Durability of Reinforced Concrete Structures, Theory vs Practice

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Introduction

- Reinforced Concrete Deterioration:

1. Concrete itself: AAR, chemical attack, freezing and thawing, abrasion and fire.
2. Corrosion of steel reinforcing bars, which is the major cause of RC durability problem.

Introduction

- Corrosion of steel: Electro-chemical reaction arises from difference in electrical potential along the steel bar.

***Anodic reactions*:**

$$Fe \rightarrow Fe^{++} + 2\,e^{-}$$
$$Fe^{++} + 2\,(OH)^{-} \rightarrow Fe(OH)_2 \quad \text{(ferrous hydroxide)}$$
$$4\,Fe(OH)_2 + 2\,H_2O + O_2 \rightarrow 4\,Fe(OH)_3 \quad \text{(ferric hydroxide)}$$

***Cathodic reaction*:**

$$4\,e^{-} + O_2 + 2\,H_2O \rightarrow 4\,(OH)^{-}$$

- Results of rusting: cracking, spalling or delamination of concretre cover, leading to easier ingress of aggressive agents and accelerate corrosion rate.

Introduction

- Conditions for corrosion:

1. Presence of oxygen and water: optimum relative humidity is 70-80%.
2. Differences in electro-chemical potential: e.g. part of concrete permanently submerged in water and a part is exposed to periodic wetting and drying; difference in cover thickness.
3. De-passivation.

Introduction

- Passivation: formation of a protective thin layer of oxide on steel surface due to high alkalinity (presence of lime, pH ~ 13) of hydrated cement paste.
- De-passivation: destruction of the protective oxide layer due to carbonation and chloride attack.

Permeability and Diffusivity of Concrete

- Durability problems: transport of fluids/ions through the concrete by:

1. Permeation (pressure gradient)
2. Diffusion (concentration gradient)
3. Sorption (capillary suction, insignificant)

Permeability of Concrete

- Permeation: Darcy's Law

$$\frac{dq}{dt}\frac{1}{A} = K\frac{dh}{dL} \qquad \text{where } K = \text{coefficient of permeability}$$

- Permeability of concrete mainly due to interconnected capillary pores with sizes of at least 120 nm.

Permeability of Concrete

- Permeability depends on capillary porosity (Fig.1), which in turn depends on W/C ratio and degree of hydration. Decrease W/C reduces permeability. (Fig.2)

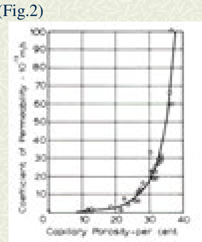

Figure 1 Effect of capillary porosity on permeability (Powers, 1958)

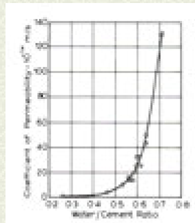

Figure 2 Effect of water/cement ratio on permeability (Powers et al, 1954)

Permeability of Concrete

- Permeability also depends on permeability of aggregates.
- Permeability of most rocks: 10×10^{-14} to 100×10^{-14} m/s, similar to hardened cement paste.(Table 1)
- However, permeability of granite commonly used in HK : larger than 1000×10^{-14} m/s !
- ***There is durability limitation when using HK granite. So don't specify impracticable durability standard !***

Type of rock	Coefficient of permeability (m/s)	W/C ratio of mature paste of the same permeability
Quartz diorite	8.24×10^{-14}	0.42
Marble	2.39×10^{-13}	0.48
Marble	5.77×10^{-12}	0.66
Granite	5.35×10^{-11}	0.70
Sandstone	1.23×10^{-10}	0.71
Granite	1.56×10^{-10}	0.71

Table 1 Comparison between permeability of rocks and cement paste (Powers, 1958)

Diffusion of Concrete

- Diffusivity: Fick's Law

$$\frac{dq}{dt}\frac{1}{A} = D\frac{dc}{dL} \qquad \text{where } D = \text{coefficient of diffusivity}$$

- Permeability and diffusivity are inter-related. They are roughly proportional to each other.
- Relative humidity/degree of pore saturation influences diffusion rate.

