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Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure – *Synthesis Report*

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Australian Government
Department of Climate Change
and Energy Efficiency

This synthesis report was prepared by Xiaoming Wang, Minh Nguyen, Michael Syme, Anne Leitch of CSIRO's Climate Adaptation Flagship, and Mark G. Stewart of the University of Newcastle, based on the three parts of research of 'An Analysis of the Implications of Climate Change Impacts for Concrete Deterioration', co-funded by Department of Climate Change and Energy Efficiency (DCCEE) and CSIRO Climate Adaptation National Research Flagship (CAF).

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PREFACE

This synthesis report is based on the three-part report of a CSIRO study *Analysis of climate change impacts on the deterioration of concrete infrastructure* that was funded by Department of Climate Change and Energy Efficiency (DCCEE) and the CSIRO Climate Adaptation Flagship.

It aims to draw together all the major outcomes from the study for the benefit of policy-makers, engineering designers, asset managers and other professionals and decision-makers in both public and private sectors to assist them to understand the potential impact of climate change on concrete infrastructure. It also aims to provide guidance and examples to assist appropriate adaptation responses at the design and maintenance stages.

The scope of the synthesis report includes the findings from the review as well as impact and adaptation assessment contained in the three parts of report:

- Part 1: Mechanisms, Practices, Modelling and Simulations.
- Part 2: Modelling and Simulation of Deterioration and Adaptation Options.
- Part 3: Case Studies of Concrete Deterioration and Adaptation.

All findings summarised in this synthesis report include references to the relevant sections in the three parts of the full report.

EXECUTIVE SUMMARY

Concrete is the predominant construction material used in Australian buildings and infrastructure. Its performance is vital to provide the nation's essential services and maintain its economic activities.

The key performance requirements for the design, construction and maintenance of concrete structures relate to safety, serviceability, and durability. The deterioration rate of such structures depends on the construction processes employed, the composition of the materials, and on the environment. Changes to climatic conditions may alter this environment, especially in the longer term, causing deterioration processes to be changed with implications for the safety, serviceability and durability of concrete infrastructure.

Decisions relating to infrastructure development, maintenance, replacement and refurbishment over the service lifecycle can have consequences for 30-200 years or more. Therefore such decisions and associated investments should take into account future climatic conditions.

Deterioration of concrete structures

Classification of exposure

Australian design standards classify environmental exposure of concrete structures on the basis of the climate zone (arid, temperate and tropical) and proximity to water bodies (>50km from the coast, between 1km and 50km from the coast, and <1km from the coast). For non-industrial environments, inland concrete structures (>50km from the coast) are classed as exposure A1 in the arid zone, A2 in the temperate zone and B1 in the tropical zone. Structures between 1km and 50km from the coast are subject to B1 exposure, while those less than 1km from the coast are under exposure B2. Structures with a periodic contact with water, known as spray zone and splash zone, are subject to exposure C. These classifications are used as guides only – the actual environmental exposure depends on the local conditions of concrete structures.

Deterioration mechanisms

Concrete deterioration can be caused by physical factors (e.g. freeze–thaw cycles, thermal mismatch between cements and aggregates), mechanical factors (abrasion, impact and erosion) and chemical factors that occur both with and external to the concrete structure.

Chemical deterioration can occur due to the penetration of chemicals from the environment, such as atmospheric CO_2 and reactive ions, together with water and oxygen. It may also occur as a result of reactions between the concrete constituents.

Chloride-induced corrosion is the major threat to the durability of maritime and coastal concrete structures.

Corrosion products cause considerable expansion, generating internal stress and causing cracking flaking or delamination.

Carbonation occurs when atmospheric CO_2 penetrates concrete, reducing the pH and increasing the vulnerability of steel reinforcement to depassivation, the loss of corrosion protection. This can result in shrinkage and pH decline which, if left unchecked, will eventually cause corrosion and cracking, followed by more severe damage.

Climate change and concrete deterioration

Chloride-induced and carbonation-induced corrosion of concrete infrastructure are directly affected by environmental factors such as temperature and humidity. Carbonation is also affected by the concentration of CO_2 in the atmosphere. All these factors – temperature, humidity and CO_2 concentration – will vary as a result of increasing greenhouse gas emissions and climate change.

Elevated carbon concentration accelerates carbonation and increases carbonation depth in concrete: this increases the likelihood that carbonation-induced reinforcement corrosion is initiated resulting in structural damage of concrete structures. Elevated temperature accelerates carbonation, chloride penetration and corrosion rate of reinforcement that exacerbates the corrosion damage. Lowered relative humidity may reduce or even stop carbonation and chloride penetration in areas where the current yearly average relative humidity is just above 40-50%. However increased humidity may result in carbonation and chloride penetration occurring in the regions where they are now negligible.

Climate change impacts on concrete corrosion in Australia

The following projected impacts are based on mid-range estimations of temperature and humidity under the emissions intensive A1FI scenario in 2100. Changes are relative to the year 2000. They should only be used as a guide, however, as the local condition of each concrete structure will be different.

In general, inland concrete structures are more vulnerable to carbonation-induced corrosion while concrete structures designed for coastal environments are more vulnerable to chloride-induced corrosion. This study has not taken into account the effect of climate change on acidity due to increased uptake of carbon dioxide by oceans, and as a consequence, may underestimate the risk to coastal concrete structures.

Carbonation

Carbonation depth may be from 15mm less to 8mm more than the baseline where climate change is not considered.

The arid zone area in central Australia, where no carbonation occurs (due to lack of moisture), will extend in the future. As temperatures rise there may be more carbonation around the New South Wales/Victoria border, and in a small area in the west of Western Australia.

Carbonation-induced corrosion initiation is likely to be higher around the boundary between the arid climatic zone in central Australia and the temperate climatic zone in the west, south and east of Australia. The main reason for this is the lower cover requirement in design for concrete structures in arid and temperate climatic zones, which are also away from coasts. Changes in carbonation-induced corrosion damage follow a similar geographic pattern.

Chloride-induced corrosion

Corrosion due to chloride penetration mostly occurs around coastal regions. In response to climate change, corrosion initiation and damage is generally more likely along the coast than other areas, with hotspots along the west coast of Western Australian and the east coast of New South Wales up to the border with Queensland. This is due to relatively higher temperature increases in those areas to 2100 in comparison with other coastal areas.

The risk of chloride-induced corrosion initiation of concrete structures along coasts increases only slightly, depending on the region. At the same time, as temperatures increase in inland areas where chloride and moisture are suitable for corrosion initiation, the risk of corrosion is likely to increase.

In contrast to carbonation-induced corrosion, which always shows a greater change in warmer regions, a greater change in chloride-induced corrosion may not necessarily happen in warm areas *per se*, but in the areas where there is a greater increase in temperature.

The impact of climate change and design considerations

The time taken for climate change to show an impact on carbonation and chloride-induced corrosion of concrete structures depends on location and environmental exposure.

In general, when carbonation-induced corrosion initiation has to be considered in the design of concrete structures, the effect of climate change impacts should at least be considered for structures at exposure A1 and A2. The effect should also be considered for structures at exposure B1 that are designed for a service life of more than 60 years, especially in regions with a warm or tropical climate. When carbonation-induced corrosion damage has to be taken into account in design, the effect of climate change impact should not be neglected for structures designed for more than 35 years for exposure A1 and 25 years for exposure A2.

For chloride-induced corrosion initiation and damage, climate change impacts should be considered for concrete structures designed for a service life of more than 50 years for exposure C2, and not be considered for structures of designed service life less than 100 years for exposure C1. In general, the effect of climate change should be considered for the design of concrete structures for high environmental exposures, especially for those classified as C2.

Climate adaptation options for concrete structures

The impact of corrosion risk in new structures can be countered at the design stage, through the development of new technologies and materials. Developing adaptation measures for existing structures is a more costly exercise, as each concrete structure has its own construction, maintenance and environmental exposure history. For this reason adaptation measures must be structure-specific. This is particularly important with regards to existing structures that do not comply with current design standards. These structures are most vulnerable to the impact of climate change. The durability of existing concrete structures can be enhanced using conventional techniques, including surface coating barriers, extraction, cathodic protection for chloride-induced corrosion, increasing cover, and increasing strength grade.

A Summary Table of Climate Change Impact and Adaptation Options for Concrete Structures

Environmental Exposure of Concrete Structures$^{(1)}$	Climate Change Impact	Adaptation Options	
		New Structures	Existing Structures
A1 – In arid climate zone and non industrial environments, all concrete structures located greater than 50 km from the coast.	Change in the risk of chloride-induced corrosion is insignificant. The arid zone area in central Australia, where no carbonation occurs (due to lack of moisture), will extend in the future. More carbonation is expected in a small area in the west of Western Australia. Change in the risk of carbonation-induced corrosion initiation should always be considered. Change in the risk of carbonation-induced corrosion damage should not be neglected for structures designed for more than 35 years.	Increasing cover and/or strength grade, or equivalent measures to delay or slow the ingress of detrimental substances into concrete. Depending on locations, up to 10mm increase of cover from the current standard of 20mm cover, or increase of the strength grade of concrete to the level for exposure B2, to account for the increased risk of carbonation-induced corrosion damage due to climate change by 2100. Increase the strength grade of concrete to the level for exposure B1.	Adaptation is site-specific and structure-specific due to each concrete structure has its own construction, maintenance and environmental exposure history. Conventional techniques can be applied, including surface coating barriers, extraction, cathodic protection for chloride-induced corrosion, and cover renewal.
A2 – in temperate climate zone and non industrial environments, all concrete structures located greater than 50 km from the coast.	Change in the risk of chloride-induced corrosion is insignificant. As temperatures rise there may be more carbonation around the New South Wales/Victoria border, and in a small area in the west of Western Australia. Increased risk around the boundary of the arid and temperate climate zones. Change in the risk of carbonation-induced corrosion initiation should always be considered. Change in the risk of carbonation-induced corrosion damage should not be neglected for structures designed for more than 25 years.	Increasing cover and/or strength grade, or equivalent measures to delay or slow the ingress of detrimental substances into concrete. Depending on locations, up to 9mm increase of cover from the current standard of 30mm cover, or increase of the strength grade of concrete to the level for exposure B2, to take into an account the increased risk of carbonation-induced corrosion damage due to climate change by 2100.	
B1 – Tropical climate zone and non industrial environments, all concrete structures greater than 50 km from the coast; or concrete structures located between 1 and 50 km of the coast.	Change in the risk of chloride-induced corrosion is insignificant. Increased risk in carbonation-induced corrosion. Change in the risk of carbonation-induced corrosion should not be neglected for structures designed for more than 60 years.	Increasing cover and/or strength grade, or equivalent measures to delay or slow the ingress of detrimental substances into concrete. Depending on locations, up to 7mm increase of cover from the current standard of 40mm cover, or increase of the strength grade of concrete to the level for exposure B2, to take into an account the increased risk of carbonation-induced corrosion damage due to climate change by 2100.	

B2 - all concrete structures located less than 1km from the coast or permanently submerged.	Corrosion due to chloride penetration mostly occurs around coastal regions. Change in the risk of chloride-induced corrosion is limited. Change in the risk of carbonation-induced corrosion is limited.	Increase of the strength grade of concrete to the level for exposure higher than C, to take into an account any increased potential risk of carbonation-induced corrosion damage due to climate change by 2100.	
C1 - all concrete structures in the spray zone (1m above wave crest level)	Increased risk of chlorine induced corrosion, however, change in the risk of chloride-induced corrosion may not be considered for structures designed for less than 100 years. Change in the risk of carbonation-induced corrosion is insignificant.	Increasing cover and/or strength grade, or equivalent measures to delay or slow the ingress of detrimental substances into concrete. Depending on locations, up to 3mm(2) increase of cover from the current standard of 50mm cover to account for the increased risk of chloride-induced corrosion damage due to climate change by 2100.	
C2 - all concrete structures in the tidal/splash zone (1 m below lowest astronomical tide and up to 1 m above highest astronomical tide on vertical structures, and all exposed soffits of horizontal structures over the sea.	Increased risk of chlorine induced corrosion, with hotspots along the west coast of Western Australian and the east coast of New South Wales up to the border with Queensland. Change in the risk of chloride-induced corrosion should be considered for structures designed for more than 50 years. Change in the risk of carbonation-induced corrosion is insignificant.	Increasing cover and/or strength grade, or equivalent measures to delay or slow the ingress of detrimental substances into concrete. Depending on locations, up to 4mm(2) increase of cover from the current standard of 65mm cover to take into an account the increased risk of chloride-induced corrosion damage due to climate change by 2100.	

(1) The classification of environmental exposures is defined in general on the basis of Australian Standard AS 3600, and used as guides only. The actual exposure also depends on the local conditions of concrete structures.

(2) Estimation ignored the effect of the change in ocean acidification. Meanwhile, in the inland areas where chloride and moisture can prove suitable for corrosion initiation, the risk of corrosion is likely to be more due to the likely higher temperature increase than coastal areas with climate change.

Melbourne City
Source: Robert Kerton, CSIRO

1. INTRODUCTION

Physical infrastructure is a key component of human settlement and comprises buildings and the structures needed to support the provision of transport, energy, water and communication. It is critical to Australia's social and economic function. The nation's wealth worth thousands of billion dollars is contained in homes, commercial buildings, ports and other physical infrastructure assets in Australia. Concrete is the predominant construction material used in buildings and infrastructure. Its performance, therefore, is vital to provide the nation's essential services and maintain its economic activities.

