Durability of Concrete Structures: Impact of Global Warming and Mitigation Measures

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Introduction

Global warming:

- Since 1880, the global temperature increased at a rate of 0.07°C per decade.
- However, after 1981, the rate doubled. Global temperature increased at a rate of 0.18°C per decade.
- Predicted a 4°C increase in global temperature during 21st century.

Introduction

Causes of global warming:

- Caused by greenhouse gas, result in melting of ice sheets and thermal expansion of seawater.
- Predicted a 500 mm sea level rise during 21st century.
- Worst case scenario: both the Greenland Ice and Antarctic Ice melt, leading to a 66 m sea level rise.

Introduction

Consequences of global warming:

- Increase in temperature, sea level and CO_2 concentration all have significant effects on the durability of concrete structures.
- Durability of reinforced concrete depends on corrosion of reinforcing steel bars.
- Concrete by itself: corrosion resistant, durable.
- Reinforcing steel bars embedded start to corrode if de-passivated due to carbonation or chloride attack, which are influenced by temperature, sea level and CO_2 concentration.

Corrosion of Steel in Concrete

- Corrosion: an electrolytic chemical reaction involving an anode, a cathode, an electrolyte, an ionic current through the electrolyte and an electron current through a closed electric circuit (Fig. 1)

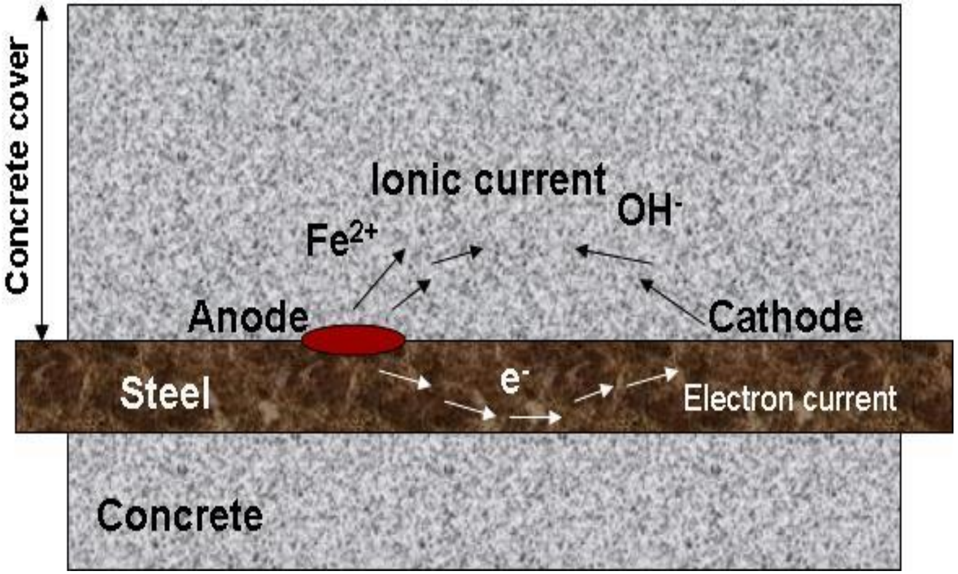

Figure 1 Corrosion of reinforcing steel (The Concrete Portal, 2021)

Corrosion of Steel in Concrete

- Passivation: formation of a protective thin layer of oxide on steel surface due to high alkalinity (pH~12-13) of hydrated cement paste.
- De-passivation: destruction of the protective thin oxide layer due to carbonation or chloride attack.
- 3 stages of corrosion: initiation, propagation and acceleration. (Fig. 2)

