Reinforced Concrete Structures in "Saline Environment"

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Ground water in coastal areas -particularly in hot climates- often contains significant quantities of salt. Many reinforced concrete structures exposed to such an environment suffer from reinforcement corrosion and deteriorate early if not protected properly.

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Opus caementitium is the ancient version of concrete developed and used by the Romans. Structures constructed with this material about 2000 years ago still exist today. The Pantheon in Rome for example held the record for the world's largest dome for 1700 years. With its diameter of slightly more than 43 meters it is still the world's largest dome made of unreinforced concrete.

From the strong and solid appearance one would assume that modern concrete is equally durable. But aggressors like carbon dioxide, biogenic acids, sulphates or simply salt can severely harm this solid material.

Weak point: reinforcing steel

Ironically the weakest point in terms of durability is the reinforcing steel, that lends modern reinforced concrete its superb strength.

Concrete, as construction material is much valued because of its high compressive strength. The tensile strength of concrete however, which is equally important for the stability of structures, is rather low. Reinforcing steel is therefore embedded in concrete to compensate for the lack of tensile strength. Concrete structures like high-rise buildings, bridges, quay walls and jetties, production facilities and foundations for infrastructure as we know them would not be possible without reinforcement.

This steel reinforcement however, is easily attacked by chlorides. The damage caused is severe. Protection of the structures against such factors is not always getting due attention during design and construction. As a result the service life of the structure is drastically reduced. Preserving such structures rather than replacing them should be given due consideration as it is likely more environmentally acceptable and cost efficient.

Mechanisms of deterioration

Unfortunately steel, or iron which is the main ingredient of steel, is not chemically stable. It is not found in nature and huge amounts of energy must be spent to create iron from its natural manifestation, iron ore. As soon as steel gets exposed to a natural environment with oxygen and moisture it starts to revert back to its original form, which is basically rust.

Fig. 1: Cross section reduced by corrosion

Usually concrete protects embedded reinforcing steel from corrosion by means of its high alkalinity. In an alkaline environment a so called passive layer forms on the surface of the steel. The passive layer is a thin, but dense layer of corroded steel which shields the steel from oxygen and moisture, thus inhibiting any significant further corrosion. Without the passive layer reinforcing steel is anything but durable.

Chlorides destroy the passive layer

Salt from sea water, salty ground water and salty soil or even from spray or salty dust can penetrate the concrete through the surface and subsequently migrate inside the material following the concentration gradient or the flow of pore water. Once the salt concentration has reached the critical level in the vicinity of the reinforcement, the chloride ions from the salt perforate the passive layer triggering corrosion.

Effects of reinforcement corrosion

Obviously the corrosion process has an impact on the strength of the reinforcement by reducing the cross section of the reinforcing bar. The cross section area is often in direct relation to the load capacity of the structural member.

But this is not the only effect. I have frequently heard statements that a certain loss in cross section area is acceptable since usually some excess steel has been built in for practical reasons.

This advice however should be scrutinized with utmost care. Reinforced concrete is a compound material and as such relies on a proper bond between the components steel and concrete. In fact a thin layer of corrosion products between steel and concrete is deemed to improve bonding properties.

Fig. 2: Typical pitting corrosion

But rust usually occupies a bigger volume - approximately three to five times bigger - than steel. On an average reinforcing bar an increase of the bar diameter of only 0.1mm by a rust layer causes already enough strain to break the concrete. Cracks propagate between bars and the concrete cover delaminates. The bond between steel and concrete is lost or at least severely compromised.

Anchorage areas of the reinforcement and lap splices are no longer working as intended and the structure cannot be considered safe anymore.

Pitting corrosion

But there is also another form of corrosion which frequently occurs when chlorides, e. g. from sea water, are involved in the corrosion process. The chloride induced pitting corrosion tends to focus on small spots.

Fig. 3: Concrete cover at basement wall delaminated by corroding reinforcement

Fig. 4: Corrosion damage at floor slab

Pitting corrosion can progress extremely fast. Cases have been reported where 12mm diameter reinforcement corroded through within six months. Ironically the chemical reaction taking place in such corroding spots is protecting larger areas of the same piece of steel from corrosion by releasing electrons into the steel. The bar diameter does not increase and no damage is visible at the surface.