  Dry pores: diffusion of gases only

  Sat. pores: diffusion of ions only

Permeability and Diffusivity of Concrete

- Curing greatly affects permeability and diffusivity (Fig.3)
- Good and prolonged curing are required.
- ***Existing common practice of removing formwork within a very short time so as to speed up construction is not appropriate!***

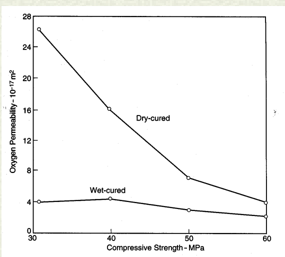

Figure 3 Effect of curing on oxygen permeability (Bassat et al, 1990)

Carbonation

- Carbonation: reaction between carbon dioxide in air and the alkalis (lime) in concrete.
- Indirectly affects durability of concrete: reduces alkalinity of concrete (to ~ pH9), leading to de-passivation of steel reinforcement and consequently corrosion.
- Highest rate at relative humidity of around 70% (close to HK condition)

Carbonation

- Depth of carbonation:

$$d_c = C\sqrt{t}$$ where C = Carbonation coefficient

- Carbonation coefficient mainly depends on diffusivity of concrete.

  Example: 15mm carbonation depth is reached after 15 years for W/C ratio of 0.6; but 100 years is required for W/C ratio of 0.45.

Carbonation

- Carbonation rate may be simply taken as a function of concrete strength since both diffusivity and strength depend on W/C ratio.
- However, curing greatly affects carbonation rate. (Fig.4)
- Therefore, carbonation is more serious in actual construction than in laboratory.

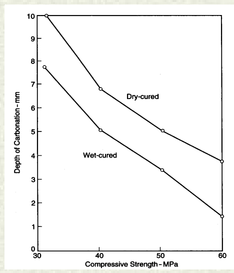

Figure 4 Effect of curing on carbonation depth (Bassat et al, 1990)

Chloride Attack

- Chloride causes de-passivation of steel, leading to corrosion.
- Chloride ions activate the surface of the steel to form an anode, the passivated surface being the cathode:

$$Fe^{++} + 2\,Cl^- \qquad FeCl_2 \text{ (ferrous chloride)}$$

$$FeCl_2 + 2\,H_2O \qquad Fe(OH)_2 + 2\,HCl$$

Chloride Attack

- Chloride attack does not causes corrosion in structures that permanently submerged in seawater (lack of oxygen).
- Corrosion due to chloride attack is the most serious at regions subjected to periodic wetting and drying. (Fig.5)

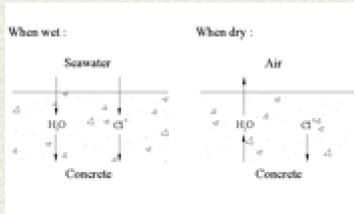

Figure 5 Ingress of chlorides in concrete subjected to regular wetting and drying

Chloride Attack

- In HK, marine structure and land structures at close proximity to the sea (probably due to sea turbulence and air-borne seawater droplets) are subjected to chloride attack.
- Experience in HK: air-borne chloride problem at a distance of 30m from the coast.
- ***Marine concrete standard is advised to be used for structure within 100m from seashore.***

Chloride Attack

- Chloride content profile: commonly obtained from saltwater immersion or spraying tests.(Fig. 6)
- Problems of these tests: low repeatability and cannot represent the actual extremely complicated situation arisen from tidal variation, wind and sunshine.

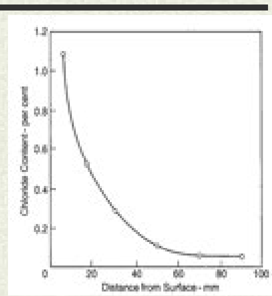

Figure 6 A typical chloride content profile in concrete (Neville, 1995)

Improving Durability by Use of HPC

- High performance concrete (HPC) emphasizes both strength and durability.
- Making HPC by lowering W/C ratio and incorporating mineral admixtures, e.g. PFA, CSF.
- Improving durability by increasing carbonation and chloride resistances.

Improving Carbonation Resistance by Use of HPC

- Effect of W/C ratio: directly affects pore structure and diffusivity. Lower W/C increases carbonation resistance.
- Carbonation resistance correlates with strength. (Table 2)

28-day strength (MPa)	Depth of carbonation after 30 years (mm)
20	45
40	17
60	5
80	2

Table 2 Correlation between depth of carbonation and strength (Parrott, 1987)

Improving Carbonation Resistance by Use of HPC

- Two opposing effects of mineral admixtures on carbonation:
  1. Pozzolanic reaction: reduces alkalinity by reacting with lime. Carbonation rate will be increased.
  2. Densification of cement paste: reduces diffusivity. Carbonation rate will be decreased.
- PFA and GGBS have only marginal effects.
- CSF increases carbonation resistance significantly.
- Adequate curing is required to maintain (or increase) carbonation resistance if mineral admixtures are added.

