CHALMERS

The Study of Concrete Durability in the Case of Jinan Yellow River Highway Bridge

Master of Science Thesis in the Master's Programme of

Infrastructure and Environmental Engineering

HUINING WANG

Department of Civil and Environmental Engineering
Division of Building Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Civil and Environmental Engineering
Division of Building Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: + 46 (0)31-772 1000

Cover picture: The picture shows the Jinan Yellow River Highway Bridge, which is a double tower and double cable planes suspension cable-stayed bridge (Broadcaster, 2012).

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Abstract

Reinforced concrete has been commonly used in China as the most popular structural material in many infrastructures. However, since these structures have served for several decades, problems of concrete durability gradually arise due to severe service environment or air pollution of increasing CO_2 concentration. The durability of the reinforced concrete structures principally depends on the optimization of five factors. They are structure design, construction operation, management and maintenance, material properties and the external environmental conditions. These five factors are closely correlated with each other so that the durability will be markedly reduced if one of them is poor. Without adequate durability, the reinforced concrete structure may deteriorate either due to concrete damages or due to reinforcement corrosion. The main reasons behind are concrete carbonation, chloride ion ingress, alkali-aggregate reactions and freeze-thaw cycles. In this study the influences of five factors on the concrete durability were analysed. Further investigation was made regarding the deterioration of reinforced concrete.

As a case study Jinan Yellow River Highway Bridge was inspected in the aspect of concrete durability. The result shows that most of the chambers inspected in Jinan Yellow River Highway Bridge are in a good condition. Concrete suffers slightly from carbonation but the thickness of carbonation depth is far less than the concrete cover. The reinforcement is not likely to be corroded. However, in some testing chambers there are problems with inadequate thickness of concrete cover and cracks. These problems can be treated by pasting cement mortar, which is for safety consideration.

Key words: concrete durability, reinforced concrete deterioration, concrete damage, reinforcement corrosion

Contents

Preface

This master thesis has been carried out from January 2014 to June 2014, at the Division of Building Technology in the Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden. The project has been performed at Shandong Highway Engineering Consulting Company, Jinan, Shandong province, China.

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Gothenburg, June 11, 2014

Huining Wang

Notations

Concrete carbonation

X - Depth of carbonation	(m)
t - Time of exposure	(s)
C - Carbonation coefficient.	-

Chloride ion ingress

C_{Cl} - Concentration of chloride ion	(%)
x - Location	(cm)
D_{Cl} - Diffusion coefficient	-

Concrete strength test

R_m - Estimation value of average concrete strength	(MPa)
$R_{m\alpha}$ - Average concrete strength in non-horizontal direction	(MPa)
$R_{a\alpha}$ - Corrected concrete strength measured in angle α	(MPa)
K_{bt} - Estimation value of strength uniformity coefficient	-
K_{bm} - Average strength uniformity coefficient	-
d_m – Carbonation depth	(mm)
R_{it} - Estimation value of average concrete strength	(MPa)
R_{im} - Conversion value of average concrete strength	(MPa)
R - Design value of concrete strength	(MPa)

Concrete cover thickness test

$\overline{D_n}$ - Average thickness of concrete cover for n points	(mm)
D_{ne} - Characteristic value of concrete cover thickness	(mm)
D_{nd} – Designed values of concrete cover thickness	(mm)
$\overline{D}$ - Average thickness of concrete cover	(mm)
K - Qualified determination coefficient	-

1 INTRODUCTION

With the rapid development of road construction in China, reinforced concrete has been commonly used as the main structural material in many infrastructures. Generally, it is not easy for the reinforcement to be corroded since it is under the protection of concrete (Neville, 1995). However after these structures have already served for several decades, aging problems gradually arise with reinforced concrete structures due to long period of time and increase of traffic loads. Severe service environment such as marine and industrial environment or polluted air with high CO_2 concentration can also degrade the performance of reinforced concrete structures. Durability of concrete, which is a well-known term, has drawn great attention in the field of building technology. Durability expresses the ability of the material to keep its original properties unchanged over time (Wang, 2006). Usually structure with inadequate durability fails to reach its expected service life, thus generating a huge amount of maintenance cost every year. Furthermore, it also causes reduction in strength and may threaten the safety of the structure.

Shandong province, which locates in the east part of China, has a large number of highways and bridges. Jinan Yellow River Highway Bridge located in Jinan (the capital city of Shandong) was built in 1978 and it has been serving for more than 30 years. It is one of the first long-span cable-stayed highway bridges in China. Due to the growing traffic loads, unfavourable environmental conditions, and material degradation, the bridge has been previously overhauled in 1995, 2003 and 2008 (Song et al., 2009). It would be interesting to check nowadays condition of the bridge and to evaluate the durability of reinforced concrete structures.

1.1 Aim and objectives

The aim of this study is to analyse the factors that influence the durability of reinforced concrete structures in China through both literature and case studies. The objectives of the work include the following points.

- Study the reasons and mechanisms of reinforced concrete deterioration,
- Evaluate the current condition of the reinforced concrete structures in Jinan Yellow River Highway Bridge,
- Investigate which kind of damages in the aspect of concrete durability, and
- Propose possible countermeasures that can improve the durability of concrete.

1.2 Methodology

A literature study on concrete durability and relevant damage in reinforced concrete structures in China will be carried out. Jinan Yellow River Highway Bridge in China will be taken as an example of case study by means of visual inspections and non-destructive testing on the selected chambers of the bridge in the aspect of durability of concrete structure, see Figure 1.

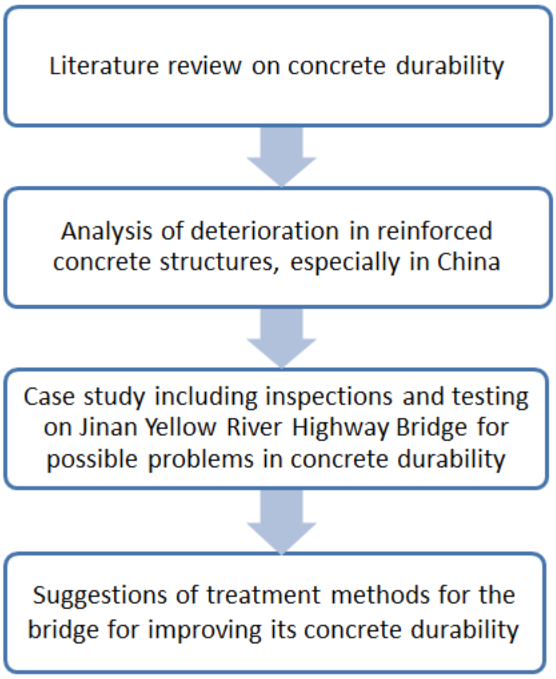

Figure 1 An overview of the work progress used in order to achieve the aim of the project.

2 FACTORS INFLUENCING CONCRETE DURABILITY

The durability of a structure is its ability to serve its anticipated purposes for a long period of time, or at least during its expected service life. In reality, durability of a structure is the ability to maintain the performance of its own functionality under natural environment, serving environment and the physical and chemical actions of internal materials (Li, 2012). However, although a durable structure is expected to serve without deterioration rehabilitation is needed before running out of its designed life; a good concrete durability is not a substitution for a good maintenance. Even though the structure has been designed for a higher durability standard, routine inspections and regular monitoring are required. Otherwise, reduced performance of the concrete structures caused by lack of durability may occur. And this can lead to the discount of bearing capacity concrete structures and in ultimate affect the safety of the whole structure (Li, 2012).

Nowadays, it is commonly recognized that the durability of the reinforced concrete structures principally depends on the optimization of five major factors. They are structure design, construction operation, management and maintenance, material properties and the external environmental conditions. As it is illustrated in Figure 2, these factors cover every step in the design, construction, use, management and maintenance of the concrete structure. They are closely correlated with each other so that the durability of reinforced concrete structures will be strongly reduced if one of them is poor.

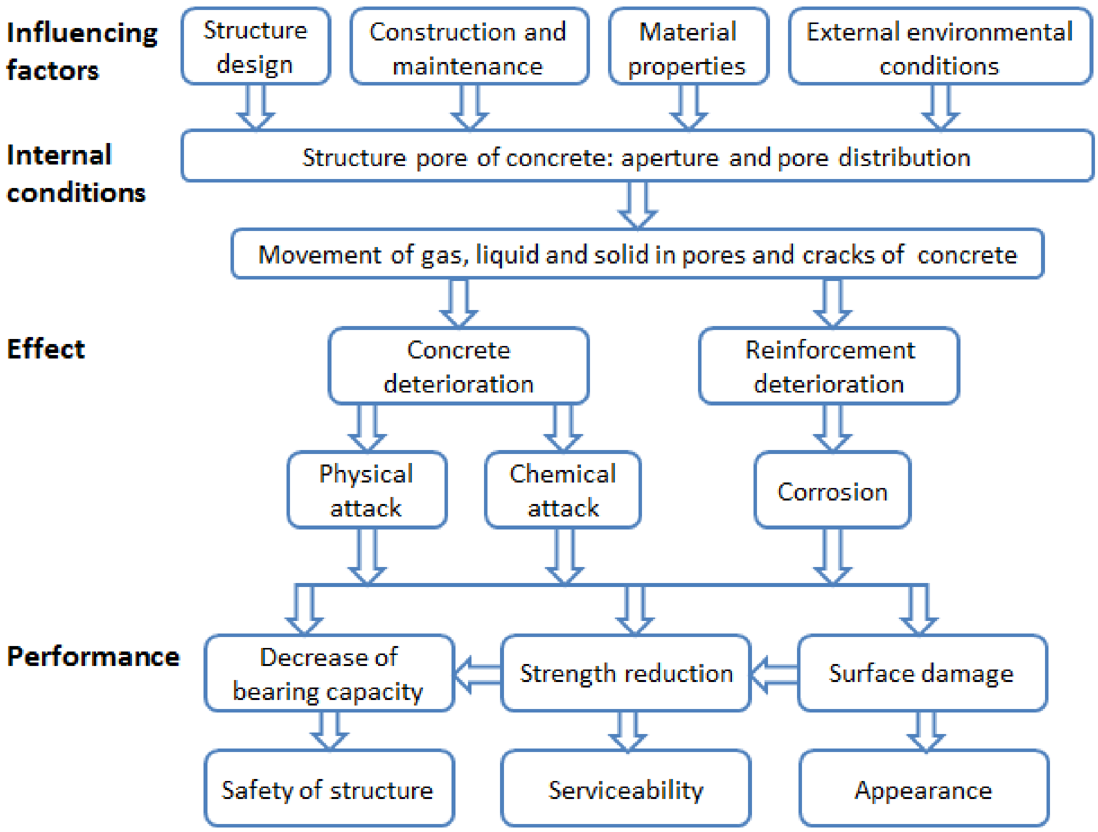

Figure 2 How the different factors influence the durability and the performance of reinforced concrete structures

2.1 Structure design

Correct design is the first requirement for a durable structure (Li, 2012). However, due to inadequate standards and technical specifications, underestimation of service loads and poor information about environmental conditions, the serviceability of the structures will be greatly shortened.

In China, structural design specifications and technical standards mainly consider the structural safety under loading, while durability design under environmental effects is regarded in a secondary position. With the change of construction condition and environmental conditions, standards in terms of structure durability cannot keep pace with the times. Regarding the specific detailed design, there are some loopholes such as the thickness of the concrete cover, bridge drainage facilities and working environment (Li, 2012). For example, the lack of concrete cover for reinforcement has been identified as a major problem associated with "failures" in reinforced concrete bridges. Those could lead to insufficient durability of the bridge structure. Deterioration of many reinforced concrete structures will occur in hostile environment.

The lack of relevant data or incorrect prediction of high traffic loads can lead to inaccurate estimation of service loads. Examples of structure damage due to underestimated loads are recorded worldwide, but they cannot equally be considered or treated. On the contrary, damage to failure of concrete structures related with loads other than those expected in the design period is more frequent.

With the rapid development of road construction in China, it was recorded that in the end of year 1998, there were 210,000 Highway bridges in China under service (Tan, 2005). After they have already served for several decades, some aging problems with reinforced concrete structures appear. However, most of the bridges are lack of routine maintenance. Furthermore, along with the increasing volume of traffic, the previous highways and bridges designed for lower vehicle load standards are still in operation. It demands the highways and bridges much to satisfy the requirements of the current vehicle load standards. Since bridges have been under overload conditions for a long time, the durability of reinforced concrete structures will be rapidly declined.

Structures damaged due to a wrong appraisal of the environmental aggressiveness happen frequently all over the places. The inferior durability characteristics of concrete may be caused by the severe environment conditions that the concrete is subjected to. It is generally recognized that the concrete durability can be influenced by the following environmental factors (Li, 2012):

- Temperature
- Moisture
- Physical factors
- Chemical factors
- Biological factors

These factors can be attributed to weathering conditions such as dramatic change in temperature or moisture, or to abrasion such as explosion to harmful liquids and gases both naturally and industrially, or explosion to biological agents.

2.2 Construction operation

In China, many bridges generate damages and deterioration problems though they have not yet reached the expected service life. Even some bridges have serious durability issues soon after they are put into operation. In most cases, the reason behind is that the construction quality of most bridges fails to meet the design requirements and technical specifications (Li, 2012). If that is the case, potential construction problems could be the bad practice in construction process.

In pursuit of the economic benefits, some construction companies in China have to adopt low-quality construction technology and methods in construction process. Examples could be the use of substandard materials, insufficient thickness of concrete cover, lack of grouting or the use of steel that has already been corroded in construction work. This does not meet the requirements of construction quality and design specifications, thus inevitably leading to deterioration in durability and posing serious threat to bridge structures.

