Climatic Change (2012) 110:941–957
DOI 10.1007/s10584-011-0124-7

Impact of climate change on corrosion and damage to concrete infrastructure in Australia

Xiaoming Wang · Mark G. Stewart · Minh Nguyen

Received: 4 November 2010 / Accepted: 18 May 2011

Abstract The durability of concrete is determined largely by its deterioration over time which is affected by the environment. Climate change may alter this environment, causing an acceleration of deterioration processes that will affect the safety and serviceability of concrete infrastructure in Australia, U.S., Europe, China and elsewhere. This investigation of concrete deterioration under changing climate in Australia uses Monte-Carlo simulation of results from General Circulation Models (GCMs) and considers high greenhouse gas emission scenarios representing the A1FI schemes of the IPCC. We present the implications of climate change for the durability of concrete structures, in terms of changes in probability of reinforcement corrosion initiation and corrosion induced damage at a given calendar year between 2000 and 2100 across Australia. Since the main driver to increased concrete deterioration is CO_2 concentration and temperature, then increases in damage risks observed in Australia are likely to be observed in other concrete infrastructure internationally. The impact of climate change on the deterioration cannot be ignored, but can be addressed by new approaches in design. Existing concrete structures, for which design has not considered the effects of changing climate may deteriorate more rapidly than originally planned.

X. Wang (✉) · M. Nguyen
CSIRO Climate Adaptation Flagship, Commonwealth Scientific
and Industrial Research Organisation (CSIRO), P O Box 56,
Graham Rd, Highett, Victoria 3190, Australia
e-mail: Xiaoming.Wang@csiro.au

M. G. Stewart (✉)
Centre of Infrastructure Performance and Reliability,
The University of Newcastle, Newcastle, New South Wales 2308, Australia
e-mail: Mark.Stewart@newcastle.edu.au

1 Introduction

Concrete is the predominant construction material used in building, bridges, power plants, wharves, and other infrastructure in Australia, U.S., Europe, China and elsewhere. Over $1.1 trillion of Australia's wealth is locked up in homes, commercial buildings, ports and other physical infrastructure assets, which is equivalent to nine times the current national budget or twice the GDP of Australia. In the U.S. there are over five million commercial buildings, 600,000 highway bridges, over 400 large airports, etc. The global construction industry is estimated to be worth $7.5 trillion annually (GCP 2010). Infrastructure performance, therefore, is vital to provide the nation's essential services and maintain its economic activities. However, infrastructure often deteriorates with age, and the annual cost of corrosion worldwide is estimated to exceed $1.8 trillion, which translates to 3% to 4% of the Gross Domestic Product (GDP) of industrialized countries (Schmitt 2009). These figures reflect only the direct cost of corrosion—essentially materials, equipment, and services involved with repair, maintenance, and replacement. It does not include the environmental damage, waste of resources, loss of production, or personal injury resulting from corrosion.

The key performance requirements for the design, construction and maintenance of concrete structures relate to safety, serviceability, and durability, which are all affected by 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 profoundly alter this environment, especially in a longer term, causing a change in deterioration processes and consequently changes in safety, serviceability and durability of concrete infrastructure. Since the direct and indirect costs of corrosion are immense, a climate-change induced acceleration of the corrosion process by only a few percent can result in increased maintenance and repair costs of hundreds of billions of dollars annually.

Climate change is defined as a change in the state of the climate that persists for an extended period, typically decades or centuries. There is widespread concern that climate change is taking place today as a result of anthropogenic effects, especially related to greenhouse gas emissions. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2007) indicated a significant increase in the concentration of carbon dioxide (CO_2) in the atmosphere, from 280 parts per million (ppm) in 1750 to 380 ppm in 2005, with an accelerating trend. The best estimate of the increase in the global temperature above pre-industrial levels that would be caused by elevated concentrations of greenhouse gases in the atmosphere is 2.1°C at 450 ppm CO_2-equivalent, 2.9°C at 550 ppm, 3.6°C at 650 ppm 4.3°C at 750 ppm, and 5.5°C at 1000 ppm (IPCC 2007).

The observed trend in mean global temperature increase, summarised in the IPCC report, was an increase from 0.045°C per decade in the past 150 years to 0.074°C per decade in the past 100 years, 0.128°C per decade in the past 50 years, and 0.177°C per decade in the past 25 years. The global mean sea level has followed a similar trend as a result of thermal expansion and the exchange of water between oceans and other reservoirs such as glaciers and ice caps. The average rate of sea level rise increased from 1.7 ± 0.5 mm/year for the twentieth century to 1.8 ± 0.5 mm/year between 1993 and 2003. Under A1B, a moderate emissions scenario, the global mean sea level is projected to rise by 0.22 to 0.44 m above 1990 levels by the mid 2090s, an average of 4 mm/year. It is a cause for concern that recent observational data suggest that this projection may be an underestimate (Rahmstorf et al. 2007).

The IPCC has also suggested that, by 2030, extreme weather events become more likely to be exceeded more frequently; this was also one of the conclusions of a CSIRO report on climate change in Australia (CSIRO 2007). It has been observed that, since the 1970s, the number of heatwaves has increased, heavy daily precipitation events that lead to flooding have become more frequent in some areas, and the intensity and duration of tropical storms and hurricanes have increased. The predicted increase in the incidence and severity of extreme weather events may have a considerable effect on the loading actions that should also be considered in concrete structural design (Wang and Wang 2009a, b). Thus, a combination of increased loadings in the future, and increased deterioration and loss of capacity, will result in an increase in the vulnerability of infrastructure. This will not be explored further in this paper, which concentrates on the implications of climate change for concrete deterioration.

Technically speaking, the deterioration of concrete structures can be affected directly or indirectly by climate change that is linked to the change in carbon dioxide (CO_2) concentration, temperature and relative humidity, as shown in Table 1. The climate-related deterioration of concrete structures is mostly caused by the infiltration of deleterious substances from the environment, such as carbon dioxide and chloride, which causes reinforcement corrosion. An increase in temperature will increase the rate of infiltration of deleterious substances (increased material diffusivity) and increase the corrosion rate of steel. For example, we will see later in the paper that corrosion rates will increase by up to 15% if temperature increases by 2°C. Since the main environmental driver to increased concrete deterioration is CO_2 concentration, temperature and humidity, then this will affect all concrete infrastructure globally, not just Australia. While the present study focuses on concrete infrastructure, changes in temperature and relative humidity will also affect the corrosion of steel structures, but these effects are beyond the scope of the present paper.

