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Damage of Concrete and Reinforcement of Reinforced-Concrete Foundations Caused by Environmental Effects

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Abstract

In the course of their service period, concrete structures are exposed to a variety of impacts. A combination of exposure to aggressive effects, poorly constructed structural details, negligence of the durability issues, construction errors and underestimation of the importance of maintenance can lead to a severe damage of reinforced concrete which is used for construction of these structures. The reinforced concrete damage issues can be divided into the concrete damage and reinforcement damage. The paper provides some of the aggressive effects which can have impact on the reinforced concrete foundations, and which can be caused by soil, ground water or weather.

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1. Introduction

The present experience in construction and service of reinforced concrete structures shows that there are numerous problems causing severe damage, and often, compromising the bearing capacity of structures. The reasons for this should be sought in the design of the structure or of its interaction with soil, then in failing to implement the required class of concrete, in inexpert construction of structural elements made of reinforced concrete, etc. [10, 11, 15, 16, 24, 25, 26].

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Often the causes of structural damage are related to reinforced concrete foundations. Most frequently, it is the incorrect assessment of moisture and water effects on:

- Foundations soil and
- Concrete of the foundations.

Damage of concrete and reinforcement in concrete affects the durability and bearing capacity of foundations. [19-22] The problems which may occur on the constructed as well as considerable finances which must be provided for the repairs, indicate that concrete and reinforcement as the material for construction of the reinforced concrete structures should be paid due attention, especially when they are exposed to aggressive environmental effects. [12, 23] It is a trend to attach great importance to the design of concrete mixes with special properties so that they are best suited to the environment in which the structure is located, thus improving the durability of structures [1, 13, 9]. The research indicated the issue of durability of reinforced concrete structures can boil down to the problems of degradation of concrete and reinforcement in concrete. This paper deals with issues of the damage of reinforced concrete as the material used for construction of the foundations in the soil.

2. Concrete Degradation

A structure made of reinforced concrete can during its service period be exposed to various aggressive effects which can cause damage. These influences can originate in the environment or be related to the use of the structure. They can be classified in three basic groups:

- Physical
- Biological and
- Chemical effects.

The most drastic form of the physical impact leading to concrete degradation is frost action. Namely, water which is retained in pores and cracks freezes in low temperatures and exposes concrete to often very high pressures (up to 220 MPa). Detrimental frost action in foundation engineering is most frequently prevented by the proper selection of foundation depth, construction of the gravel layer below the foundations, construction of the proper drainage and construction of adequate moist and water insulation of the parts of the buildings which are in the ground [8, 18].



Fig. 1. Concrete degradation caused by frost action.

The other forms of physical degradation of concrete and concrete structures are related to the onset of cracks due to shrinking, temperature variations and due to different thermal expansion of the aggregate and cement rock etc. In addition, one should mention exceeding the concrete bearing capacity and cyclical loading and unloading of the structure which causes onset of cracks and paves the way for other aggressive effects.

The mentioned harmful mechanisms usually attack the concrete immediately above the ground level, and very seldom higher than 50cm above it, depending on the height of the capillary rise of water. The biological effects comprise the impact of vegetation, which causes the existing cracks to widen as the root systems of trees expand.

Particularly detrimental in these terms are fig, willow and liquidambar (it is common in warm climates, grown locally as decorative tree whose leaves and fruit resemble those of a chestnut tree) [7]



Fig. 2. Degradation of concrete caused by the tree roots and vegetation.

The chemical effects causing concrete degradation are usually impacts which are a consequence of chemical reactions of aggressive compounds from the structure environment and the constituents of the cement rock themselves. Their detrimental effects cause concrete corrosion. The following types of degradation should be mentioned here:

- Aggregate expansion,
- Salt weathering,
- Carbonation, and
- Leaching.

2.1. Aggregate expansion

Mineral constituents of some aggregates are often quartz, opal, chalcedon whose basic compound is silicon. Silicon reacts (in the presence of water) with the alkali in concrete (K_2O and Na_2O which come mostly from cement) and causes a chemical reaction known as alkali-silicate reaction (ASR). Its product are expansive compounds, which firstly create cracks and damage on the concrete surface and afterwards comes up to 2-3cm high.

Similar damage occurs due to expansive compounds, when the aggregate constituent is dolomite. In that case magnesium carbonate reacts with hydroxyl ions and produces magnesium hydroxide and carbonate ions. The similar effects, but in rare cases, are produced by the reaction of pyrite (iron sulphide) from the concrete aggregate which generates expansion by forming iron oxide and ettringite [6].

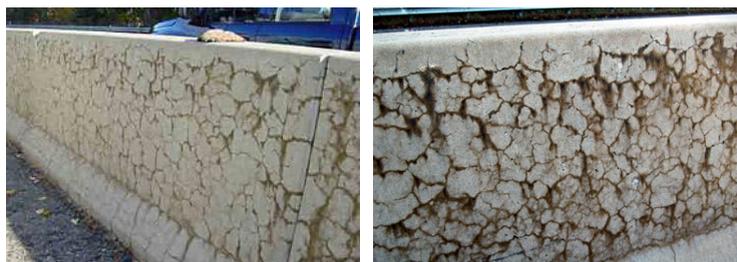


Fig. 3. Degradation by the aggregate expansion paving the way to the further concrete degradation.