The costs of a construction project include time, personnel and equipment. Any cost saving effort is therefore justified, but any possible solution should not decrease the durability and the service life of the concrete structure. In China, because of the rising costs of labour, advanced demolding and shortening construction period become the major solution to the project costs. Traditional cement products with long developing period of early strength are replaced by rapid Portland cement with fast developing of early strength and admixture products (Li, 2012). This is because the rapid Portland cement is able to meet the strength requirements within 24-72 hours. However, it brings the shortcomings that the late strength of concrete is no longer growing. And this affects the durability of reinforced concrete structures since the performance of reinforced concrete structures exposed to severe environments depends on the maximum strength that can be achieved rather than the 28-day strength (Liu, 2013). The strength of traditional concrete can grow gradually at a later stage, instead nowadays the strength of the concrete in some cases is only increased by 5%, and sometimes the strength of the concrete has even reduced (Liu, 2013).

When it comes to the raw materials in concrete production, in some developing areas in China, aggregate processing equipment is far from advanced, and thus poor quality of aggregates is obtained. Poor aggregates may have the problems such as bad grain shape, excess flakiness particles, large porosity, poor grading, etc. Therefore, when the concrete is formulated for the same strength class and workability, cement content are significantly higher than the level established by the standards of good practice in advanced areas. In order to improve the workability of the mixes, the unit volume of water should be therefore higher. Thus the water to cement (W/C) ratio is increased. The limitation of W/C ratio is perhaps the most essential specification that affects the strength and durability of reinforced concrete (Lin, 2013). Higher W/C ratio can lead to a lower strength, larger permeability and lower durability of reinforced concrete structures (Lin, 2013). The stability of volume in hardened concrete also decreases. This will make the concrete easy to generate cracks.

Curing aims to provide the concrete the best final performance. Correct curing involves preserving the suitable moisture content in concrete until the hydration of concrete has completely finished (Liu, 2005). Appropriate temperature is another important factor in curing stage. Due to the improvement of current grade of concrete, the use of cement grade also increases with accelerated hydration rate (Liu, 2005). With a small W/C ratio, bleeding is significantly reduced. Though this helps to enhance the strength of aggregate and the strength at cement interface, it can easily lead to plastic shrinkage cracks due to insufficient supplement of surface water evaporation. This will not only affect the development of concrete strength, the durability of reinforced concrete structures will be significantly weakened as well.

2.3 Management and maintenance

In China, general contractors are used to undertake most of the concrete work and subcontract part of its work to other small companies. Then subcontractors separate the project work to each process. This behaviour can break the continuity of concrete construction and the quality of the reinforced concrete structures cannot be guaranteed.

In order to shorten the construction period and keep the costs down, some construction companies in China rush contract progress and drive time limit. As a consequent, the quality of the construction usually cannot be guaranteed. This will bring danger to the safety and durability of the structure sooner or later.

Even some construction engineers fail to understand correctly the drawings and blindly guide the construction work. Some supervisors cannot strictly fulfil their responsibilities of controlling the construction quality in every step. This will result in defects in construction quality.

The durability of the reinforced concrete structure is closely related to the reasonable usage and proper maintenance. Maintenance includes normal inspection, continuous monitoring of the structure, as well as repair and rehabilitation. They are necessary to ensure normal bridge operations. Inspection is meant to detect any sign of deterioration before the deteriorating process becomes too advanced. Durability issues will occur if the personnel fail to discover the durability problems during the bridge inspection or have already discovered without attention. Even little damage is not properly maintained in time; the damages can be cumulative over time and cause danger to the reinforced concrete structures.

2.4 Material properties

In reinforced concrete, the most critical property of concrete is permeability and diffusion. Gases, liquids and ions in the concrete can move through concrete when there is a difference in the pressure of air or water, or in the concentration of ions (Zhang et al., 2007). Pressure caused by the difference in humidity or temperature also makes gases or water enter the concrete. Under the influence of chemical potential or electric field, transport of fluids or ions through the concrete can also occur.

Gases, liquids and ions can travel through concrete in three different ways: permeation, diffusion, and sorption (Zhang et al., 2007). Permeation means they can flow under a pressure gradient. Diffusion occurs under a concentration gradient. And flow under capillary suction is referred to sorption. The main reason why the concrete material has a certain degree of transport properties is that there exist a large number of pores and cracks in concrete. The pore structure of the concrete includes pores in cement slurry, pores in the aggregates, pores at the interface between aggregates and paste (Zhang et al., 2007). Adverse construction can also result in some honeycomb structures. The porosity in general aggregates is normally not more than 5%, and the porosity in the concrete is about 15% (Liu, 2013).

As previously described, all processes causing deterioration of the concrete or corrosion of the reinforcement bars involve transport phenomena through the pores and cracks of the concrete. When the harmful substances penetrate into the concrete, chemical reactions occur between the substances and the component of the concrete. It damages the structure of concrete, resulting in durability problems in concrete structures. There are three fluids/gases principally relevant to the durability of the concrete: they are pure water, water with aggressive ions (Cl^-), and harmful gases such as carbon dioxide, oxygen and sulphur dioxide (Vagelis et al., 1991). The fluids may move in the concrete in different manners, the mobility depends on the permeability of the concrete.

The deterioration process of concrete is revealed in Figure 3. Firstly, the environmental erosion factors destroy the surface concrete, leading to reinforcement corrosion and alkali-aggregate reaction in concrete. Most of these changes are accompanied by the volume expansion. Stresses derived from concrete expansion generate more cracks in concrete (Li, 2012). Therefore, the permeability of concrete is further increased, making the invasion of substances more rapidly. This will cause a wide range of cycle of damages to concrete structures.

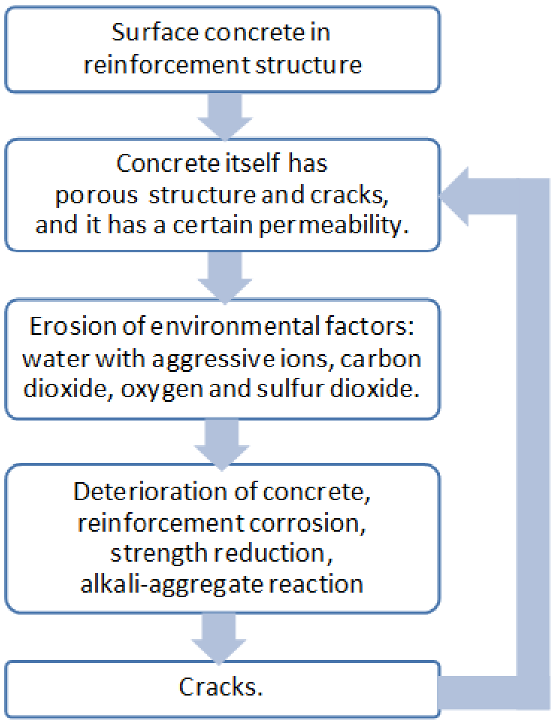

Figure 3 The deterioration process of reinforced concrete due to material properties and external environmental factors

Freeze-thaw resistance is one important indicator closely related to the durability of concrete. Dry concrete will not suffer from frost damage. When the moisture content in concrete exceeds a critical value and the surrounding temperature decreases, water in some of the pores becomes freezing with volume expansion (Lulu et al., 2001). This forces the water in unfrozen pores migrating outward through the frozen zone. Hydrostatic pressure is generated as a result. When the hydrostatic pressure exceeds the meso strength of concrete, the concrete pore wall structures get destroyed. Internal crack in concrete gradually extends outward (Lulu et al., 2001). With the cyclical changes of surrounding temperature, water inside the concrete becomes ice and then ice melts into water. After a few cycles, damages in the internal structure of concrete continue to accumulate, eventually leading to the destruction of the concrete. And these are all closely related to the permeability of concrete.

Figure 4 shows the relationship between water absorption and concrete resistance to freeze-thaw cycles. The logarithmic of water absorption capacity of the concrete is inversely proportional to the logarithmic of freeze-thaw cycling resistance of the concrete. It can be seen that the lower the water absorption capacity of concrete, the better the freeze-thaw cycling resistance.

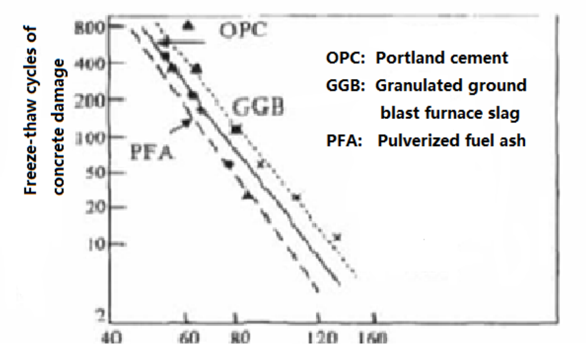

Figure 4 The relationship between water absorption ability of concrete and the resistance to freeze-thaw cycles (freeze-thaw cycles when concrete is damaged) (Liu, 2013).

2.5 External environmental condition

Concrete structures are normally located in the aggressive environment that can generate various kinds of external attacks. Usually, the external environment provides agent that can cause corrosion in reinforcement. It mainly includes water, oxygen, carbon dioxide and aggressive ions. There are also external actions that can cause uneven stress distribution in concrete such as freeze-thaw action, wetting and drying conditions, heating and cooling effects, loading and unloading on the structure, and etc. Acid attack, sulphate attack, microbiological attack and other kinds of physical and chemical attack could also damage the concrete exposed to the surrounding environment (Vagelis et al., 1991). Marine structures and structures close to coastal waters are particularly in danger of the reinforcement corrosion due to the ingress of chloride ions from sea water splash and coastal air.

Gas types, concentration and surrounding moisture content determine the extent of concrete eroded by gases. As it is shown in Table 1, with increasing moisture content in external environment, concrete become much eroded. Compared to the plain concrete, reinforced concrete turns more easily eroded since the reinforced bars are more vulnerable to the aggressive environment than the concrete.

Table 1 The influence of aggressive gases or aggressive ions to plain or reinforced concrete under different moisture content and different concentration of gases (Zhang, 2012)

Moisture content (%)		≥75		60-75		≤60	
Agents	Conc. (mg/m^3)	Plain concrete	Rein-forced concrete	Plain concrete	Rein-forced concrete	Plain concrete	Rein-forced concrete
Cl_2	1-5 0.1-1	Slight No effect	Serious Medium	Slight No effect	Medium Slight	No effect No effect	Slight No effect
HCl	1-15 0.05-1	Medium Slight	Serious Medium	Slight No effect	Serious Medium	No effect No effect	Medium Slight
NO_2	5-25 1-10	Medium Slight	Serious Medium	Slight No effect	Medium Slight	No effect No effect	Slight No effect
H_2S	10- 100001- 10	Slight Slight	Medium Medium	Slight No effect	Medium Slight	No effect No effect	Slight No effect
HF	10-50	No effect	Slight	No effect	Slight	No effect	No effect
SO_2	10-200 1-10	Slight Slight	Serious Medium	Slight No effect	Medium Slight	No effect No effect	Slight No effect
H_2SO_4	Much Less or no	Medium Slight	Serious Medium	No effect No effect	Slight Slight	No effect No effect	Slight Slight
CH_3CO OH	Much Less or no	Medium Slight	Serious Medium	No effect No effect	Slight Slight	No effect No effect	Slight Slight
CO_2 NH_3 Alkali steam	>2000 >20 Much	No effect No effect Medium	Slight Slight Medium	No effect No effect No effect	Slight Slight Slight	No effect No effect No effect	No effect No effect No effect

When it comes to liquid ingress, groundwater is an important carrier of many corrosive ions. The chemical composition of groundwater is closely related to the rock composition, characteristics of soil, the ingredients of supplied water, the distance from rivers and other surface water and local climatic conditions (Zhang, 2012). Microorganisms also have an impact on the chemical composition of groundwater. In mineralized groundwater, the concentration of SO_4^{2-} possibly is very high as well as a large amount of cations combined with SO_4^{2-} such as Ca^{2+}, Mg^{2+}, Na^+ and K^+. In deep groundwater, there also contains a lot of CO_2 (Zhang, 2012). The influence of aggressive ions in liquids to the concrete structure is shown in Table 2, and there is no difference in the corrosion of reinforced concrete and plain concrete.

Table 2 The influence of aggressive ions in liquids to plain or reinforced concrete under different ion concentration (Zhang, 2012)

Agents	Concentration	Plain concrete	Reinforced concrete
H^+ (pH)	1-3 3-4.5 4.5-6	Serious Medium Slight	Serious Medium Slight
CO_2 (mg/L)	>40	Slight	Slight
SO_4^{2-} in sulfate (mg/L)	>4000 1000-4000 250-1000	Serious Medium Slight	Serious Medium Slight
Cl^- in chlorine salt (mg/L)	>5000 500-5000 <500	Medium Slight No effect	Medium Slight No effect
Mg^{2+} in magnesium salt (mg/L)	>4000 3000-4000 1500-3000	Serious Medium Slight	Serious Medium Slight
NH_4^+ in ammonium salt (mg/L)	>1000 800-1000 500-800	Serious Medium Slight	Serious Medium Slight
Na^+/K^+ in caustic alkali (mg/L)	50000-100000 <50000	Slight No effect	Slight No effect

Possible solid agents in contact with the concrete structure that can cause erosion are: dry soil with salt compounds, fertilizers, pigments, pesticides, herbicides and other unconsolidated chemical products. The humidity of the suspended powder substance determines to what extent the concrete structure is eroded. Because erosion happens only when solid agents are in the liquid phase. Otherwise when the solid agents absorb water from atmosphere, groundwater and surface water, it produces solution in concrete and erosion occurs. Category of solids agents is shown in detail in Table 3.