Table 1 Consequences of climate change for concrete structures

Climate change	Implications
Increase of carbon concentration	Elevated carbon concentration accelerates carbonation and increases carbonation depth in concrete, which 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 corrosion initiation and structural damage
Change of humidity	Lowered relative humidity may reduce or even stop carbonation and chloride penetration in areas with yearly average RH currently above 40–50%, while increased humidity may allow carbonation and chloride penetration in regions where they are now negligible

The long service life (30–200 years or more) of buildings and infrastructure suggests that their design, maintenance and replacement 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 relied on by human settlements and the economy. Probabilistic methods utilising event-based Monte Carlo simulation can assist with this decision making, as it helps to assess impacts even when there are extensive uncertainties of future climate (e.g., Stewart and Peng 2010). Its use may inform us about the extent to which change in design and maintenance is required to maintain the current level of safety, serviceability and durability for any of the many existing climate change scenarios. However, while there is much research on concrete deterioration, there has been very little research on the effect of a changing climate on concrete deterioration. Stewart et al. (2002) found that the ambient CO_2 concentration attributable to a typical urban environment is approximately 5–10% higher than CO_2 concentrations in a rural environment. Carbonation depths were then calculated for Reinforced Concrete (RC) structures assuming a climate change prediction of up to 450 ppm for service lives of up to 100 years (Stewart et al. 2002). The probabilistic analysis showed that variability in carbonation depths can be high due to uncertainty and variability of environmental and material properties. Peng and Stewart (2008) used a simplified deterioration model and the latest CO_2 concentration data to predict the likelihood and extent of carbonation-induced corrosion and cover cracking and safety loss to RC and prestressed concrete beams in flexure and shear. Stewart and Peng (2010) then conducted a life-cycle cost assessment to assess the cost-effectiveness of increasing design cover as an adaptation measure to mitigate the effects of carbonation of concrete. The effect of climate change on chloride-induced corrosion appears to have also been the subject of relatively little research, however, Bastidas-Arteaga et al. (2010) have calculated 5–15% increases in probability of corrosion initiation due to climate change.

The present paper describes a probabilistic and reliability-based approach that predicts the probability of corrosion initiation and damage (severe cracking) for concrete infrastructure subjected to carbonation and chloride-induced corrosion resulting from elevated CO_2 levels and temperatures across Australia. This study seeks to provide insights into the likely impacts of climate change on the durability and damage risks of concrete structures in Australia, under a range of climate change scenarios, which will have similar implications for other countries.

2 Simulations and probabilistic modelling

The simulation of carbonation and chloride penetration induced corrosion of concrete was implemented using a conventional probabilistic approach to Monte-Carlo simulation, as demonstrated in Fig. 1. This considers probabilistic modelling of material property, dimensional, model error and environmental variables and their uncertainties, including concentration of carbon dioxide, yearly mean temperature and relative humidity. A computer program named CIRCAA-RC (Climate Impact Risks for Corrosion Adaptation Assessment-Reinforced Concrete) was developed to calculate the climate impact risks for above ground OPC (Ordinary Portland Cement) concrete infrastructure, but it can be extended for other types of concrete.

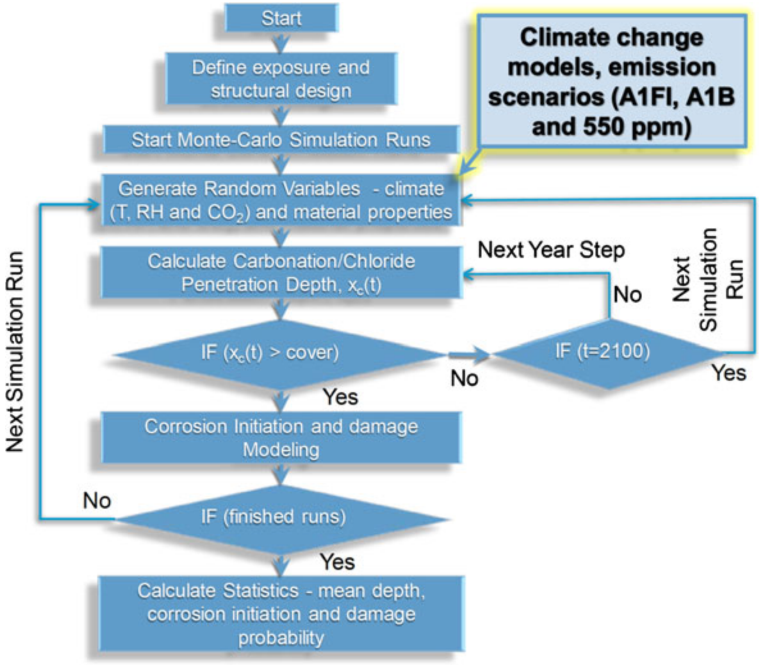


Fig. 1 Flowchart of simulation of concrete deterioration under climate change

For more details of the simulation modelling see Stewart et al. (2011) and Wang et al. (2010).

The simulation runs on a yearly increment, and relates several models that consider carbonation and chloride penetration depth, corrosion initiation and damage. The results provide the distributions of penetration depth and their means, as well as the probability of corrosion initiation and damage. As shown in Fig. 1, a major difference from a general concrete deterioration simulation is the consideration of future climate variability projected by climate models or Atmosphere-Ocean General Circulation Models (AOGCMs) given carbon emission scenarios. These are used to model the stochastic characterisation of CO_2 concentration, temperature and relative humidity predictions that are fed into the simulation. Stochastic modelling of climate change variables, as well as differing carbon emission scenarios, bring more complexity to the simulation process.

2.1 Emission scenarios and climate modelling

Future climate was projected by defining carbon emission scenarios in relation to changes in population, economy, technology, energy, land use and agriculture - a total of four scenario families, i.e., A1, A2, B1 and B2 are defined (IPCC 2000). The 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. 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, scenarios of CO_2 stabilisation at 450 and 550 ppm by 2150 were also introduced to consider the effect of policy intervention (Wigley et al. 1996). Recently, new scenarios are being developed to explore the potential consequences of different mitigation and adaptation options as well as land use and land cover change (Moss et al. 2010). While our entire investigation will cover A1FI, A1B and 550 ppm stabilisation scenarios representing high, medium emission scenarios and policy intervention scenarios (Wang et al. 2010), respectively, this paper will present only the results based on the A1FI emission scenario. More details can be found in IPCC's special report on emission scenarios (IPCC 2000).