Improving Chloride Resistance by Use of HPC

- Depends on pore structure and diffusivity.
- Can increase the resistance by lowering W/C ratio and adding mineral admixtures.
- W/C ratio: directly reduces the diffusivity.
- Mineral admixtures:
  1. Improves packing of bulk cementitious powders.
  2. Reduce porosity in hardened cement paste by reacting with soluble lime to form insoluble gel.
- CSF is particularly effective due to its high fineness.

Improving Durability by Use of HPC

- Example of using HPC: Port Works Design Manual: Part 1

Mix parameter	Acceptable limits
Water/cementitious content ratio	Not exceeding 0.38
Cementitious content	380 – 450 kg/m^3
Supplementary cementitious materials	Either PFA or GGBS, and CSF to be incorporated
If PFA added, PFA content	25 – 40 %
If GGBS added, GGBS content	60 – 75 % (normal application) or 60 – 90 % (low heat application)
CSF content	5 – 10 %
Characteristic strength	45 MPa

Table 3 Specification for marine concrete in Port Works Design Manual

Improving Durability by More Careful Crack Control

- Cracks:
  1. Non-structural: Due to sedimentation, shrinkage or thermal movement.
  2. Structural: Excessive tensile stress.
- Impairs water-tightness of concrete cover to steel and provides an access for aggressive chemicals, affecting durability of concrete.

Improving Durability by More Careful Crack Control

- Non-structural cracks:

1. At plastic stage: plastic settlement cracks and plastic shrinkage cracks.
2. At curing stage: early thermal cracks due to internal or external restraints.
3. At long-term stage: cracks due to presence of restraints, e.g. rigid walls or support, which prevents thermal and shrinkage movements.

Improving Durability by More Careful Crack Control

- Avoidance of non-structural cracks:

1. Cracks at plastic stage: Avoid by improving mix design and shielding top surface of fresh concrete.
2. Cracks at curing stage: Avoid by providing insulation for internal restraints or using internal cooling for external restraint. ***Must distinguish types of restraints and then use correct preventive measure!***
3. Cracks at long term stage: Alleviate by providing movement joints, or using late-cast strips and shrinkage reducing agent in case of shrinkage cracks.

Improving Durability by More Careful Crack Control

- Structural cracks:

1. Due to development of excess tensile stress from applied loadings.
2. Almost unavoidable; but crack widths can be controlled by limiting the tensile stresses developed and putting in crack control reinforcement.

Improving Durability by More Careful Crack Control

- Attitudes in the industry:
  Material engineers say: it is the responsibility of structural engineers.
  Structural engineers say: it is the responsibility of material engineers.
  Consultants say: bad workmanship.
  Contractors say: inappropriate specification and design.
- In fact, we have not done enough on crack control.
- Things we should do: ***rewrite existing specification, train the site staff about correct curing methods, develop methods of temperature control during curing, conduct research on thermal and shrinkage movement analysis.***

Improving Durability by Use of Corrosion Inhibitors

- Corrosion inhibitors: Nitrites of sodium and calcium.
- Action of nitrite:
  1. Converts ferrous ions into stable passive layer of ferric oxide (more resistant to chloride attack).
  2. Preferentially reacts with chloride ions.
- Effectiveness varies with type of cement, quality of concrete, cover thickness and also environmental conditions. May not be effective indefinitely.
- Corrosion inhibitor serve only as an additional safeguard; they are not substitute for good quality concrete.

Improving Durability by Use of Protective Coating

- Protective coating on concrete surface: barriers to stop ingress of aggressive fluids/ions.
- Considerations: ratio of size of cathode to anode (if only parts of the structure are coated), surface preparation, UV resistance, crack bridging capability, re-application of coating (life cycle cost analysis).
- Protective coating on steel reinforcement:
  1. Galvanizing zinc: Protection by sacrificing; limited effective life.
  2. Epoxy coating: Prevent direct contact with aggressive chemicals; reduce bond strength and require special reinforcement detailing.

Conclusion

- Durability of concrete: needs to be dealt with by both theoretical studies and practical evaluations.
- Deep collaboration between university and industry is the key to the ultimate solution.

  University: Theoretical studies and controlled experiments, more site visits to improve understanding on practical problems.

  Industry: More field tests, field trials and monitoring, may also provide sponsorship for research.

Conclusion

- Future works:

1. Focus on concrete itself, e.g. newly adopted specification for marine concrete (Grade 50) is a good starting point.
2. Develop reliable test methods for measuring carbonation resistance and chloride diffusivity so as to pave way for gradual migration to performance specification.
3. Revised, or even redraft, the existing specifications (curing, temperature control).
4. Long term research in collaboration with industry on cracks control and corrosion protection

Q & A