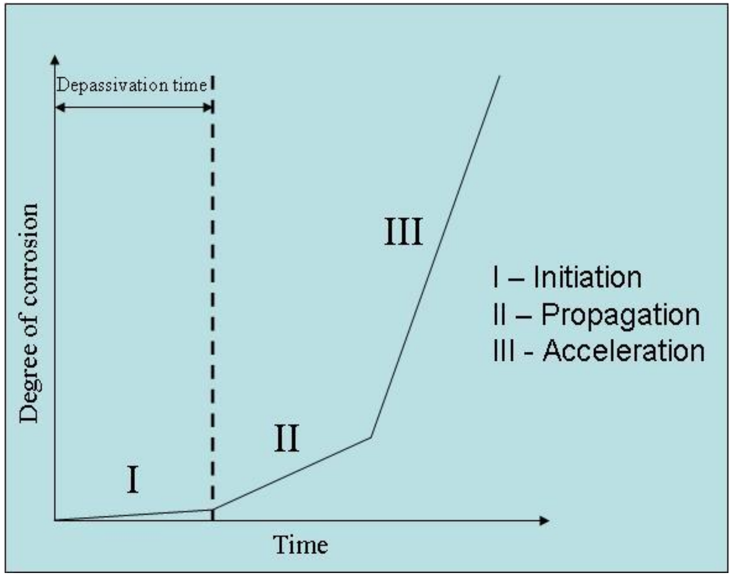

Figure 2 Acceleration of corrosion rate (The Concrete Portal, 2021)

Carbonation

- Carbonation: reaction between carbon dioxide in air and the alkalis (lime) in concrete, starts when fresh concrete is exposed to the air.

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

- Phenolphthalein is sprayed on the surface of concrete to depict carbonation. (Fig. 3)

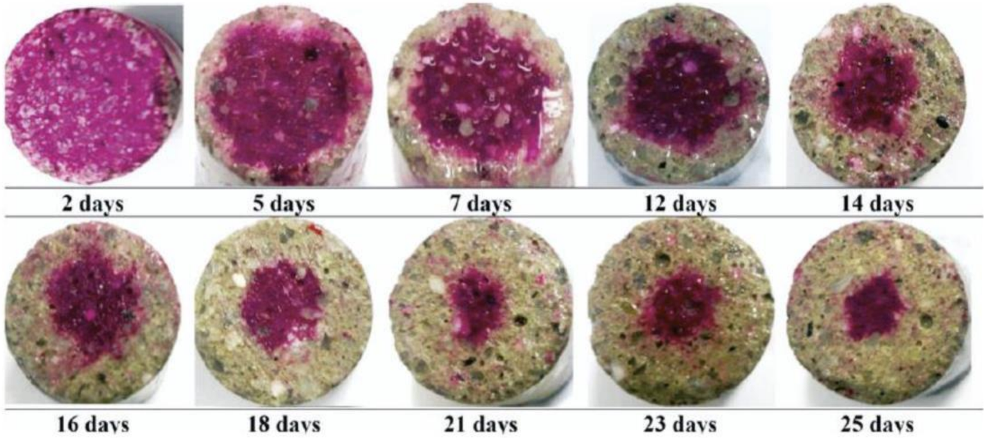

Figure 3 Carbonation of concrete at early age (Lacerda et al., 2017)

Carbonation

- Degree of carbonation is expressed in terms of carbonation depth, i.e. the depth of concrete that has become carbonated.
- When the carbonation depth exceed concrete cover, the carbonation front will reach the surface of the steel reinforcing bar and the concrete is considered as de-passivated.
- As a result, corrosion of the steel reinforcing bars starts.

Chloride Attack

- Chloride ions: negatively charged ions, corrosive to metals.
- Chloride ions react with the protective iron oxide film, being regenerated, attack the iron oxide again. (Fig. 4)