To project spatially dependent future climates under different emission scenarios, various climate models have been developed based on physical principles at the continental scale or AOGCMs. Selecting the AOGCM 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, it is necessary to use multiple models to take into account the uncertainties of models in any impact assessment. In our on-going investigation, climate projections from nine climate models were used upon data availability. The models provide nine sets of time series about future climate projection including temperature and relative humidity, which are applied for both carbonation and chloride penetration induced corrosion. However, only one model (CSIRO Mk3.5) will be applied in this study to reduce computation intensity, but without a loss of a general trend to demonstrate the impact of climate change on concrete deterioration.

2.2 Corrosion damage modelling

Corrosion of steel reinforcement can occur by (1) carbonation of the concrete cover, or (2) when chloride concentration at the level of the steel reinforcement exceeds a critical level. In both cases, expansive corrosion products place tensile stresses on the concrete which causes cover cracking and eventually spalling and loss of structural capacity. This type of corrosion damage is disruptive to society and costly to repair.

Most existing concrete deterioration models assume a static (non-changing) environment; however, Saetta et al. (1993), Ababneh et al. (2003) and Bastidas-Arteaga et al. (2010, 2011) have modelled the time-varying effect of temperature and humidity on chloride penetration. Nonetheless, many deterioration models need to be modified to account for time-dependent changes in CO_2 concentration, temperature and relative humidity. These are now described (for more details see Stewart et al. 2011).

2.2.1 Carbonation penetration depth models

The carbonation depth model is based on the model proposed by Yoon et al. (2007) and DuraCrete (1998) and corrected for time-dependent $CO_2(t)$ and temperature $f_T(t)$. It is described by:

$$x_c\left(t'\right) \approx \sqrt{\frac{2f_T\left(t'\right) D_{CO_2}\left(t'-1999\right)}{a} k_{urban} \int_{2000}^{t'} C_{CO_2}\left(t'\right)dt' \left(\frac{1}{t'-1999}\right)^{n_m}} \qquad (1)$$

where

$$D_{CO_2}(t) = D_1 t^{-n_d} \quad a = 0.75 C_e C_a O \alpha_H \frac{M_{CO_2}}{M_{CaO}}$$

$$f_T(t') \approx e^{\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273+T_{av}(t')}\right)} \quad T_{av}(t') = \frac{\sum_{t'_0=2000}^{t'} T(t')}{t'-1999}$$

t is the number of years; t′ is the calendar year starting from 2000, $C_{CO2}(t)$ is the time-dependent mass concentration of ambient CO_2 (10^{-3} kg/m^3); $D_{CO2}(t)$ is CO_2 diffusion coefficient in concrete; D_1 is CO_2 diffusion coefficient after 1 year; n_d is the age factor for the CO_2 diffusion coefficient; C_e is cement content (kg/m^3); C_aO is ratio of CaO content in cement; α_H is a degree of hydration; M_{CaO} is molar mass of CaO and M_{CO2} is molar mass of CO_2. The age factor for microclimatic conditions (n_m) associated with the frequency of wetting and drying cycles (assuming $n_m = 0$ for sheltered outdoor and $n_m = 0.12$ for unsheltered outdoor); $f_T(t')$ is the temperature factor of the diffusion coefficient in comparison with one at 20°C, E is the activation energy of the diffusion process in kJ/mol, and R is the gas constant.

It is understood that carbonation may occur in the range up to relative humidity (RH) RH = 40–75%, or 50–70% (Russell et al. 2001). Al-Khaiat and Fattuhi (2002) report that little or no carbonation occurs below a RH of 30%, whereas Russell et al. (2001) state that below 50% RH there is insufficient moisture for carbonation reactions to take place. Most carbonation models assume RH > 50%. To be conservative, assume that if RH(t)<40% then the carbonation front ceases to advance. Since climate projections show only a 1% increase in relative humidities (see Fig. 4d) the effect of high humidity on carbonation is not considered herein.

2.2.2 Chloride penetration depth model

The chloride penetration model is developed on the basis of the widely used diffusion equation (DuraCrete 2000). The chloride concentration, C(x,t), over depth x at time t or a calendar year t′, t′ = t+1999 is described by:

$$C(x,t) = C_o\left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{k_e \cdot k_t \cdot k_c \cdot f_T(t'-1999) \cdot D_c\left(\frac{1}{t'-1999}\right)^n \cdot (t'-1999)}}\right)\right] \tag{2}$$

where C_0 is the surface chloride concentration depending on environment exposure; D_c is the diffusion coefficient; n is the age factor; k_e is the environmental factor depending on the environment exposure of concrete; k_c and k_t are the curing factor and test method, respectively. The effect of change of relative humidity on chloride penetration is not considered herein, and since relative humidity tends to decrease due to climate change this will result in Eq. 2 slightly over-estimating chloride penetration.

2.2.3 Corrosion propagation

An increase in temperature will increase corrosion rate, and the model described by DuraCrete (2000) is used:

$$i_{corr}(t) = i_{corr-20}\left[1 + K(T(t) - 20)\right] \tag{3}$$

where $i_{corr-20}$ is the corrosion rate at 20°C (DuraCrete 1998), and $K = 0.025$ if $T(t) < 20°C$ and $K = 0.073$ if $T(t) > 20°C$. DuraCrete (2000) notes that Eq. 3 is a close correlation to Arrhenius equation, at least for temperature below 20°C, but may be conservative for $T(t) > 20°C$. Based on Eq. 3, a 2°C temperature increase will increase the corrosion rate by 15%.

2.2.4 Probability of corrosion initiation

It is assumed that the corrosion will be initiated when the carbonation depth reaches the surface of the reinforcing bar or the chloride concentration at the level of reinforcement exceeds critical chloride concentration. The cumulative probability of corrosion initiation, at time t or calendar year t′, is described by:

$$p_i\left(t'\right) = \begin{cases} \Pr\left[h - x_c\left(t'\right) < 0\right] & \text{for carbonation} \\ \Pr\left[C\left(h, t'\right) - Cr < 0\right] & \text{for chloride penetration} \end{cases} \tag{4}$$

where h is the concrete cover; $x_c(t)$ is the carbonation depth; $C(h,t)$ is the chloride concentration; and C_r is the critical chloride concentration; the time t is defined from the calendar year 1999, or $t = t' - 1999$.