Table 3 The influence of aggressive solids to plain or reinforced concrete under different solubility and moisture content (Zhang, 2012)

Solubility in water	Agents	Moisture content (%)	Plain concrete	Reinforced concrete
Hard	Silicate,$CaPO_3$,$CaCO_3$,$BaCO_3$ $PbCO_3$,$CaSO_3$,$BaSO_4$,$PbSO_4$, MgO,Fe_2O_3,CrO,Al_2O_3,SiO_2, and Hydroxide	≥75 60-75 <60	No effect No effect No effect	Slight No effect No effect

Solubility in water	Agents	Moisture content (%)	Plain concrete	Reinforced concrete
Easy	NaCl, KCl, LiCl	≥75 60-75 <60	No effect No effect No effect	Serious Medium Slight
	Na_2SO_4,K_2SO_4,Li_2SO_4 $(NH_4)_2SO_4$, NH_4Cl	≥75 60-75 <60	Slight No effect No effect	Slight Medium Slight
	KNO_3, $NaNO_3$, NH_4NO_3, $LiNO_3$	≥75 60-75 <60	Serious Medium Slight	Medium Slight Slight
	Na_2CO_3, K_2CO_3, $(NH_4)_2CO_3$ $NaHCO_3$, $KHCO_3$, NH_4CO_3	≥75 60-75 <60	Slight Slight No effect	Slight Slight No effect
	$MgCl_2$, $CaCl_2$, $AlCl_3$, $ZnCl_2$ $FeCl_2$, $FeCl_2$, $CuCl_2$	≥75 60-75 <60	Medium Medium Slight	Slight Medium Medium
	$CdSO_4$, $MgSO_4$, $NiSO_4$, $MnSO_4$,$ZnSO_4$,$FeSO_4$, $Fe_2(SO_4)_3$, $CuSO_4$	≥75 60-75 <60	Serious Medium Slight	Slight Medium Slight
	$NaNO_3$, $Zn(NO_3)_2$, NH_4NO_3, $NaNO_2$, $Zn(NO_2)_2$ NH_4NO_2, $CO(NH_2)_2$	≥75 60-75 <60	Slight Slight No effect	Slight Slight No effect
	NaOH, KOH	≥75 60-75 <60	Medium Slight Slight	Medium Slight Slight

3 REINFORCED CONCRETE DETERIORATION

A reinforced concrete structure may deteriorate either due to deterioration of the concrete itself or due to the corrosion of reinforced bars inside the concrete. There are different causes of concrete deterioration such as alkali-aggregate reactions, chemical attack by acids, sulphates, and alkalis, freeze-thaw cycles, fire and abrasion (Li, 2012). In reinforced concrete, the most serious deterioration mechanisms are those leading to the corrosion of the reinforcement, resulting in a reduction in effective cross-section area of reinforcement bars. This will ultimately disrupt the concrete caused by the cracking of the concrete covers.

However, there is always misunderstanding that the carbonation and penetration of chloride ions would be the reason of concrete deterioration. As it happens, reinforcement corrosion occurs only after de-passivation of steels in concrete due to carbonation of the surrounding concrete, chloride ingress or a combination of both. Carbonation and chloride ingress would not cause any harm to the concrete itself. Deterioration of concrete is not the common problem. Generally, if there is any problem related to the durability of the concrete structure, it is mostly the corrosion of the reinforcement bars that are more likely to be the main reason.

3.1 Carbonation

Early concrete is generally alkaline and the pH value is as high as 13, which generates a layer of dense oxide (always called passivation layer) on the surface of reinforced concrete (Wang, 2006). It plays an important role of protecting the steels in concrete from rusting. When acidic substances from air, soil or groundwater go through the concrete surface, they can react with the alkalis in concrete and neutralization occurs. Since the carbon dioxide in the air is the most common agent that has an effect on concrete, the process of neutralization is called carbonation.

Carbonation does not cause deterioration of concrete itself but it has an important effect on the durability of reinforced concrete structures. Nowadays, with the increasing development of urbanization, the level of atmospheric CO_2 comes to rise for a long time. In addition, a large amount of excreted waste from factories gradually raises the concentration of CO_2 in rivers and groundwater. Carbonation of concrete becomes the most common problem of many reinforced structures in China.

3.1.1 Carbonation mechanism

The process of concrete carbonation can be expressed by the Equations (1), (2) and (3). When carbon dioxide diffuses into the concrete, if water is available, it reacts with calcium hydroxide to form calcium carbonate (Wang, 2006). In concrete if there is sufficient calcium hydroxide in concrete and the reaction of Equation (3) is insignificant in the most cases. Thus no significant damage of concrete occurs due to carbonation.

$$CO_2 + H_2O \rightarrow H_2CO_3 \tag{1}$$

$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2\,H_2O \tag{2}$$

$$3\,CaO \cdot 2\,SiO_2 \cdot 3\,H_2O + 3\,H_2CO_3 \rightarrow 3\,CaCO_3 + 2\,SiO_2 + 6\,H_2O \tag{3}$$

Calcium carbonate produced from carbonation of concrete may exist in crystalline forms. Carbonation takes place even at very small CO_2 content. For example, it can happen at the CO_2 content of 0.03%, which is a common value in rural areas (Kwan & Wong, 2005). In an unventilated room, the concentration of CO_2 may rise to about 0.1% typically. In large cities, CO_2 content can be at present of 0.3% on average and exceptionally up to 1% (Kwan & Wong, 2005). It may be slightly higher in industrial areas. The highest concentration of CO_2 is most likely to be observed in vehicle tunnels since the exhaust emission from motor vehicles contribute to a large part of CO_2.

The mechanism of carbonation is that it can gradually reduce the alkalinity of concrete to a pH value of around 9. Once carbonation front progresses to the surface of reinforcement is reached with the pH of the concrete surrounding the steels dropping to below 10, the concrete fails to protect the reinforcement bars from corroding (Li, 2012). The passive layer of the steel surface will be dissolved. When there is presence of water and oxygen, the reinforcement start to corrode.

The development of concrete carbonation is usually a very slow process. For compacted concrete with a reinforced protective layer of 20 mm or more, it often takes several decades for the concrete to completely carbonized (Li, 2012). Concrete which is less compacted or has a protective layer smaller than 20 mm, carbonation process may be takes place with one to two years.

3.1.2 Environment factors influencing carbonation

The main relevant factors influencing concrete carbonation are surrounding environment and material properties. The effect of external environment mainly refers to the concentration of CO_2 in surrounding environment of the concrete, moisture content, temperature, and coatings.

High concentration of CO_2 in the environment can cause large concentration gradient, which acts as a driving force for carbonation. Large concentration gradient makes it more easily for the ingress of CO_2 into the pore system of the concrete as well as achieving a higher speed of carbonation process. The diffusion of CO_2 usually takes place through the already carbonated surface zone of concrete. Assuming the reaction front develops after all alkaline material is transformed; the carbonation rate is mainly controlled by diffusion (Lulu et al., 2001). The CO_2 diffusion coefficient in carbonated concrete is the characteristic transport coefficient. It is assumed that the diffusion coefficient is constant for the carbonated layer (Lulu et al., 2001). So the depth of carbonation can be derived from Fick's first law of diffusion as it is depicted in Equation (4).

$$X = C\sqrt{t} \tag{4}$$

Where X=depth of carbonation at time (m), t=time of exposure (s), and C=carbonation coefficient.

However, such diffusion is a slow process if the pores of hydrated cement paste in concrete are filled with water. The reason is that the diffusion of CO_2 in water is four orders of magnitude slower than that in the air (Li, 2012). In contrast, under dry condition CO_2 remains gaseous. Carbonation process is very slow since the chemical reaction of carbonization process can only be carried out in liquid condition. So the carbonation rate also depends on the moisture content of the concrete. According to previous experiments, the highest rate of carbonation occurs when the relative humidity of the surrounding environment is around 50-75% (Li, 2012). In a humid environment, the corrosion of steel develops much faster, which may cause greater damage to the durability of the reinforced concrete structure.

Surrounding temperature also has great effect on the rate of concrete carbonation. The process of carbonation develops faster with increasing temperature. Temperature variation is also conducive to the diffusion of CO_2.

Concrete surface coating can delay the action of carbonation on concrete structure. Coatings can be divided into two groups; one is coatings containing carbonized materials, such as paste or paper reinforced plaster ash; the other one is free of carbonized materials, such as asphalt, paints, tiles, etc (Li, 2012). Previous experiments show that by increasing the coverage thickness or improving the density of layers, it can noticeably protect the concrete against carbonation.

3.1.3 Material properties influencing carbonation

The most important factors that affect carbonation of concrete are the density of concrete and alkaline preservation (Parrott, 1987). That is the permeability of concrete and the content of $Ca(OH)_2$ or other alkaline material in concrete. The smaller the porosity is, the higher the density of concrete will be. Generally greater cement content contains more alkaline material per unit volume of concrete. The more $Ca(OH)_2$ and other alkaline substances exist in the concrete, the better resistance of carbonation the concrete will have. However, if there is excess amount of cement, it is prone to generate early cracks in concrete (Parrott, 1987). This will in turn accelerate carbonation and reduce the durability of concrete structures. Therefore, cement content should be determined and controlled based on the actual situation of the project.

Water to cement ratio is the main factor that determines the concrete pore structure and porosity. Free water content is also related to the pore saturation. Therefore, in the same content of binding materials, the smaller the W/C ratio is, the denser the concrete will be. And this makes it more difficult for CO_2 and water to move into concrete, thus lowering the carbonation rate. Broadly speaking, for the concrete with a W/C ratio of 0.6 a depth of carbonation of 15 mm would be reached after 15 years (Gao, 2013). However, in concrete with a W/C ratio of 0.45 the same depth of carbonation would not be reached until after 100 years (Gao, 2013).

The dosage of mineral admixtures also influences the concrete carbonation. Basically, the mineral admixtures are pozzolanic materials (Gao, 2013). They can have chemical reaction with $Ca(OH)_2$ to produce gels in the cement paste. Therefore, the $Ca(OH)_2$ content in concrete containing mineral admixtures is lowered and the depth of carbonation will likely increase at a faster rate. On the other hand, denser microstructure of concrete is achieved by adding mineral admixtures. This causes a reduced diffusivity, and carbonation can take place at a slower rate.

When the concrete is mixed with additives, such as water reducing agent, air entraining agent or air-entraining water-reducing agent, W/C can be reduced and closed small air bubbles can be introduced to the concrete. This will effectively cut off the capillary channel and reduce the diffusion coefficient of CO_2, making carbonation rate significantly slower.

3.2 Chloride ion penetration

In coastal area, concrete structures are subject to the long-term contamination of chloride ions. Reinforcement corrosion of reinforced concrete structures has become a growing phenomenon in the marine environment. In China, the design of many harbours fails to reach the service life requirements and as a result they have to be renovated. This consumes a lot of human and material resources. As the most dangerous substance initiating corrosion of steel, chloride is widely existence in de-icing salt on highway structures, various industrial environments, marine environment, concrete raw materials, salt lake, saline pools and some chemical reactions when the structure is subjected to fire.

3.2.1 Chloride ion penetration mechanism

Since the chloride ion can be only transported in liquid, there are two ways for the chloride ion penetrating into the concrete. One is capillary absorption, which means the chloride-containing water can be absorbed when the capillary pores in the material are relatively dry (Chi et al., 2001). The other one is free chloride ion diffusion caused by the concentration differences of chloride ion when the capillary pores are relatively saturated. Diffusion is the major transport mechanism of chloride ion. In reality the chloride ion can penetrate into the concrete in the following ways: using additives containing chlorine ions, mixing concrete in an environment with high salinity, and ingression of the atmospheric chloride ions through apparent damages on concrete (Chi et al., 2001).

The action of concrete containing chloride is very complex. The chloride induced corrosion of steel in concrete can be divided into three steps: damage of passivation layer, generation of electro-chemical cell and depassivation (Deng, 2012).

In the early ages after the concrete construction, the hydration of cement is completed and the concrete structure is in a high alkaline environment. There will gradually growing a passivation layer on the surface of embedded steel. Though the main components of the passivation layer are some iron oxides, recent studies have shown that it also contains the Si-O bond, which can effectively protect the steels from corroding (Deng, 2012). However, the Si-O bond is only stable at a high alkaline environment. If the pH drops due to some carbonation reasons, the Si-O bond will gradually become less stable (Deng, 2012). As it has been mentioned, when the pH value is lowered to below 10, the passivation layer may be damaged forever and will no longer be generated due to the change of surrounding environment. When the chloride ion is absorbed on the passivation layer, the pH value is quickly lowered through a series of chemical reactions, which are shown in Equations (5) and (6) (Deng, 2012). Then passivation layer on the steel surface will be completely destroyed.

$$Fe^{2+} + 2\,Cl^{-} + 4\,H_2O \rightarrow FeCl_2 + \ 4\,H_2O \tag{5}$$

$$FeCl_2 + \ 4\,H_2O \rightarrow Fe(OH)_2 + 2\,Cl^{-} + 2\,H^{+} + 2\,H_2O \tag{6}$$

If the chloride is not evenly distributed in the concrete structure, localized concentration facilitates the destruction of passivation layer on the surface of steel. It will form an electrical potential difference along the steel bars between the unprotected steels and the protected steels. The unprotected steels serve as the anode while the protected steel is treated as the cathode. Therefore, an electro-chemical cell is formed as it is shown in Figure 5. The corrosion can be either pitting corrosion or general corrosion. Pitting corrosion means a small anode is surrounded by a large zone of cathode (Kwan & Wong, 2005). General corrosion occurs due to a homogeneous distribution of micro anodes and cathodes. Though the total loss of iron is large in general corrosion, pitting corrosion causes more loss in cross-sectional area and hence is more dangerous.