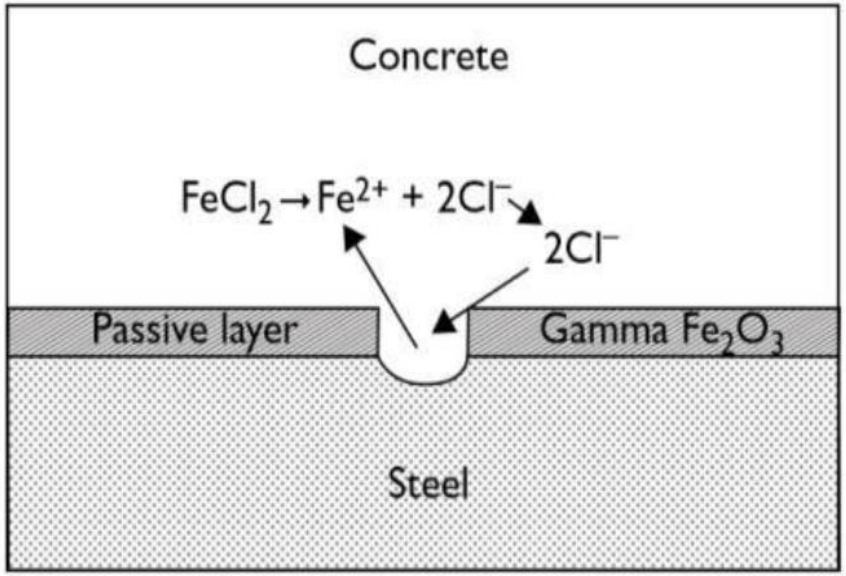

Fig. 4 Regeneration of chloride ions (Anbarasan et al., 2021)

Chloride Attack

- Concentration of chloride ions decreases with the depth from the concrete surface.
- Corrosion of steel reinforcing bars starts when the concentration of chloride ions at the depth of the outermost surface of the steel reinforcing bars exceeds threshold level.

Effect of Temperature on Carbonation

- Carbonation depth is linearly proportional to temperature. (Fig. 5)
- An increase in temperature of 20°C would lead to an increase in carbonation depth of about 11 to 15 mm
- A 4°C of temperature rise in 21st century can result in an increase of 3 mm carbonation depth.

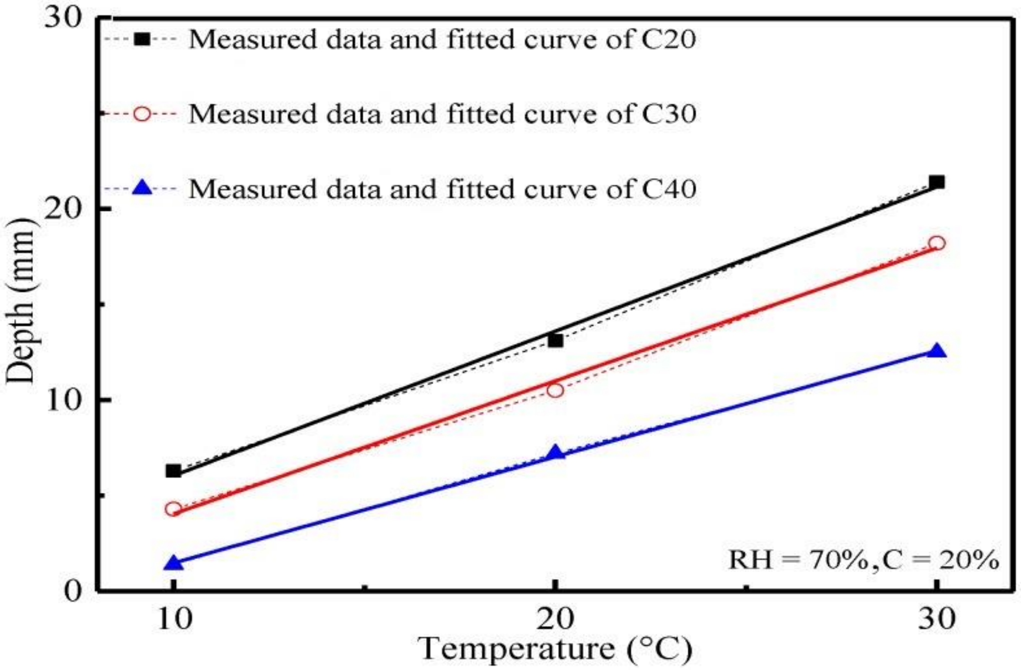

Figure 5: Effect of temperature on carbonation depth (Chen et al., 2018)