The key performance requirements for the design, construction and maintenance of concrete structures relate to safety, serviceability, and durability. The deterioration rate of such structures depends not only on the construction processes employed and the composition of the materials used but also on the environment. Changes to climatic conditions may alter this environment, especially in the longer term, causing deterioration processes to be changed and consequently change in the safety, serviceability and durability of concrete infrastructure.

Decisions relating to infrastructure development, maintenance, replacement and refurbishment over the service lifecycle can have consequences for 30-200 years or more. Therefore such decisions and associated investments should take into account future climatic conditions. The analysis of the implications of climate change is vital for effective decision-making on the protection of infrastructure and the human settlements that rely on it.

The synthesis report is based on full investigation in the three parts of the report, i.e.

Part 1 Mechanisms, Practices, Modelling and Simulations – A Review considers the mechanisms of common deterioration processes in concrete structures, modelling of the deterioration process, common design practices to enhance the durability of concrete structures, and challenges faced by concrete infrastructure due to climate change.

Part 2 Modelling and Simulation of Deterioration and Adaptation Options outlines the probabilistic methodology used to simulate the impacts of future climate change on new concrete infrastructure in Australia, and especially major urban centres, and explores adaptation design options to reduce the impacts.

Part 3 Case Studies of Concrete Deterioration and Adaptation looks at the impacts of climate change on existing concrete infrastructures, considering their historical environmental exposures, and assesses various adaptations to reduce chloride and carbonation induced corrosion under a changing climate. It includes case studies of existing concrete bridges in a temperate climate zone and port structures in a tropical climate zone in Australia.

The synthesis report summarises the findings around five areas, including:

1. Deterioration of concrete structures. It describes the common deterioration mechanisms occurring among concrete structures, and designs and maintenance to increase the durability of concrete structures.
2. Deterioration of concrete structure under changing climate. It describes the relationship between the deterioration of concrete structures and climate change in terms of changes in atmospheric carbon dioxide concentration, temperature and humidity.
3. Climate change impact on deterioration of new concrete structures and adaptations. It presents the extent to which there are changes in the likelihood of corrosion initiation and damage under different emission scenarios, and it also gives adaptation options in design by change cover, strength grade and any others to reduce the diffusion of deleterious substances such as carbon dioxide or chloride.
4. Climate change impact on deterioration of existing concrete structures and adaptations. It presents the extent to which the changes in the likelihood of corrosion initiation and damage of existing concrete structures, such as bridges and port structures, under different emission scenarios, and it also gives adaptation options in maintenance as well as their cost-effectiveness.
5. Uncertainties and limitation of the study are also discussed. Nine Atmosphere-Ocean General Circulation Models (AOGCMs) are considered to simulate the climate change under A1FI, A1B and 550 ppm stabilisation emission scenarios that represents high emission, medium emission and emission under policy intervention. Deterioration models consider the uncertainties of concrete material properties, but are limited to ordinary Portland cement (OPC) though the methodology can be extended to any other type of cements without any difficulty.

Deteriorated concrete columns of bridge structures (source: RTA)

2. DETERIORATION OF CONCRETE STRUCTURES

Concrete deterioration can be caused by physical, mechanical and chemical factors both external and internal to the concrete structure. Physical deterioration can be caused by freeze–thaw cycles, and by thermal mismatch between cements and aggregates. Typical mechanical deterioration is caused by abrasion, impact and erosion. Chemical deterioration can occur due to the penetration of chemicals from the environment, such as atmospheric CO_2 and reactive ions, together with water and oxygen. It is also due to reactions between the constituents of the concrete. Deterioration of concrete due to the direct and indirect impacts of climate change occurs predominantly through the chemical deterioration. This is particularly through the corrosion of concrete reinforcement, which may eventually result in structural damage in terms of cracking and spalling of concrete (Part 1: 1.2). In practice, measures to reduce the deterioration and increase concrete structural durability have been defined by various standards for general and specific concrete structures.

2.1 Processes of Concrete Deterioration

Chloride-induced corrosion is the major threat to the durability of maritime and coastal concrete structures. Steel reinforcement in concrete is covered by a thin passive layer of oxide that protects it from oxygen and water which may cause corrosion and produce rust. This passive layer can only be maintained at high pH values (pH greater than 12). The passive layer can be destroyed by a process known as ‘depassivation’, when chloride ions penetrate the concrete and accumulate to a critical level on the surface of steel reinforcement. Corrosion on the steel surface follows and the corrosion products cause considerable expansion, generating internal stress and causing cracking and spalling or delamination (see Figure 2-1).

Figure 2-1 Corrosion of steel reinforcement in concrete structures

Source: Port of Melbourne Corporation

Carbonation in concrete is caused essentially by the penetration of atmospheric CO_2 which significantly reduces alkalinity and in turn increases the vulnerability of steel reinforcement to corrosion due to depassivation. The consequences of carbonation are shrinkage and decline in pH which, if left unchecked, will eventually cause corrosion and cracking followed by spalling (see Figure 2-2). Carbonation can also have a considerable impact on durability, especially of above-ground structures and structures exposed to high CO_2 concentrations.

Figure 2-2 Corrosion and spalling induced by carbonation.

Source: RTA

Deterioration of concrete infrastructure due to chloride-induced and carbonation-induced corrosion results in considerable economic losses in Australia because of a loss of serviceability and an increase in the maintenance required to preserve structural integrity. The economic costs are likely to increase as more people move into coastal regions and with the associated investment in concrete infrastructure in those regions.

Chloride-induced and carbonation-induced corrosion of concrete infrastructure is directly affected by environmental factors such as temperature and humidity. Carbonation is also affected by the concentration of CO_2 in the atmosphere. All these factors – temperature, humidity and CO_2 concentration – will vary as a result of increasing greenhouse gas emissions and climate change.

Other causes of concrete deterioration include:

- sulphate attack, which is of particular concern for concrete structures in low-lying coastal areas in the Northern Territory, Queensland and New South Wales because of the acid sulfate soils in these areas
- reactions between alkalis and the aggregate, a key component of concrete, which results in expansion and cracking
- freeze-thaw cycles, which cause expansion of water trapped in pores in the concrete or absorbed by capillary action.

2.2 Current Practices for Preventing Concrete Deterioration

In general, existing standards in Australia, Europe and other countries that are relevant to preventing concrete deterioration, address the need to take into account environmental exposure. They also specify requirements for durability, which is defined as the capacity of structures to resist deterioration given expected and unexpected environmental attack.

In Australia, environmental exposure is classified on the basis of the macroclimate represented by *arid*, *temperate* and *tropical* climatic zone, as shown in Figure 2-3, and the microclimate represented by the proximity to water bodies (Part 1: 3.1; Part 2: 4.1).

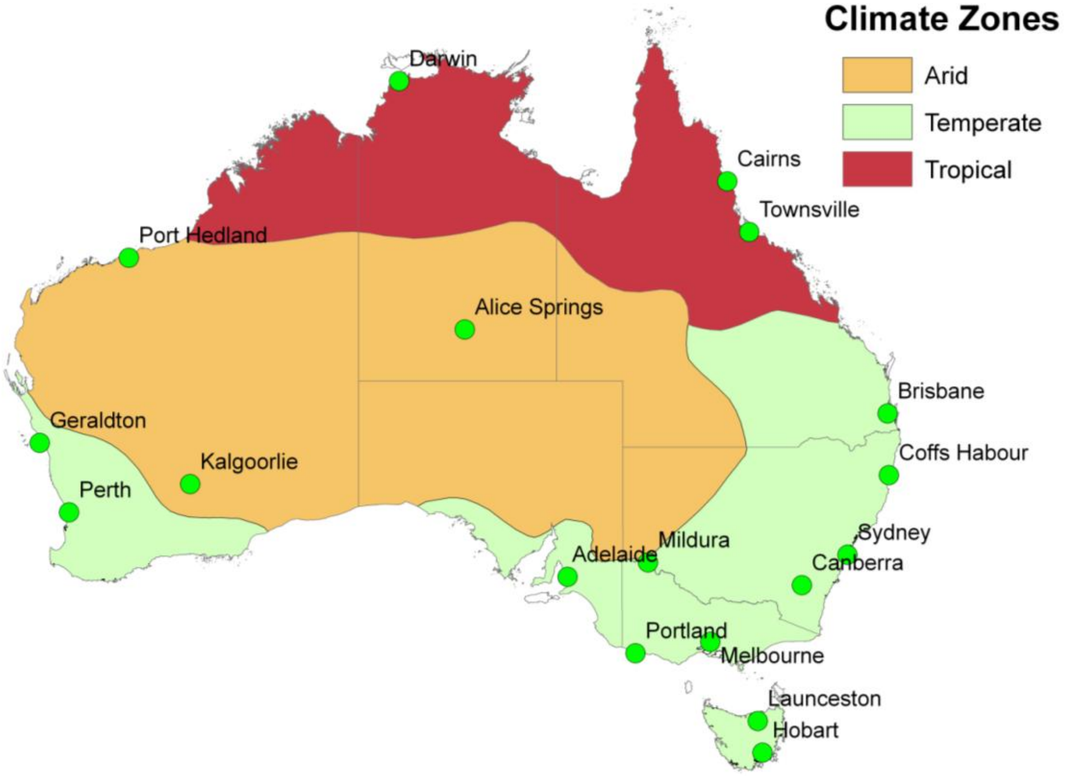


Figure 2-3 Climatic zones defined by AS 3600

As a result, the classifications of environmental exposure are represented by A1, A2, B1, B2, C1 and C2 (or C), indicates increasing severity. For non-industrial environment, inland concrete structures (or >50km from the coast) will be in either of three exposures, i.e. exposure A1 in arid climatic zone, A2 in temperate climatic zone, and B1 in tropical climatic zone. Structures near the coast (or between 1km and 50km from coast) are subject to B1 exposure, while they are subject to exposure B2 in the area less than 1km from coast. Structures with a periodical contact with water, known as spray zone and splash zone, are subject to exposure C. In this regard, environmental exposure of concrete structures in Australia can be approximated by Figure 2-4. However, it should be pointed out that the actual environmental exposure depends on the local conditions of concrete structures (Part 2: 4.1).

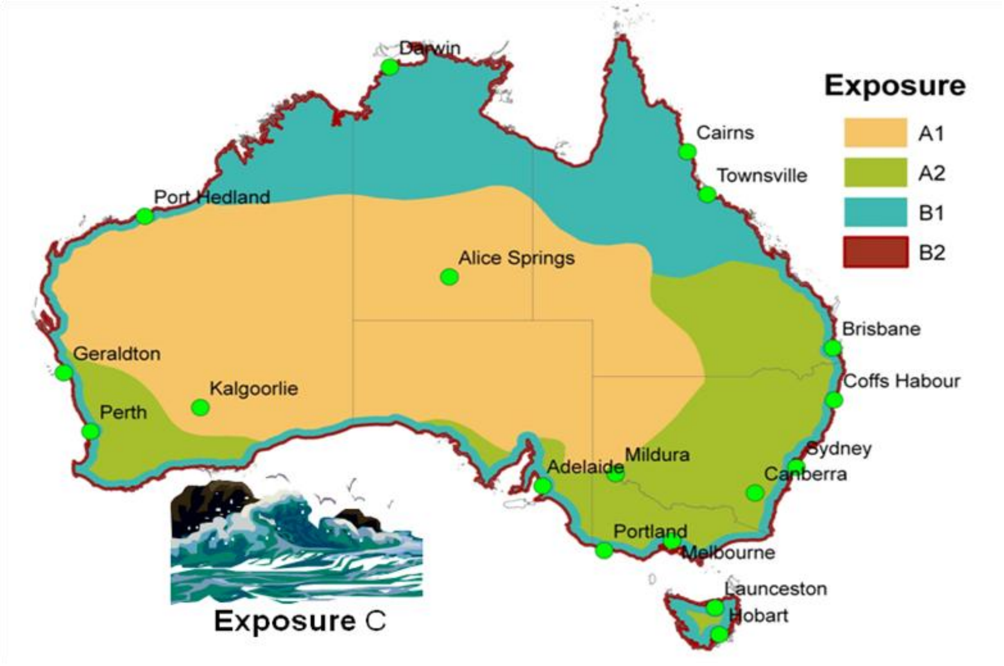


Figure 2-4. Environmental exposure of concrete structures in Australia

A common approach in the design of concrete structures is based on the environmental exposure that determines the minimum requirement of concrete strength, concrete cover, cement mix, water/cement ratio and other properties to maintain appropriate durability of concrete structures (Part 1: 3.2 and 3.3). In general, the increase of cover and strength grade of concrete material and the use of stainless steel reinforcement are the most practical solutions to increase the durability, which should be considered in the design of new concrete structures. This should not exclude the applications of more advanced concrete materials and structures (Part 1: 3.6).

For existing concrete structures, the maintenance options to enhance their durability includes the creation of exposure barriers; preventing the penetration of deleterious substances; the extraction of deleterious substances; and the removal and replacement of deteriorated parts of structures (Box 2-1) (Part1: 3.5).