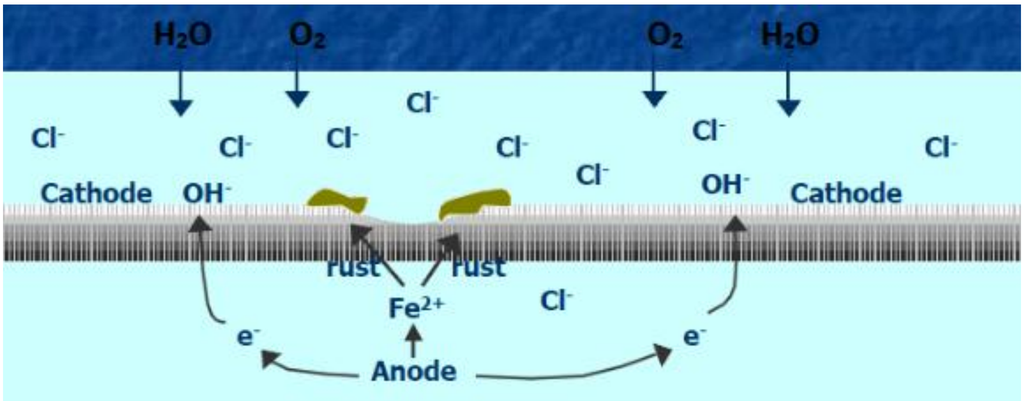

Figure 5 Chloride ion ingress occurs in the reinforced bars with the presence of oxygen and water. An electro-chemical cell is formed with the unprotected steels serving as the anode and the protected steel serving as the cathode. Rust is generated.

Depassivation means accelerating anode polarization process in the unprotected steels to start active corrosion (Deng, 2012). And chloride ions play an important role in the whole process. In the damaged passivation layer, it is usually gathered a lot of Fe^{2+} and they can be combined with chloride ions to form $FeCl_2$. And the products will be transported promptly after the reaction under the effect of electro-chemical cell. This not only achieves a smooth process but also accelerates the overall reaction. It can be seen that the chloride ion is not consumed in the process since it always plays the role of porter. Usually the $FeCl_2$ cannot be found because it is a soluble substance. Then it precipitates into $Fe(OH)_2$, and further oxidized to rust see Equation (7). The following reactions show the steel corrosion initiated by chloride ions.

$$4\,Fe^{2+} + 8\,Cl^- + 10\,H_2O + \,O_2 \rightarrow 4\,Fe(OH)_3 + 8\,Cl^- + 8\,H^+ \tag{7}$$

It can be seen that, oxygen is consumed and water is needed for the process to continue. Therefore, no corrosion occurs in dry concrete that has a relative humidity lower than 60% nor is there corrosion in concrete fully immersed in water (Kwan & Wong, 2005). The optimum relative humidity for corrosion is around 70 to 80%. If the relative humidity is very high, the diffusion of oxygen through the concrete will be significantly reduced (Kwan & Wong, 2005).

3.2.2 Chloride ion and diffusion influencing chloride ingress

The diffusion coefficient of chloride ion plays an important role in the process of chloride penetration. The Fick's second law illustrates the relationship among diffusion time, diffusion coefficient and chloride concentration, see Equation (8). It is assumed that the diffusion process is simply one-dimensional with a certain concentration of chloride ion on the concrete surface (Deng, 2012). Once the concrete surface is exposed to chloride ions, penetration of chloride begins. It is also assumed that the diffusion coefficient does not change in the process. And concentration of chloride ions increases linearly after diffusion occurs (Deng, 2012).

$$\frac{\partial c_{Cl}}{\partial \mathrm{t}} = \frac{\partial}{\partial \mathrm{x}}\left(D_{Cl}\frac{\partial c_{Cl}}{\partial \mathrm{x}}\right) \quad (8)$$

Where C_{Cl} = concentration of chloride ion (%), t = time, x =location (cm), and D_{Cl} = diffusion coefficient.

Diffusion coefficient of chloride ions can be associated with many factors. It includes the internal pore structure of concrete, the degree of cement hydration, and the concrete material itself. It may be also affected by temperature, the type of additives, and curing period. W/C ratio is closely related to the diffusion coefficient. Table 4 shows the relationship between W/C ratio and diffusion coefficient based on a previous experiment. It can be seen that the diffusion coefficient increases with higher value of W/C ratio.

Table 4 The relationship between W/C ratio and diffusion coefficient (Deng, 2012)

W/C	0.29	0.33	0.35	0.40	0.50
Diffusion coefficient/($\times 10^{-8}$ cm/s)	3.79	5.14	5.35	7.51	11.0

3.2.3 Concrete properties influencing chloride ingress

Cement mixed with additives can improve the ability to resist various chemical attacks and protect the reinforcement from rapid corrosion (Chi et al., 2001). When the concrete is mixed with fly ash in mixtures, the concrete alkaline is reduced. However at the same time, the pore structure of concrete becomes fine. This can effectively reduce the penetration of the aggressive in external environment, which creates a favourable condition to prevent steel corrosion.

As it has been mentioned, concrete pore structure determines the ability to resist permeation of concrete. Under aggressive environment, the pore structure of concrete needs to be appropriately fined and the thickness of protective layer needs to be increased in order to prolong the service life of concrete structures.

Another important factor that influences reinforcement corrosion in concrete is the chloride ion content. Normally, the chloride content in reinforced concrete structure should be as less than 1% by weight of cement (Deng, 2012). When casting, the concrete must be completely compacted by vibration.

3.2.4 Reinforcement corrosion due to chloride ingress

The corrosion of reinforcement generates rust, which has a low adhesive strength with the concrete (Kwan & Wong, 2005). The final components of rust depend on the supply of oxygen and water. The volume expansion of the rust becomes greater when the degree of oxidation is higher. In reality, the main component of the rust is $Fe_2O_3 \cdot Fe_3O_4 \cdot H_2O$ and it has a lower density than steel. As corrosion occurs, the volume increases 2 to 3 times of magnitude as it is shown in Figure 6.

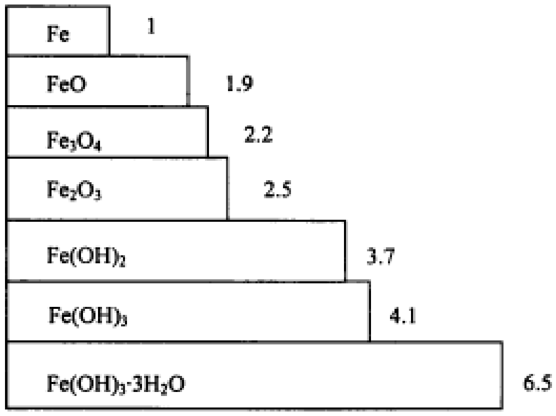

Figure 6 The volume expansion of the rust becomes greater when the degree of oxidation is higher (Deng, 2012).

Bursting stresses are induced by the rust because the expansion is restrained by the surrounding concrete (Chi et al., 2001). This will lead to cracks, spalling or delamination in the protective layer of the concrete. These cracks again can accelerate the concrete carbonation with a subsequent increase in the of reinforcement corrosion. The corrosion of reinforcement reduces the cross-section of steels and results in decreasing of strength and rigidity of components. Bearing capacity gradually declines as well as the durability of reinforced concrete structure.

3.3 Concrete alkali-aggregate reactions

Alkali-aggregate reaction is the destructive expansion reaction between the certain types of aggregates and hydroxyl ions (OH^-) associated with alkali in the cement. Usually, the alkali comes from Portland cement, other ingredients in concrete, or surrounding environment. Alkali-aggregate reaction is different from other durability damages in concrete because it usually destructs the structure integrally. Alkali-aggregate reaction can cause considerable volume expansion and cracking of concrete, changing the microstructure of concrete, leading to significant decrease of strength and other mechanical properties such as elastic modulus (Li, 2012). Concrete deterioration caused by alkali-aggregate reaction is generally slow, but progressive. Once it happens, it is not only difficult to prevent but difficult to repair as well.

3.3.1 Types of reactions

Depending on the reactive ingredient in concrete aggregates, alkali-aggregate reactions can be divided into three types: alkali-silica reaction, alkali-carbonate reaction, and alkali-silicate reaction. Among them, alkali-silica reaction is the most common form of alkali-aggregate reaction and the alkali-silicate reaction remains controversial.

Alkali-silica reaction refers to the expansion reaction between the alkali in concrete and reactive silica (SiO_2) in aggregates. Major mineral component of concrete aggregate is SiO_2. It exists in the form of quartz and cristobalite. Quartz has a good crystallization and has a stable chemical bond. Therefore it is inert and usually does not react with acid or alkali (Li, 2012). However, cristobalite has a poor crystallinity and potential activity of reacting with alkali is greatly increased. Furthermore, SiO_2 has a unique structure that can combine water to create amorphous hydrated silica, which makes SiO_2 easy to react with alkali (Li, 2012). The first step of alkali-silica reaction is dissolving SiO_2 of aggregate in alkaline solution. Then the silicate gel is produced in chemical reactions. The product of the alkali-silica reaction is a gel that absorbs water and increases in volume. The swelling gel also generates pressures, leading to internal ruptures in aggregate particles. This may cause cracks that can extend to the surrounding concrete.

Alkali-carbonate reaction is less common. It is the reaction between certain dolomitic limestone aggregates with the OH- in the cement (or other sources such as de-icing salts). This reaction can cause swelling in the limestone particles and cause concrete to expand and crack (Chi et al., 2001). However, the mechanism of alkali-carbonate reaction is still not well understood. It is commonly known that the alteration of dolomite to calcite is involved and clay minerals may also play a role in the alkali-carbonate reaction. The reaction results in cracks in the concrete similar to those caused by alkali-silica reaction. It should be noted that limestone aggregates may be susceptible either to alkali-silica reaction, or alkali-carbonate reaction, or a combination of the two.

3.3.2 Conditions that cause alkali-aggregate reaction

Harmful alkali-aggregate reaction occurs when all of the three following requirements are satisfied (Li, 2012):

- Appropriate alkali content in concrete (mainly Na_2O and K_2O);
- Reactive minerals in aggregates;
- Enough moisture is present to sustain the reaction.

The alkali in concrete mainly comes from Portland cement, additives, admixtures, aggregates, and mixing water. But it may also come from the surrounding environment, such as de-icing salt solutions or sea fog penetrating into the concrete structures near coastal water. Usually, the critical alkali content must be less than 3 kg/m^3 in order to prevent adverse reaction (Li, 2012). However, when the moisture content remains high around some mass structures such as dams, harmful reactions have been recorded with alkali contents as low as 2 kg/m^3.

Alkali-aggregate reaction only occurs in a wet environment when the relative humidity is greater than 80% or the concrete is directly in contact with water (Li, 2012). Otherwise, even if the concrete contains excess alkali and aggregates have good alkali reactivity, the alkali-aggregate reaction is very slow and does not produce destructive expansion cracks. Therefore, cutting off from the water source is an effective measure to prevent damage caused by alkali-aggregate reaction.

3.3.3 Concrete damage due to alkali-aggregate reaction

The deteriorative effects from alkali-aggregate reaction can be cracking and swelling of concrete. For non-reinforced or lightly reinforced concrete, equally dimensional pattern crack is the typical type of crack. When there is a considerable amount of reinforcing bars, cracks use to be more prominent parallel to the reinforcement. And cracks due to alkali-aggregate reaction usually become evident after 5 to 10 years.

The amount of swelling or volume expansion depends on the alkalinity of the cement solution, reactivity of the aggregates, and the moisture conditions of the concrete structure. Expansions of over 0.1% can be commonly found. It results in an increase in length of 1 cm for every 10 m length of an unreinforced structure (Chi et al., 2001). In many structures this amount of expansion may not cause problems. However in long sidewalks or median barriers, for example, the expansion may cause compression and heaving.

3.4 Freeze-thaw cycles

Freeze-thaw damage of concrete is the volume expansion after water is frozen, resulting in small cracks in the concrete (Jin & Jiang, 2011). Repeated freezing and thawing cycles make crack extending and cause spalling of concrete. Concrete frost resistance is the ability of concrete to resist freezing and thawing cycles and it is an important indicator to evaluate the durability of concrete in cold regions.

3.4.1 Mechanism of freeze-thaw cycles

Concrete is a porous material consisting of cement mortar and coarse aggregates. When mixing the concrete, in order to get required workability, the mixing water is usually added more than the total water for hydration of cement. This excess water occupies a certain volume and is retained as free water in connected capillary pores of the concrete. This free water in the capillary pores is the major internal factors that can lead to the frost damage in concrete.

It should be noticed that under normal situations the frozen water in capillary pores of the concrete does not cause severe damage to the internal structure. Because despite of the capillary pores, there are also many gel pores created after the cement hydration and some non-capillary pores or voids due to other reasons (Jin & Jiang, 2011). Gel pores are always filled with water because they are so fine and water can easily condense in them. When the water freezes and expands in the capillary pores, a part of the unfrozen water will be squeezed into the voids. Therefore the non-capillary voids play a role of buffer, thus effectively reducing the swelling pressure (Jin & Jiang, 2011). This can prevent the concrete structure from damage.

