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MINISTRY OF EDUCATION,
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Rehabilitation of concrete structures

Basic degradation factors acting on the reinforced concrete structure

Concrete is a composite building material consisting of filler, cement and pores, and may contain various additives. Mainly coarse and fine aggregate is used as a filler, binder is hydrated mortar, usually cement.

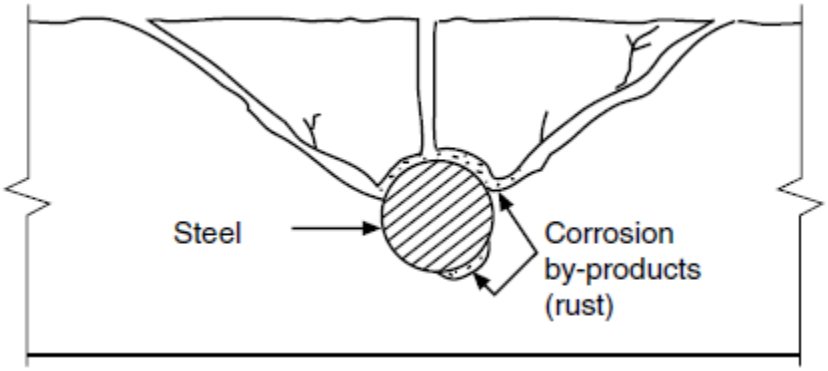
Durability of concrete - the ability to resist weathering action, chemical attack, abrasion, or any process of deterioration.

- A durable concrete is one that performs satisfactorily under anticipated exposure conditions during its life span. The material and mix proportions used should be such as to maintain its integrity and, if applicable, to protect embedded metal from corrosion. Even though concrete is a durable material requiring a little or no maintenance in normal environment but when subjected to highly aggressive or hostile environments it has been found to deteriorate resulting in premature failure of structures or reach a state requiring costly repairs.

One of the main properties affecting the durability of concrete is its permeability to water, oxygen, carbon dioxide, chlorides, sulphates and other potentially harmful substances. **Permeability** is defined as the property that controls the rate of fluid flow into a porous solid.

- Most of the durability problems in the concrete can be attributed to the volume change in the concrete. Volume change in concrete is caused by many factors. The entire hydration process is nothing but an internal volume change, the effect of hydration, the pozzolanic action, the sulphate attack, the carbonation, the moisture movement, all type of shrinkages, the effect of chlorides, corrosion of steel, comes under the aspects of volume change in concrete.
- The internal and external restraints to volume change in concrete results in cracks. It is the crack that promotes permeability and thus it becomes a part of cyclic action, till such time that concrete deteriorates, degrades, disrupts, and eventually fails.

Corrosion of Embedded Metals



The expansion of corroding steel creates tensile stresses in the concrete, which can cause cracking, delamination, and spalling.

- **Concrete and the passivating layer**

The alkaline environment of concrete (pH of 12 to 13) provides steel with corrosion protection. At the high pH, a thin oxide layer forms on the steel and prevents metal atoms from dissolving.

This passive film does not actually stop corrosion; it reduces the corrosion rate to an insignificant level. For steel in concrete, the passive corrosion rate is typically 0.1 µm per year. Without the passive film, the steel would corrode at rates at least 1,000 times higher

- **The role of chloride ions**
- **Carbonation**

  Carbonation occurs when carbon dioxide from the air penetrates the concrete and reacts with hydroxides, such as calcium hydroxide, to form carbonates. In the reaction with calcium hydroxide, calcium carbonate is formed:

  $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

This reaction reduces the pH of the pore solution to as low as 8.5, at which level the passive film on the steel is not stable.

- **Dissimilar metal corrosion**
  - Below is a list of metals in order of electrochemical activity:
    1. Zinc - 2. Aluminium - 3. Steel - 4. Iron - 5. Nickel - 6. Tin - 7. Lead - 8. Brass - 9. Copper - 10. Bronze - 11. Stainless Steel - 12. Gold
  - When the metals are in contact in an active electrolyte, the less active metal (lower number) in the series corrodes.