Box 2-1 Options to Mitigate Deterioration

Option 1: Creation of exposure barriers

- Moisture barriers, such as waterproofing
- Protective coatings for additional protection: e.g. epoxy (non-breathable moisture barrier), polyesters, acrylics (which allow water diffusion), polyurethane, bitumen, copolymer, and anti-carbonation coating (acrylic materials)
- Coatings on steel reinforcement
- Surface preparation of concrete and reinforcement

Option 2: Preventing the penetration of deleterious substances

- Polymer impregnation, such as percolating into concrete substrate

Option 3: Extraction of deleterious substances

- Cathodic protection that migrates chloride ions from the steel surface towards an anode
- Chloride extraction, by which chlorides are transported out of the concrete to an anode surface
- Re-alkalization by applying an external anode to the concrete surface (with the steel reinforcement inside the concrete acting as the cathode) and an electrolytic paste (comprising sprayed cellulosic fibre in a solution of potassium and sodium carbonate); the electrolyte moves into the concrete, increasing alkalinity

Option 4: Removal and replacement of deteriorated parts of structures

- Patch repair systems, such as the renewal and/or preservation of the passivity of steel reinforcement and the restoration of structural integrity by applying mortar or concrete to areas where deterioration occurs; materials for patch repair can be cementitious or epoxy-based, or comprise similar resinous materials (e.g. polymer concrete and polymer-modified concrete)
- Concrete removal: e.g. the removal of damaged or deteriorated areas

To our knowledge, current practices assume a static climate and so do not consider the influence of a changing climate or environment on durability. In fact, environmental exposure of concrete structures may be considerably affected by climate change-related factors such as increasing concentrations of atmospheric CO_2, rising temperatures and sea level rise as well. This may place concrete structures at risk when the impacts of climate change on deterioration of concrete structures such as buildings, bridges, piles, footings, pipes and maritime structures cannot be neglected.

Strategies to maintain the long-term performance of concrete infrastructure in the face of climate change could include modifying existing designs and maintenance measures. However, it is unclear so far what is required in terms of the nature and extent of the changes to current practices to maintain the current level of structural reliability and durability in concrete infrastructure. This is investigated in this project.

Cracked concrete bridge structures (source: RTA)

3. DETERIORATION OF CONCRETE STRUCTURES UNDER A CHANGING CLIMATE

The durability of concrete is largely determined by its deterioration over time. The deterioration rate of concrete structures depends not only on the construction processes employed and the composition of the materials used but also on the environment. Climate change may alter this environment, especially in the long term, causing an acceleration of deterioration processes and consequently affecting the safety and serviceability of concrete infrastructure.

3.1 Climate Change and Environmental Exposure of Concrete Structures

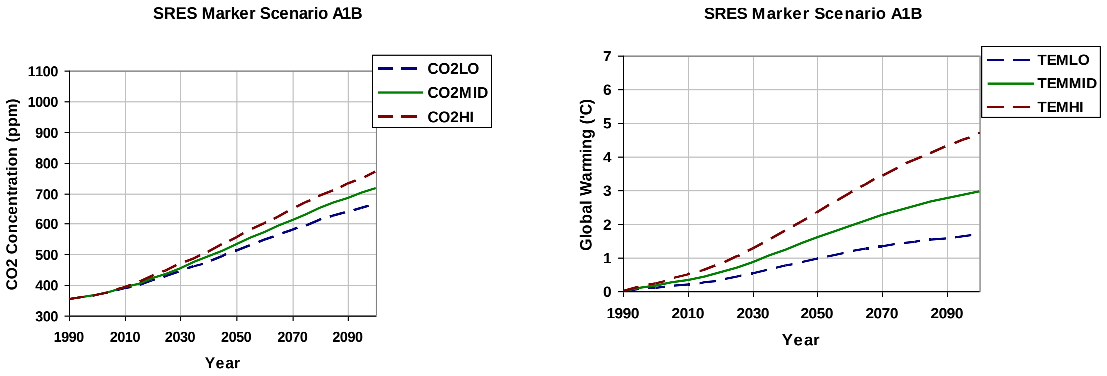
Historical study of atmospheric concentration of CO_2 indicates the relatively stable change between 260 and 280ppm for the early ten thousands of years, but dramatic increase from 280ppm in 1750 to 380 ppm in 2005. Atmospheric CO_2 is roughly 0.038% by molar content/volume in the air. The increase of CO_2 concentration, a major component of greenhouse gas, may alter the longwave radiation from Earth reflected back towards space, leading to global warming or climate change, which is often described in terms of the change of the mean and variability of temperature, humidity and other climate variables over a period of time (Part 1: 4.1 and Part 2: 2), determining the potential change in environmental exposure of concrete structures.

The atmospheric concentration of CO_2 is closely related to the carbon emission from population, economy, technology, energy, land use and agriculture. To project the anthropogenic impact due to emissions, the International Panel for Climate Change defined a total of four scenario families, i.e., A1, A2, B1 and B2 (Part 2: 2).

- A1 scenarios indicate very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies, as well as substantial reduction in regional differences in per capita income.
- A2 scenarios represent a very heterogeneous world with preservation of local identities, continuous increase of population, regionally oriented economic development, more fragmented per capita economic growth and technological change.
- B1 scenarios assume the same population trend as A1, but rapid change in economic structures towards a service and information economy, reduction in material intensity, and introduction of clean and resource efficient technologies.
- B2 scenarios emphasise local solutions to economic, social and environmental sustainability, continuous increase of global population at a rate lower than A2, intermediate levels of economic development and less rapid and more diverse technological change than those in B1 and A1.
- Sub-categories of A1 scenario include A1FI, A1T and A1B, which represent the energy in terms of fossil intensive, non-fossil energy and a balance across all sources, respectively. In addition, the scenarios of CO_2 stabilisation at 450 and 550ppm etc were also introduced to consider the effect of policies.

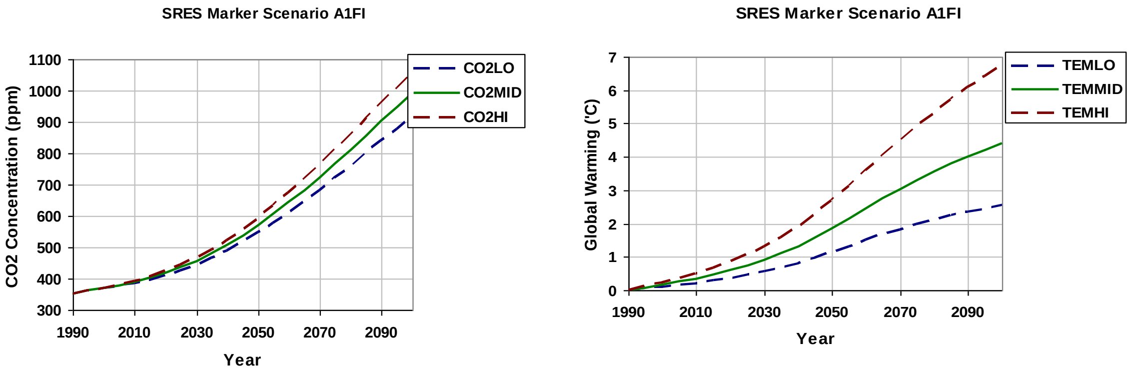
To project spatially dependent climates in the future under different emission scenarios, there have been developed various climate models or Atmosphere-Ocean General Circulation Models (AOGCMs): these are based on physical principles at the continental scale. Selecting AOGCMs to be used in an impact assessment is not a trivial task, given the variety of models. The IPCC suggested that due to the varying sets of strengths and weaknesses of various AOGCMs, no single model can be considered the best. Therefore, the current study uses multiple models to take into account the uncertainties of models in any impact assessment (Part 2: 2).

In the study, climate variability at a specific region in Australia can be simulated using *OZClim* with different GCMs from the global CO_2 concentration and global warming projections obtained by MAGICC for a given emission scenario, such as A1FI, A1B and 550 ppm stabilisation scenarios, as shown in Figure 3-1. *OZClim* is a climate change projection software developed by CSIRO, which is based on WCRP CMIP3 multi-model dataset developed by the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and the Working Group on Coupled Modelling (WGCM) of World Climate Research Programme (WCRP) (Part 2: 2). The climate variability is then applied to determine the change in environmental exposure of concrete structures.



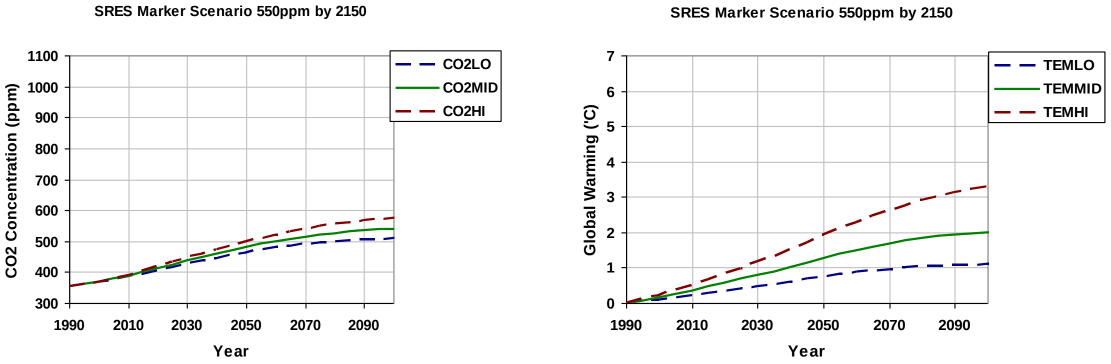
(a) CO_2 concentration (A1B)

(b) Temperature (A1B)



(c) CO_2 concentration (A1FI)

(d) Temperature (A1FI)



(e) CO_2 concentration (550 ppm stabilisation)

(f) Temperature (550 ppm stabilisation)

Figure 3-1 Projections of atmospheric CO_2 concentration and global warming to 2100

3.2 Effects of Changing Climate on Deterioration of Concrete Structures

The deterioration can be affected directly or indirectly by climate change impacts, in association with the change in carbon dioxide (CO_2) concentration, temperature and relative humidity, as shown in Table 3-1. The climate-related deterioration of concrete structures is mostly caused by the infiltration of deleterious substances from the environment, for example carbon dioxide and chloride, which causes reinforcement corrosion.

In practice, the time scale of climate change is similar to the service lifecycle of buildings and infrastructures which can be 30–200 years or more. Therefore decisions and relevant investments in association with their design, maintenance, replacement and refurbishment should take into account future climatic conditions. Understanding the implications of climate change is vital for effective decision-making to protect concrete buildings and infrastructure that underpin human settlements and the economy. Considering the factors of extensive uncertainties and the limited knowledge of future climate, simulation is deemed as an effective approach that may provide insights into how likely and how much the future climate would impact on concrete structures. More importantly, taking the precautionary principle, it may inform the necessary extent of change in design and maintenance required to maintain the current level of safety, serviceability and durability at given the likely climate change scenarios.

Table 3-1 Factors and consequences of climate change in association with concrete structures

Climate Change	Implications
Increase of carbon concentration	Elevated carbon concentration accelerates carbonation and increases carbonation depth in concrete: this increases the likelihood of concrete structures exposed to carbonation induced reinforcement corrosion initiation and structural damage
Change of temperature	Elevated temperature accelerates carbonation, chloride penetration and corrosion rate of reinforcement that exacerbates the corrosion damage
Change of humidity	Lowered relative humidity may reduce or even stop carbonation and chloride penetration in the area with yearly average RH currently just above 40-50%, while increased humidity may result in them occurring in the regions where they are now negligible.

Bridge Construction (Source: CSIRO)

4. CLIMATE CHANGE IMPACT ON DETERIORATION OF NEW CONCRETE STRUCTURES AND ADAPTATIONS

Climate change impact on the carbonation and chloride penetration induced corrosion of concrete structures is assessed by simulation based on a conventional probabilistic approach, known as the Monte Carlo simulation. The approach considers environmental variables and their uncertainties, including concentration of carbon dioxide, yearly mean temperature and relative humidity, in addition to uncertainties of the behaviour of concrete materials under the attack of carbonation and chloride penetration. (Part 2: 3)

The simulation runs on a yearly increment and involves several crucial models related to carbonation and chloride penetration depth, corrosion initiation and propagation models, reinforcement loss and damage models. The results may provide the probability distributions of penetration depth and their means, as well as the probability or likelihood of corrosion initiation and damage.

A major difference of the simulation from a general concrete deterioration simulation is the consideration of future climate variability that is projected by climate models at given carbon emission scenarios. They are then used to modify future CO_2 concentration, temperature and relative humidity that are fed into the simulation. Meanwhile the uncertainties of climate change modelling, as well as carbon emission scenarios, bring in more complexity in the simulation (Part 2: 3).

In the simulation of climate change impact on new concrete structures, it is deemed that all designs of concrete structures under a specified environment exposure satisfy the minimum requirement of concrete strength grade and reinforcement cover: i.e. they follow the Australian standard of AS 3600 – Concrete Structure. In this regard, concrete structures designed for higher exposures are required to possess a higher strength grade and thicker reinforcement cover. In addition, cement contents and water/cement ratio are deemed to meet Australian standard of AS 5100.5 – Bridge Design: Part 5 Concrete (Part 2: 4.2). Other parameters relevant to all corrosion and damage models comply with previous studies in referred journals and research documents (Part 2: 4.3).