Effect of CO_2 concentration on carbonation depth

- Carbonation depth increases with the CO_2 concentration at a decreasing rate. (Fig. 6 and Fig. 7)

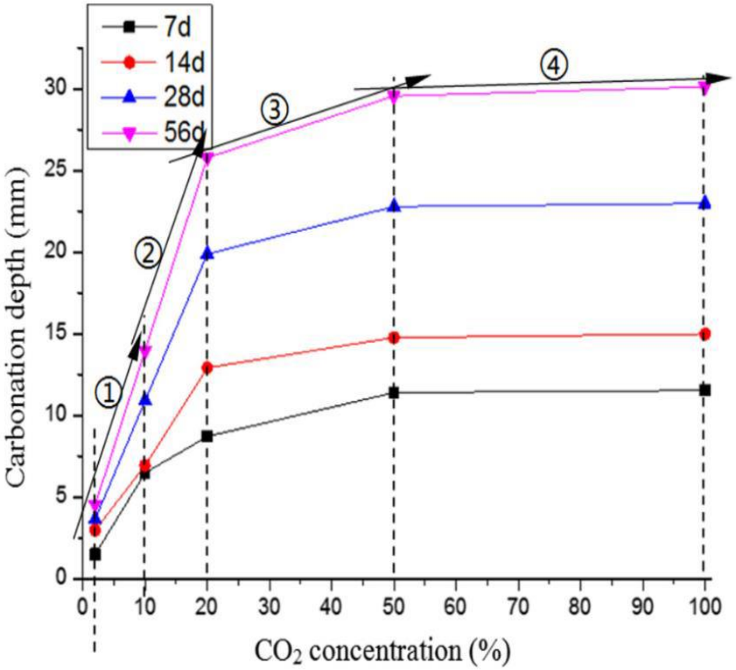

Figure 6 Effect of CO_2 concentration on carbonation depth (Cui et al., 2015)

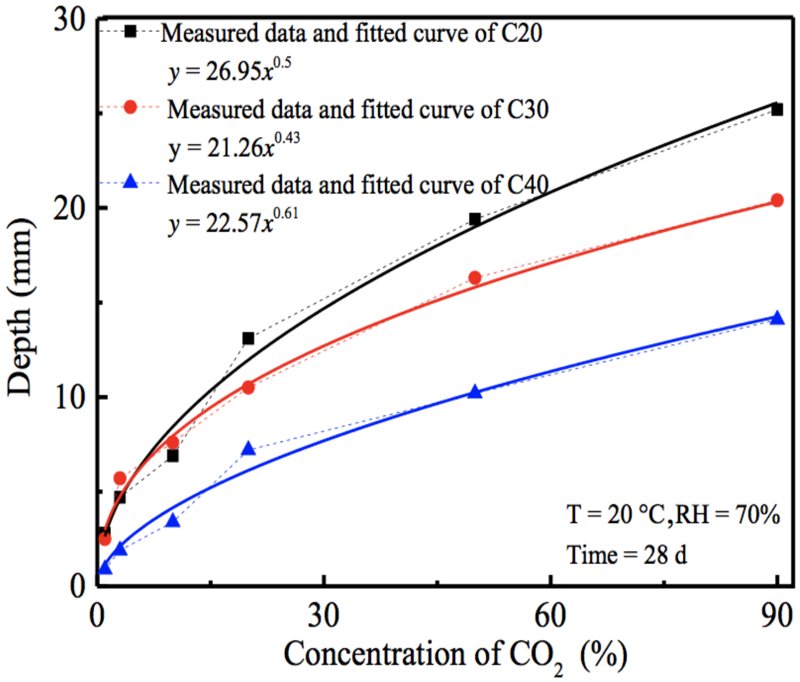

Figure 7 Carbonation depth - CO_2 concentration relation (Chen et al., 2018)

Effect of CO_2 concentration on carbonation depth

- Carbonation depth is more or less a power function of the CO_2 concentration in the form of $y = a(x)^n$
- Assume n = 0.5, carbonation depth can be taken as a square root function of the CO_2 concentration.
- Then, a 10% increase in CO_2 concentration would lead to a 5% increase in carbonation depth.