Freeze-Thaw Deterioration

When water freezes, it expands about 9%. As the water in moist concrete freezes, it produces pressure in the capillaries and pores of the concrete. If the pressure exceeds the tensile strength of the concrete, the cavity will dilate and rupture. The accumulative effect of successive freeze-thaw cycles and disruption of paste and aggregate can eventually cause significant expansion and cracking, scaling, and crumbling of the concrete

- De-icer scaling

De-icing chemicals used for snow and ice removal, such as sodium chloride, can aggravate freeze-thaw deterioration. The additional problem caused by de-icers is believed to be a build-up of osmotic and hydraulic pressures in excess of the normal hydraulic pressures produced when water in concrete freezes. In addition, because salt absorbs moisture, it keeps the concrete more saturated, increasing the potential for freeze-thaw deterioration. However, properly designed and placed air-entrained concrete can withstand de-icers for many years.

- Aggregate expansion
- Freezing of Fresh Concrete

Chemical Attack

- Acids
- Salts and alkalis
- Sulfate attack.

Alkali-Aggregate Reactivity

In most concrete, aggregates are more or less chemically inert. However, some aggregates react with the alkali hydroxides in concrete, causing expansion and cracking over a period of years. This alkali-aggregate reactivity has two forms—alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). ASR is of more concern than ACR because aggregates containing reactive silica materials are more common.

- Alkali-silica reactivity.
  1. Alkalis + Reactive Silica → Gel Reaction Product
  2. Gel Reaction Product + Moisture → Expansion
- Alkali-carbonate reactivity

  Reactions observed with certain dolomitic rocks are associated with alkali-carbonate reaction (ACR). Dedolomitization, or the breaking down of dolomite, is normally associated with expansive alkali-carbonate reactivity. This reaction and subsequent crystallization of brucite may cause considerable expansion.
- Heat-Induced Delayed Expansion

Abrasion /Erosion

Abrasion damage occurs when the surface of concrete is unable to resist wear caused by rubbing and friction. Although wind-borne particles can cause abrasion of concrete, the two most damaging forms of abrasion occur on vehicular traffic surfaces and in hydraulic structures, such as dams, spillways, and tunnels.

- Traffic surfaces
- Hydraulic structures

Cavitation

The formation of bubbles or cavities in a liquid. In hydraulic structures, the liquid is water and the cavities are filled with water vapour and air. The cavities form where the local pressure drops to a value that will cause the water to vaporize at the prevailing fluid temperature. Cavitation damage is produced when the vapour cavities collapse, causing very high instantaneous pressures that impact on the concrete surfaces, causing pitting, noise, and vibration.

Fire /Heat

Restraint to Volume Changes

Restraint to drying shrinkage is the most common cause of concrete cracking.

- Plastic shrinkage cracking
- Drying shrinkage cracking
- Thermal stresses

Overload and Impact, Earthquake damage

Loss of Support

Settlement can cause a variety of problems in concrete structures, from cracking and performance problems to structural failure.

- Slab curling.

Surface Defects

- Formed surfaces

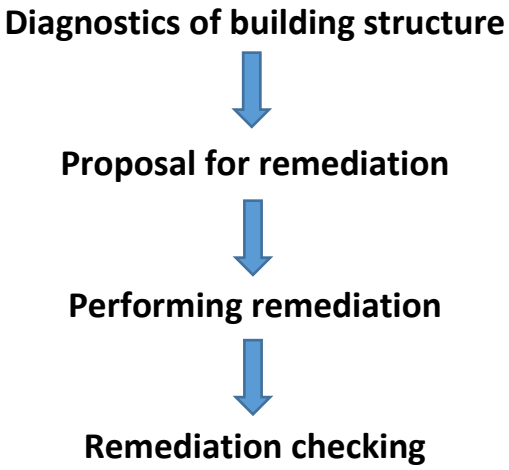
Surface air voids (bug holes), Honeycomb, Form tie holes, Cold joints, Form streaks, Sand streaking, Form offsets

- Finished surface

Delaminations, Blister, Dusting, Popout, Subsidence cracks, Crazing

General requirements for repairs of reinforced concrete structures

In order to carry out proper remediation work, ie repair and extension of the life of the structure, the principles of proper work progress must be observed.



1. Diagnostics of reinforced concrete structure

Required characterization of the state of construction in terms of static reliability and corrosion state of the structure. Within the framework of diagnostics, so-called structural engineering research is carried out, the purpose of which is:

- Obtaining of available documents
- Building survey
- Diagnostics of material properties
- Evaluation of the obtained results and results

1.1. Building and technical survey

Preliminary investigation

Contains:

- documentation analysis;
- dimensions control;
- preliminary measurements and evaluation;
- search for critical points and critical materials, components or structures;
- installation of measuring bases;
- establishing a further exploration process in alternatives;
- draft a plan of detailed investigation;
- immediate action.