2.2. Salt weathering

This occurs in concrete due to the capillary rise of water rich in salts through the soil and foundation structure. It is prevalent in the areas with the considerable concentration of chlorides in the soil, ground water and atmosphere, which is mostly the case in the coastal areas of the warm seas or in the structures where defrosting salt is often used

(road structures). Nevertheless, the mechanism of the crystallization process is similar to frost action. Namely, the pressure caused by crystallization brings about the onset of cracks in the pore walls and afterwards the cracks, due to crystallization in them grow bigger. This process, in presence of new amounts of water rich in salts, continues, causing massive concrete degradation. The basis of this process is the reaction of calcium chloride (CaCl_2) and sodium chloride (NaCl) which causes changes in the Portland cement and causes generation of calcium hydroxide ($\text{Ca}(\text{OH})_2$) [5].

This kind of concrete degradation, known also as chloride aggression, is particularly prominent in those cases when the structures are positioned near the warm seas, in the conditions of high concentration of chlorides in the sea water, soil and air. Warmer climate, in comparison to the areas with the continental and temperate continental climate enhance salt weathering. In addition, high temperatures have an additional detrimental effect because concretes, for the reasons of better workability are made with a high water/cement ratio which causes, in the concrete hydration process, an increase in the concrete paste porosity, which facilitates capillary rise of chloride-saturated water after concrete hardening. The higher temperatures are the cause of the faster initial hydration of cement which leads to the increased porosity of concrete and facilitates capillary rise and crystallization of chlorine ions [3].



Fig. 4. Concrete degradation caused by crystallization of road defrosting salt.

2.3. Carbonation

Sulphate aggression which causes sulphate corrosion of concrete is also a form of salt crystallization in concrete. It comprises a reaction of the compounds from concrete with the sulphate ions (SO_4) which are often soil constituents (most frequently in the form of gypsum – $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Apart from calcium, ground waters contain also magnesium, sodium and potassium sulphates which can also react with the compounds of hydrated Portland cement such as calcium hydroxide ($\text{Ca}(\text{OH})_2$) and selit II (tricalcium-aluminate $3\text{CaO} \cdot \text{Al}_2\text{O}_3$). In contact with these concrete components, sulphate ions lead to creation of highly expansive compound of crystal structure – ettringite ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$) which is a basic cause to the onset of high pressures, cracks and sulphate corrosion of concrete. The intensity of sulphate corrosion of concrete is affected by the concentration of sulphate in water and alternate drying and damping of concrete is beneficial for it, which is a common case with concretes.

The sulphate corrosion is considered replacement of Na, K, and Mg cations in their sulphates (Na_2SO_4 , MgSO_4 , K_2SO_4) in contact with potassium hydroxide ($\text{Ca}(\text{OH})_2$) from the cements paste, which creates gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and the appropriate alkaline. Conversion of calcium hydroxide into gypsum is also followed by the increase of volume which causes onset of cracks and degradation of cement paste.

The intensity of sulphate aggression depends on multiple factors, the most important being type, concentration and duration of exposure to sulphates. The relatively wide distribution on one hand, and serious damage which may be caused by the aggressive sulphate action on the other hand, make this type of aggressive impact very important [2].

A very important chemical process which causes concrete degradation is carbonation. This comprises reaction of calcium hydroxide ($\text{Ca}(\text{OH})_2$), with carbon dioxide (CO_2) from the air. Firstly, the carbon dioxide is dissolved in the pore water and creates carbonic acid, and it in turn reacts with calcium hydroxide in concrete forming calcium carbonate (CaCO_3). Calcium carbonate created in this way has impact on the increase of mechanical strength and

reduction of porosity and permeability of concrete. However, if water is replenished (which is often the case with the foundations that are adjacent to ground water or are in an environment with the potential capillary rise of water) the excess of carbon dioxide will cause dissolution of calcium carbonate which leads to it being washed away, and thus to reduction strength and to the increase of porosity and permeability of concrete. The increased water permeability and porosity of concrete facilitate other forms of concrete degradation [4].

The carbonation process has influence on decomposition of other properties of cement rock, except calcium hydroxide, and leads to formation of hydrates of oxides of silicon, aluminum and iron. However, the basic consequence of concrete carbonation is the decline of alkaline nature of concrete, which is an important precondition for onset of reinforcement corrosion.



Fig. 5. Concrete carbonation paved the way for frost action.

2.4. Leaching

On its way through the cracks in concrete, water may dissolve various minerals present in the hardened cement paste or aggregate. In the beginning, water is not saturated with dissolved minerals, such as, calcium and various kinds of salts, but on further movement of water the mineral concentration in the solution increase until it reaches the critical point, after which the minerals start to leach from the solution and to form deposits in the cracks and on the external surfaces of concrete [4].



Fig. 6. Leached salts and minerals on concrete surface.

3. Reinforcement corrosion

Reinforcement corrosion is a complex electrochemical process, where the progress of the process depends on the permeability, electric potential and electric resistance of concrete.