2.2.5 Probability of corrosion damage

Once corrosion is initiated, reinforcement corrosion may lead to cover cracking and damage. In the present paper 'corrosion damage' is defined to occur when crack

Table 2 Statistical parameters for corrosion parameters, material properties and dimensions (adapted from Stewart et al. 2011)

Parameters	Mean	COV	Distribution
$f_c(28)$	$1.03F'_c$	0.18	Normal
CO_2 Diffusion Coefficient (D_1)	$0.47–2.22 \times 10^{-4}$ cm^2 s^{-1}	$\sigma = 0.15$	Normal
Age Factor - Carbonation (n_d)	0.19–0.240	0.12	Normal
Age Factor - Chlorides (n)	0.37–0.65	$\sigma = 0.07$	Normal
Environmental Factor (k_e)	0.265–0.924	$\sigma = 0.05 - 0.16$	Normal
Diffusion Coefficient (D_c)	$7–15 \times 10^{-12}$ m^2 s^{-1}	0.285	Normal
Model Error for Crack Propagation	1.04	0.09	Normal
k_{urban}	1.15	0.10	Normal[a]
Cover	$C_{nom} + 6$ mm	$\sigma = 11.5$ mm	Normal[b]
Surface Chloride Concentration	1.15–7.35 kg/m^3	0.5–0.7	Normal
Critical Chloride Concentration	3.35 kg/m^3	0.375	Normal[c]
Corrosion Rate ($i_{corr-20}$) - Carbonation	0.17–0.43 μA/cm^2	$\sigma = 0.086 - 0.259$ μA/cm^2	Lognormal
Corrosion Rate ($i_{corr-20}$) - Chlorides	2.586–6.035 μA/cm^2	$\sigma = 1.724 - 3.448$ μA/cm^2	Lognormal
f_t	$0.53(f_c)^{0.5}$	0.13	Normal
E_c	$4600(f_c)^{0.5}$	0.12	Normal

[a] Truncated at 1.0
[b] Truncated at 10 mm (stirrup diameter)
[c] Truncated at 0.35 kg/m^3

widths exceed 1.0 mm. This constitutes ‘severe cracking’ which will need maintenance, repair or close monitoring. The crack initiation and propagation models used in the simulation analysis to calculate time to severe cracking and spalling (T_{sp}) are described elsewhere (El Maaddawy and Soudki 2007; Mullard and Stewart 2011), and are influenced mainly by cover, concrete strength and corrosion rate.

The probability of corrosion damage is then given by

$$p_s(t) = \Pr\left[t \geq T_{sp}\right] \tag{5}$$

Table 2 summarises the random variables for corrosion parameters, material properties and dimensions. See Stewart et al. (2011) and Wang et al. (2010) for more details of the probabilistic analysis and the random variables for corrosion parameters, material properties, dimensions, model error and environment.

3 Probabilistic analysis of concrete deterioration in Australia

Concrete deterioration is closely dependent on environment exposures which have been classified by many standards. Eurocode EN206–1 (ES 2000) defines the exposure in relation to the form of deterioration, while the Australian Standard for Concrete Structures AS3600 (AS3600 2009) classifies the exposure in relation to the location of the concrete structure, especially the distance relative to the coast or water, and climatic (arid, temperate and tropical) and industrial zones as well. The exposure classification in AS3600 will be applied in this study and is divided into A1, B2, B1, B2, C1 and C2 (or C). It should be noted that they are different from the categories of emission scenarios defined by IPCC (2000), but they are kept to maintain the consistency with AS3600 (AS3600 2009).

Considering a non-industrial environment, inland concrete structures (or >50 km from the coast) are subject to 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 coastal locations (or between 1 and 50 km from the coast) are subject to B1 exposure, while they are under exposure B2 in the area less than 1 km from the coast. Structures with periodical contact with water, known as spray zone and splash zone, are subject to exposure C1 and C2 (or C). In this regard, environmental exposure of concrete structures in Australia can be approximately demonstrated by Fig. 2, which would be changed depending on the local environment of the structure.

As a kind of ‘baseline’ investigation, concrete is assumed to be designed following AS3600, with its cover defined in Table 3. The minimum cement content and water/cement ratio are extracted from AS 5100.5 (AS5100 2008), as shown in Table 4. As indicated by the standards, concrete with enhanced durability is required for more aggressive environments, such as coastal or marine environments (Exposure C).

In addition, the carbon dioxide concentration is described by Fig. 3 in relation to A1FI carbon emission scenario. It is estimated by MAGICC, known as Model for the Assessment of Greenhouse-gas Induced Climate Change, developed by Dr. Wigley of the National Centre for Atmospheric Research, USA, and it has been one of primary models used by IPCC since 1990 to produce projections of future

