

The micro-climate of animal housing structures and also of some storehouses is an important corrosion factor. The construction of large-scale installations, the concentration of animals in this space and difficulty in ventilation create an adverse micro-climate for the structures. This especially refers to higher humidity, and the occurrence of sulphate and ammonia. Owing to high relative humidity, its condensation and the dilution of gaseous products that originate from the biological processes of excrements of stabled animals and also from their breathing, diluted solutions of acids are created. These are particularly H₂CO₃, HNO₃ and H₂SO₄. These acids act corrosively on all surfaces including ceilings and walls. The corrosive acid H₂SO₄ also originates by the oxidation from H₂S, formed by the bacterial decomposition of organic substances.
Besides animal housing structures, problems with a corrosive environment may also occur in other places, e.g. in storehouses for potatoes where the temperature is maintained at 2–4°C and the humidity at about 90%. In such facilities a high concentration of SO₂ or H₂S was found. SO₂, on the one hand, causes concrete sulphation and, on the other hand, hydrates to corrosive aqueous solutions of SO₂ – SO₂ and 6H₂O [9].

Corrosive solutions from different farm products or wastes represent other corrosive media. One of these are, e.g. silage juices – turbid dark-coloured liquids of pH 3.5 that originate from anaerobic lactescent fermenting processes. These substances contain a relatively large amount of saccharides and acids (lactic acid, butyric acid, acetic acid). Silage pits are constructed with non-reinforced concrete, which better resists corrosion, but nevertheless, the damage used to be frequent even after several years as a result of frost effects, variations in temperatures and humidity. So that the structure may be in the long term usable, it must be constructed with dense well-processed concrete or provided with painted surfaces.

Mechanical damage to concrete by biological effects is not frequent, but trees or other plants may damage concrete by their roots in the cracks of the material. The growth of plants such as moss (see Fig. 40), lichens and algae on concrete surfaces causes little mechanical damage to the concrete surface itself. Rather, the harmful effect is represented particularly by the fact that these plants retain water on the surface. Then, the cause of the damage is the crystallisation pressure at subzero temperatures.

Bio-corrosion through the action of bacteria consists in the chemical action of the products of bio-chemical processes, e.g. products of sulphur. Bacterial damage
Figure 40: This picture shows an interesting form of damage to the paint of the interior part of stables where the paint is covered with a thin layer of organic residue. For operational reasons, there is a cyclic desiccation of the environment, which results in the development of the tensile stress that causes the separation of the paint from the base. The adhesion of a biological material to the paint surface is larger than that between the paint and concrete.

to concrete used to be time-limited, which leads to the situation where the potential origin of the damage by bio-corrosion is not taken into consideration at all.

5.3 Bio-corrosion of concrete

- Sulphate attack: Sulphur bacteria are contained in stagnant water, soil and in all places where sufficient sulphur and water is present. Sulphur bacteria in the presence of O₂ in water oxidise hydrogen sulphide (H₂S) to corrosive H₂SO₄. On the contrary, under the condition of the absence of air access, aerobic microorganisms take oxygen from sulphates dissolved in water and reduce dangerous H₂SO₄ to a relatively harmless H₂S. These bacteria are especially active in the sewerage system. After 5 years of exposure, concrete can be attacked up to 30 mm of depth (2–3 pH) [10].
- Nitrification: A similar action based on nitrogen decomposition.

6 Deterioration of other structures

This section describes the deterioration caused by the environment of structures other than those mentioned in the previous sections.
Environmental Deterioration of Building Materials

6.1 Damage to materials containing polymers

Materials utilised in the construction industry which contain polymers may be divided into three groups [11]:

- purely polymer materials (products of plastic materials, polymer surfaces – floors),
- materials in which a polymer is used as a binder (polymer concrete – PC), and
- polymer is used as an additive (polymer-cement concrete – PCC).

Owing to the relatively higher resistance of polymers to different corrosive environments and chemical agents, the damage is usually not too distinctive compared with silicate materials. The diversity of polymer materials used in the construction industry is so large that in general, it is not possible to specify their corrosion resistance. Generally, polymer materials do not resist higher temperatures and are prone to ageing due to UV radiation. The majority of failures in structures used to be caused by improper execution or application under inappropriate conditions, e.g. by the sensitivity of most polymers to humidity or insufficient temperature for polymerisation.

As far as the negative action of water and temperature on coating materials is concerned, the damage caused by polymers may be classified according to the following mechanisms:

- When water is trapped under the layer of a building material together with a polymer, water gradually changes into vapour that afterwards induces tensile
stress (e.g. due to the insolation of a wet structure provided with a non-permeable paint) (see Fig. 41).

- When water is trapped under the layer of a building material together with a polymer, and water condensation occurs, and owing to low temperatures water is changed into ice.
- Mixing a wet aggregate with a binding polymer component during the production of polymer concrete causes the slowdown or even the prevention of polymerisation (also, the moisture condensation on the aggregate’s cool surface is prevented).

6.1.1 Paints

Besides the effects on the durability of polymer materials mentioned above in paint systems, the following inter-connected effects may be designated [12]:

- insufficient thickness of the paint system makes water penetration possible, but conversely, this prevents its evaporation,
lower water tightness and together with frost induced damage of the whole system independently or even with the base, and

high diffusion resistance prevents evaporation, increases water condensation under the paint and prevents subsequent secondary failures (see Fig. 42).

6.2 Piles

Besides the damage by stray current to the reinforcement in reinforced concrete (see Section 1 in Chapter 2), plain concrete may also be damaged by the transport of corrosive ions through the soil. Figure 43 shows a specific example of a pile strongly damaged by sulphate expansion (see Chapter 4, Section 2.1.1). As a result of the action of stray current, $\text{SO}_4^{2-}$ ions from groundwater were transported through the soil as far as to the unprotected part of the structure. A part of the pile embedded in the highly corrosive groundwater was protected by a hydro-insulation foil.

![Figure 43: Chart of pile corrosion by corrosive ions from ground.](image)

References