Application of so-called detection methods:

- provides qualitative data;
- defines areas of occurrence of a certain phenomenon;
- for example, moisture (microwave methods) and crack (digital photography) are considered.

Detailed investigation

Contains:

- verification of load and environmental condition;
- focus on critical point;
- determination of physical – mechanical properties of materials;
- data application for structural analysis.

Application especially of proof methods:

- correspond to quantitative methods;
- evaluation of degradation extent;
- contains results based on building monitoring.

1.2. In addition, indicative, complementary and operational types of surveys can be used.

Historical building investigation

Investigates the origin, performance and historical values of each part of the object.

The output is basic information about the architectural and building development of the structure, the passport of the building with the indication of the historical elements and facade.

- Partially destructive methods can be used.
- Historical building investigation contain:
- primary measuring of structures,
- study of materials about building development,
- architectural analysis of the structures,
- art history evaluation,
- evaluation of the state and possibilities of protection,
- draft of the principles of technical building investigation.

The output is a text report about the investigation, containing a graphical outputs.

Restoration investigation

Restoration investigation is designed to gain information for performance of restoration works (painting, sculpture, artistically craft activity).

Operative investigation:

- records new findings during performed work,
- usually carried out for buildings in emergency situation, for uncovering of originally inaccessible spaces etc.

Exploration before building demolition

- Investigation especially of the structural design of building and stiffness of joining elements.
- Evaluation of building materials, components and structures for further use.
- Occurrence of hazardous waste from health and environmental aspect.
- Threatening the surrounding area by demolition (static, hygienic, ecological).

1.3. Basis for conducting exploratory work:

- design documentation of the construction,
- information on the progress and changes in the implementation (building diary),
- Data on the age of the structure, the foundation conditions, its use, the load, and surveys conducted so far,
- Reconstruction, repair, and emergency data.

1.4. Construction survey

The surveys are generally undertaken to help property owners understand the condition of a property, recording risks and potential expenditure that may be required, enabling them develop the appropriate remedial or maintenance plans.

Aims of a building survey

- Documenting the present condition of the property, highlighting areas of failure or concern.
- Identifying causes of past, or ongoing, deterioration.
- Identifying issues that need attention to prevent serious damage.
- Identifying things that need further enquiries to pre-empt problems in the future.
- Presenting conservation and maintenance recommendations.
- Providing an estimate of the cost of any works that may be required.

- Determination of actual state of construction and comparison with existing documentation

- the dimensions and layout of the decisive structural elements, the casing, the deformation of the supporting elements, their deflections, the quality of the joints and details
- Concrete quality of structural elements, range of concrete failure:
    - Area X local violation.
    - Depth of the degraded concrete layer,
    - the actual thickness of the concrete cover over the reinforcement,
    - salt content of salts (especially chloride) in surface layers of concrete,
    - absorption of surface layers of concrete,
    - the tensile strength of the surface layers of concrete,
    - compressive strength of concrete.
- method of reinforcement and structural design of statically significant structural (position, diameter and amount of reinforcement), quality / type of reinforcement, corrosion state of the reinforcement.
- extent of failure of additional structures.
- Monitoring of structures at time intervals
- visual and acoustic tracing methods, percentages of violations, cavities, cracks
    - crack length - band, meter,
    - crack width - magnifiers and hand-held microscopes with dipsticks, crawling crawler cards,
    - depth of cracks - visually, visually using core boreholes, non-destructive methods (ultrasound, acoustic emission)

1.5. Diagnostics of material properties

- On-site tests (IN SITU)
- Testing in the laboratory

- Physical-mechanical
- Physically-chemical

- Destructive
- Non-destructive
- Semi-destructive

- **Most frequent on-site tests (IN SITU)**
    - Physical-mechanical
        - Tensile strength of surface layers, adhesion
        - Compressive strength - non-destructive method
        - Position, diameter and amount of reinforcement, quality / type of reinforcement, corrosion state of the reinforcement.

    - Visual and acoustic tracing methods (cracks, cavities, gravel nests, leachates, formwork remains, traceability of individual layers of concrete)
    - Surface absorption, humidity conditions

- Physico-chemical
    - - FF test - pH test of concrete using phenolphthalein, indicative determination of depth of carbonation. Phenolphthalein in alkaline medium (above pH 9.6) stains violet, otherwise it remains colorless.