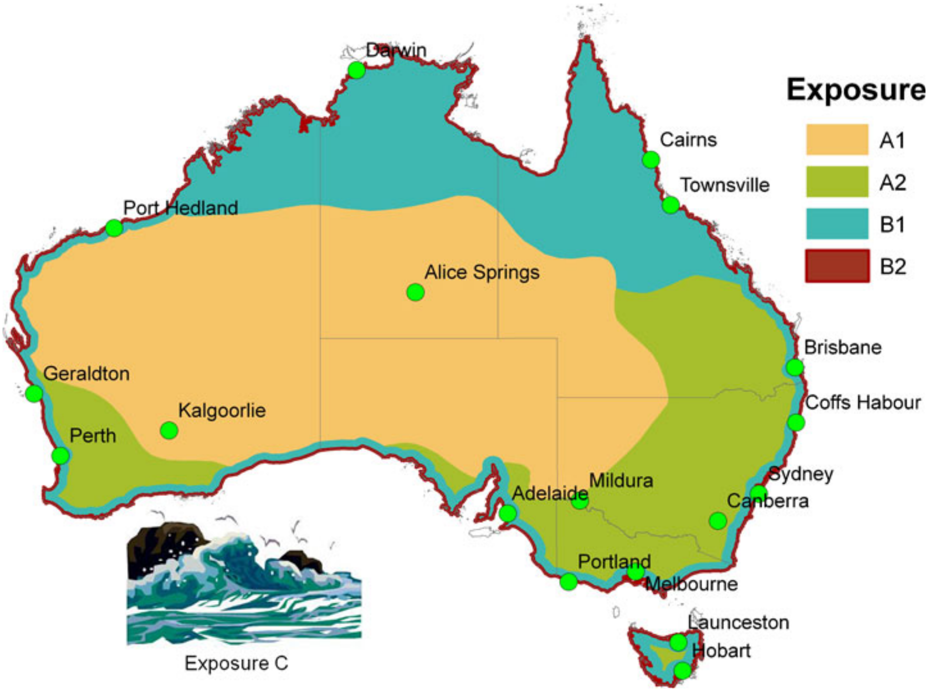


Fig. 2 Environment exposures of concrete structures in Australia

global mean temperature and sea level rises. If low and high values shown in Fig. 3 are taken as 10th and 90th percentiles, respectively, of a normal distribution then the statistical parameters for CO_2 concentrations are: mean $\mu_{CO2}(t)$ is equal to mid value, and standard deviation $\sigma_{CO2}(t)$ is (high–low)/2.56. For the reference (best) emission scenario based on constant year 2000 CO_2 concentration then $\mu_{CO2}(t) = 369.2$ ppm and $\sigma_{CO2}(t) = 0$. In all cases the probability distributions are censored at year 2000 CO_2 concentration.

A number of studies have shown elevated CO_2 levels in urban environments due to higher pollution, exhaust fumes, etc. Stewart et al. (2002) recorded CO_2 concentrations of up to 575 ppm in Brno (Czech Republic), with CO_2 concentrations higher near street level. George et al. (2007) found that CO_2 concentrations in an urban site

Table 3 Nominal cover for standard formwork and compaction according to AS 3600 (AS 2009)

Exposure	Nominal cover for concrete characteristic strength				
classification	20 MPa	25 MPa	32 MPa	40 MPa	≥50 MPa
A1	20	20	20	20	20
A2	(50)	30	25	20	20
B1	–	(60)	40	30	25
B2	–	–	(65)	45	35
C	–	–	–	(70)	50
C1					50
C2					65

Table 4 Minimum cement content and maximum water/cement ratio given exposure according to AS 5100.5 (AS 2008)

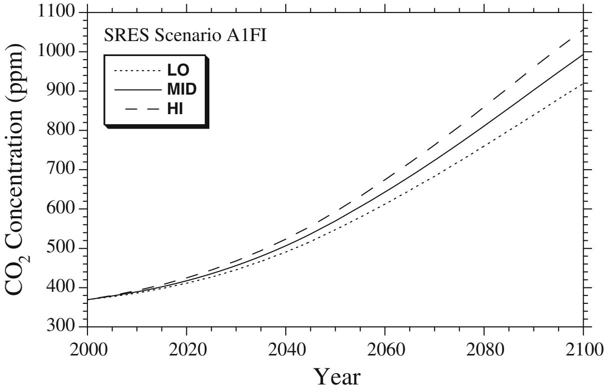
Exposure classification	Minimum cement content (kg/m^3)	Maximum water/ cement ratio
A	320	0.56
B1	320	0.50
B2	370	0.46
C	420	0.40

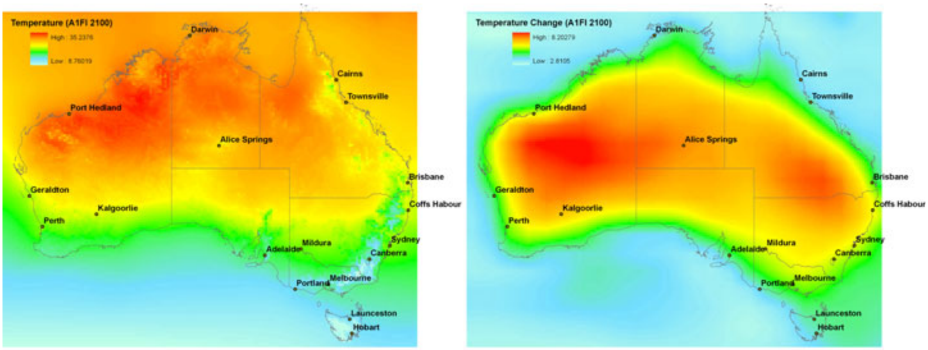
(Baltimore) were on average 16% higher than a rural site, and increases of 21–31% were reported in the literature. Day et al. (2002) observed an average enhancement over the course of the day in CO_2 concentration near an urban centre (Phoenix) of 19 ppm. Considering that the most infrastructure is located in urban environments, the effects of urban environment on atmospheric CO2 concentrations should be considered. If infrastructure is located in urban environments, then atmospheric CO_2 concentrations will be increased by a new factor k_{urban}. In this paper, and in the absence of any statistical data on k_{urban}, k_{urban} is assumed normally distributed with mean of 1.15 and COV of 0.10.

The projection of temperature and relative humidity in Australia with GCMs is obtained by using OZClim, climate change projection software developed by CSIRO, which is based on the 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 the World Climate Research Programme (WCRP). It is designed specifically for future climate projection in Australia. Figure 4 illustrates temperature and humidity projections for 2100 based on CSIRO Mk3.5 GCM. For an A1FI scenario by 2100, the yearly mean temperature range over Australia is estimated between 8°C to 36°C and its increase ranges from 2°C to 8°C. The relative humidity is in the range of 9% and 90% by 2100, and its change is between 16% decrease to 1% increase. It should be indicated that different changes may be provided by other GCM models, but they appear mostly to provide very similar trends. Within such a range, changes in carbonation and chloride penetration induced corrosion may not be small enough to be ignored.