4.1 Climate Change Impacts on Concrete Corrosion in Australia

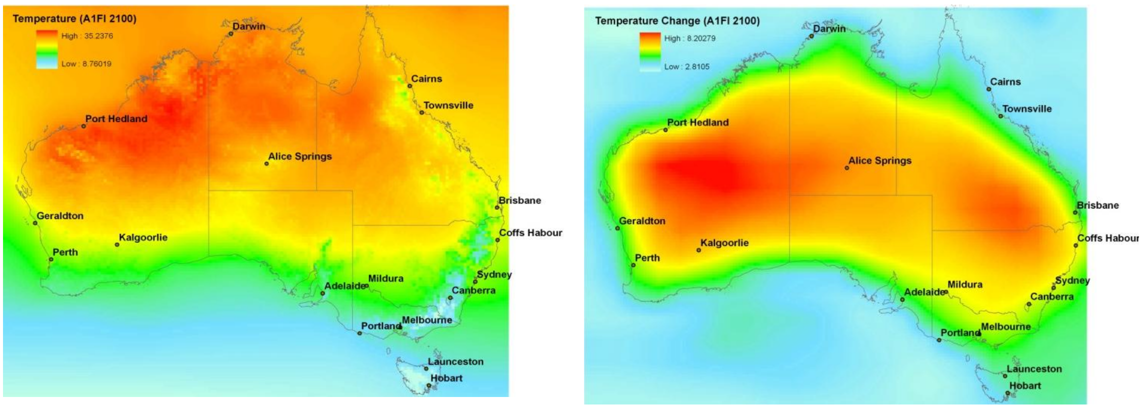
Carbonation depth of concrete structures can change depending on the location of the concrete structure Figure 4-2, and climate change may accelerate or decelerate the carbonation (Part 2: 5.1):

- Climate change may cause carbonation depth change by 2100 in the range of 15 mm less to 8mm more than the baseline where climate change is not considered,
- In the arid zone in central Australia, a lack of moisture prevents carbonation. This area is extended when the future climate becomes drier around central Australia.
- Around the border between New South Wales and Victoria, a temperature increase pushes carbonation higher.
- In a small area in the west of Western Australia, the impact of a decrease in relative humidity is not sufficient to offset an increase in temperature, leading to an increase in carbonation.

The probability of corrosion initiation falls in the range from 0 to 28 percentage points for the baseline where climate change is not considered, and it changes as a result of climate change, as shown in Figure 4-3:

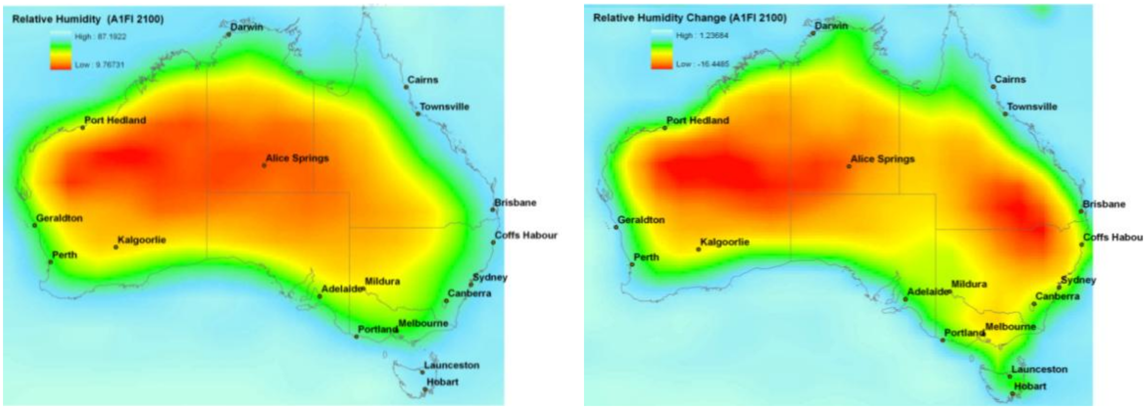
- Climate change may lead to the change in probability of carbonation-induced corrosion initiation from 22 percentage points less to 27 percentage points more than the baseline by 2100, depending on the region.
- The probability is higher around the boundary between the arid climatic zone in central Australia and the temperate climatic zone in the west, south and east of Australia, as defined in Figure 2-3 (Part 2: 5.1). This is mostly caused by a lower cover requirement in design for concrete structures in arid and temperate climatic zones, which are also away from coasts, as indicated in the previous section 2.2.

The methods used to determine the above impacts of climate change included a full scale spatial assessment of carbonation and chloride penetration induced corrosion in Australia, the projection of the local climate is based on CSIRO Mk3.5 climate model, with its medium estimation of temperature and relative humidity by 2100 at A1FI emission scenario, as shown in Figure 4-1 (Part 2: 5). Environmental exposure of concrete structures at each location is defined by Figure 2-4, and the properties of concrete structures can subsequently be determined (Part 2: 4.3). Monte-Carlo simulation is then applied to estimate the deterioration of concrete structures over the period from 2000 to 2100, including carbonation depth, probability or likelihood of carbonation and chloride penetration induced corrosion initiation and damage.



(a) Temperature by 2100

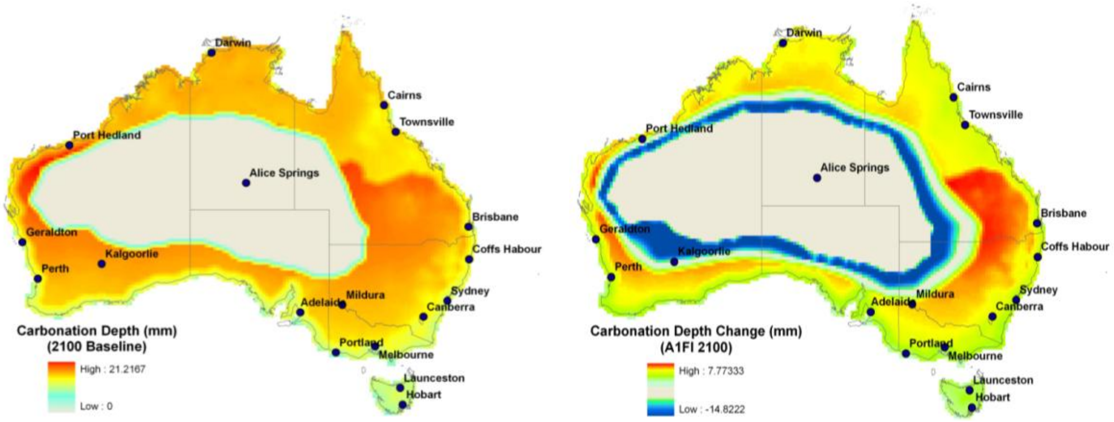
(b) Temperature increase by 2100



(c) Relative humidity by 2100

(d) Relative humidity change by 2100

Figure 4-1. Temperature and relative humidity projection by CSIRO Mk3.5 climate model

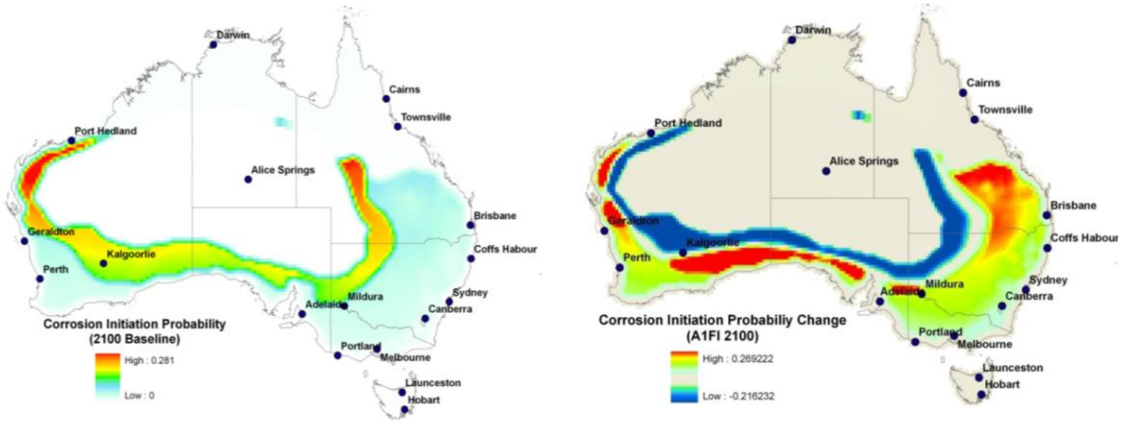


(a) Carbonation depth without the effect of climate change

(b) Change in carbonation depth due to climate change

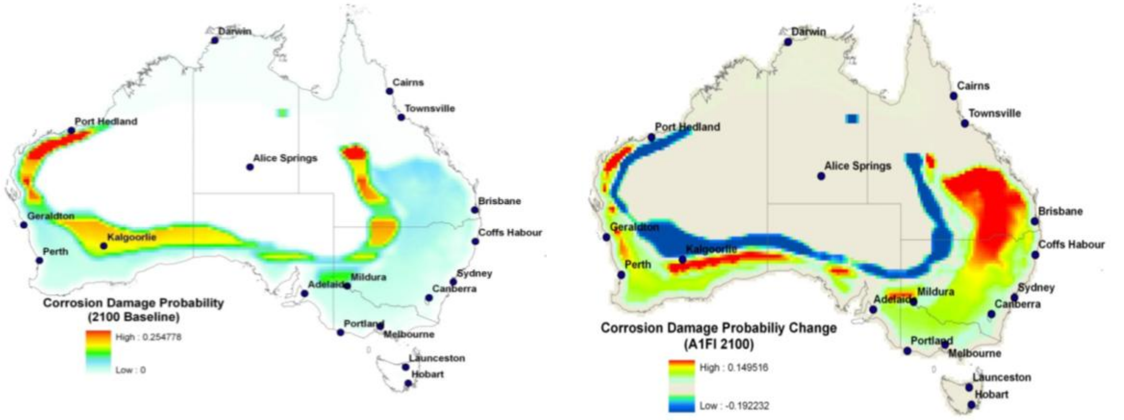
Figure 4-2. Projections of carbonation depth (mm) and its change due to climate change by 2100

Similarly, the probability of carbonation induced corrosion damage is in the range of 0 to 25 percentage points for the baseline when climate change is not considered. It changes due to climate change in a range from 19 percentage points of decrease to 15 percentage points of increase. Its spatial patterns are similar to those of corrosion initiation. (Part 2: 5.1)



(a) Corrosion Initiation probability without the effect of climate change

(b) Change in corrosion initiation probability due to climate change



(c) Corrosion damage probability without the effect of climate change

(d) Change in corrosion damage probability due to climate change

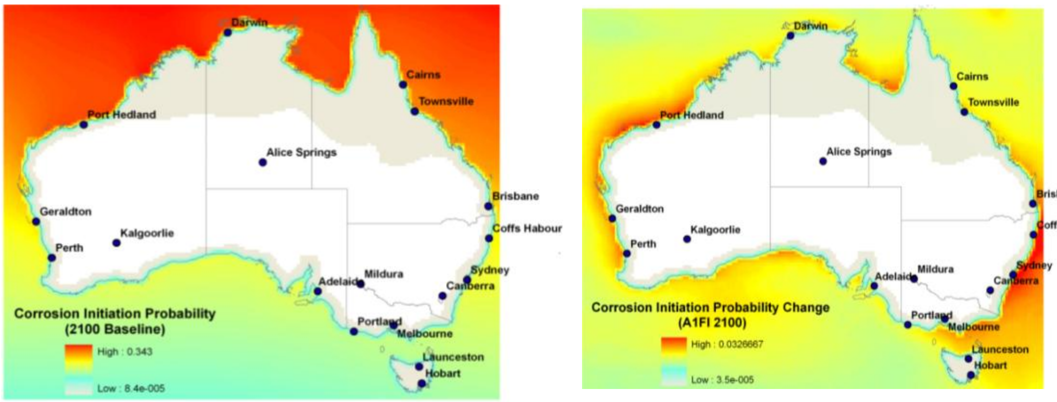
Figure 4-3. Temperature Projections of carbonation-induced corrosion initiation and damage probability and its change due to climate change by 2100 (The probability is represented by decimal numbers)

A full scale spatial assessment of chloride penetration induced corrosion in Australia and impact by climate change are also carried out, as shown in Figure 4-4 (Part 2, 5.2):

- The chloride penetration induced corrosion mostly occurs around coastal regions. Without consideration of climate change, the probability or likelihood of corrosion initiation and damage ranges from 0 in the south part of Australia to 34 percentage points in the north, mostly affected by regional temperature.

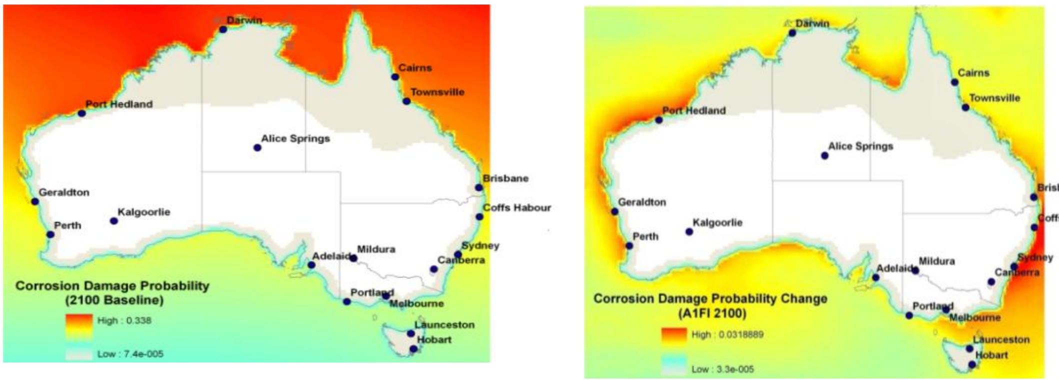
- In response to climate change, an increase in the probability of corrosion initiation and damage is generally more along the coast than other areas, with hotspots along the west coast of Western Australian and the east coast of New South Wales up to the border with Queensland. This is caused by the relatively higher increase in temperature to 2100 in those areas.
- Due to climate change, the risk of chloride induced corrosion initiation increases in the range 0 to 3.5%, depending on the region. This lower change in risk profile may be due to the fact that under climate change there is likely to be less marked increases in temperature in coastal areas compared to inland areas. A corollary is that in inland areas, where chloride and moisture prove suitable for corrosion initiation, the risk of corrosion is likely to increase more as temperature increases under climate change.

