



Climate change adaptation for corrosion control of concrete infrastructure

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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, especially in the longer term, causing an acceleration of reinforcement corrosion that will affect the safety and serviceability of concrete infrastructure in Australia, US, Europe, China and elsewhere. This paper reviews advanced simulation procedures to predict increases in damage (corrosion) risks under a changing climate in Australia in terms of changes in probability of reinforcement corrosion initiation and corrosion induced damage due to (i) increase in the concentration of CO₂ in the atmosphere, and changes to (ii) temperature and (iii) humidity. These time and spatial variables will affect the penetration of aggressive agents CO₂ and chlorides into concrete, and the corrosion rate once corrosion initiation occurs. The effectiveness of adaptation measures for new and existing buildings, bridges, and other concrete infrastructure is then assessed. Carbonation-induced damage risks may increase by more than 16% which means that one in six structures will experience additional and costly corrosion damage by 2100. We show that the impact of climate change on infrastructure deterioration cannot be ignored, but can be addressed by changes to design procedures including increases in cover thickness, improved quality of concrete, and coatings and barriers. For example, an increase in design cover of 10 mm and 5 mm for structures where carbonation or chlorides govern durability, respectively, will ameliorate the effects of a changing climate.

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1. Introduction

Concrete is the predominant construction type used in buildings, bridges, power plants, wharves, and other infrastructure in Australia, US, Europe, China and elsewhere. Over \$140 billion is spent annually in Australia on homes, commercial buildings, bridges, dams, ports and other physical infrastructure assets [1]. In the US there are over 5 million commercial buildings, 600,000 highway bridges, over 400 large airports, etc. 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 3–4% of the Gross Domestic Product (GDP) of industrialised countries [22]. 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.

Corrosion of steel reinforcement can occur by (i) carbonation of the concrete cover, or (ii) 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. The deterioration of concrete structures can be affected directly or indirectly by climate change that is linked to the change in carbon dioxide (CO₂) concentration, temperature and relative humidity. 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, corrosion rates will increase by up to 15% if temperature increases by 2 °C [27]. Since the main environmental driver to increased concrete deterioration is CO₂ 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

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structures, but these effects are beyond the scope of the present paper.

Stewart et al. [27] and Wang et al. [32–35] have developed advanced probabilistic and reliability-based methods to predict concrete deterioration under a changing climate in Australia, in terms of changes in probability of reinforcement corrosion initiation and corrosion induced damage due to (i) increase in the concentration of CO_2 in the atmosphere, and changes to (ii) temperature and (iii) humidity. These time and spatial variables will affect the penetration of aggressive agents CO_2 and chlorides into concrete, and the corrosion rate once corrosion initiation occurs [27]. It has been shown by Wang et al. [34] that additional carbonation-induced damage risks for the A1FI emission scenario is up to 16% higher if there are no changes to how concrete structures are designed or constructed. In practical terms, this is equivalent to expecting that an additional 16% of all concrete surfaces by the year 2100 will be damaged and in need of costly maintenance or repair. While there is much research on deterioration of concrete studies, there is relatively little research on how deterioration is affected by a changing climate. Stewart and Peng [26] used a simplified deterioration model and global IPCC [15] CO_2 concentration and temperature change data to conduct 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. This preliminary analysis found that increasing design cover may not be cost-effective, but results were sensitive to repair costs and user disruption. Stewart et al. [27] developed a more accurate formulation of carbonation and chloride-induced corrosion that predicted the probability of corrosion initiation and damage (severe cracking) for concrete infrastructure for the Australian cities of Sydney and Darwin. It was found that carbonation-induced damage risks increases to 20–40% for A1FI, A1B and 550 ppm emission scenarios. The additional damage risks for chloride-induced corrosion is only 3% over the same time period due to temperature increase, but without consideration of ocean acidity change in marine exposure. 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. [5] have calculated 5–15% increases in probability of corrosion initiation due to climate change.