- **Most frequent tests in the laboratory**
    - Physical-mechanical
        - Concrete strengths (compression, bend stroke, stroke ...), on boreholes of min. 100mm.
        - Modulus of elasticity
        - Tensile strength of reinforcement
        - Surface absorption
        - Durability characteristics, especially frost resistance, resistance to CHRL
    - Physico-chemical
        - Chemical analysis
        - RTG (crystalline substances, qualitative assessment), DTA (Quantitative Evaluation), REM, SEM, TEM, etc.
        - pH

1.6. Evaluation of the obtained results and results

2. Proposal for remediation

Design of remediation technology

The design of the remediation process depends on the state of the sanitary structure that we find using STP. The purpose of remediation is to prevent or at least significantly reduce the penetration of degradation factors into the concrete structure. Part of the redevelopment is (not necessarily) to improve and reinforce the entire concrete structure in order to increase durability.

Options for redevelopment of the concrete structure

- Preventive intervention - performing maintenance
- Aesthetic appreciation - Extending the life of the structure - Repairing top layers, such as peeling coats.
- Removing corrosively damaged structures without damaging their static function
- Remediation of statically damaged structures - financially demanding reinforcement of the structure

Basic phases of the proposal

1. **Structure management** - state and history of construction
2. **Assessment process** - classification of defects and disorders and identification of causes
3. **General Design** - Variants, Principles and Methods
4. **Design of protection and repair** - definition of the intended use of the product - requirements, background, production, specification work, documentation
5. **Protection and repair** - selection of products and equipment, testing and quality control, safety
6. **Acceptance** - tests, defects and defects, documentation

General requirements for remediation systems

- Freeze-thaw resistance, resistance to CHRL
- Watertightness
- Volume stability - humidity, temperature
- Physical-mechanical similarity with the original construction material (tensile strength, pressure, modulus of elasticity)
- High diffusion resistance against the penetration of CO_2, SO_x and other degrading gases
- Good workability even under harsh conditions - working in confined conditions, working under different environmental conditions (temperature, humidity, running water ...)

Factors influencing the selection of remedial materials of technological processes

- Suitability for a given type of construction
- Suitability for the type of defects and failures
- Fitness for the environment
- Suitability for current or contemplated design use, operating conditions
- Suitability for the intended remediation target - e.g. due to the life of the structure
- The resulting remediation cost
- Overall damage to the structure
- Speed of remediation
- Technological knowledge and equipment of the supplier
- Ensure the compatibility of used materials with the original design and with each other

Principles of remediation

1. **Pre-treatment of the concrete surface**
2. **Cleaning and protecting of the reinforcement**
3. **Surface treatment**
4. **Application of the secondary protection system**

Pre-treatment of the concrete surface

The purpose of surface pre-treatment is to remove disturbed, degraded surface layers of concrete and to form a solid concrete bearing substrate for the application of paving materials. Part of this technological operation must also be the cleaning of reinforcement from corrosion products.

The technological operations suitable for removing the surface layers of concrete include in particular:

- High pressure water jet.
- Cutting ("shredding") manually or using electric picking hammers.
- Sandblasting.
- Brokering.
- Pneumatic hammering.
- Milling.
- Grinding.
- Brushing with steel rotary brushes..

Materials for rehabilitation

Materials for rehabilitation must meet the following requirements in particular:

- high coherence with the substrate,
- good water tightness, low absorption,
- Frost resistance at least at T 100 level, or larger according to specific exposure conditions,
- Minimum volume changes due to changes in humidity and temperature,
- limited shrinkage cracks,
- the lowest modulus of elasticity,
- Compressive strength, resp. in a bend stroke at the same or a slightly higher level than the underlying concrete,
- Resistance to aggressive media according to specific exposure conditions.

For mortars, the binders of which are macromolecular substances, resistance to alkaline environment must also be demonstrated.

Are divided into three groups:

- Cement mortars and concrete (CC).
- Cementitious mortars and concrete modified with polymeric additives (PCC).
- Mortars and concrete bonded by polymer resin (PC).

Surface protection systems (secondary protection)

Surface protection systems form an additional barrier to the penetration of undesirable media, especially steel reinforcement, on the surface of the reinforced concrete structure. This is mainly carbon dioxide and water penetration, but it can also be a whole range of other aggressive media according to a specific exposure of the reinforced concrete element. At the same time, surface protection systems unify the surface of the reinforced concrete structure and improve its overall appearance.

Due to the limited time effectiveness of surface protection systems, it cannot be considered as a full replacement of a sufficiently thick cover layer of concrete or mortar over the reinforcement.