However, if the concrete structure is in saturation, the situation will be completely different. When the water in the capillary pores is frozen, the ionic concentration in the surrounding unfrozen water will be increased, producing an osmotic pressure, under which the water from the gelling pores permeates into the capillary pores, resulting in further expansion in volume of ice in the capillary pores (Lu, 1997). It can be seen that, when the concrete is saturated and suffered to frost, the capillary walls of concrete is subjected to both swelling pressure and osmotic pressure.

When either or both of the pressures exceed the tensile strength of concrete, the concrete will crack (Chi et al., 2001). After repeated freeze-thaw cycles, the cracks in concrete will be linked with each other. The strength of concrete will be gradually reduced, or even completely lost. This will lead to the destruction of concrete structures from outside to the inside. It also need to be noted that the saturation degree of capillary pores in concrete increases with freeze-thaw cycles. But the rate of increase becomes lower. Therefore, the serviceability of concrete is not proportional to the frost resistance level or the frost resistance in terms of durability.

3.4.2 Factors influencing freeze-thaw cycles

Based on the mechanism of freeze-thaw cycles, there are a lot of factors influencing the concrete frost resistance, such as the internal pore structure, water saturation, concrete strength, etc. The pore structure and the strength of concrete mainly depend on the type of cement, W/C ratio, type of aggregates, type of additives and curing methods.

If the concrete is suffered from frost in the early stage, the type of cement and its composition determine the degree of cement hydration, thus influencing the amount of freezing water and the early strength of concrete. Therefore, in winter early-strength Portland cement should be used in the concrete construction to prevent freeze-thaw damage (Liu, 2013).

Concrete aggregates influence frost resistance of concrete mainly in the water absorption by aggregates and the frost resistance of aggregate itself. Ordinary gravels and pebbles can satisfy the requirements of concrete frost resistance. However, if the concrete is mixed with aggregates that have a saturation of more than 91.7%, the aggregates and surrounding paste will be destroyed (Liu, 2013). Therefore, aggregates with high water content cannot be used when mixing concrete for high frost resistance.

W/C ratio is an important aspect when considering frost resistance of concrete because it directly controls the porosity and pore structure of concrete. With raised W/C ratio, the amount of freezing water is increased; the strength of the concrete is lower, consequently reducing the frost resistance of concrete considerably. When W/C ratio is less than 0.35 the fully hydrated concrete can have a higher frost resistance even without air-entraining (Li, 2012). In order to prevent the concrete from frost damage, it is important to control W/C ratio or even by adding some air-entraining additives and antifreeze agents when necessary.

Air-entraining additives can introduce a certain amount of air bubbles to the concrete mortar (Zhang, 2012). The air voids can reduce the hydrostatic pressure and osmotic pressure in the pores so as to obtain a better frost resistance of concrete. In addition to the necessary air voids, it must also ensure that the pores are evenly distributed in the concrete mortar. It is required that the average bubble spacing should be less than 0.25 mm (Zhang, 2012).

4 BACKGROUND DESCRIPTION

This chapter represents background information about the Jinan Yellow River Highway Bridge, general description of the Yellow River, geographical environment description of the bridge, hydrogeological information of the bridge site, and the meteorological characteristics of Jinan. Finally the environmental division regarding concrete durability is illustrated, together with the level of environmental action where the bridge belongs to.

4.1 Description of Jinan Yellow River Highway Bridge

Jinan Yellow River Highway Bridge locates in the north area of Jinan, which is the capital city of Shandong province. It is a double tower and double cable planes suspension prestressed concrete cable-stayed bridge (See Figure 7). It is one of the first long-span cable-stayed highway bridges in China. Jinan Yellow River Highway Bridge was built in 1978 and open to traffic in 1982 (Song et al., 2009).

Figure 7 Jinan Yellow River Highway Bridge is a double tower and double cable planes suspension prestressed concrete cable-stayed bridge.

The total length of the bridge is 2023 meters together with approach bridges on both sides of the river. The main bridge is 448 meters long, which is divided into five spans with the length of 40+94+220+94+40 meters. The total width is 19.5 meters including 15 meters of two way-four lane carriageways, two meters of sidewalks on both sides and 0.25 meters of railings. The design load includes car group of 20 tons, trailer of 100 tons and passenger load of 350 kg/m^2 (Song et al., 2007). The bridge clearance is the channel of class four.

The main girder in the main bridge is a two-chamber closed trapezoidal shaped box girder. See Figure 8. The concrete used in the girder is C45. There are totally 129 boxes in the main girder and the main girder has a thickness of 2.75 meters as it is shown in Figure 9. In the chamber, the roof, which is the top plate of the girder, is 16.8 meters wide and has a thickness of 20 cm. The straight web has a thickness of 25 cm and the inclined web has a thickness of 17.9 cm. Contiguous chambers are connected by the deck and diaphragms. Every diaphragm has a manhole and neighbouring diaphragms have a spacing of four meters. The main girder has the reinforcement of 24Φ5 with three-dimension prestressing (Tongji University, 2008). There are longitudinal prestressed steel beams arranged in the roof and floor. At the bottom of the diaphragms, there are transverse prestressed steel beams. And the vertical prestressed steel beams are arranged in the straight and inclined webs.

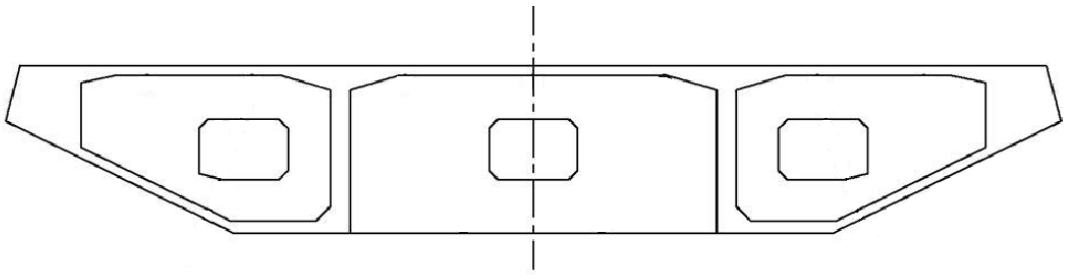

Figure 8 The main girder is a box girder. It has two closed chambers with trapezoidal shape.

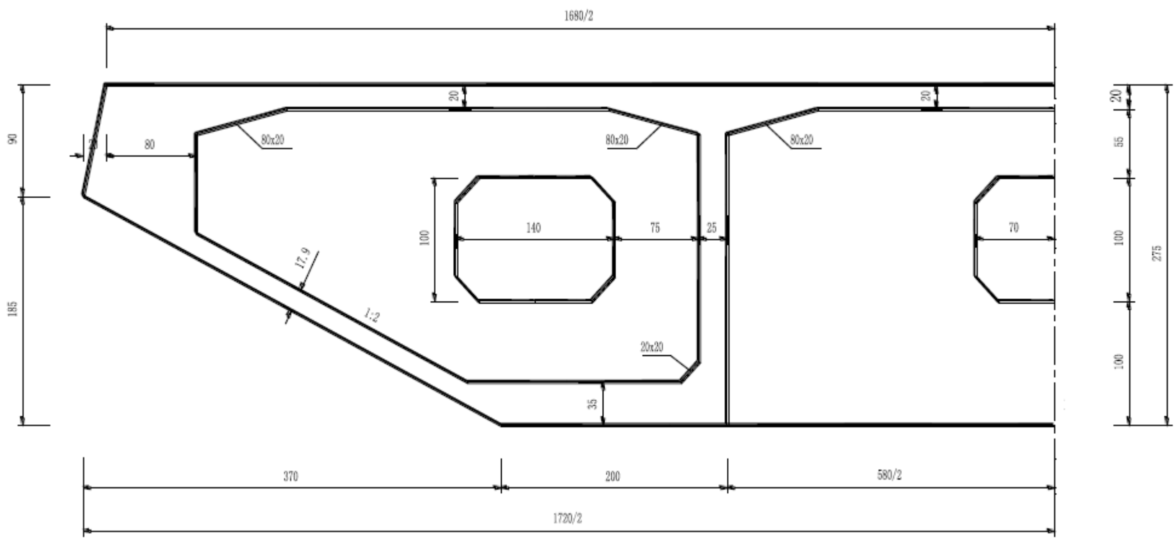

Figure 9 Every chamber is made up of roof, floor, straight web, inclined wed, and diaphragm. There a manhole in the middle of the diaphragm.

The cable-stayed bridge consists of two towers, eleven pairs of cables on each cable plane and the main girder. See Figure 10. The new cables are high-strength galvanized steel wires twisted together and have a diameter of 7 mm. The towers are A-shape dimensional structures with the concrete of C40 and have a height of 68.4 meters. The towers are consolidated with piers and separate from the main girder.

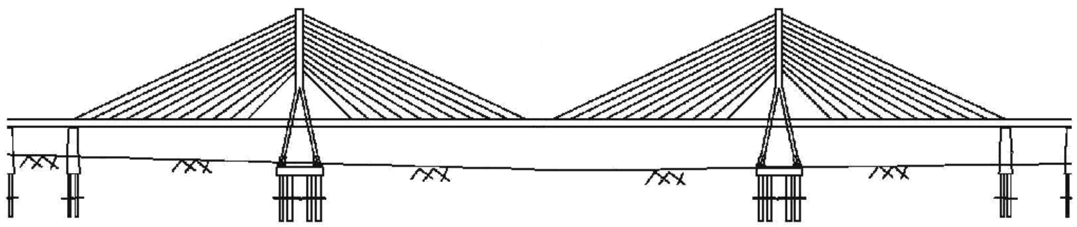

Figure 10 The cable-stayed bridge consists of two towers, eleven pairs of cables on each cable plane and the main girder (Song et al., 2007).

4.2 Previous inspection and maintenance

Due to the increasing of traffic loads, unfavourable environmental factors, and material degradation, the bridge structures deteriorated. It has been overhauled in 1995, 2003 and 2008 (Song et al., 2009).

In history, it was found in 1986 that there was splitting problem in the bridge with the aluminium sheath in the cables and some rust of steel wires. Cement slurry was re-pressed into the aluminium sheath two meters above the bridge pavement sealed with epoxy resin. In 1990, it was found varying degrees of rust in steel wires and some seriously damaged steel beam with crescent-shaped and a corrosion depth of 42 mm.

In 1994, results of inspections showed aluminium sheath corrosion in cables, cracking of welded joints, broken of steel wire, and serious problem of leakage. As a result, in 1995 thorough maintenance was done in order to deal with the existing damages. All the cables are replaced by the double PU+PE sheathed cables instead of aluminium sheathed cables. The overhaul also includes pasting steel plate to the cracking place in main bridge tower beams and renovating bridge pavement. Meanwhile, the concrete strength, carbonation depth, cable tension force and deflection were tested.

In 2003, an overhaul of the bridge was again conducted; repairs were mainly carried out for the bridge approaches. At the same time, treatment of serious damages in the main bridge was made. In 2008, crack at the diaphragm in the main bridge was patched by infusion of polymer mortar. CFRP was pasted to some of the crack in the roof and diaphragm (Song et al., 2009). Steel plate was pasted to the straight and inclined webs see Figures 11 and 12. Rust in the corroded anchor head at both ends of the beam was cleaned and removed. And water leakage problem in the concrete on the main girder was properly treated.

Figure 11   In 2008, CFRP was pasted to the roof and diaphragm in order to control cracks.

Figure 12   In 2008, steel plate was pasted to the webs.

4.3 Geographical environment

The Jinan Yellow River Highway Bridge is located in the north of Jinan, Shandong Province, which is one of the most important economical provinces in the east of China. The bridge locates at the north exit of Jinan and it combines the State Road of 104 and 220, making it become a busy hub in highway transportations see Figure 13.

The bridge lies at the downstream of Yellow River, which is the second longest river in China. Tracing the Bayan Har Mountains, it flows northeast and crosses nine provinces. It runs 5,464 km until it empties into the sea, draining a basin of 745,000 km see Figure 14 (Li, 2005). This river carries a huge amount of muds and sands, thus it becomes yellow in colour.

Figure 13   The Jinan Yellow River Highway Bridge is located in north of Jinan, and it combines the State Road of 104 and 220.

Figure 14   The Bridge lies at the downstream of Yellow River as it can be seen at the red dot.

The Yellow River flows from west to east and alluvial plains are generated on the both sides of the bridge as it is shown in Figure 15. On the north side of the river, there is broadened flood detection area, which has a width of 4 km. The plain on the south of the river has relatively low terrain. It is flat and open, which is mostly used as farmland. Part of the area is made into artificial ponds and ditches. The Queshan Reservoirs locates in the west of the bridge.

Figure 15 The Yellow River flows from west to east. And the Queshan Reservoirs locates in the west of the bridge.

4.4 Hydrogeological description

The bridge site area is covered by Quaternary strata, mainly alluvial sediments. The bridge site engineering geological strata mainly consist of the Quaternary fluvial clay, which is mixed with silty clay, fine sand, medium sand, thin layers of clay and lenses see Figure 16. The layer of silty clay is relatively impermeable compared to other layers of aquitard or permeable layers (Li, 2005). Piles lie in the weathered rock layers and this gives small settlements of the bridge.

The surface water in the bridge site area is mainly the river. Waters from ditches on both sides and ponds accounts for a very small part. Due to the large amount of sediments carried by the Yellow River, the water is turbid and muddy as it is shown in Figure 17. The groundwater is directly affected by precipitation and surface water supply. It discharges in the form of evaporation and infiltration. Since the groundwater is mainly controlled by seasons and the water level of the Yellow River, the water level and the amount of the groundwater vary.