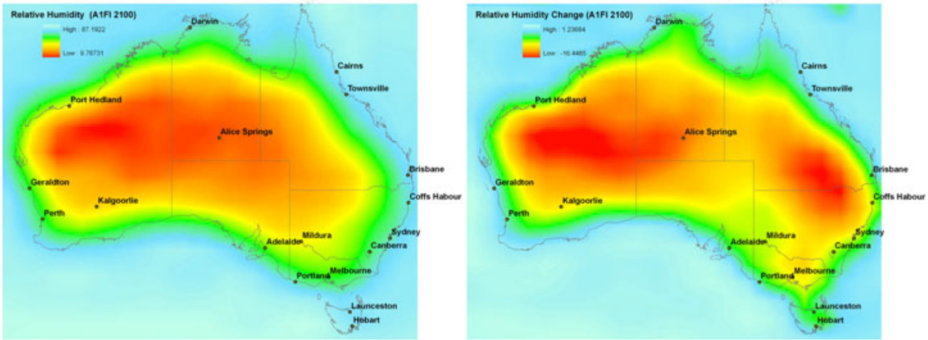
As a result, the carbonation depth and the probability of corrosion initiation and damage without consideration of climate change (or called as a baseline), as well

Fig. 3 Projection of carbon dioxide concentration for A1FI emission scenario





(a) Temperature by 2100 (b) Temperature change by 2100

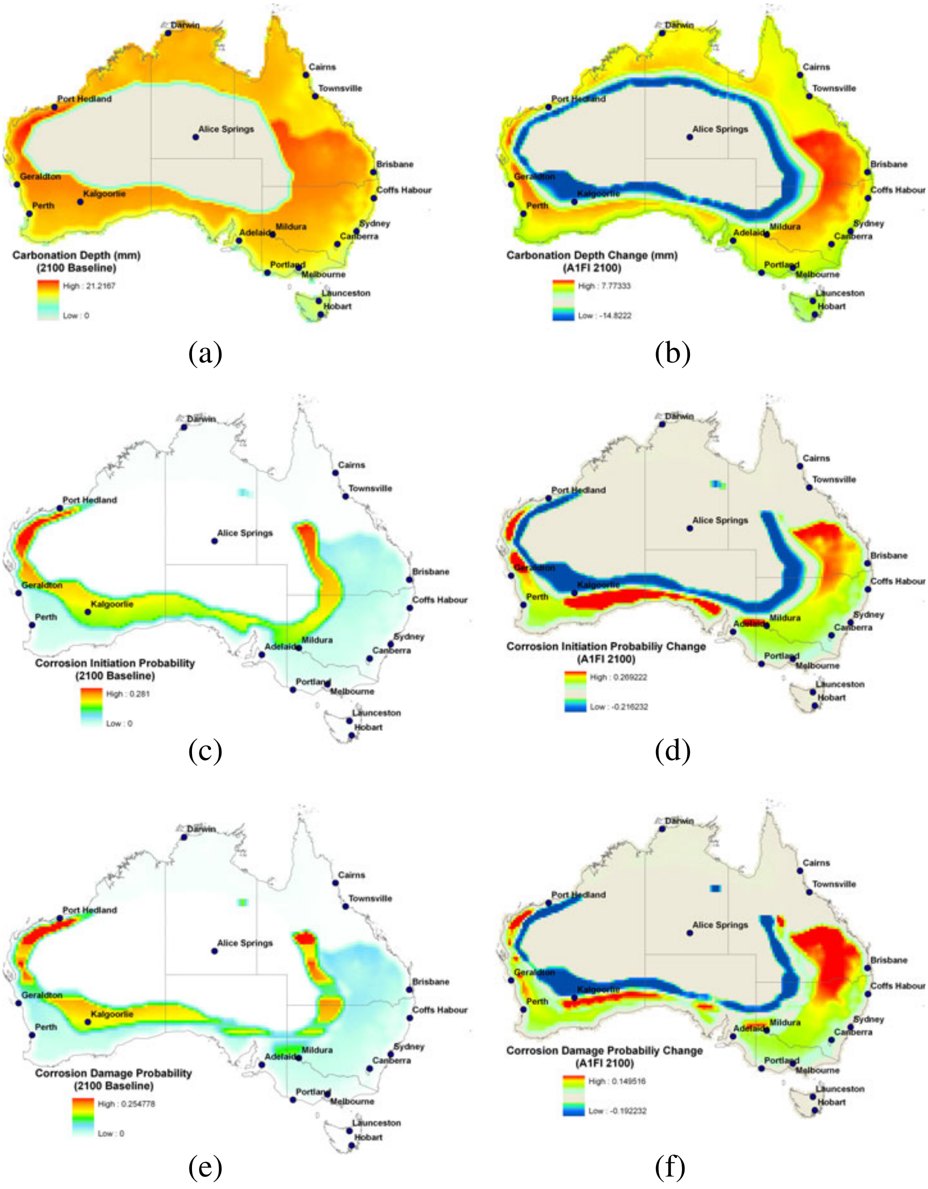


(c) RH by 2100 (d) RH change by 2100

Fig. 4 **a–d** Projection of temperature and relative humidity by CSIRO Mk 3.5 climate model

as their changes for A1FI emission scenario by 2100, are presented by Fig. 5. The mean carbonation depth for the baseline is in the range of 0 to 21 mm. Under climate change (A1FI emission scenario), the mean carbon depth by 2100 can reduce by up to 15 mm or increase by up to 8 mm when compared to the baseline case, depending on the location of the concrete structure. Within the area of the arid zone in central Australia, carbonation does not occur due to a lack of moisture. The area is extended when the future climate becomes drier around central Australia. Meanwhile, around the border between New South Wales and Victoria, a relatively greater increase of temperature also pushes carbonation higher. In a small area in the west of Western Australia, the decrease in relative humidity is not sufficient to offset an increase in temperature, leading to an increase in carbonation.