It should be noted that this analysis has not taken into account the effect of climate change on acidity due to increased uptake of carbon dioxide by oceans. As a consequence, this analysis may also underestimate the risk to coastal concrete structures. (Part 2: 5.2)



(a) Corrosion Initiation probability without the effect of climate change

(b) Increase in corrosion initiation probability due to climate change



(c) Corrosion damage probability without the effect of climate change

(d) Increase in corrosion damage probability due to climate change

Figure 4-4. Projections of chloride-induced corrosion initiation and damage probability and its change due to climate change by 2100 (The probability is represented by decimal numbers)

In general, concrete structures designed for exposures A1 and A2, which are normally located inland, are more vulnerable to carbonation-induced corrosion while concrete structure designed for coastal environmental exposure are more vulnerable to chloride-induced corrosion.

4.2 Climate Change Impacts on Corrosion in Urban Centres

Carbonation and chloride induced corrosion of concrete structures are investigated under all classes of environmental exposure in major nine major urban centres (except of Alice Springs due to its less sensitive to corrosion in general) are investigated, as shown in Figure 4-5. The effect of urban environment on carbon concentration is also considered, assuming 15% more than the normal level defined by the projections (Part 2: 3.1.1).

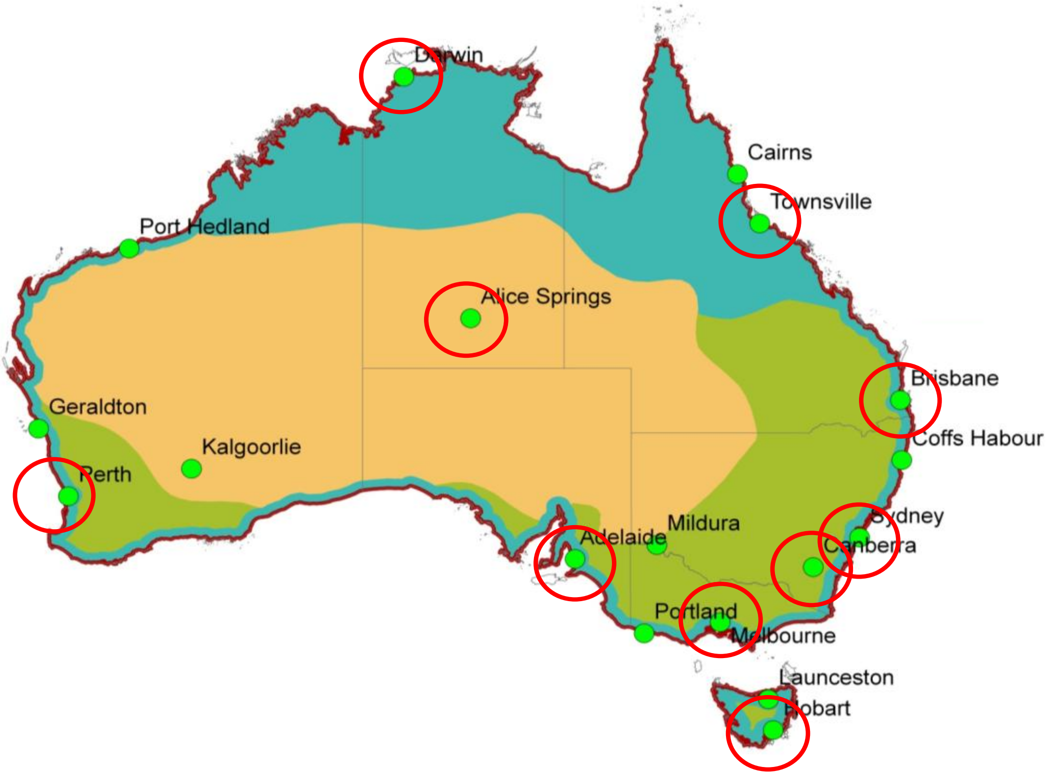


Figure 4-5. Major urban centres in Australia considered in the assessment

Concrete structures designed for higher exposure categories at the same location may have a considerably lower corrosion risk. This is due to a combined effect of an increased cover and reduced diffusion coefficient. The increased requirement for cover extends the penetration time of carbonation, and the requirement for decreased water/cement ratio reduces the diffusion coefficient of carbon dioxide.

For example, for the nine urban centres, the mean carbonation depth of structures decreases with the increase of environment exposure (Part 2: 6.1.1):

- For A1/A2 environment exposure without climate change effects the mean carbonation depth may range from 12mm in Hobart (a cold climate) to 17.4mm in Darwin (a tropical climate) in 2040, which rises to 17.0mm and 24.6mm, respectively, by 2100.
- For B1 exposure, the mean carbonation depth is in the range of 9.2mm and 13.4mm in 2040, and 13.0mm and 19.0mm in 2100.
- For B2 exposure, the range further drops within 6.5mm and 9.4mm in 2040, and 9.2mm and 13.4mm in 2100.
- The range of mean carbonation depth gets even smaller for C exposure.

The corrosion initiation probability follows a similar trend (Part 2: 6.1.1):

- For concrete structure experiencing exposure A1, the probability of corrosion initiation is in the range from 3.3 percentage points in Hobart to 16 percentage points in Darwin by 2040. The range increases to 14.6 and 40 percentage points, respectively, by 2100.
- For exposure A2, the probability of corrosion initiation is significantly reduced to the range of 0.7 to 4.2 percentage points by 2040, and 4 to 15.3 percentage points by 2100 in the major urban centres.
- For structures exposed to B1, B2 and C, the probability of corrosion initiation becomes very small or negligible.

For carbonation-induced corrosion damage, the probability in Darwin may rise to 13 percentage points by 2070 and 24 percentage points by 2100 for exposure A1, and 7.1 percentage points by 2070 and 12.6 percentage points by 2100 for exposure A2. Similar to the probability of carbonation-induced corrosion initiation, it is negligible for all other exposures. (Part 2: 6.1.1)

In comparison with the carbonation at the baseline level when climate change is not considered, the amount of increase in carbonation depth also appears to decrease with an increase in exposure. For a higher environmental exposure, the increase in carbonation depth is smaller. (Part 2: 6.1.2)

- The increase in carbonation depth due to climate change in Hobart is 2.1mm by 2040, 4.40mm by 2070 and 7.6mm by 2100 for exposures A1/A2 at A1FI emission scenario, its increase is reduced to only 1.1mm, 2.4mm and 4.1mm, respectively, for exposure B2.
- In Darwin subject to a tropical climate condition, the increase is 3.2mm by 2040, 6.6mm by 2070 and 11.5mm by 2100. The increase is reduced to 1.7mm, 3.6mm and 6.2mm, respectively, for exposure B2.

The simulations also indicate that the increase of probability of carbonation-induced corrosion initiation may also be significant due to climate change. For A1FI emission scenario (Part 2: 6.1.3):

- There is 10 percentage points increase in the probability of corrosion initiation by 2040, 24 percentage points by 2070, and 38 percentage points by 2100 for concrete at exposure A1 in Darwin in a tropical region.
- The increase is 4 percentage points by 2040, 14 percentage points by 2070 and 29 percentage points by 2100 in Hobart that is subject to a cold climate.

- In comparison with the baseline (no climate change effects), as shown in Table 4-1, there is up to 174% increase for exposure A1, 319% for exposure A2 and 616% for exposure B1 by 2100. It should be pointed that the high percentage change in the corrosion initiation probability can be caused by the low value of the baselines. (Part 2: 6.1.3)

Meanwhile, the increase in probability of corrosion damage among the urban centres is up to 6.4 percentage points by 2040, 24 percentage points by 2070 and 38 percentage points by 2100 for concrete under exposure A1 in Darwin. (Part 2: 6.1.5)

Chloride-induced corrosion is driven by surface chloride concentration which is highest in coastal areas, particularly in spray and splash zones. As a result, corrosion is most likely to affect concrete structures in exposure categories C1 and C2 (or C as defined in the early version of AS 3600). Without consideration of climate change effects (Part 2: 6.2.1):

- For exposure C in Hobart, the probability of chloride induced corrosion initiation is 10 percentage points by 2040, 17 percentage points by 2070 and 22 percentage points by 2100.
- For exposure C1 in Hobart, the probability is 0.093 percentage points by 2040, 0.26 percentage points by 2070 and 0.47 percentage points by 2100
- For exposure C2 in Hobart, the probability is 3.9 percentage points by 2040, 7.9 percentage points by 2070 and 12 percentage points by 2100.
- In comparison with the initiation probability in Hobart, the probability of chloride induced corrosion initiation is 146% more by 2040, 101% more by 2070 and 80% more by 2100 for exposure C in Darwin. The corresponding percentage increase is 551%, 396% and 324% respectively for C1 exposure, and 270%, 176% and 137% respectively for exposure C2.

Table 4-1 Increase in percentage of carbonation-induced corrosion initiation probability under A1FI emission scenario in comparison with the baselines without the effect of climate change

Exposure		ADE	BRN	CAN	DAR	HOB	MEL	PER	SYD	TOW
A1	2040	94%	75%	117%	61%	130%	110%	96%	89%	65%
	2070	117%	101%	133%	84%	134%	128%	119%	116%	89%
	2100	152%	126%	174%	95%	173%	166%	155%	150%	105%
A2	2040	118%	102%	142%	92%	154%	134%	119%	115%	93%
	2070	181%	170%	199%	155%	193%	190%	183%	184%	160%
	2100	289%	265%	319%	223%	302%	303%	296%	296%	236%
B1	2040	-	180%	-	142%	-	-	-	-	149%
	2070	314%	294%	381%	281%	400%	355%	322%	313%	282%
	2100	566%	566%	616%	568%	578%	582%	577%	600%	573%

An increase in chloride-induced corrosion is determined by both regional climate and projected climate change in terms of temperature and relative humidity. In contrast to carbonation-induced corrosion, which always shows a more change in warmer regions (determined by regional climatology), the simulation indicates that a higher change in chloride-induced corrosion may not necessarily happen in warm areas, but in the areas with a greater increase of temperature. As shown in Table 4-2 (Part 2: 6.2.2):

- For exposure C, a percentage increase of probability of corrosion initiation in comparison with the baseline without the effects of climate change is no more than 12% by 2100 among the nine urban centres, with a relatively larger change occurring in the Sydney region (including Canberra) along the east coast and Perth region along the west coast.
- For exposure C2, a percentage increase of probability of corrosion initiation is no more than 17% among the urban centres. For those urban centres along the coast, the change in percentage is no more than 15%.

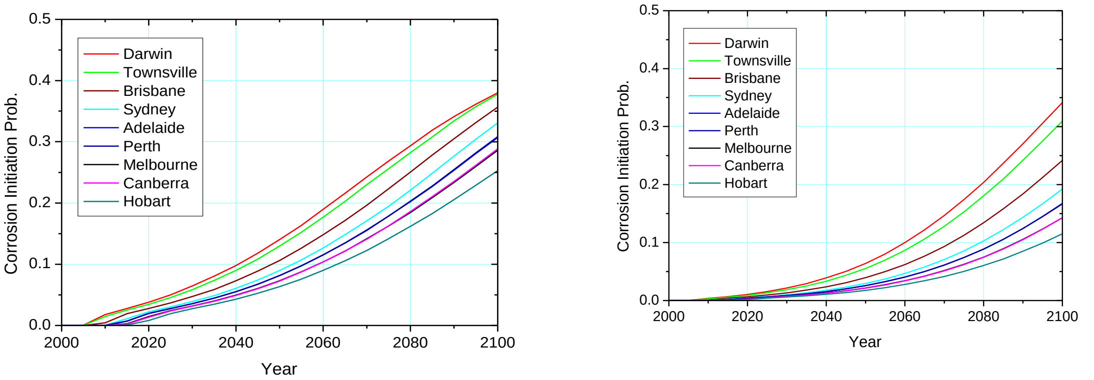
4.3 Timing to Consider the Impact of Climate Change in Design

The time taken for impacts of climate change on carbonation and chloride induced corrosion of concrete structures depends on location and environmental exposure. Therefore timing to consider climate change impact in design should be treated differently for different locations and exposures. (Part 2: 6.1.4, 6.1.5, 6.2.3, and 6.2.4).

As shown in Figure 4-6 for carbonation induced corrosion and Figure 4-7 for chloride induced corrosion, the climate change starts to show an effect on corrosion damage at the earliest in Darwin and the latest in Hobart among nine urban centres.