Effect of Sea Level on Chloride Attack

- Dependent on the location of the structural component.
  - Permanently immersed
  - Within the tidal zone
  - Within the splash zone
  - Above the splash zone
- A structural component originally expected to be above the splash zone could become within the splash zone due to sea level rise.
- Suggestion: assume 500 mm sea level rise at the design stage, raising the quay deck level of the marine structure.

Effect of Temperature on Chloride Attack

- Both chloride diffusion rate and oxygen diffusion rate increase with the temperature according to the Arrhenius equation.
- Arrhenius Equation:

$$k = a \exp\left(-\frac{\Delta E}{RT}\right)$$

where k = diffusion rate, a = constant factor, ΔE = activation energy, R = ideal gas constant, and T = absolute temperature

- Express in natural logarithmic form:

$$\log(k) = \log(a) - \left(\frac{\Delta E}{R}\right)\left(\frac{1}{T}\right)$$

Effect of Temperature on Chloride Attack

- An increase in temperature of 10°C would lead to more than 100% increases in the chloride diffusion rate and oxygen diffusion rate.
- Expect a 4°C temperature rise, increases in the chloride diffusion rate and oxygen diffusion rate would be around 100% and 40%.
- Therefore, effect of temperature should be taken into account in the design of marine concrete structures.

Effect of Temperature on Corrosion Rate

- Both macrocell and microcell methods show that steel corrosion rate increase with temperature. (Fig. 8)
- Corrosion rate doubles with every 10°C increase in temperature.
- Upper layer corrodes faster due to lower quality of concrete there.