In the absence of climate change, the probability of carbonation-induced corrosion initiation is in the range of 0–28% (Fig. 5c and d). Under a changing climate it can, depending in region, be 22% less than the baseline to 27% more than the baseline by 2100. The corrosion risk is higher around the boundary between the arid climatic zone in central Australia and the temperate climatic zone in the west, south as well as east of Australia (Fig. 5d). This is mostly caused by a lower cover requirement for concrete structures in arid and temperate climatic zones, which are also away from coasts. The environmental exposure in those areas is generally



(a) (b)

(c) (d)

(e) (f)

Fig. 5 Carbonation induced corrosion of concrete structures by 2100: **a** mean carbonation depth without consideration of climate change, **b** change in carbonation depth for A1FI emission scenario, **c** probability of corrosion initiation without consideration of climate change, **d** change in probability of corrosion initiation for A1FI emission scenario, **e** probability of corrosion damage without consideration of climate change, **f** change in probability of corrosion damage for A1FI emission scenario

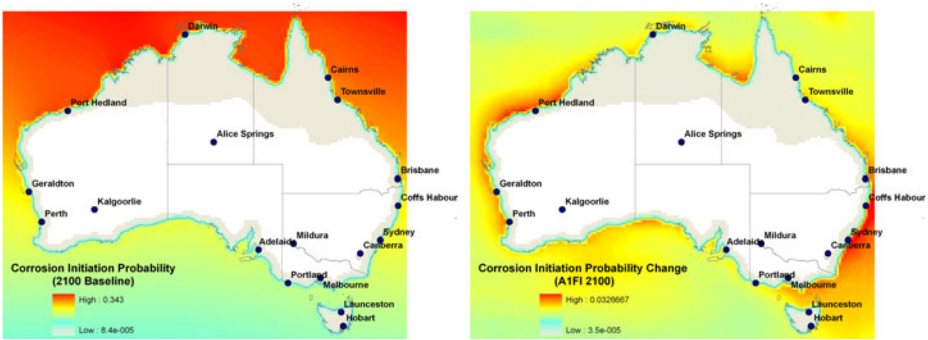
classified as A1 and A2, while the exposure of near-coastal and coastal areas is classified as B1, B2 or C (or C1/C2) where a higher cover thickness is required. Meanwhile, a greater increase in the probability of corrosion initiation due to climate change is also found in the areas with a spatial pattern similar to the changes of carbonation depth.

In the absence of climate change, carbonation induced corrosion damage (severe cracking and spalling) is in the range of 0 and 25%, depending on region (Figs. 5e and f). Under climate change, corrosion damage risks varies regionally from a 19% decrease to a 15% increase, with a spatial pattern similar to that for corrosion initiation.

Unlike carbonation induced corrosion, chloride penetration induced corrosion mostly occurs around coastal regions and inland areas where salinity and water exposure are high. As shown in Fig. 6, the probability of chloride induced corrosion initiation varies widely by region, from 0 in southern Australia to 34% in the north. Chloride induced corrosion initiation is much less sensitive to climate change than carbonation induced corrosion. In response to climate change the risk of chloride induced corrosion increases by only 0 to 3.5%, depending on region. However, the proportional increase in damage risks can easily exceed 10%. This lower change in risk profile may be related to the fact that under climate change temperature rises in coastal areas are likely to be much less marked than those occurring inland (Fig. 4). A corollary of this is that, where chloride and moisture prove suitable for corrosion initiation at inland locations, the risk of corrosion is likely to increase significantly under climate change.

This analysis has not taken into account the effect of climate change on acidity due to increased uptake of carbon dioxide by oceans (McNeil and Matear 2008). As a consequence, it may underestimate the risk to coastal concrete structures.

As shown in Fig. 6b, while the change in the probability of corrosion initiation is generally higher along the coast than other areas, there are '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 larger increase in temperature to 2100 in those areas. For chloride induced corrosion damage, the probability pattern is very similar, but its magnitude is slightly lower.



(a) (b)

Fig. 6 The probability of chloride penetration induced corrosion of concrete structures by 2100: **a** probability of corrosion initiation without consideration of climate change (baseline), **b** change in probability of corrosion initiation considering A1FI emission scenario

4 Discussion

The simulation analyses described have indicated that climate change may have a sizeable impact on damage risks of concrete structures and consequently their durability. In many instances the magnitude of change in risk is such that it should not be ignored either in Australia or internationally as the main driver of deterioration is CO_2 and temperature increase which will affect many, if not all, locations globally.

The impact assessment is focused primarily on the relative change in corrosion initiation and damage risks due to enhanced CO_2 levels and temperature when compared to year 2000 levels, and not on the absolute estimates of risk. The deterioration models are mostly derived from the 1996–1999 European Duracrete project which has formed the basis for the probabilistic durability design of many important structures, however, these models assume a static environment. A key research challenge is how time and spatially dependent climatic variables will affect concrete deterioration. This paper makes some progress in this direction, as does Bastidas-Arteaga et al. (2010, 2011) and others. If other deterioration models are deemed more appropriate then these can readily be incorporated into the stochastic and reliability framework developed in the present paper. While different deterioration models will produce different estimates of absolute risk, deterioration model selection should have less influence on comparative risks.

Responses to this change in risk will depend not only on the perception of that risk but on the efficacy and cost of repair, maintenance or adaptation measures. For new, yet to be built, 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. The options generally include cover design, cement and mix selection, surface coating barriers, extraction, and cathodic protection. In addition to reducing environmental exposure as much as possible, solutions in a new design may come from increasing cover and strength grade, or any approaches that reduce material diffusion coefficient without compromising the reliability and serviceability of concrete. The extent of design change required to maintain current levels of concrete structure durability will be reported from our on-going research. As this report shows, the adaptation response required to maintain durability will be highly dependent on the location of the structure and its environmental exposure.

Many existing concrete structures, for which design did not take into an account the effect of changing climate, are likely to suffer from increases risk of damage as a consequence of climate change. The economic consequences are immense, as even a small percentage increase in damage risks can lead to hundreds of billions (or even trillions) of dollars in increased maintenance and repair costs. As this risk varies widely with location, environmental exposure and material design – and is therefore difficult to predict for every individual structure – a precautionary approach would suggest that increased monitoring and maintaining of concrete structures would be wise. Clearly, the costs and benefits of such an approach which, as this paper shows, will vary widely by location will be critical for efficient practical implementation. A preliminary cost-benefit assessment of adaptation measures is described by Stewart and Peng (2010), but there is much scope for further research.

5 Conclusions

A time-dependent probability analysis has been conducted to assess the probabilities of corrosion initiation and corrosion damage for existing concrete infrastructure in Australia subject to change of climatic variables to 2100. The atmospheric CO_2 concentration and local temperature and humidity changes with time over the next 100 years were projected spatially across the Australian continent. The probabilistic analysis included the uncertainty of CO_2 concentration, deterioration processes, material properties, dimensions, and predictive models. It was found that carbonation-induced damage risks can increase significantly for specific locations in Australia. Damage risks for chloride-induced corrosion increase by less than 10%. The results were most sensitive to increases in atmospheric CO_2. Since the main driver to increased concrete deterioration is CO_2 concentration and temperature, then the increased damage risks to Australian infrastructure will most likely also be observed for many concrete infrastructure globally. Existing concrete structures, for which design has not considered the effects of changing climate may deteriorate more rapidly than originally planned.