Figure 16 There is silty clay in the bridge site area.

Figure 17 Since the Yellow River carries large amount of sediments by the Yellow River, the water is turbid and muddy.

4.5 Meteorological characteristics

The bridge site belongs to the warm temperate zone semi-humid monsoon climate zone. It has four distinctive seasons and obviously wet and dry seasons. Summer is hot and rainy; while winter is cold and dry. Annual precipitation is between 650 mm and 700 mm, which concentrate in June to September (Li, 2005). Rainfall is also rich or poor among every year, thus droughts and floods often occur. Annual average temperature is above 14^{o}C with frost-free period of 250 days. According to the China's meteorological administration, the lowest temperature appears in January with the average lowest temperature of -4^{o}C during year 1997 to 2006 see Figure 18 (CMA, 2014). Usually from the middle of December, there is ice flow in the Yellow River. The river is usually frozen up in beginning of January the following year. And early spring thaw comes in the middle of February.

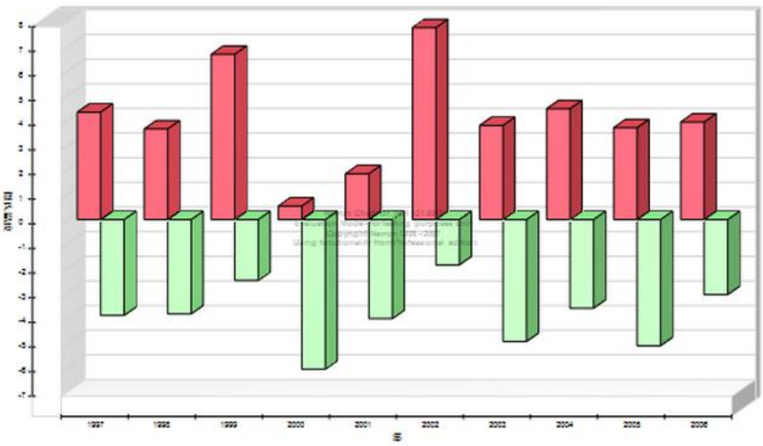

Figure 18 The green bar represents the average lowest temperature in January from year 1997 to 2006, while the red bar represents the average highest temperature in January (CMA, 2014).

4.6 Environmental classification based on concrete durability

The road environment influencing structures is closely related to the durability of concrete structure. As a matter of fact, durability of concrete structure is designed to resolve the conflict between environmental action and structure's resistance. According to design specifications domestic and abroad, the working environments of the concrete structure are classified based on the erosion mechanism of environment action and the erosion degree under different circumstances.

In China, based on the erosion mechanism, the category of environment composes of normal environment, freeze-thaw environment, marine chloride environment, other chloride environment such as deicing salt and chemical corrosion environment see

Table 5 (Wu, 2012). Different levels of environmental action are further divided in Table 6.

By considering the surrounding environment of the Jinan Yellow River Highway Bridge, the bridge is assumed belonging to level I-B. This means that the bridge is in a normal environment and suffers from mild environmental actions. The damage from external environment is mainly the reinforcement corrosion of protective layer caused by concrete carbonation. Level II, which is the freeze-thaw environment, has also been considered when the environmental classification has been made. This is because according to local meteorological information, the bridge suffers from freeze-thaw damage from December to next February. However, due to the lack of level II-B (level II-B cannot be found in Table 6), the category of environment for the Yellow River Highway Bridge falls to level I-B.

Table 5 The category of environment and their erosion mechanisms by considering the concrete durability (Wu, 2012)

Category of environment		Erosion mechanism
I	Normal environment	Reinforcement corrosion of protective layer caused by concrete carbonation
II	Freeze-thaw environment	Concrete damage caused by repeated freeze-thaw
III	Marine chloride environment	Reinforcement corrosion caused by chloride
IV	Other chloride environment (deicing salt)	Reinforcement corrosion caused by chloride
V	Chemical corrosion environment	Concrete corrosion caused by sulphates or other chemicals

Table 6 Different levels of environmental actions and the category of environment (Wu, 2012)

Level of environmental action / Category of environment	A Slight	B Mild	C Medium	D Serious	E Very serious	F Extremely serious
Normal environment	I-A	I-B	I-C	-	-	-
Freeze-thaw environment	-	-	II-C	II-D	II-E	-
Marine chloride environment	-	-	III-C	III-D	III-E	III-F
Other chloride environment such as deicing salt	-	-	IV-C	IV-D	IV-E	-
Chemical corrosion environment	-	-	V-C	V-D	V-E	-

5 METHOD AND MEASUREMENT

Based on background description and environmental analysis of Jinan Yellow River Highway Bridge, the concrete structure of the bridge mainly suffers from concrete carbonation, which can cause reinforcement corrosion in the protective layer of the steel bars. The box girder in the south side-span and south part of mid-span were chosen for inspection. Preliminary visual inspection was made in order to detect the types of damages on the surface of reinforced concrete structures and evaluate the current conditions of the concrete. Then non-destructive test in terms of concrete carbonation and corrosion of reinforced bar was carried out.

The chamber in the main girder is composed of diaphragm, roof, floor, straight web and inclined web. Every component inside the chamber was inspected. The upstream side of the chamber is the right chamber and is named with the letter R. The downstream side of the chamber is the left chamber and is named with the letter L. The middle chamber is in the middle of the girder and is named with letter M. The number of the chamber is based on the number of the diaphragm. For example, the upstream chamber between diaphragm 5# and 6# is named as R-5#. The number of the diaphragm starts from 0# to 65# from south to north. Diaphragm 0# is the first diaphragm at the south auxiliary pier in the anchor span. Diaphragm 65# is at the middle of mid-span. Inspections in the south part of main girder start from diaphragm 11# at the south anchor pier to the diaphragm 65# at the middle of mid-span see Figure 19.

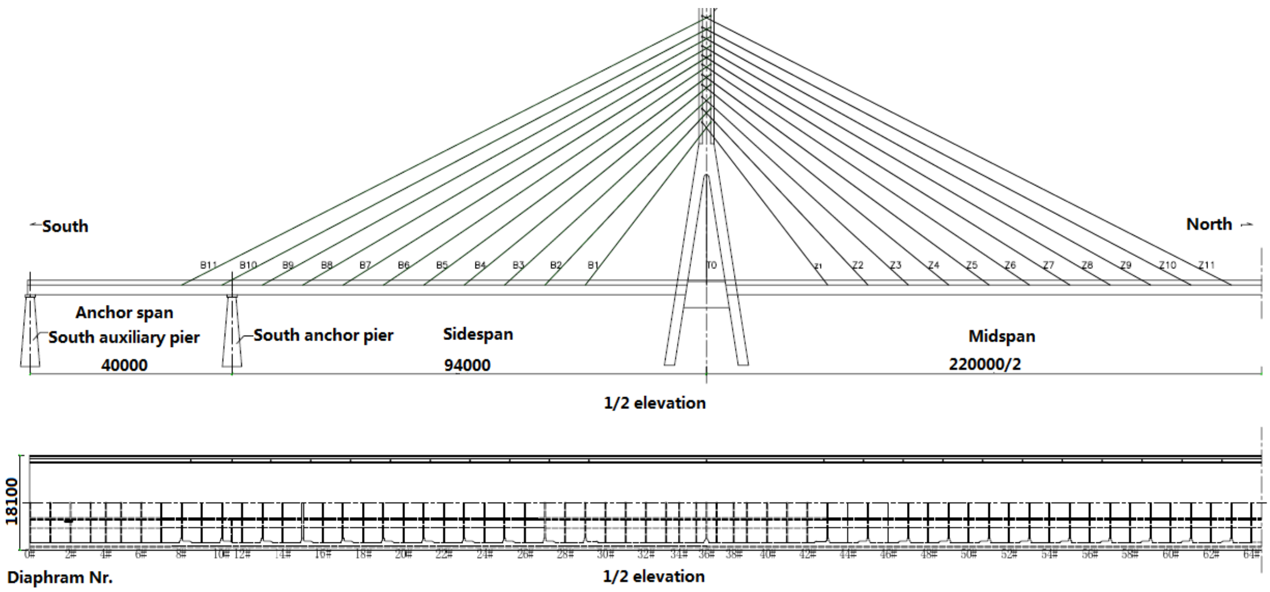

Figure 19 The number of the diaphragm starts from 0# to 65# from south to north. And the inspections start from diaphragm 11# at the south anchor pier to the diaphragm 65# at the middle of mid-span.

5.1 Visual inspection

The concrete damage detection is mainly based on the visual inspection. Visual inspection was made inside the upstream and downstream chambers in the main girder. Tape, chalk, hammer, camera, crack width gauge, and laser rangefinder were used, see Table 7. If there is problem with steel bars corrosion, concrete surface defects, or concrete seepage, colour chalk was used to mark the damage and the range of damage. Cracks may indicate lack of structural bearing capacity. Large cracks are unfavourable since they can lead to reinforcement corrosion and reduce the durability of concrete structures. If there are cracks on the surface of the concrete, the distribution, location, strikes of the cracks need to be marked. For the more serious cracks, rules and crack width gauge was used to measure the crack length and width. Photos were taken for the typical damages. Table 8 shows the detailed visual inspection items.

Table 7 Tools and devices for visual inspection

Devices	Model	Application	Comment
Tape	-	Distance measurement	-
Chalk	-	Mark	-
Hammer	-	Concrete quality control	-
Crack width gauge	DJCK-2	Crack width measurement	Figure 20
Camera	-	Taking photos	-

Table 8 Detailed visual inspection items

Visual inspection	Detailed inspections
Surface damage	Concrete damage: Voids and pits, defects, flaking, seepage
	Steel bars: Exposure of reinforcement, corrosion
Cracks	Longitudinal cracks, temperature crack, Cracks due to concrete shrinkage, Cracks due to structure stress
	Measuring the crack length, crack width, Crack depth that exceeds the limit

The preliminary inspection gives an overview of the current conditions of the reinforced concrete. After the visual inspection, the reasons of concrete damages and the degree of corrosion should be evaluated.

Figure 20 Crack width gauge is used to measure the crack width

5.2 Non-destructive test

After the preliminary inspections, detailed testing was made on site to assess the concrete carbonation and corrosion of reinforcement. Testing items and devices are listed in Table 9. Four chambers (including diaphragm, roof, floor, straight web and inclined web) were chosen to be testing chambers. The first testing chamber is at the 1/4L of the south side-span and it is between diaphragms 16# and 17#. The second testing chamber is at the 1/2L of the south side-span and it is between diaphragms 22# and 23#. The third testing chamber is at the 1/4L of the mid-span and it is between diaphragms 50# and 51#. The last testing chamber is at the 1/2L of the mid-span and it is between diaphragms 64# and 65#, see Figure 21.

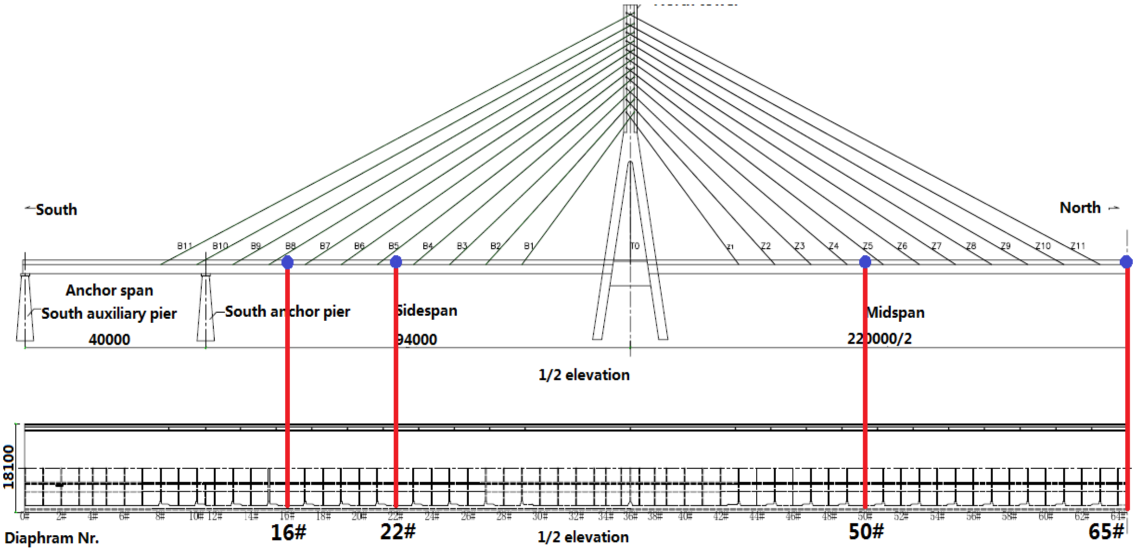

Figure 21 The location of four testing chambers

Table 9 Testing items and devices for visual inspections

Testing name	Devices	Model	Comment
Concrete strength	Resiliometer	HT-225W	Figure 22
Concrete carbonation depth	Phenolphthalein	-	Figure 23
Reinforcement position and concrete cover	Reinforcement position and cover thickness measuring device	PROFOMETER5	Figure 24
Corrosion of reinforcement	Reinforcement corrosion tester	CANIN	Figure 25
Concrete resistivity	Resistivity tester	ZXL-4000A	Figure 26

Figure 22 Resiliometer for concrete strength measurement

Figure 23 Phenolphthalein for concrete carbonation depth measurement

Figure 24 Reinforcement position and cover thickness measuring device

Figure 25 Reinforcement corrosion tester

Figure 26 Resistivity tester for concrete resistivity measurement

The strength of the concrete is measured by the resiliometer on site. The rebound area on the concrete is 15 cm $\times$ 15 cm square. For every test, 10 rebound areas were tested in order to determine the concrete strength. For each rebound area, there were 16 measurement points. To get the average rebound values, three maximum and three minimum rebound values were removed from the measured 16 measurement points. According to "Technical specification of compressive strength of concrete measurement by the rebound method", the rebound value needs to be corrected. By considering the influence of non-horizontal direction and different angles in testing planes, estimation values of the concrete strength were calculated according to Equation (9).

$$R_m = R_{m\alpha} + R_{a\alpha} \tag{9}$$

where R_m= estimation value of average concrete strength, $R_{m\alpha}$= average concrete strength measured in non-horizontal direction, $R_{a\alpha}$= corrected concrete strength measured in angle α.