The corrosion of reinforcement steel occurs in the presence of water and oxygen where iron oxide is formed, known as rust. By development of corrosion, brown stains form on the concrete surface and characteristic cracks form along reinforcement bars, especially in the corners of the elements where they are exposed to penetration of aggressive matter into concrete. Since rust occupies a larger volume than steel, development of rust brings about cracking and failing of concrete and facilitates further penetration of aggressive matter.

One should point out that the cracks of up to 0,4 millimeter are usually filled with dirt and rust, and therefore are not dangerous for the durability of structure, and for this reason this is a permissible size of a crack in a weakly aggressive environment (BAB 87).

In the normal conditions of a dry environment, high quality concrete, owing to its alkaline character, protects steel reinforcement from corrosion. High pH value of cement rock, which originates from calcium hydroxide and other alkali crated in the cement hydration process, facilitates a thin protective layer made of stable ferric-oxides on the surface of steel which create the so called passive protection of the reinforcement, preventing the further development of rust. This layer is impermeable and stable as long as the pH-value of concrete is sufficiently high ($\text{pH} > 11$). However, when the layer of stable ferric-oxides is disrupted either by the action of concrete carbonation or by the action of acidic solutions which reduce the alkalinity of the environment, or if the amount of chlorides in the pore water around reinforcement bars is considerable, the reinforcement is depassivized and it starts to rust.

The most important cause of steel corrosion in concrete is contamination by chlorides. The onset of depassivization through chloride action depends on the ratio of Cl/OH ions in the pore water in contact with the reinforcement. If the ratio is higher than 0,6 iron is no longer protected from corrosion, and the protective layer becomes unstable and permeable for chlorides. Chlorine ions which have penetrated to the reinforcement start a chemical reaction with it and iron chloride is produced, which in contact with water becomes iron hydroxide (rust). Because of the unreliable data regarding the quantity of bound and free chlorides in a specific concrete, the most of the regulations and professional recommendations states the total amount of chlorides (bound and dissolved) in respect to the mass of cement in concrete as the permissible limit of chlorine ions in concrete. This value is usually 0,4% to 0,6%. This limit is decisively affected by the quality and dampness of concrete. The quality of concrete is determined by the thickness and permeability of the protective layer which depends on the water/cement ratio and the quality of concrete curing.

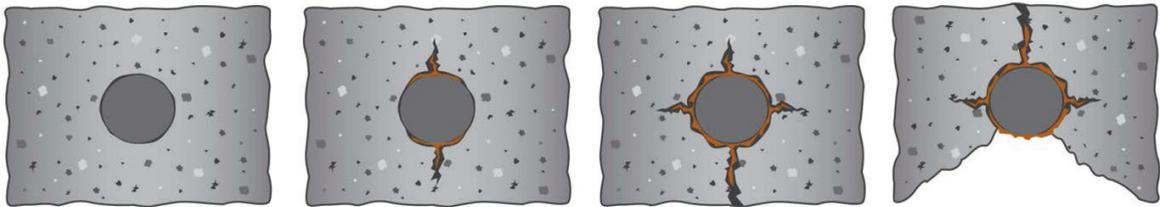


Fig. 7. Development of corrosion of a reinforcement bar in concrete.

Chlorides can get into concrete in various ways. Thus aggregate and water can contain chlorides, and the high content of chlorides in concrete can be the consequence of calcium chloride as an additive for acceleration of cement hydration. For this reason, usage of chloride-based additives is prohibited in the recent period. Chlorides may penetrate concrete from sea water and atmosphere, and in our area most frequently because of the application of defrosting salt [17].

As it is already said, the concrete carbonation process decreases the pH value of concrete which creates conditions for depassivization of reinforcement. Most researches and field measurements indicate that the carbonation process reduces the pH value of concrete to 8 to 9 which is sufficient to cause destruction of the protective oxide coating and to facilitate reinforcement corrosion.

Construction soil is very complex and varied in its composition, which inevitably affects its aggressiveness towards concrete and reinforcement. Apart from soil composition, the climate factors such as the quantity of precipitation and temperature considerably influence the soil composition and its aggressiveness. Thus the aggressiveness of the soil towards concrete and reinforcement can range from negligible to very intensive.

The soil aggressiveness is primarily affected by the damp content, that is, content of water in pores and capillaries. In the fine grain soil (dust and clay) it is considerable even in the periods without rainfall (due to the capillary rise), while the coarse grain soil (sand and gravel) are less aggressive for the same reasons [14].



Fig. 8. Reinforcement corrosion of the structure parts in contact with soil.

4. Summary

The damage of the reinforced concrete used for construction of reinforced concrete foundations are directly related to the exposure of the soil to moisture, i.e. water. The properties of the components used for designing of the concrete mix, and thus the properties of the hardened concrete affect the durability of reinforced concrete foundations in such environment. All the previous has influence on the corrosion of reinforcement in concrete. Since the foundations are difficult for access after construction, it is necessary to take into consideration all the possible harmful impacts to concrete and reinforcement of the foundations, when designing concrete mixes.

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