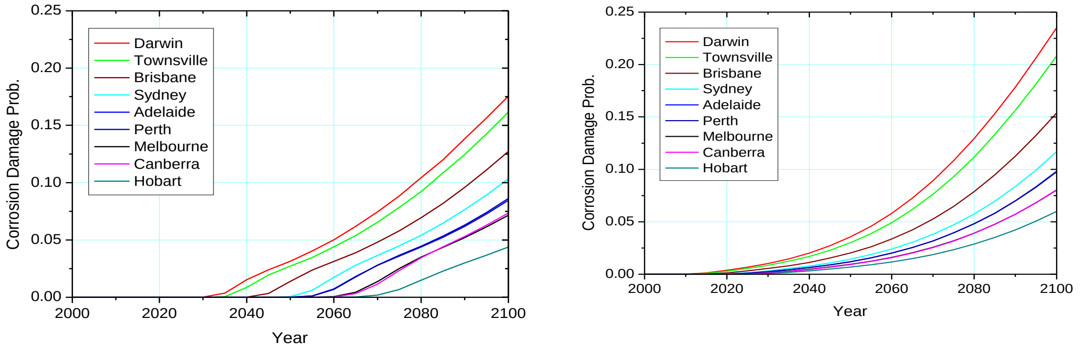
Table 4-2 Percentage increase in the probability of chloride-induced corrosion initiation in terms of percentage at A1FI emission scenario, in comparison with the baseline at a stationary climate

		ADE	BRN	CAN	DAR	HOB	MEL	PER	SYD	TOW
C	2040	5%	4%	6%	3%	5%	5%	5%	5%	4%
	2070	6%	6%	9%	5%	7%	7%	7%	8%	5%
	2100	9%	8%	12%	6%	8%	10%	10%	10%	7%
C1	2040	-	-	-	-	-	-	-	-	-
	2070	-	14%	-	12%	-	-	-	-	12%
	2100	21%	21%	27%	18%	-	22%	22%	25%	19%
C2	2040	6%	6%	9%	5%	6%	7%	7%	7%	5%
	2070	10%	9%	13%	7%	9%	11%	10%	12%	8%
	2100	13%	12%	17%	9%	13%	15%	14%	15%	10%



(a) Carbonation induced damage at exposure A1

(b) Carbonation induced damage at exposure A2



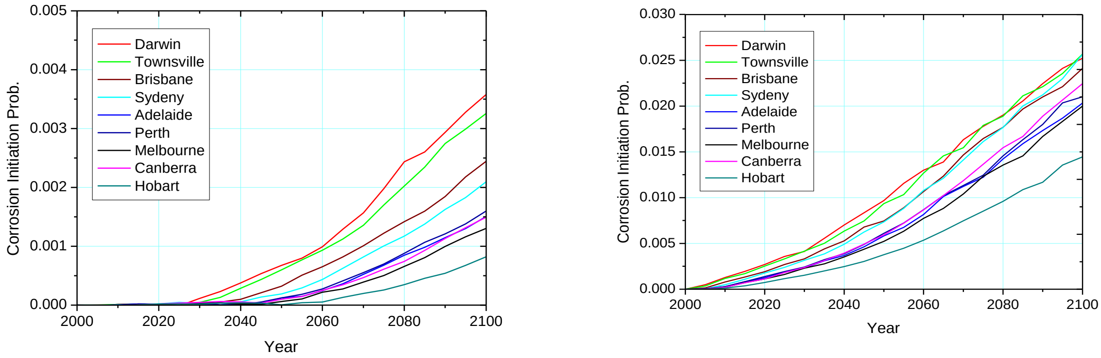
(c) Carbonation induced damage at exposure A1

(d) Carbonation induced damage at exposure A2

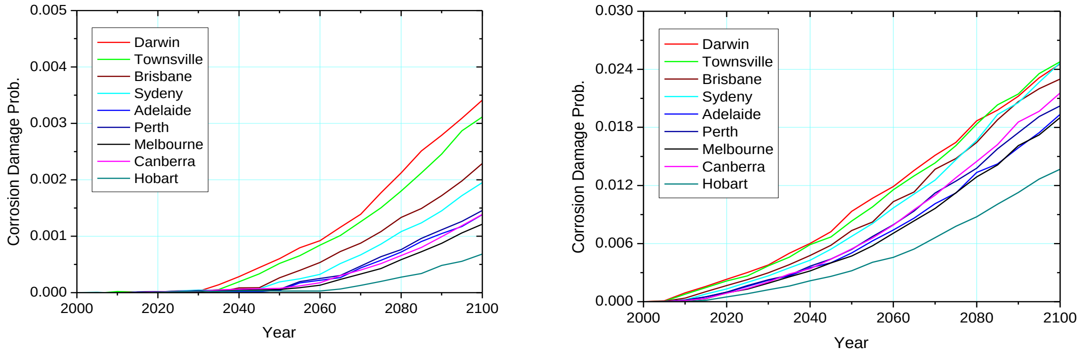
Figure 4-6 Increase in probability of carbonation induced corrosion initiation and damage of concrete structures under exposure A1 and A2 for A1FI emission scenario (The probability is represented by decimal numbers)

Table 4-3 indicated the years for concrete structures constructed in 2000 to have a first noticeable impact of climate change on carbonation induced corrosion initiation and damage when an increase in probability of corrosion initiation or damage exceeds a specific threshold and the climate change impact becomes noticeable. For example, the impact on corrosion initiation becomes first noticeable after 5 years for exposure A1 and 15 years for exposure A2 in Darwin, and 20 years for exposure A1 and 35 years for exposure A2 in Hobart.

In general, when carbonation-induced corrosion initiation has to be considered in the design of concrete structures, the effect of climate change impacts should at least be considered for structures at exposure A1 and A2. The effect should also be considered for structures at exposure B1 that are designed for a service life of more than 60 years, especially in regions with a warm or tropical climate. When carbonation-induced corrosion damage has to be taken into account in design, the effect of climate change impact should not be neglected for structures designed for more than 35 years for exposure A1 and 25 years for exposure A2. (Part 2: 6.1.3)



(a) Chloride induced initiation at exposure C1 (b) Chloride induced initiation at exposure C2



(c) Chloride induced damage at exposure C1 (d) Chloride induced damage at exposure C2

Figure 4-7 Increase in probability of chloride induced corrosion initiation and damage of concrete structures under exposure C1 and C2 for A1FI emission scenario (The probability is represented by decimal numbers)

Table 4-3 The minimum years for structures constructed in 2000 when the change in probability of carbonation-induced corrosion initiation and damage due to climate change is greater than 0.01 (1 percentage points)

Exposure		DAR	TOW	BRN	SYD	ADE	PER	MEL	CAN	HOB
A1	initiation	5	5	10	10	15	15	15	15	20
A2		15	20	25	30	30	30	35	35	35
A1	damage	35	40	45	55	60	60	65	65	75
A2		25	30	35	40	45	45	50	50	55

Similar to Table 4-3, Table 4-4 shows for concrete structures constructed in 2000 how many years until the first noticeable impact of climate change on chloride penetration induced corrosion initiation and damage. As indicated in the table, for chloride-induced corrosion initiation and damage, climate change impacts should be considered for concrete structures designed for a service life of more than 50 years for exposure C2, and not be considered for structures of designed service life less than 100 years for exposure C1. In general, the effect of climate change should be considered for the design of concrete structures for high environmental exposures, especially for those classified as C2. (Part 2: 6.2.2, 6.2.4)

Table 4-4 The minimum years for structures constructed in 2000 when the change in probability of chloride-induced corrosion initiation and damage due to climate change is greater than 0.01 (1 percentage points)

Exposure		DAR	TOW	BRN	SYD	ADE	PER	MEL	CAN	HOB
C1	initiation	>100	>100	>100	>100	>100	>100	>100	>100	>100
C2		50	50	60	55	60	60	65	60	80
C1	damage	>100	>100	>100	>100	>100	>100	>100	>100	>100
C2		50	55	65	60	65	65	70	65	80

4.4 Climate Adaptation Options for Concrete Structures

Simulations indicate that climate change may have a sizeable impact on the deterioration of concrete structures and consequently their durability. In many instances the magnitude of change in risk is such that it should not be ignored. Responses to this change in risk will depend not only on the perception of that risk but on the efficacy and cost of design, repair, maintenance or adaptation measures. For new structures new technologies and materials can be developed to counter the impact of corrosion risk. For existing structures, there is a wide range of options that can enhance the durability of concrete structures, and these can be applied to reduce the impact of climate change.

In addition to reducing environmental exposure as much as possible, design solutions may come from increasing cover and strength grade, or from any approaches that reduce the material diffusion coefficient without compromising the reliability and serviceability of the concrete. For existing structures the options may include surface coating barriers, extraction, and protection (e.g. cathodic protection for chloride induced corrosion) which will be discussed later.

Climate adaptations for concrete structures should be designed at least to maintain the probability of corrosion initiation, probability of corrosion damage and mean rebar loss of concrete structures for specific exposures under changing climate, which is no more than those without the influence of climate change. They are defined here adaptation criterion 1, 2 and 3, respectively, specifically for concrete structure design and its maintenance design considering the impact of climate change. On the basis of the criteria, adaptation options can be selected, as shown in Figure 4-8.

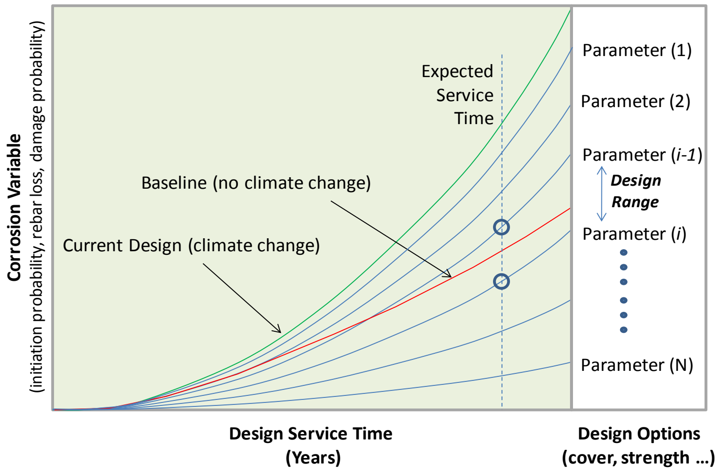


Figure 4-8. Selection of design options for climate adaptation

Increase in the thickness of concrete covering can increase the time of carbonation and chloride ingress to reach concrete reinforcement and in turn delay carbonation- and chloride-induced corrosion. This is one of the most straightforward adaptation options in the design of concrete infrastructure to maintain structural durability and serviceability under climate change.

For exposures A1, A2 and B1 the current cover design requirement is a minimum of 20mm, 30mm and 40mm respectively. Considering adaptation criterion 1 for carbonation induced corrosion, as shown in Table 4-5, the cover is required to increase up to 10mm for exposure A1 and A2, and 8mm for exposure B1 to counteract the impact of climate change on carbonation-induced corrosion. This is an increase in cover up to 50% for exposure A1, 30% for exposure A2 and 20% for exposure B1.

Concrete structures in warm regions require a greater increase in cover than in cold regions. For example, concrete structures in Darwin designed for a service life to 2100 in exposure A1 require a 10mm increase in cover to counter the impact of climate change whereas structures in Hobart require an 8mm increase in cover. Reduced greenhouse emissions may lower the cover increase required and urban effects may increase the cover increase required. (Part 2: 7.1.1)

Ignoring ocean acidification, the increase of cover required to counteract chloride-induced corrosion is within a more moderate range of up to 5mm in high environmental exposures C, C1 and C2, as shown in Table 4-6. Increase of cover in Sydney is relatively more than in other areas, which may be caused by the fact that temperature increase due to climate change is greatest here among the nine urban centres studied. Considering adaptation criterion 1, the cover for structural design life to 2100 is required to increase up to 4mm for exposures C and C1 and 5mm for C2. In comparison with the current cover requirement of 50mm for exposures C and C1 and 65mm for exposure C2, this is about an 8% increase for all exposures. Greenhouse emission reduction may also reduce the requirement to increase cover. (Part 2: 7.1.2)

Table 4-5 The minimum cover increase (mm) required to counteract the impact of climate change (A1FI emission scenario) on carbonation-induced corrosion on the basis of criterion 1

Exposure		DAR	TOW	BRN	SYD	ADE	PER	MEL	CAN	HOB
A1	2040	2.6	2.6	2.7	3.0	3.0	3.0	3.3	3.5	3.6
	2070	5.7	5.6	5.5	5.5	5.3	5.4	5.4	5.6	5.4
	2100	10.0	9.8	9.2	9.0	8.6	8.7	8.6	8.8	8.2
A2	2040	2.1	2.2	2.2	2.3	2.2	2.2	2.4	2.6	2.6
	2070	5.1	5.0	4.7	4.7	4.5	4.5	4.5	4.6	4.4
	2100	9.3	9.0	8.4	8.1	7.6	7.7	7.5	7.7	7.1
B1	2040	2.0	2.2	2.7	3.2	3.7	3.8	3.9	3.9	4.8
	2070	4.0	3.9	3.9	4.0	4.1	4.1	4.5	4.7	4.8
	2100	7.3	7.1	6.6	6.5	6.2	6.2	6.2	6.4	6.0

Table 4-6 The minimum cover increase (mm) to be required to counteract the impact of climate change (A1FI emission scenario) on chloride-induced corrosion initiation on the basis of criterion 1

Exposure		DAR	TOW	BRN	SYD	ADE	PER	MEL	CAN	HOB
C	2040	0.8	0.8	0.8	0.9	0.7	0.7	0.7	0.9	0.6
	2070	1.9	1.8	1.9	2.0	1.6	1.7	1.7	2.0	1.3
	2100	3	3.0	2.9	3.2	2.7	2.9	2.8	3.1	2.2
C1	2040	0.7	0.6	0.6	0.6	0.4	0.5	0.4	0.6	0.2
	2070	1.5	1.6	1.6	1.5	1.3	1.3	1.3	1.5	0.9
	2100	2.8	2.7	2.5	3.0	2.3	2.6	2.3	2.8	1.6
C2	2040	1.3	1.2	1.2	1.3	1.1	1.2	1.1	1.3	0.9
	2070	2.4	2.4	2.3	2.5	2.1	2.4	2.3	2.6	1.9
	2100	3.7	3.8	3.6	4.0	3.3	3.6	3.4	4.2	2.8

In addition to the option of increasing cover, a reduction of the diffusion coefficient is another effective way to increase the time of carbonation or chloride penetration to reach concrete reinforcement. Considering the adaptation criterion 1, the reduction of carbon dioxide diffusion coefficient to mitigate climate change impact on carbonation-induced corrosion is at least 15% for a design service life of concrete structures up to 2040. The reduction is 30% and 45% for a design service life up to 2070 and 2100, respectively. For chloride penetration, the diffusion coefficient has to be reduced at least

5-8% for structure designed to service by 2100 for exposure C1, and 5-7% for exposure C2. (Part 2: 7.2.1, 7.2.2)

In practice, selecting a high strength grade of concrete may reduce the diffusion coefficient and therefore enhance the adaptive capacity of concrete structures to counteract climate change impacts. For example, using the strength grade of concrete designed for exposure B1 will reduce carbonation-induced corrosion initiation of concrete structures at exposure A1 and A2 from 21% to 8.7% by 2040, from 45% to 24% by 2070, and from 71% to 44% by 2100. Considering adaptation criterion 1, as shown in Table 4-7, it is generally considered enough to use the strength grade for exposure B2 for concrete structures actually in exposures A1, A2 and B1 exposures. (Part 2: 7.2.1)

To counteract the impact of changing climate on chloride-induced corrosion, a strength grade for exposure B2 should be selected for concrete structures designed for exposure B1, and a strength grade of C should be applied for concrete structures designed for exposure B2. For concrete structures at exposure C an even higher strength grade is required. (Part 2: 7.2.2)

Finally, the preliminary simulation of the effect of surface barriers indicated that the surface coating, such as polyurethane, silane and polymer modified cementitious coating are effective to reduce the impact of climate change as long as their performance can be maintained over the period similar to the designed structural service life. This will be discussed again in the adaption options for existing concrete structures.