Estimation value of strength uniformity coefficient K_{bt} and average strength uniformity coefficient K_{bm} were also calculated. They reflect the degree of variation in concrete strength compared with the average concrete strength, see Equations (10) and (11).

$$K_{bt} = \frac{R_{it}}{R} \tag{10}$$

$$K_{bm} = \frac{R_{im}}{R} \tag{11}$$

where K_{bt}= estimation value of strength uniformity coefficient, K_{bm}= average strength uniformity coefficient, R_{it}= estimation value of average concrete strength, R= design value of concrete strength, R_{im}= conversion value of average concrete strength, which was derived from the estimation value of average concrete strength corrected by considering the carbonation depth.

Concrete carbonation depth was measured at the representative positions in the testing areas. Three testing areas were selected in the 10 rebound areas to measure the concrete carbonation depth. The average value for the carbonation depth was calculated from the three testing areas. Phenolphthalein was used to find the boundary between the carbonized concrete and normal concrete. Then the carbonation depth d_m was measured. Concrete carbonation depth was used to evaluate the reinforcement corrosion by comparing the average carbonation depth to the average thickness of the concrete cover.

When measuring the reinforcement position and the thickness of concrete cover, totally 10 testing areas including diaphragm, roof, floor, straight web and inclined web were chosen from the side-span and mid-span, respectively. 50 cm × 50 cm squares were arranged in the testing areas. PROFOMETER 5 was used to see if the steel bars are still in the designed position. The average thickness of concrete cover was also obtained. Then the characteristic value of the thickness of concrete cover D_{ne} was calculated from Equations (12), (13) and (14). The ratio between the characteristic value of the thickness of concrete cover and the design value of the thickness of concrete cover was evaluated to determine the influence of concrete cover to the durability of reinforced structures.

$$D_{ne} = \overline{D} - KS_D \tag{12}$$

$$\overline{D}_n = \frac{\sum_{i=1}^{n} D_{ni}}{n} \tag{13}$$

$$S_D = \sqrt{\frac{\sum_{i=1}^{n} (D_{ni})^2 - n(\overline{D}_n)^2}{n-1}} \tag{14}$$

where $\overline{D_n}$= average thickness of concrete cover for n points, n= number of measuring points, D_{ne}= characteristic values of the thickness of concrete cover, $\overline{D}$= average thickness of concrete cover, K= qualified determination coefficient, which can be calculated from Table 10, S_D= standard value of the thickness of concrete cover.

Table 10 The relationship between qualified determination coefficient and testing points

n	10-15	16-24	≥25
K	1.695	1.645	1.595

In order to evaluate the reinforcement corrosion, two testing zones in the side-span and mid-span were selected. 80 cm × 80 cm square was arranged to find the potential level, which reflects the likelihood of steel bars corrosion and corrosion activity. Then the possibility of reinforcement corrosion was determined. The concrete resistivity was also measured to see the rate of reinforcement corrosion.

For testing the chloride concentration in concrete, it was not measured this year. Data from year 2008 was used to analyse the chloride ion ingress. And only the data within the testing zones, that is, the chambers from diaphragm 11# to 65#, were selected.

6 RESULT

This chapter displays the result from visual inspection and non-destructive tests. Preliminary visual inspection was done to detect the types of damages on the surface of reinforced concrete structures and to evaluate the current conditions of the concrete. In order to assess the concrete carbonation and corrosion of reinforced bar, non-destructive tests was done.

6.1 Concrete damage by visual inspection

The roof, floor, both sides of the webs, and diaphragm in the chamber were inspected in order to find damages on the surface of the concrete.

Generally, the roof which has been refurbished in 2008 is in a good condition since the CFRP has not drop and there is no cracking of CFRP. However, the main problem with the roof is the longitudinal cracks at some junctions between the roof and diaphragm. Several longitudinal cracks appeared as L-shaped and extended to diaphragm. Mostly, the crack width was between 0.05 - 0.15 mm and the length was 20 - 40 cm. And all the width of the cracks does not exceed the limit, which is 0.20 mm. Table 11 shows the description and numbers of cracks. Table 12 shows the major damages on the concrete in the roof.

Table 11 There are totally 38 cracks on the roof of the testing chambers with the crack width between 0.05 - 0.15 mm.

Types of crack	Description	Total length/ number	Crack width exceeding the limit	Comment
Longitudinal crack	Crack width is between 0.05 - 0.15 mm. Crack length is between 20 - 40 cm.	810 cm/27	-	Figure 27
L-shaped crack	Crack width is between 0.05 - 0.1 mm. Crack length is 40 cm.	440 cm/11	-	Figure 28

Table 12 Major concrete damages are found in the roof of the testing chambers with no serious damages.

Types of damage	Location	Total area/number	Comment
Concrete damage	Toothed plate at L-40, L-50, L-52, and R-47#	3200 cm^2/5	-
Exposure of reinforcement	Toothed plate at L-52 and R-61#	1300 cm^2/2	Figure 29
Seepage and	Anchor head at the toothed	1800 cm^2/1	Figure 30

bleaching	plate at L-22#		
Rusting of anchor head	Anchor head at the toothed plate at L-28, L-29#	1200 cm^2/2	Figure 31
Cavity of concrete	Toothed plate at L-52, L-55, and L-58#	1425 cm^2/3	-
Rusting of reserved prestressing pipe	Toothed plate at R29 and R-39#	9000 cm^2/9	Figure 30

Figure 27 Longitudinal crack is found in the roof of some testing chambers.

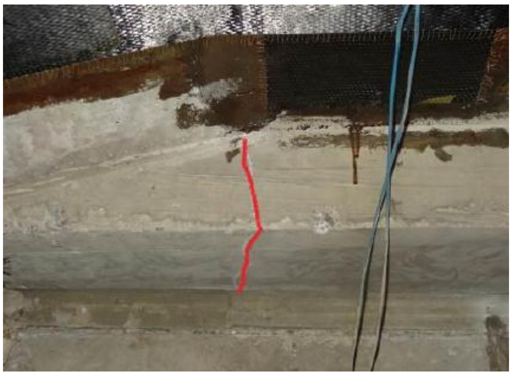

Figure 28 L-shaped crack is found in the roof of some testing chambers.

Figure 29 Exposure of reinforcement is found in the toothed plate at L-52#.

Figure 30 Seepage and bleaching is found in anchor head at the toothed plate in L-22#.

Figure 31 Rusting of anchor head is found at the toothed plate at L-29#.

Figure 32 Rusting of reserved prestressing pipe is found in the toothed plate at R-29#.

From the inspection results, no damage was found in the floor in the chambers. This means that the floor is in a good technical condition.

The webs are in a better overall condition although there were a few damages in the webs. All the straight webs are in a very good condition since no problem has been detected. For the inclined webs, several diagonal cracks were spotted in the left chambers. Concrete damages such as voids and pits, exposure of reinforcing bars and seepage with bleaching problems were also detected in the left chambers. Detailed inspections are shown in Tables 13 and 14.

Table 13 There are totally 4 cracks on the inclined web of the testing chambers with the crack width between 0.05 - 0.1 mm.

Types of crack	Description	Location	Total length/ number	Crack width exceeding the limit	Comment
Diagonal crack	Crack width is between 0.05 - 0.1 mm. Crack length is between 80 - 150 cm.	L-19, L-58#	450 cm/4	-	Figure 33

Table 14 Major concrete damages are found in the inclined web of the testing chambers with no serious damages.

Types of damage	Location	Total area/number	Comment
Voids and pits	Inclined web at L-23#	$1200\ cm^2/1$	Figure 34
Exposure of reinforcement	Inclined web at L-17#	$1800\ cm^2/1$	Figure 35
Seepage and bleaching	Inclined web at L-17#	$2000\ cm^2/1$	-

Figure 33 Diagonal crack is found in the inclined web at L-19#.

Figure 34 Voids and pits on concrete is found in the inclined web at L-23#.

Figure 35 Exposure of reinforcement is found in the inclined web at L-17#.

The diaphragms are also in a good overall condition although there were also a few damages in the diaphragm. The inspection results also show no serious damage in the diaphragm. The main damage is the diagonal crack and U-shaped crack, which appears around the manhole at some of the diaphragms. However, the crack width does not exceed the limit. Detailed inspections are shown in Table 15 and Table 16.

Table 15 There are totally 9 cracks on the diaphragm of the testing chambers with the crack width between 0.05 - 0.2 mm.

Types of crack	Description	Location	Total length/ number	Crack width exceeding the limit	Comment
Transverse crack	Crack width is 0.05 mm. Crack length is 100 cm.	L-34#	100 cm/1	-	Figure 36
Diagonal crack	Crack width is between 0.05 - 0.2 mm. Crack length is between 30 - 100 cm.	L-12, L-20, L-60#	280 cm/4	-	Figure 37
L-shaped crack	Crack width is 0.05 mm. Crack length is 60 cm.	L-28#	60 cm/1	-	Figure 38
U-shaped crack	Crack width is between 0.05 - 0.2 mm. Crack length is between 60 - 100 cm.	L-34, L-50, R-9#	240 cm/3	-	-

Table 16 Major concrete damages are found in the diaphragm of the testing chambers with no serious damages.

Types of damage	Location	Total area/number	Comment
Voids and pits	L-61#	300 cm^2/1	-
Exposure of reinforcement	L-19#	800 cm^2/1	Figure 39
Seepage and bleaching	L-51#	100 cm^2/1	-

Figure 36 Transverse crack is found in the diaphragm at L-34#.

Figure 37 Diagonal crack is found in the diaphragm at L-12#.

Figure 38 L-shaped crack is found in diaphragm at L-28#.

Figure 39 Exposure of reinforcement is found in diaphragm L-19#.

6.2 Concrete strength and carbonation depth

Based on the concrete strength measurement, it can be seen that for the most part of the concrete, they have the strength larger than the designed strength, see Table 17. Only three values didn't reach the designed values. When evaluating the strength condition, strength uniformity coefficients K_{bt} and K_{bm} were used. It is shown that most of the concrete has a very good strength conditions with the condition levels 1 and 2. Concrete in two testing zones has a relatively poor strength conditions with the condition level 3, which means the concrete fails to meet the requirement according to the strength uniformity coefficients. And only one testing result shows a very poor strength condition with the condition level 5, which means the concrete is in danger.

In regard to the concrete carbonation depth, the values vary from 0.5 mm to 5.0 mm. And they are far less than the thickness of concrete cover which has a designed value of 37.5 mm, implying that the concrete is slightly suffered from carbonation. For normal Portland cement concrete, carbonation will slightly increase the strength due to the filling of pores. However, the result shows that for some testing zones the larger the carbonation depth was; the smaller the estimation value of concrete strength, and the lower the strength of concrete. Probably carbonation reduced the hardness of concrete surface, resulting in a lower rebound value when using the resiliometer.

Table 17 Result of concrete strength and carbonation depth in testing chambers

Testing zones	$\overline{R}$ (MPa)	S_D (MPa)	$R_{min.}$ (MPa)	d_m (mm)	R_m (MPa)	R (MPa)	K_{bt}	K_{bm}	Strength Condition
Diaphragm 16#	71.4	5.9	48.1	1.0	61.6	40	1.54	1.20	1
Roof (diaphragm 16#-17#)	59.9	7.4	48.5	4.0	47.7	50	0.95	0.97	2
Str. web (diaphragm 16#-17#)	75.8	5.4	51.9	1.0	66.9	50	1.34	1.04	1
Inc. web (diaphragm 16#-17#)	53.2	4.4	41.4	4.0	46.0	50	0.92	0.83	5
Diaphragm 22#	75.1	2.3	54.2	1.0	71.4	40	1.79	1.36	1
Roof (diaphragm 22#-23#)	73.1	6.5	54.4	4.0	62.5	50	1.25	1.09	1
Str. web (diaphragm 22#-23#)	77.9	4.1	54.0	1.0	71.1	50	1.42	1.08	1
Inc. web (diaphragm 22#-23#)	68.6	5.6	47.6	5.0	59.5	50	1.19	0.95	2
Diaphragm 50#	56.2	12.6	40.8	1.0	35.4	40	0.89	1.02	3
Roof (diaphragm 50#-51#)	71.1	4.9	54.8	1.0	63.1	50	1.26	1.10	1
Floor (diaphragm 50#-51#)	81.5	8.0	56.4	1.0	68.3	50	1.37	1.13	1
Str. web (diaphragm 50#-51#)	73.4	4.0	52.9	1.0	66.7	50	1.33	1.06	1
Inc. web (diaphragm 50#-51#)	94.5	5.9	85.2	0.5	84.7	50	1.69	1.70	1
Diaphragm 65#	66.4	5.4	49.7	1.0	57.6	40	1.44	1.24	1
Roof (diaphragm 64#-65#)	69.0	6.4	51.4	3.0	58.3	50	1.17	1.03	1
Floor (diaphragm 64#-65#)	58.3	5.0	50.7	3.0	50.1	50	1.00	1.01	1

Testing zones	$\overline{R}$ (MPa)	S_D (MPa)	$R_{min.}$ (MPa)	d_m (mm)	R_m (MPa)	R (MPa)	K_{bt}	K_{bm}	Strength Condition
Str. web (diaphragm 64#-65#)	69.7	6.2	49	1.0	59.5	50	1.19	0.98	2
Inc. web (diaphragm 64#-65#)	80.5	9.1	47	1.0	65.6	50	1.31	0.94	3

6.3 Reinforcement position and concrete cover

According to the measurement, half of the concrete cover on the reinforcement has a smaller thickness compared with the designed value of 37.5 mm, see Table 18. The measured minimum thickness of the protective layer is as low as 22.3 mm. Based on the influence of the thickness of steel protective layer to the durability criteria, six of the testing zones shows the concrete cover criterion of 5. This means that the reinforced bars are very likely to lose alkaline protection and suffer from corrosion. The result from one testing zone shows the criterion of 4, which means that it will have a great impact on the durability of reinforced concrete. Two testing zone shows the criterion of 3, which means that the durability may be influenced by the concrete cover.