Climate adaptation in terms of the enhancement of adaptive capacity can be done by developing new technologies and materials to counter the impact of increasing corrosion risk under a changing climate. On the other hand, there is a wide range of existing and 'low-tech' options that can enhance the durability of concrete structures and these can be applied to reduce the adverse effects of climate change. The design options generally include the selection of cover, concrete mix, surface coating barriers, extraction, and cathodic protection. In addition to reducing environmental exposure as much as possible, practical adaptation 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 paper describes a spatial and time-dependent analysis of damage risks for the Australian continent. It will then assess and compare the effectiveness of adaption strategies that will improve the durability performance of concrete structures in a changing climate. In particular, results and adaptation measures will be proposed for the largest nine urban centres (cities) in Australia ranging in population from 4.5 million (Sydney) to 125,000 (Darwin), and which account for 65% of Australia's population, and is also where most infrastructure is located. This includes increases to design cover (thickness of concrete protecting steel reinforcement), increases in concrete quality, and application of surface treatments and barriers. Since (i) the main driver to increased con-

crete deterioration is carbonation caused by CO_2 concentration, and (ii) many Australian cities, just like many cities in Europe and the US, are located in temperate climates, then damage risks and adaptation measures for Australia will be highly relevant to other concrete infrastructure internationally.

2. Probabilistic modelling of damage risks

2.1. Anthropogenic aspects of climate change

Future climate was projected by defining carbon emission scenarios in relation to changes in population, economy, technology, energy, land use and agriculture, represented by a total of four scenario families, i.e., A1, A2, B1 and B2 [15]. Sub-categories of the A1 scenario included differing energy sources (fossil intensive, non-fossil energy and a balance across all sources, for example, A1FI, A1T and A1B, 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 [36]. Our entire investigation will cover A1FI, A1B and 550 ppm stabilisation scenarios representing high, medium emission scenarios and policy intervention scenarios, respectively. The A1FI emission scenario predicts CO_2 concentrations increasing by more than 160% to 1000 ppm by 2100, see Fig. 1. Their low and upper bounds are also described to consider CO_2 projection modelling errors. Fig. 2 shows the predicted median temperatures for the nine Australian cities, for the A1FI emission scenario using the CSIRO Mk3.5 Climate Model which is an updated model of CSIRO Mk3.0 (IPCC [15]). To illustrate the uncertainty of temperature predictions, Fig. 2 also shows low and high temperature projections for Sydney based on nine General

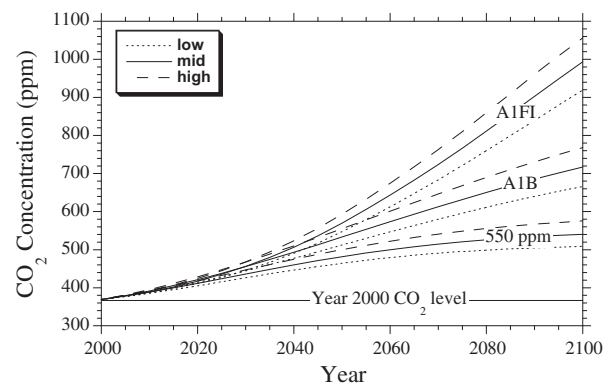


Fig. 1. Predicted low, mid and high estimates of CO_2 concentrations.

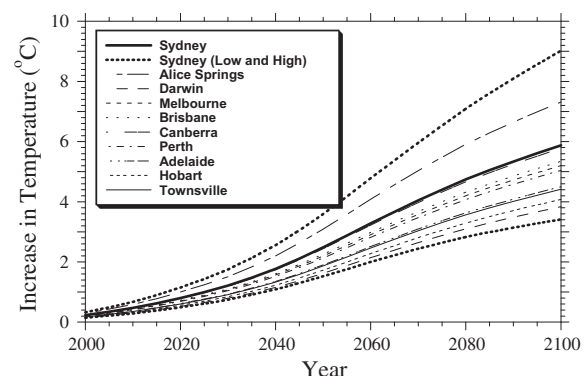


Fig. 2. Predicted median temperatures, and low and high estimates for Sydney, using CSIRO Mk3.5 climate model for the A1FI emission scenario.

Circulation Models (e.g., [27], and the uncertainty is typical for all cities, and is also included in the probabilistic analysis conducted herein. Relative humidity may increase by up to 1% in many coastal locations, but can decrease by up to 15% for inland locations.