Table 4-7 Exposure indicator for the minimum strength grade required to counteract the impact of climate change (A1FI emission scenario) on carbonation-induced corrosion initiation on the basis of criterion 1

Exposure		A1FI	A1B	550 ppm
	2040	B1	B1	B1
A1	2070	B1	B1	B1
	2100	B2	B1	B1
	2040	B1	B1	B1
A2	2070	B1	B1	B1
	2100	B2	B1	B1
	2040	B2	B2	B2
B1	2070	B2	B2	B2
	2100	B2	B2	B2
	2040	>C	>C	>C
B2	2070	>C	>C	>C
	2100	>C	>C	>C

Adaptation measures to reduce deterioration (source: CSIRO and RTA)

5. CLIMATE CHANGE IMPACT ON DETERIORATION OF EXISTING CONCRETE STRUCTURES AND ADAPTATIONS

Many existing concrete structures that were not designed with a changing climate in mind are likely to experience decreased durability as a consequence of climate change. As this risk varies widely with location, a history of environmental exposure and material design it is difficult to predict this risk for every individual structure. Therefore it is advisable to use a precautionary approach that increased monitoring and maintaining of concrete structures. The costs and effectiveness of such an approach, which also vary widely by location, will be critical for efficient practical implementation.

In general, the selection of maintenance options for adaptation is based on the cost and the effectiveness, an adaptation effectiveness diagram, such as shown in Figure 5-1. In the diagram, each bar represents an adaptation option

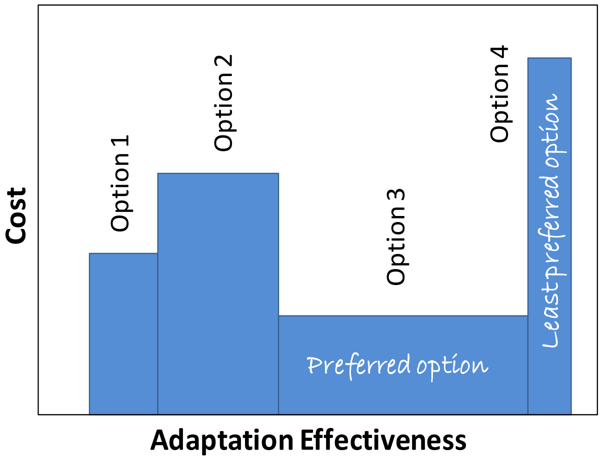


Figure 5-1 Conceptual illustration of adaptation effectiveness diagram

with its width representing adaptation effectiveness and height representing cost. The optimal option is low cost and great effectiveness. It can be established to inform decision-makers to select proper adaptation options.

The benefit due to the implementation of adaptation options in changing climate is defined by the reduction of risks of corrosion, that is:

Benefit = Risk (before adaptation) – Risk (after adaptation)

The benefit can be rewritten as:

Benefit = Benefit1 + Benefit2 – Loss

where ’Benefit1’ represents the benefit contributed by an adaptation option to mitigate the risk of corrosion completely due to climate change, ’Benefit2’ gives the benefit to increase corrosion resistance or adaptive capacity by the maintenance in the absence of climate change (the maintenance option is the same as adaptation option, applied to mitigate corrosion risk as usual but nothing to do with climate change), and ’Loss’ describes the loss of the benefit due to the reduced effectiveness of the adaptation option as a result of climate change. In another word, the cost is to offset the loss of effectiveness of adaptation options due to climate change. (Part3: 5.2)

The benefit also represents the degree of the reduction of corrosion risk when an adaptation option is applied, and can thus be considered as the representation of adaptation effectiveness. An option is not recommend when ‘Benefit≤0’. The maximum benefit or adaptation effectiveness can be achieved when the risk approaches zero after an adaptation option implemented.

Similar to the previous assessment, the assessment of climate change impact on existing concrete structures and cost/efficacy of adaptation option is carried out by Monte-Carlo simulation. More than the previous assessment, modelling and simulation of existing concrete structures are calibrated through field testing. Meanwhile, modelling of adaptation measures for concrete, in many cases, is directly implemented by estimating the correction factors that influence carbonation depth, diffusion coefficient, chloride concentration, critical chloride concentration or corrosion rate. (Part 3: 2)

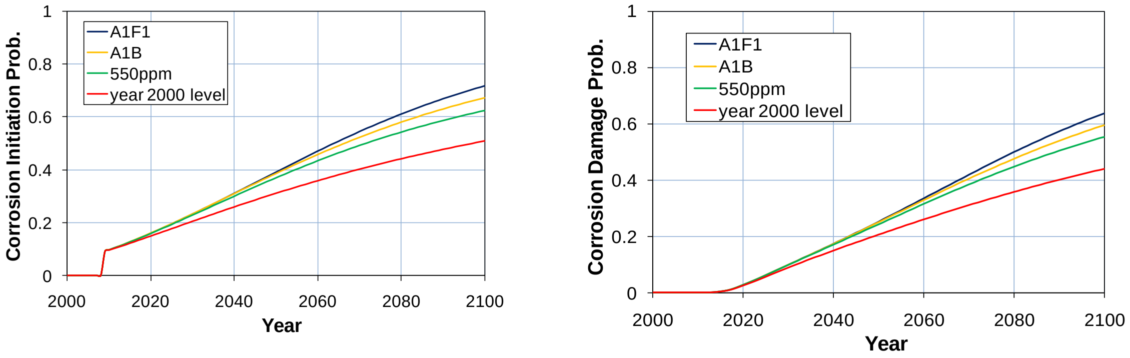
5.1 Impact of Climate Change on Existing Bridges and Port Structures

Eleven existing bridges located within temperate climate zones in NSW are investigated as case studies of climate change impacts on carbonation and chloride-induced corrosion. The bridges represent different construction periods at different regions including pre-1959, 1959-1970, 1971-1994, and post-1995. The profiles of carbonation and chloride concentration were tested in 2008 at various locations of the bridges including more than one metre above the water level or spray zones (C1) and less than one metre above the water level or splash or tidal zones (C2). Port structures in a typical tropical climate zone were also field tested in the same way. The structures tested were concrete slab soffits and columns from a berth that is managed by Port of Townsville Limited.

Results of field testing found that although all investigated structures are under exposure C2, the concrete cover does not necessarily meet the current standard (AS 3600-2009) which requires 65mm. In fact, the cover of a few bridges in this case study is less than 65mm. This emphasises how important it is to specifically assess the durability of existing bridges, especially when considering how climate change will affect concrete durability through carbonation- and chloride-induced corrosion.

Due to improper concrete cover of some of the older bridges, climate change may lead to a considerable impact on carbonation-induced corrosion. For example, the bridge constructed in 1925 in Sydney, as shown in Figure 5-2, has a tested structure with only a 29mm concrete cover. As shown in Figure 5-3, the probability or likelihood of corrosion initiation is up to 72 percentage points under one future climate scenario, in comparison with 51 percentage points estimated in the absence of climate change. Meanwhile, the probability of corrosion damage is 63 percentage points in comparison with 44 percentage points estimated in the absence of climate change, implying a significant increase due to climate change.(Part 3: 3.2)

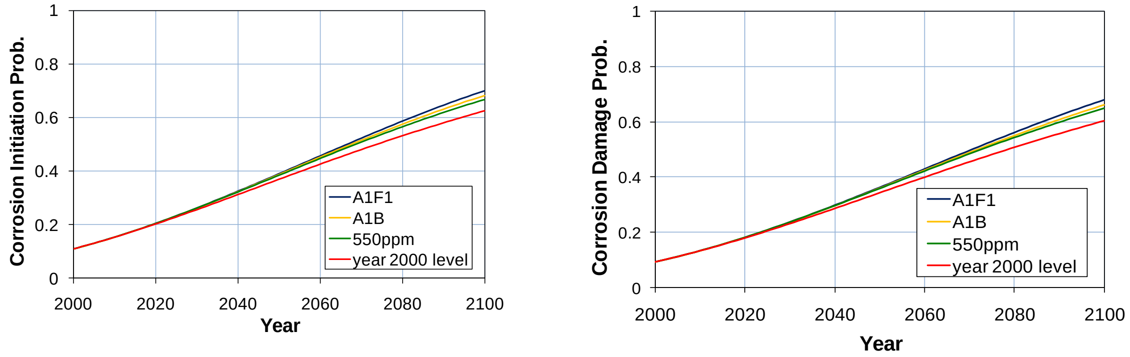
Figure 5-2 Bridge BB1 constructed in 1925 and 1959, in Sydney (Source: RTA)



(a) Corrosion initiation probability (b) Corrosion damage probability

Figure 5-3 Probability or likelihood of carbonation-induced corrosion initiation and damage and mean rebar loss of concrete structures of Bridge BB1 (1925) in a temperate climate zone, with the effect of climate change in comparison with the baseline in the absence of climate change. The 'year 2000 level' is the relevant value in the absence of climate change (The probability is represented by decimal numbers).

As discussed before, the effect of climate change on chloride-induced corrosion of concrete structures which design follows AS3600 and AS5100.5 is less than an increase of 3.5 percentage points in probability by 2100. In practice, the change of the probability can be higher due to non-binding on the standards or lack of quality assurance in construction, for example, use of lower concrete cover. The bridges in Sydney, constructed in 1925 with 29mm cover, show that the climate change can lead to an increase up to 8 percentage points in corrosion initiation and damage probability by 2100, which is equivalent to 13% increase in percentage, as shown in Figure 5-4. Even for a modern bridge in the northern region of NSW, constructed in 1984, the structure on the bridge at exposure C1 and C2 may experience an increase of up to 5-7 percentage points in probability by 2100. (Part 3: 3.1)



(a) Corrosion initiation probability (b) Corrosion damage probability

Figure 5-4 The probability of chloride-induced corrosion initiation and damage of Bridge BB1 (1925) in a temperate climate zone, with the effect of climate change in comparison with the baseline in the absence of climate change. The 'year 2000 level' is the relevant value in the absence of climate change (The probability is represented by decimal numbers).

The tests for carbonation of port structures including columns and slab soffits, as shown in Figure 5-5, in Townsville were done at 37 locations for the concrete slab soffit of the berth in 2008. The slab has a cover of 50mm. The test of core sample from the slab shows carbonation depth in the range of 22mm to 55mm in 2008. On the basis of the test, it is very unlikely that there would be any occurrence of carbonation-induced corrosion initiation and damage by 2008.

As shown in Figure 5-6, by 2100, the probability of carbonation-induced corrosion initiation is projected to reach 91 percentage points for A1FI emission scenario, 89 percentage points for A1B emission scenario, and 86 percentage points for 550 ppm stabilisation emission scenario in comparison with 76 percentage points in the absence of climate change. In the term of percentage change, the climate change leads to an increase of 20%, 17% and 13%, respectively. In fact, climate change leads to the largest impact on the probability of corrosion initiation around 2080, when there is an increase of 31% in the term of percentage change (Part 3: 4.2).