Obviously this type of corrosion is very dangerous, because the corrosion may proceed undetected until the structure fails. The collapse of a parking structure in Syracuse, N. Y., in 1993 (surely Google will find the photo for you), which is frequently referred to by corrosion specialists in their lectures, is one graphic example of such corrosion activity.

Sources of salt contamination

To prevent salt contamination the designers, supervising staff and site personnel must be aware of the possible sources of salt.

Concrete and steel may already get contaminated during construction. Examples of common sources of this are: contaminated or insufficiently desalinated mixing water, salty aggregate, reinforcing steel that has been stored on salty ground without protection, salt carried to slab reinforcement by workers walking on salty ground, salty curing water or salty ground water in flooded construction pits.

Fig. 5: Corrosion on coated reinforcing steel at a quay wall

Fig. 6: Corrosion on coated reinforcing steel

Existing structures may be affected by salt ingress through the surface of the more or less porous material or through cracks. Exposure of concrete surfaces to salt water may be reduced by a properly designed and installed waterproofing.

Methods of prevention and rectification

Corrosion activity requires water, oxygen and a low level of alkalinity or the presence of salt. Eliminating any of these factors will stop the corrosion.

Preventive measures therefore may include the following:

- *Selection of a suitable, dense concrete mix with low porosity;*
- *suitable thickness of the concrete cover strictly kept in any location;*
- *controlling the width of unavoidable cracks by planning a suitable steel content, proper curing, and other well known measures;*
- *planning a suitable geometry of the building to limit exposed surfaces, provide expansion joints at suitable intervals;*
- *design of waterproofing system with due attention to details;*
- *design of protective coatings;*
- *avoiding contamination of reinforcement, only clean reinforcing bars must be installed;*
- *in certain cases the use of rustproof reinforcing material may be considered;*
- *provisions for or installation of cathodic protection systems;*
- *installation of monitoring systems such as reference electrodes.*

For rehabilitation and protection of structures already suffering from the effects of chloride induced corrosion it is highly advisable to start with a comprehensive investigation by a qualified and experienced specialist.

The mechanisms behind corrosion effects are complex. Many factors are interlinked and influence each other. It requires a very sound understanding of the matter to design successful protection measures.

Modifying any of the factors promoting corrosion may produce unforeseen results if the mechanism of deterioration is not understood. An increase of the moisture in the concrete for example can trigger corrosion. It can also stop corrosion, if it is limiting the ingress of oxygen as can be observed at underwater structures.

Likewise the replacing of contaminated concrete around reinforcing steel by fresh concrete may result in an increased corrosion rate in adjacent parts of the structural member, because the (now eliminated) corrosion activity had protected these areas by releasing electrons into the steel. It may start corrosion in areas that seemingly were fully intact.

If the reasons for the corrosion are fully understood the following measures may be applied:

- *Replacing defective concrete and steel,*
- *reducing or increasing moisture content, reducing ingress of oxygen and carbon dioxide by coatings,*
- *protecting the reinforcing steel with a cathodic protection system,*
- *reducing the chloride content to a tolerable level by electrochemical methods.*

The investigation of affected structures, design of protection measures and installation of the same will be the subject of future Fortytwo-Infoletter articles.

Fig. 7: Contaminated reinforcement

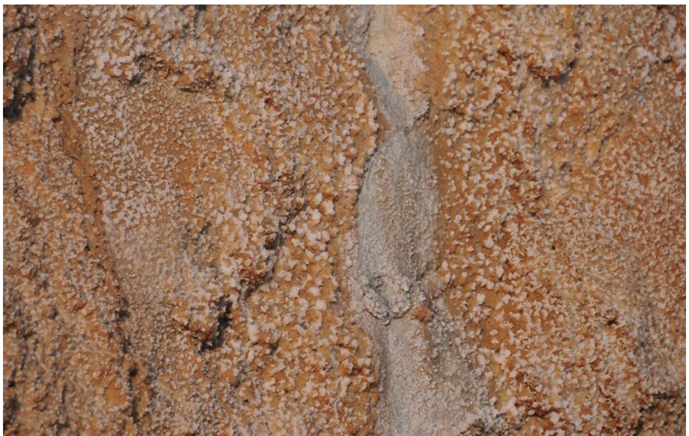

Fig. 8: Salty ground

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