The following criteria are decisive for selecting a suitable surface protection system:

- The overall function of a reinforced concrete element or structure,
- Mechanical load of the surface of the concrete structure,
- Possible action of special aggressive media such as spreading salts,
- Water vapour and carbon dioxide permeability requirements,
- Watertight,
- Requirements for bridging stable or moving cracks.

Depending on the thickness, we distinguish these coating systems:

Hydrophobic coatings

Made by special solutions that absorbs into the treated surface and prevent the intrusion of non-pressure rainwater into the surface layers of the structure.

Impregnating coatings

Made with non-pigment and low viscosity substances. This treatment partially reduces the penetration of liquid media into the concrete and its main effect is to strengthen the surface.

Thin Film Coating

Thickness of about 0.1 to 0.3 mm. The coating can be both colour and colourless. It closes the surface of the structure and limits the penetration of both liquid and gaseous media. The surface can be both smooth (easy to clean) and rough (antiskid properties).

Multilayer coat

With a thickness of 0.2 to 1 mm, it perfectly closes the surface of the structure and, when properly assembled, increases its durability considerably.

Depending on the utility parameters, we divide the coatings or coating systems into the following groups:

- Hydrophobization or penetration, limiting partial penetration of liquid media into the surface of the structure.
- Coatings that block the penetration of carbon dioxide and water into the surface of the structure, while being well-penetrable for water vapour.
- Coatings that block the penetration of gaseous and liquid media into the surface layers of the structure, particularly resistant to specific aggressive media.
- Coatings, blocking gaseous and liquid media penetration into the surface of the structure, capable of bridging static or possibly active cracks of defined width.

3. Execution of remediation

The treatment, application and care of repairs is done exactly according to the manufacturer's instructions given in the relevant technological regulations.

For good repairs, it is necessary to pre-prepare the surface of the sanitary materials of the structure.

Reinforcement - removing corroded or otherwise damaged reinforcement parts, cleaning, reinforcement by replacing and replenishing bars.

Pre-treatment methods

- Needle rust removal
- high pressure water jet (up to 70MPa)
- compressed air and abrasive material
- mechanically wire brush

Pre-treatment of concrete - The main purpose of the pre-treatment of concrete surfaces is the removal of residues of older surface coatings, so-called paints, dust, algae, release agents, surface contamination, removal of disturbed, carbonated or aggressive media of contaminated surface layers of concrete and the achievement of a bearable concrete substrate, so that grains of fine or coarse aggregate are visibly exposed. Part of this technological operation may also be the cleaning of reinforcement from corrosion products.

Pre-treatment methods

- Cruel agitation and destruction of matter

  Pressure waves, expansion gases or cements, blasting hammers

- Fine agitation

  Mechanically, diamond discs, needle guns, abrasive blasting, shotgun, burner blasting, or high pressure water jet

Remediation methods of reinforcement

- Protection or restoration of passivation:
  - Increase the thickness of the cover layer
  - Replacement of contaminated or carbonated concrete
  - Electrochemical re-alkalization
  - Diffuse re-alkalization
  - Electrochemical removal of chloride causing corrosion
- Increasing the electrical resistance of the concrete
  - Moisture protection with surface protection
  - Limiting oxide content by impregnation or surface coating, cathodic protection
- Modification of the cathodic area
  - Limiting the oxygen content (by cathode) by impregnation or surface coating
- Cathodic protection
  - Application of electrical potential
- Anodic area adjustment
  - Creating conditions under which potentially anodic regions of reinforcement are not able to take part in the corrosion reaction.
  - Reinforcement coatings with substances containing active pigments
  - Reinforcement coatings with barrier coatings
  - Application of inhibitors to concrete by impregnation or diffusion

Remediation methods of concrete

- Limiting or preventing the penetration of pollutants.

  Impregnation, surface protection, crack banding, surface treatment, crack filling.

- Influence of humidity.

  Impregnation, Surface Protection, Shielding and Casing, Electrochemical Protection.

- Restoration or replacement of concrete.

  Manual mortar application, torture, concreting, element replacement, separate injection grouting, trowel and cover layers.

- Reinforcement of the structure.

  Adding and replacing reinforcement, bonding reinforcement to concrete holes, adding mortar or concrete - reprofilation, injection of cracks, voids or voids, filling of cracks and voids, joint seals, additional prestressing.

4. Remediation control

Performing control tests and works serves to collect information on the quality of the remediation. Checks are carried out both during repairs and periodically after completing the work at appropriate intervals. The scope of inspection work is usually determined by the contractor.