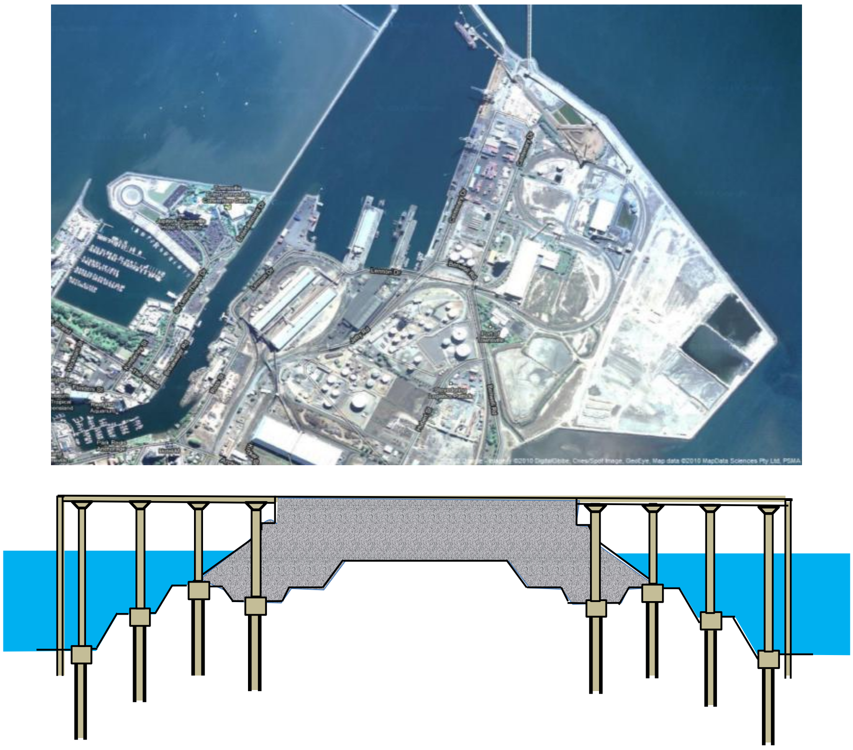
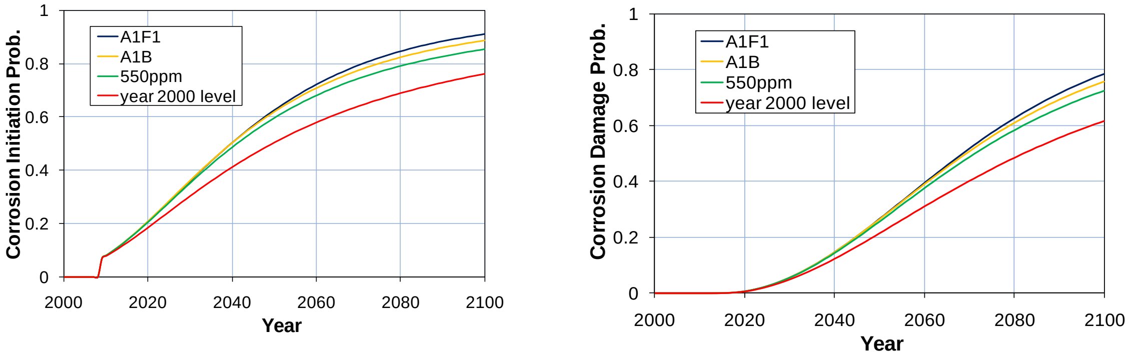


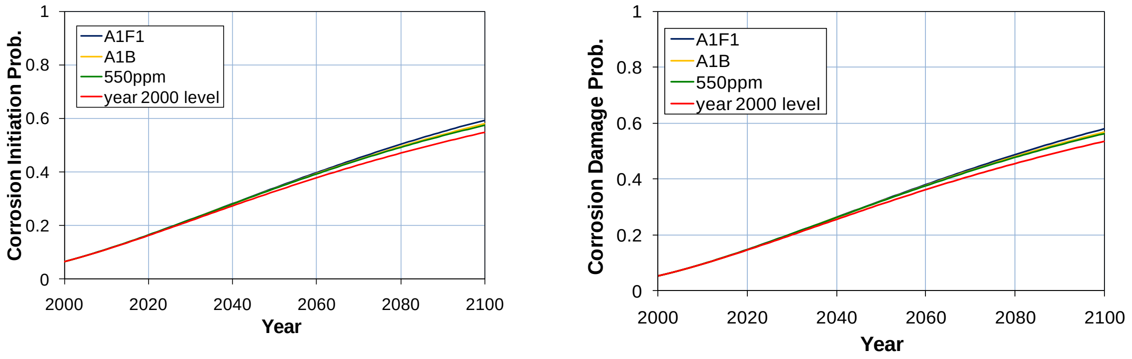
Figure 5-5 View of Port Townsville and its berths by Google Map and Concrete slabs/columns of the berth

As shown in Figure 5-7, the probability of corrosion initiation is projected to reach 59 percentage points by 2100 for A1FI emission scenario, 58 percentage points for A1B emission scenario and 57 percentage points for 550ppm stabilisation emission scenario in comparison with 55 percentage points in the absence of climate change. The probability of corrosion damage is 58 percentage points, 57 percentage points and 56 percentage points for the three emission scenarios respectively in comparison with 54 percentage points estimated without the effect of climate change. In this regard, the impact of climate change by 2100 is limited within 4 percentage points increase in probability value of corrosion initiation and damage, which is equivalent to an increase of 7.4% in terms of percentage change. (Part 3: 4.1)



(a) Corrosion initiation probability (b) Corrosion damage probability

Figure 5-6 Probability of carbonation-induced corrosion initiation and damage of concrete structures of slab soffits in a tropical climate zone, with the effect of climate change in comparison with the baseline in the absence of climate change. ‘Year 2000 level’ is the relevant value in the absence of climate change. (The probability is represented by decimal numbers)



(a) Corrosion initiation probability (b) Corrosion damage probability

Figure 5-7 Probability of chloride-induced corrosion initiation and damage of concrete structures of a slab soffit in a tropical climate zone, with the effect of climate change in comparison with the baseline in the absence of climate change. The ‘year 2000 level’ is the relevant value in the absence of climate change (The probability is represented by decimal numbers).

5.2 Adaptation Options and Their Costs/Benefits for Existing Concrete Infrastructure

Both chloride-induced and carbonation-induced corrosion show the potential experience of a sizeable impact of climate change, which should be considered for maintenance planning. Adaptation options should also be developed and optimised to alleviate the impact, and enhance the adaptive capacity, of concrete structures to changing climate.

For existing concrete structures under changing climate, adaptation can be enhanced by developing new technologies for maintenance to counter the impact of increasing corrosion risk under changing climate. On the other hand, there is a wide range of conventional maintenance and retrofitting options that can enhance the durability of concrete structures and these can be applied to reduce the adverse affects of climate change.

Creating a surface barrier by coating is more appropriate for reducing the exposure of concrete structure to external stimuli. Meanwhile, extraction and cathodic protection is more commonly used for structures with high corrosion risk to reduce the penetration of deleterious agents. The cover replacement is most effective, but also the most expensive option. This is followed by cathodic protection that also has a high operating cost and then realkanisation or chloride extraction. The surface coating is the cheapest option, but is also less effective.

Simulations of climate change adaptation options to determine their cost and effectiveness are implemented considering the worst scenario of climate change impact (i.e. A1FI) and the options to reduce corrosion damage of concrete structures. This included five options that are considered to reduce chloride-induced corrosion including electrochemical chloride extraction, polyurethane sealer, polymer-modified cementious coating, cover replacement and cathodic protection. Two options to reduce carbonation-induced corrosion including realkalisation and cover replacement are also discussed.

Cost and adaptation effectiveness were also examined to quantify the adaptation options in order to identify the best option for a specific concrete structure, such as a slab or column. The cost includes the costs of initial implementation and operating, which were all converted to their present value in 2010 with a discount rate ranging from 1% to 10% selected for sensitivity assessment. The effectiveness, also known as a ‘proxy of benefit’ due to the implementation of adaptation options, is defined as the amount of reduction in corrosion risk from business as usual after implementing adaptations. As a result, adaptation effectiveness is demonstrated by combining cost with adaptation effectiveness, which can support the decision-making for the most costs effective adaptation strategies. The study indicates that the cost contributes to three factors: 1) reducing the impact of climate change; 2) increasing adaptive capacity to resist corrosion; and 3) offsetting the loss of adaptation effectiveness due to climate change. In general, the greater the offsetting in 3) the less effective is the option.

As shown in Figure 5-8, the case study of concrete bridges indicates that the replacement of concrete cover is often thought to be the most effective option, but it is also the most expensive one. Surface coating is the least costly, but is usually, though not always, less effective. For the bridge constructed in 1925 in Sydney, cathodic protection can be the preferred adaptation response to alleviate chloride-induced corrosion damage due to its greater effectiveness and moderate cost. Among the total cost, 22% is contributed to alleviate the increase corrosion damage risk due to climate change, 78% is contributed to increase adaptive capacity to resist corrosion, and nothing is contributed to offset the loss of adaptation effectiveness due to climate change. It should be pointed out the effectiveness of cathodic protection is affected by sea level rise which may change the cost for offseting the loss of effectiveness. At the same time, the use of polyurethane sealer is the least preferred due to its very low effectiveness though low cost. For this, 46% of the total cost is contributed to offset the loss, which is not really beneficial to the enhancement of adaptive capacity to counteract corrosion damage. (Part 3: 5.3)

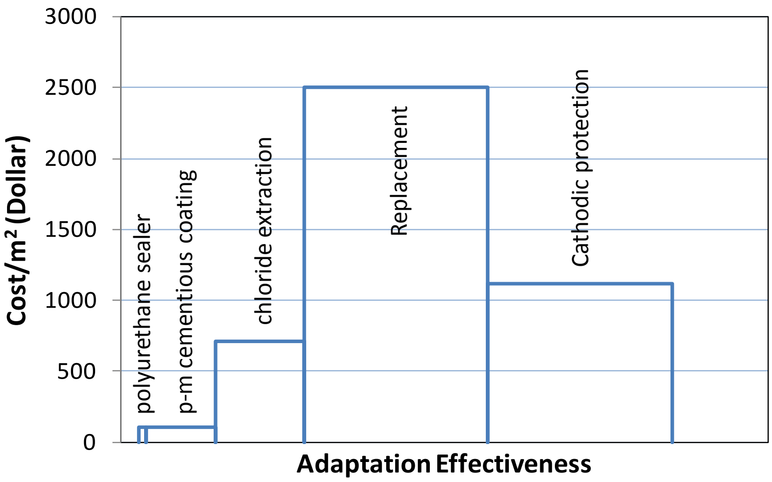


Figure 5-8 Cost and effectiveness of adaptation options for chloride-induced corrosion of concrete structures of Bridge BB1 (1925) in NSW, at a discount rate of 3%.

Depending on residual risk of corrosion damage of concrete structures after implementing adaptation options, the preferred adaptation option can vary. For a bridge constructed in 1967 in the northern region of NSW shown in Figure 5-9, polymer-modified cementious coating appears the most preferable due to its great effectiveness, with 24% of the total cost contributed to mitigate the increasing risk as a result of climate change, 57% contributed to strengthen the adaptive capacity, and only 4% contributed to offset the loss of adaptation effectiveness in comparison with 14% for polyurethane sealer and 10% for cathodic protection. The cost is much lower than the other options of cover replacement, cathodic protection and chloride extraction. (Part 3: 5.3)

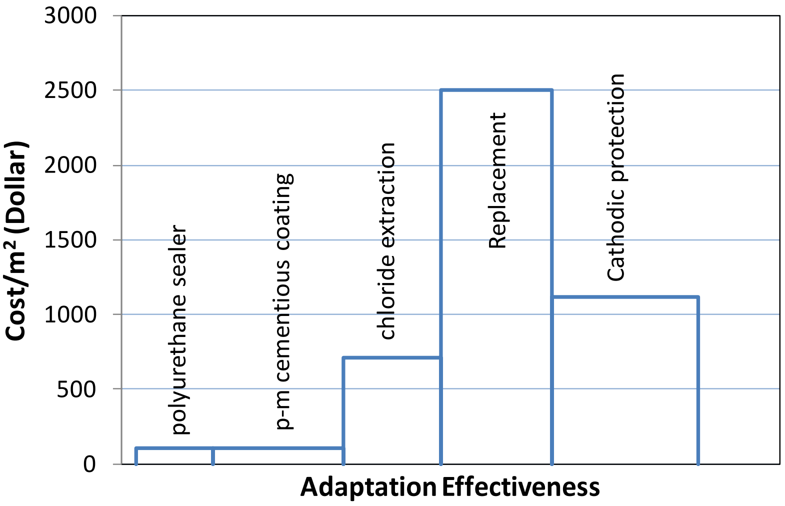


Figure 5-9 Cost and effectiveness of adaptation options for chloride-induced corrosion of concrete structures of Bridge BD2 (1967) in the northern region of NSW, at a discount rate of 3%.

A similar approach was applied for the cost/benefit assessment of adaptation options for carbonation-induced corrosion of port structures in relation to realkalisation and cover replacement (Part 3: 5.3).

Gold Coast, Queensland
Source: CSIRO

6. CONCLUSIONS AND DISCUSSION

In summary this study shows that climate change impact assessment of the aspects of design that follow the Australian standards may provide general rules for concrete structural design taking into account effects of changing climate. However, impacts on existing concrete infrastructure and appropriate adaptation are specific. This is due to the uniqueness of individual structures, especially regarding their different local environment exposure history, as well as the uncertainties in construction and maintenance. Therefore, an effective adaptation option should be developed at the level of individual existing concrete structures. Finally, cost and benefit assessment should also be developed to consider the lifecycle of concrete infrastructure.

It should be noted that although uncertainties in climate variability, concrete material properties, dimensions and model errors have been simulated to the best of our knowledge, the construction and maintenance process may complicate the uncertainties. Meanwhile, uncertainties in environmental exposure for concrete structures may change the deterioration process. Even for the same structural component, those at different locations with a different facing orientation may also experience different degrees of deterioration. This is why it is important that an effective adaptation options need to be considered for individual structures. However, the expected change in design provided in the study provides guidance on how a new design should be developed in response to climate change.

Meanwhile, the models and simulations in the study were carried out on the basis of assumption of concrete with ordinary Portland cement. While the same approach can be applied to assess climate change impacts and adaptation options for other types of cements, especially considering the use of different cement-type materials, the projected deterioration and adaptation effectiveness may be different. This should be further investigated through simulation. In practice, this should be carefully addressed.

Nevertheless, the simulation analyses described have indicated that climate change may have a sizeable impact on the deterioration of concrete structures and consequently their durability. In many instances the magnitude of change in risk is such that it should not be ignored in design and also for medium to long-term maintenance strategies. Design and maintenance standards of concrete structures should consider addressing the issue, especially for critical infrastructure. Potential impacts of climate change and adaptation options to respond to the impacts should also be taken into account in the planning of concrete structures such as bridges and port infrastructures which are crucial to national and local economy as well as communities.

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