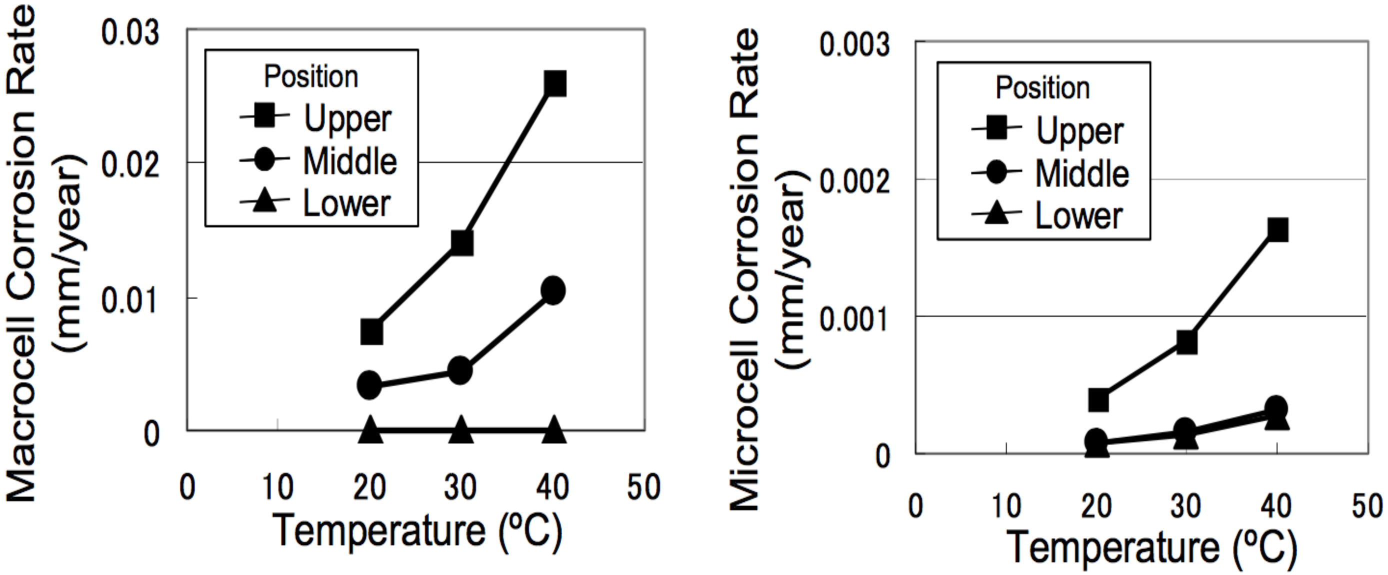

Figure 8 Corrosion rate - temperature relation (Otsuki et al., 2009)

Effect of Temperature on Corrosion Rate

- Assuming a 4°C temperature rise, increase in the steel corrosion rate would be around 40%.
- Therefore, effect of temperature rise on the steel corrosion is quite substantial and should be taken into account in the design of marine concrete structures.

Effects of Global Warming on Service Life

- Service life: time to corrosion damage (severe cracking or spalling).
- 3 stages of steel bar corrosion in corrosion model
  1. corrosion initiation (T_{i}, time to de-passivation of steel bars);
  2. crack initiation (T_{1st}, time to first cracking – hairline crack of 0.05 mm width);
  3. crack propagation (T_{sev}, time for the crack to develop from crack initiation to a limit crack width, w).
- Service life T_{sp} is the sum of 3 stages.

$$T_{\mathrm{sp}} = T_{\mathrm{i}} + T_{\mathrm{1st}} + T_{\mathrm{sev}}$$

Effects of Global Warming on Service Life

- Corrosion initiation period T_i is dependent on whether the corrosion is initiated by carbonation or chloride diffusion.
- If initiated by carbonation, should consider effect of global warming and increase in CO_2 concentration.
- Assume a temperature rise of 4°C and an increase in CO_2 concentration of 10%.
- As a result, 5 mm increase in carbonation depth (3 mm due to temperature rise and 2 mm due to increase in CO_2 concentration).
- Shorten T_i by 24% if the original design carbonation depth at end of service life is 35 mm.

Effects of Global Warming on Service Life

- If initiated by chloride diffusion, should consider increase in chloride diffusion rate due to global warming.
- Assume a temperature rise of 4°C.
- As a result, an increase in chloride diffusion rate of about 100%.
- Shorten T_i by 50%.

Effects of Global Warming on Service Life

- Corrosion propagation period ($T_{1\mathrm{st}}$ + T_{sev}) is dependent mainly on the rate of steel corrosion.
- Assume a temperature rise of 4°C.
- As a result, an increase in corrosion rate of around 40%.
- Shorten the corrosion propagation period ($T_{1\mathrm{st}}$ + T_{sev}) by 29%.

Effects of Global Warming on Service Life

- Resulting percentage shortening of the service life T_{sp} is dependent on the relative magnitudes of T_{i} and ($T_{\mathrm{1st}} + T_{\mathrm{sev}}$).
- For concrete structure with high durability standard and long initiation period T_{i}.
  - If initiated by carbonation: service life will be shortened by 24%.
  - If initiated by chloride diffusion: service life will be shortened by 50%.
- For concrete structure with low durability standard and short initiation period T_{i}.
  - Service life will be shortened by 29%.
- Maintenance and other additional protection measure also affect shortening of service life.

Mitigation Measures

- Increasing the concrete cover
- Addition of supplementary cementitious materials
- Improving crack control

Increasing the Concrete Cover

- Concrete buildings
  - – Not subjected to chloride attack.
  - – Except the toilet areas due to the use of seawater as flushing water.
  - – Thicken the cover by 5 mm and provide waterproofing.
- Marine concrete structures
  - – Currently, 75 mm cover is adopted.
  - – Not advisable to further increase the concrete cover.