Acknowledgements The authors thank the Department of Climate Change and Energy Efficiency (DCCEE) and the CSIRO Climate Adaptation Flagship for funding this research.

The authors also express their appreciation to Jo Mummery, Catherine Farrell, Robert Davitt and Mark Eslake of DCCEE, Allen Kearns, Seona Meharg, Phillip Paevere and Greg Foliente of CSIRO, and Roger Jones of the University of Victoria, for their valuable advice and generous support. The authors also appreciate the assistance of Michael Netherton and Xiaoli Deng from The University of Newcastle. Finally, the authors thank all members of the project's expert panel for their inputs, and Peter Stone for his valuable comments on this paper.

References

Ababneh AN, Benboudjema F, Xi Y (2003) Chloride penetration in unsaturated concrete. J Mater Civ Eng 15(2):183–91

Al-Khaiat H, Fattuhi N (2002) Carbonation of concrete exposed to hot and arid climate. J Mater Civ Eng 14(2):97–107

AS (2008) Bridge design—part 5: concrete. AS 5100.5. Standards Australia, Sydney

AS (2009) Concrete structure. Australian Standard 3600–2009. Standards Australia, Sydney

Bastidas-Arteaga E, Chateauneuf A, Sanchez-Silva M, Bressolette Ph, Schoefs F (2010) Influence of weather and global warming in chloride ingress into concrete: a stochastic approach. Struct Saf 32:238–249

Bastidas-Arteaga E, Chateauneuf A, Sanchez-Silva M, Bressolette Ph, Schoefs F (2011) Comprehensive probabilistic model of chloride ingress in unsaturated concrete. Eng Struct 33(3):720–30

CSIRO (2007) Climate change in Australia. Technical Report. CSIRO, Melbourne

Day TA, Gober P, Xiaong FS, Wentz E (2002) Temporal patterns in near surface CO2 concentrations over contrasting vegetation types in the phoenix metropolitan area. Agric For Meteorol 110:229–245

DuraCrete (1998) Modelling of degradation, DuraCrete - probabilistic performance based durability design of concrete structures. EU - Brite EuRam III, Contract BRPR-CT95–0132, Project BE95–1347/R4–5, December 1998, p 174

DuraCrete (2000) Statistical quantification of the variables in the limit state functions, DuraCrete - probabilistic performance based durability design of concrete structures. EU - Brite EuRam III, Contract BRPR-CT95–0132, Project BE95–1347/R9, January 2000, p 130

El Maaddawy T, Soudki, KA (2007) A model for prediction of time from corrosion initiation to corrosion cracking. Cem Concr Compos 29(3):168–175

ES (2000) Concrete – Part 1: specification performance, production and conformity. EN 206–1, European Standards

GCP (2010) Global construction: a global forecast for the construction industry over the next decade to 2020. Global Construction Perspectives and Oxford Economic, London

George K, Ziska LH, Bunce JA, Quebedeaux B (2007) Elevated atmospheric CO2 concentration and temperature across an urban-rural transect. Atmos Environ 41:7654–7665

IPCC (Intergovernmental Panel on Climate Change) (2000) Emission scenarios. In: Nakicenovic N, Swart R (eds) Special report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

IPCC (2007) Climate change 2007—the fourth assessment report. Cambridge University Press, Cambridge

McNeil BI, Matear RJ (2008) Southern ocean acidification: a tipping point at 450-ppm atmospheric CO_2. PNAS 105(48):18860–18864

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747–756

Mullard JA, Stewart MG (2011) Corrosion-induced cover cracking: new test data and predictive models. ACI Struct J 108(1):71–79

Peng J, Stewart MG (2008) Carbonation-induced corrosion damage and structural safety for concrete under enhanced greenhouse conditions. Research Report No. 270.11.2008, Centre for Infrastructure Performance and Reliability. The University of Newcastle, Newcastle

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE, Somerville RCJ (2007) Recent climate observation compared to projections. Science 316:709

Russell D, Basheer PAM, Rankin GIB, Long EA (2001) Effect of relative humidity and air permeability on prediction of the rate of carbonation of concrete. Proc Inst Civ Eng 146(3):319–326

Saetta A, Scotta R, Vitaliani R (1993) Analysis of chloride diffusion into partially saturated concrete. ACI Mater J 90(5):441–451

Schmitt G (2009) Global needs for knowledge dissemination, research, and development in materials deterioration and corrosion control. World Corrosion Organization, New York

Stewart MG, Peng J (2010) Life cycle cost assessment of climate change adaptation measures to minimise carbonation-induced corrosion risks. Int J Eng Uncertain: Haz Assess Mitig 2(1–2):35–46

Stewart MG, Teply B, Kralova H (2002) The effect of temporal and spatial variability of ambient carbon dioxide concentrations on carbonation of RC structures. 9th international conference on durability of building materials and components, CSIRO, Paper 246 (CD-ROM)

Stewart MG, Wang X, Nguyen M (2011) Climate change impact and risks of concrete infrastructure deterioration. Eng Struct 33(4):1326–1337

Wang C-H, Wang X (2009a) Hazard of extreme wind Gust in Australia and its sensitivity to climate change. Technical Report of National Research Flagships – Climate Adaptation. CSIRO, Melbourne

Wang C-H, Wang X (2009b) Hazard of extreme wind gusts to buildings in Australia and its sensitivity to climate change. 18th world IMACS/MODSIM congress, Cairns, Australia, 13–17 July 2009

Wang X, Nguyen M, Stewart MG, Syme M, Leitch A (2010) Analysis of climate change impacts on the deterioration of concrete infrastructure – part 2: modelling and simulation of deterioration and adaptation options. Published by CSIRO, Canberra, p 444. http://www.csiro.au/resources/concrete-durability-report-part-2.html

Wigley TML, Richels R, Edmonds JA (1996) Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. Nature 379:240–243

Yoon IS, Copuroglu O, Park KB (2007) Effect of global climatic change on carbonation progress of concrete. Atmos Environ 41:7274–7285