2.2. Deterioration and probabilistic modelling

Most, if not all, existing concrete deterioration models assume a static (non-changing) environment. Hence, existing deterioration models need to be modified to account for time-dependent changes in CO₂ concentration, temperature and relative humidity. Existing deterioration models for corrosion initiation and propagation are taken mainly from DuraCrete [9–11] and crack propagation (time to severe cracking and damage) from Mullard and Stewart [18]. The models were then modified to consider the effect of time-dependent changes in CO₂ concentration, temperature and relative humidity on time to corrosion damage [27]. 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 and the fib Model Code for Service Life Design [12]. However, many other deterioration models have been developed for concrete durability, which if deemed more appropriate, can readily be incorporated into the stochastic and reliability framework developed used herein. While different deterioration models will produce different estimates of absolute risk, deterioration model selection will have significantly less influence on comparative risks. For example, since carbonation depth is a function of the square root of CO₂ concentration (e.g., [9]) then a doubling of CO₂ concentration will increase carbonation depth by 41%.

In the present paper ‘corrosion damage’ is assumed to occur when crack 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 [18], and are influenced mainly by cover, con-

crete strength and corrosion rate. The probability of corrosion damage is

$$p_s(t) = \Pr[t \geq T_{sp}] \quad (1)$$

If the material, dimensional and corrosion parameters are assumed homogeneous for the structure (i.e. spatial variability is ignored), then the mean proportion of corrosion damage is $p_s(t) \times 100\%$ [28]. See Stewart et al. [27] and Wang et al. [32–35] for more details of the probabilistic analysis.

The simulation of carbonation and chloride penetration induced corrosion of concrete was implemented using a conventional probabilistic approach using Monte-Carlo simulation, as demonstrated in Fig. 3. This considers the variability of cover, concrete strength, water–cement ratio, diffusion coefficient, surface chloride concentration, critical chloride concentration, age factor, corrosion rate, model errors, and environmental variables, including time-dependent concentration of CO₂, 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 cements. The analysis predicts (i) probability of corrosion initiation, (ii) probability of corrosion damage (severe cracking), and (iii) corrosion loss of reinforcement for concrete infrastructure subjected to corrosion resulting from higher CO₂ levels and temperatures. As shown in Fig. 3, 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 modify future CO₂ concentration, temperature and relative humidity data that are fed into the simulation. Uncertainties of climate change modelling as well as carbon emission scenarios bring more complexity to the simulation process. This analysis has not taken into account the effect of climate change on acidity due to increased uptake of carbon dioxide by oceans [16]. As a consequence, it may underestimate the risk to coastal concrete structures.

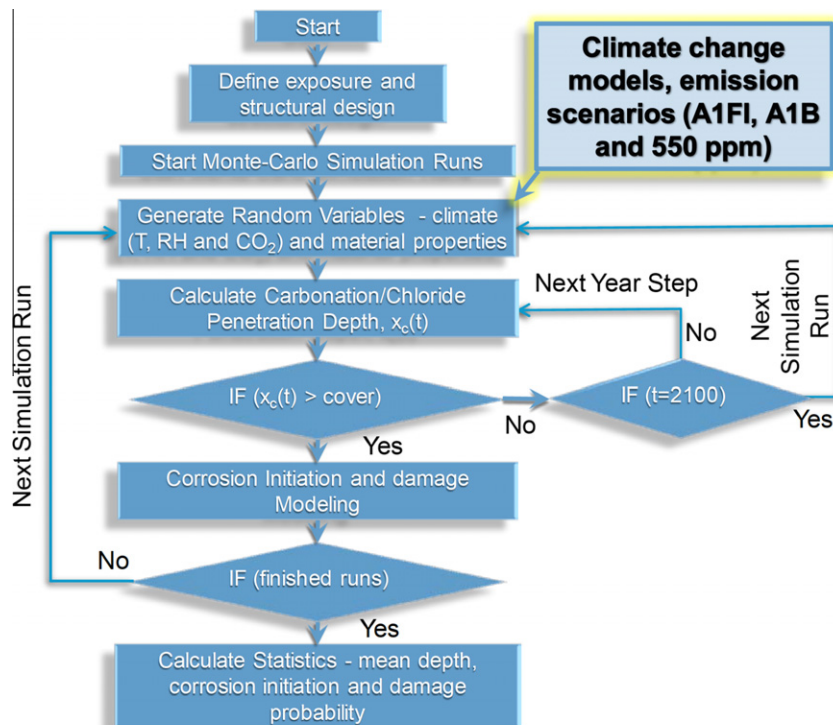


Fig. 3. Flowchart of simulation of concrete deterioration under climate change.