Addition of Supplementary Cementitious Materials

- Addition of supplementary cementitious materials can significantly improve the durability of concrete, especially chloride resistance.
- Supplementary cementitious materials:
  - PFA (pulverized fuel ash)
  - GGBS (ground granulated blastfurnace slag)
  - SF (silica fume)
  - MK (metakaolin)

Addition of Supplementary Cementitious Materials

- Ternary blending of cement with two supplementary cementitious materials of successively finer particle size would more effectively improve the durability.
- Supplementary cementitious materials fill the void between the cement grains and the void between larger size particles.
- SF is the most effective.
- 5-10% SF content for marine concrete structures
- At least 8% SF content for some highway projects.

Addition of Supplementary Cementitious Materials

- Chloride ion penetrability is associated with the total charge passed. (Table 1)
- The specified chloride ion penetrability is usually “Very low”.

Total charge passed (Coulombs)	Chloride ion penetrability
> 4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very low
< 100	Negligible

Table 1 Chloride ion penetrability based on RCPT results (ASTM C1202)

Addition of Supplementary Cementitious Materials

- 45% GGBS is as good as 25% PFA. (Table 2)
- At a W/CM ratio of 0.40 and with no SF added, 55% or 65% GGBS could effectively lower the chloride ion penetrability to “Very low”.

Concrete mix no.	Total cementitious materials (kg/m³)	Supplementary cementitious materials added	Total charge passed (Coulombs)	Chloride ion penetrability
1	450	Nil (pure cement)	2951	Moderate
2	450	25% PFA	1104	Low
3	450	35% GGBS	1291	Low
4	450	45% GGBS	1075	Low
5	450	55% GGBS	787	Very low
6	450	65% GGBS	762	Very low

Note: W/CM ratio = 0.40; age at RCPT test = 28 days.

Table 2 Some RCPT results of GGBS concrete using a particular source of GGBS

Addition of Supplementary Cementitious Materials

- GGBS (ground granulated blastfurnace slag) is an effective means of improving the chloride resistance of concrete.
- Can even perform better than the current RCPT requirement of not higher than 1000 Coulombs.
- 500 Coulombs is expected to be reached if W/CM ratio lowered to 0.38 or 0.35 and with at least 5% SF added.

Addition of Supplementary Cementitious Materials

- Concerns about GGBS:
  - Actual performance of the GGBS is dependent on the chemical compositions and fineness of the GGBS.
  - Different sources may have different chloride resistance performance.
  - Therefore, each source of GGBS should be subjected to performance evaluation before use.
  - Moreover, specification should be a performance specification based on the RCPT.

Improving Crack Control

- Cracks are unavoidable.
- Crack width limit: < 0.1 mm (wet concrete), < 0.2 mm (dry concrete).
- Common types of cracks: thermal cracks, shrinkage cracks, temperature movement cracks.
- Crack width are often larger than expected and may even exceed the crack width limit.
- If crack width limit is exceeded, immediate repair is required.
- Otherwise, corrosion will soon start and accelerate and thereby cause severe consequence.

Conclusions

- 4°C temperature rise and 500 mm sea level rise could have significant effects on the durability of reinforced concrete infrastructures.
  - Increase the carbonation depth by 5 mm.
  - Double the chloride diffusion rate.
  - Increase the corrosion rate by 40%.
  - Shorten the service life of concrete structure by up to 50%.
- Urgent need to impose certain mitigation measures and upgrade our durability standard.

Conclusions

- Mitigation measures:
  - Increase the concrete cover so as to delay corrosion initiation.
  - Add supplementary cementitious materials to reduce chloride and oxygen ingress.
  - Exercise better crack control by imposing more stringent requirements on the dimensional stability of concrete and carrying out more detailed design of movement joints.

Conclusions

- Upgrade the durability standard of marine concrete:
  - Lower the W/CM ratio.
  - Increase the PFA/GGBS/SF contents.
  - Lower the limit on the RCPT total charge passed to 500 Coulomb.

Acknowledgement

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Q & A