Table 18 Result of concrete cover in testing chambers

Testing zones	$\overline{D}$ (mm)	S_D (mm)	D_{ne} (mm)	D_{nd} (mm)	D_{ne}/ D_{nd}	Comment
Diaphragm 16#	42.2	14.1	18.3	37.5	0.49	5
Roof (diaphragm 16#-17#)	43.7	13.0	21.7	37.5	0.58	5
Floor (diaphragm 16#-17#)	31.4	6.2	20.9	37.5	0.78	3
Str. web (diaphragm 16#-17#)	28.0	9.6	11.8	37.5	0.31	5
Inc. web (diaphragm 16#-17#)	50.3	12.9	28.4	37.5	0.76	3
Diaphragm 65#	47.9	5.3	38.8	37.5	1.04	1
Roof (diaphragm 64#-65#)	43.7	10.8	25.4	37.5	0.68	4
Floor (diaphragm 64#-65#)	23.6	8.6	9.1	37.5	0.24	5
Str. web (diaphragm 64#-65#)	31.0	11.8	10.9	37.5	0.29	5

Inc. web (diaphragm 64#-65#)	22.3	9.8	5.7	37.5	0.15	5

6.4 Reinforcement corrosion

The potential measurement shows that the potential level in all the testing zones is between -192 mV and -1 mV with Cu/$CuSO_4$ reference electrode, see Table 19. According to the criteria, the steel bars have no corrosion activity or the corrosion activity is uncertain. This means the reinforcement in all testing zones is not very likely to be corroded.

Table 19 Result of reinforcement corrosion in testing chambers

Testing zone	Str. web (diaphragm 16#-17#)					
Zone number	Testing points and potential measurement (mV)					Potential level (mV)
	1	2	3	4	5	
1	-31	-26	-10	-6	-9	-35 - -5
2	-30	-15	-11	-10	-11	
3	-26	-20	-9	-10	-15	
4	-28	-6	-15	-5	-8	
5	-35	-6	-15	-26	-14	
Testing zone	Roof (diaphragm 22#-23#)					
Zone number	Testing points and potential measurement (mV)					Potential level (mV)
	1	2	3	4	5	
1	-40	-49	-57	-51	-50	-192 - -23
2	-77	-27	-23	-64	-56	
3	-78	-65	-60	-43	-67	
4	-102	-136	-49	-142	-101	

5	-80	-143	-104	-95	-192	
Testing zone	Inc. web (diaphragm 50#-51#)					
Zone number	Testing points and potential measurement (mV)					Potential level (mV)
	1	2	3	4	5	
1	-187	-135	-84	-25	-151	-187 - -25
2	-145	-78	-175	-75	-169	
3	-144	-85	-72	-71	-79	
4	-68	-62	-67	-72	-82	
5	-72	-145	-149	-171	-169	
Testing zone	Inc. web (diaphragm 64#-65#)					
Zone number	Testing points and potential measurement (mV)					Potential level (mV)
	1	2	3	4	5	
1	-46	-120	-12	-5	-1	-120 - -1
2	-64	-2	-12	-14	-7	
3	-31	-11	-2	-14	-7	
4	-77	-10	-9	-38	-17	
5	-63	-10	-71	-35	-19	

6.5 Concrete resistivity

The resistivity measurement shows that the concrete resistivity in all the testing zones is between 10330 and 19850 Ω cm, see Table 20. According to the criteria, the rate of corrosion of steel bars is very slow.

Table 20 Result of concrete resistivity in testing chambers

Testing zone	Str. web (diaphragm 16#-17#)					
Zone number	Testing points and concrete resistivity (Ω·cm)					Resistivity (Ω·cm)
	1	2	3	4	5	
1	18700	15500	10200	10450	19450	10200-19850
2	15960	18410	13530	10880	11110	
3	15500	10950	19850	19200	14500	
Testing zone	Roof (diaphragm 22#-23#)					
Zone number	Testing points and concrete resistivity (Ω·cm)					Resistivity (Ω·cm)
	1	2	3	4	5	
1	17200	14800	17770	14060	15800	11130-17770
2	11130	16700	16200	17500	17300	
3	11490	11420	11520	11680	11600	
Testing zone	Inc. web (diaphragm 50#-51#)					
Zone number	Testing points and concrete resistivity (Ω·cm)					Resistivity (Ω·cm)
	1	2	3	4	5	
1	14670	15750	15610	14880	15800	10330-17570
2	10330	15660	17570	15450	17460	
3	14700	15000	13940	14200	14070	
Testing zone	Inc. web (diaphragm 64#-65#)					

Zone number	Testing points and concrete resistivity (Ω·cm)					Resistivity (Ω·cm)
	1	2	3	4	5	
1	14260	13450	14250	14850	11950	11780-16620
2	11780	12800	14210	13700	13400	
3	14740	16620	13510	13310	14910	

6.6 Chloride concentration in concrete

Measurement data from year 2008 was used to analyse the impact of chloride ion ingress to the reinforcement corrosion. As it is shown in Table 21, the chloride ion concentration in all testing zones is between 0.15% and 0.4% by weight of cement, which belongs to the criterion level 2. This means that it is uncertain about the corrosion of steel bars due to chloride ion.

Table 21 Result of chloride concentration in concrete

Location	Chloride concentration (%)	Criteria
Roof (diaphragm 13#-14#)	0.23	2
Str. web (diaphragm 13#-14#)	0.21	2
Floor (diaphragm 64#-65#)	0.32	2
Inc. web (diaphragm 52#-53#)	0.25	2

6.7 Summary

According to the visual inspection, the concrete in the testing chambers is generally in a good condition. The roof which has been already refurbished by CFRP has few problems with cracking and the crack width does not exceed the limit. However slight concrete damages have been detected, such as concrete damage, exposure of reinforcement and rusting of anchor head. There was no damage in the floor in the chamber. There were few damages in the webs such as cracks, voids and pits in concrete and water seepage. There was no serious damage in the diaphragm except for some cracks and slight concrete damages.

The results from non-destructive tests show that most part of the concrete in testing zones has a very good strength conditions. The thickness of carbonation depth is far less than the designed value of concrete cover though the concrete suffers slightly from carbonation. In regard to the concrete cover, the durability of the reinforcement can be influenced by the concrete cover. Half reinforced bars in testing zones are very likely to lose alkaline protection and suffer from corrosion. Fortunately, the potential measurement shows that the bars have no corrosion activity or the corrosion activity is uncertain. This means the reinforcement in all testing zones is not likely to be corroded. The resistivity measurement shows that if the steel bar has been corroded, the rate will be very slow.

7 DISCUSSION AND SUGGESTIONS

In this chapter the result presented above will be discussed and some suggestions will be given. According to the measurement, most of the testing chambers in Jinan Yellow River Highway Bridge are in a good technical condition, except for issues with inadequate thickness of concrete cover, some slight concrete damages, and cracks.

It is detected that almost half of the concrete cover on the reinforcement has a smaller thickness compared to the designed value of 37.5 mm, which means that the concrete cover may probably have an impact on the durability of reinforced concrete according to the criteria. Generally, concrete cover is used to protect the reinforcement from corrosion. Inadequate cover thickness may lead to reinforcement corrosion. Fortunately the results from the reinforcement corrosion test shows that steel bars have no corrosion activity or the corrosion activity is uncertain, which means that the reinforcement is to a large extent, in a good condition and not very likely to be corroded. However, it is recommended that cement mortar or concrete that has a higher grade of strength than the original concrete could be pasted for safety’s sake.

Some slight concrete damages are found in some chambers. Concrete surface damages are mainly the voids and pits, concrete damage, and exposure of reinforcement. Voids and pits is the most common damage and it is owing to the poor-compacting during concrete casting. Minor and slight pitted surface can be easily patched by using polymer cement mortar followed by scraping and wiping concrete surface. For more severe concrete damages such as stripping, concrete damage, or concrete absent, damaged concrete should be removed until the surface of fresh concrete can be seen. Then acrylic emulsion mortar can be used to mix with proper coarse aggregates and patched onto the clean surface. Finally, the surface should be scraped and wiped. For the exposure of reinforcement, all the loose concrete should be removed by cutting or chiselling. Then acetones or alcohol is used to clean the inner surface of the trenches. Finally, acrylic emulsion mortar is used to seal the cuttings.

All the cracks inspected have a crack width less than 0.20 mm. According to criteria, crack with the width less than 0.20 mm will not cause corrosion of the reinforcement. This optimistic result is largely attributed to the pasting of CFRP on the roof and steel plates on the webs in year 2008. However, in order to improve the durability of reinforced concrete structures, the cracks could be sealed by polymer mortar. Then a smooth and uniform surface could be achieved with no cracking or shedding.

The chloride concentration in concrete, which was measured in year 2008, shows that it is uncertain about the corrosion of steel bars due to chloride ion. This means that it is likely for the bridge to be influenced by the ingress of chloride ion, such as deicing salts used in the winter. Since six years have passed, the current concentration of chloride in concrete is unknown. Therefore it is highly recommended to make the measurement again in order to make sure if the chloride ion has an influence on the reinforced concrete or not.

The environmental classification in terms of concrete durability is based on single environmental action and erosion mechanism. However, the natural environment is often affected by a combined effort of different environmental factors. Therefore, this environmental classification cannot reflect the environmental influence on the structure in a good way. By considering the surrounding environment of the Jinan Yellow River Highway Bridge, the bridge is assumed belonging to level I-B. That means that the bridge is in a normal environment and suffers from mild environmental actions such as carbonation of concrete. This assumption is a little conservative since the bridge may suffer from freeze-thaw damage from December to next February. However, it is considered that the influence of freeze-thaw cycles will not be that severe because the average lowest temperature in January is only -4 ^{o}C based on the local meteorological information. It would be interesting to make further investigations to see if how the freeze-thaw cycles influence the reinforced concrete structures on the bridge.

8 CONCLUSIONS

Based on the literature study and the results from the visual inspections and non-destructive tests, the following conclusions can be drawn.

- Most of the testing chambers in Jinan Yellow River Highway Bridge are in a good technical condition.
- The concrete suffers slightly from carbonation but the thickness of carbonation depth is far less than the designed value of concrete cover.
- The reinforcement in all testing zones is not likely to be corroded.

However in some testing chambers, there are problems with inadequate thickness of concrete cover, slight concrete damages, and cracks. In order to improve the durability of the reinforced concrete structures on the bridge, it is suggested that these problems can be treated by pasting cement mortar or acrylic emulsion mortar, which is also for safety consideration.

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10 APPENDIX

Table A-1 Concrete strength condition criteria (Liu, 2013)

K_{bt}	K_{bm}	Strength condition	Criteria
≥ 0.95	≥ 1.00	Very good	1
0.90 - 0.95	≥ 0.95	Good	2
0.81 - 0.89	≥ 0.90	Moderate	3
0.70 - 0.80	≥ 0.85	Bad	4
≤ 0.70	< 0.84	Dangerous	5

Table A-2 The influence of concrete cover to reinforcement durability (Liu, 2013)

D_{ne}/ D_{nd}	Influence on durability	Criteria
> 0.95	No influence	1
0.85 - 0.95	Slightly	2
0.70 - 0.85	Moderate	3
0.55 - 0.70	Great	4
< 0.55	Reinforcement is likely to be corroded.	5

Table A-3 Probability of reinforcement corrosion according to potential level test (Liu, 2013)

Potential level (mV)	Reinforcement corrosion	Criteria
0 - -200	No corrosion or uncertain corrosion activity	1
-200 - -300	Probable corrosion	2
-300 - -400	Corrosion probability more than 90%	3
-400 - -500	Very likely to have corrosion	4
< -500	Corrosion occurs.	5

Table A-4 Speed for reinforcement corrosion according to resistivity (Liu, 2013)

Resistivity (Ω·cm)	Possible corrosion speed	Criteria
> 20000	Very slow	1
15000-20000	Slow	2
10000-15000	Moderate	3
5000-10000	Fast	4
< 5000	Very fast	5

Table A-5 Probability of reinforcement corrosion due to chloride ion (Liu, 2013)

Concentration of chloride ion in cement (%)	Probability for reinforcement corrosion	Criteria
< 0.15	Very little	1
0.15 - 0.4	Uncertain	2
0.4 - 0.7	Moderate	3
0.7 - 1.0	Sure	4
> 1.0	Already corroded	5