2.3. Summary of corrosion damage risks for Australia

The projection of the local climate is based on CSIRO Mk3.5 climate model interpolated into 169×137 grids in a grid size of 0.25° for temperature and relative humidity to 2100. The durability design requirements specified in Australian Standards for Concrete Structures and Bridges [3,4] relate to minimum concrete cover and concrete compressive strength, and assumes standard formwork and compaction. For each location in Australia the environmental exposure determines the cover and concrete durability specification selected from AS5100-2008 and AS3600-2009, see Table 1. Environmental exposure of structures in each grid is defined by Fig. 4, where Exposure C to C2 are for coastal splash and tidal zones. Note that the 2001 and earlier editions of the Australian Concrete Code AS3600 had a single exposure classification for members in water (exposure classification C). However, the revised (2009) edition now provides more guidance by removing exposure classification C and replacing it with more specific exposure classifications C1 and C2. As nearly all existing infrastructure is designed to AS3600-2001 or earlier then it is important to include exposure classification C in the reliability analyses. Monte-Carlo simulation with minimum 500,000 samples is carried out for each grid to estimate the deterioration of concrete structures over the period from 2000 to 2100, including carbonation depth, probability of corrosion initiation and damage. The

reference or baseline case is where CO_2 concentration, temperature and humidity are held constant at year 2000 levels.

The spatial assessment shown in Fig. 5 indicates that the carbon depth can change in a range from 15 mm less than the baseline to 8 mm more than the baseline by 2100, depending on the location of the concrete structure, for the A1FI emission scenario. In 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. Under a changing climate the probability of carbonation-induced corrosion damage can, depending on the region, be 19% below the baseline to 16% above the baseline by 2100. Reductions in damage risks occur mainly in inland Australia (where there is little infrastructure) due to reductions in humidity. The probability 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. 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 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 (see Table 1).

Table 1

Durability design specifications for concrete structures in Australia [3,4].

Exposure	Classification	Cover (mm)	F'_c (MPa)	w/c ratio
<i>Members in exterior environments</i>				
Inland (>50 km from coast)				
Non-industrial and arid climate	A1	20	20	0.56
Non-industrial and temperate climate	A2	30	25	0.56
Non-industrial and tropical climate	B1	40	32	0.50
Non-industrial and any climate	B1	40	32	0.50
Near-coastal (1–50 km), any climate	B1	40	32	0.50
Coastal (up to 1 km, excluding tidal and splash zones), any climate	B2	45	40	0.46
<i>Surfaces of members in water</i>				
Splash and tidal zones	C	50	50	0.40
In spray zone (>1 m above wave crest level)	C1	50	50	0.40
Splash and tidal zones	C2	65	50	0.40

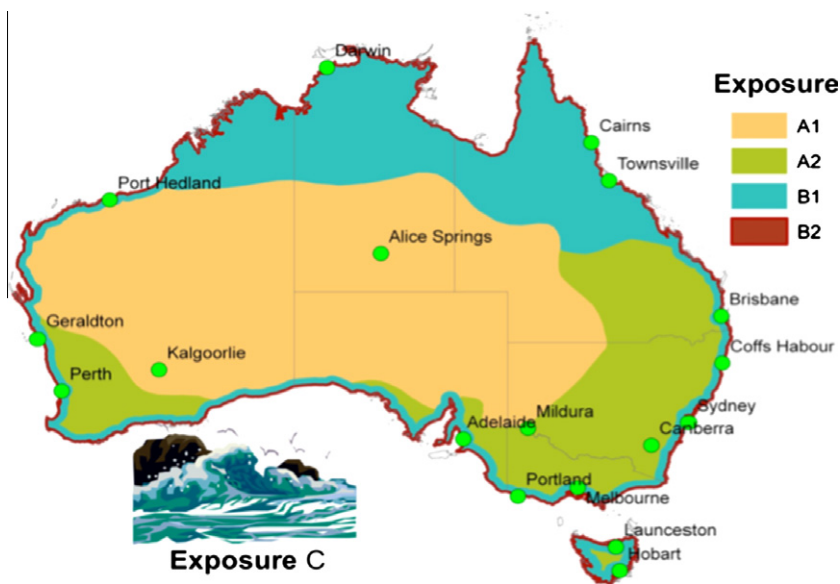


Fig. 4. Environmental exposure of concrete structures in Australia.

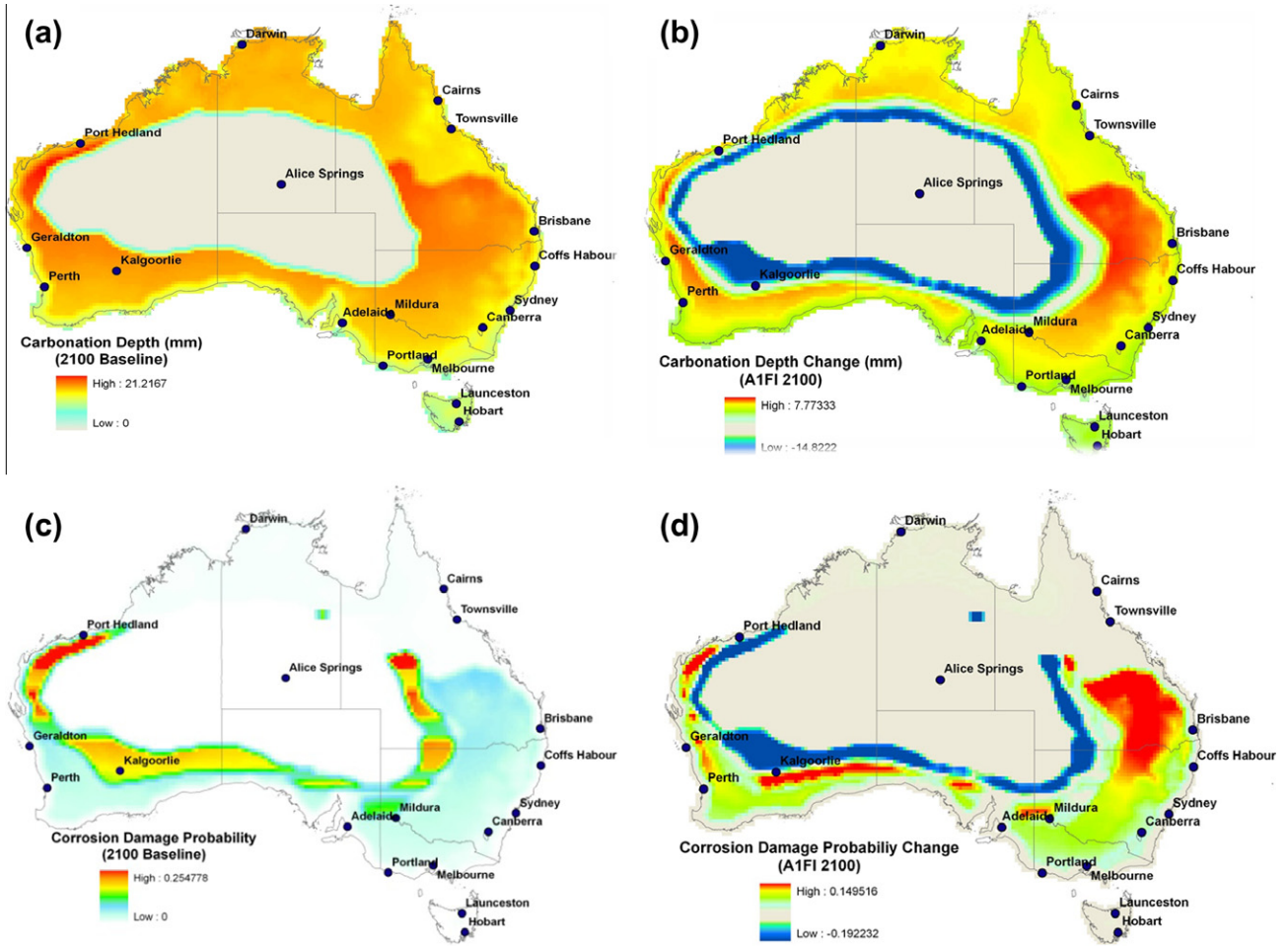


Fig. 5. Carbonation-induced corrosion of concrete structures by 2100: (a) Mean carbonation depth without consideration of climate change, (b) Change in carbonation depth for A1FI emission scenario, (c) Probability of corrosion damage without consideration of climate change, (d) Change in probability of corrosion damage for A1FI emission scenario [34].

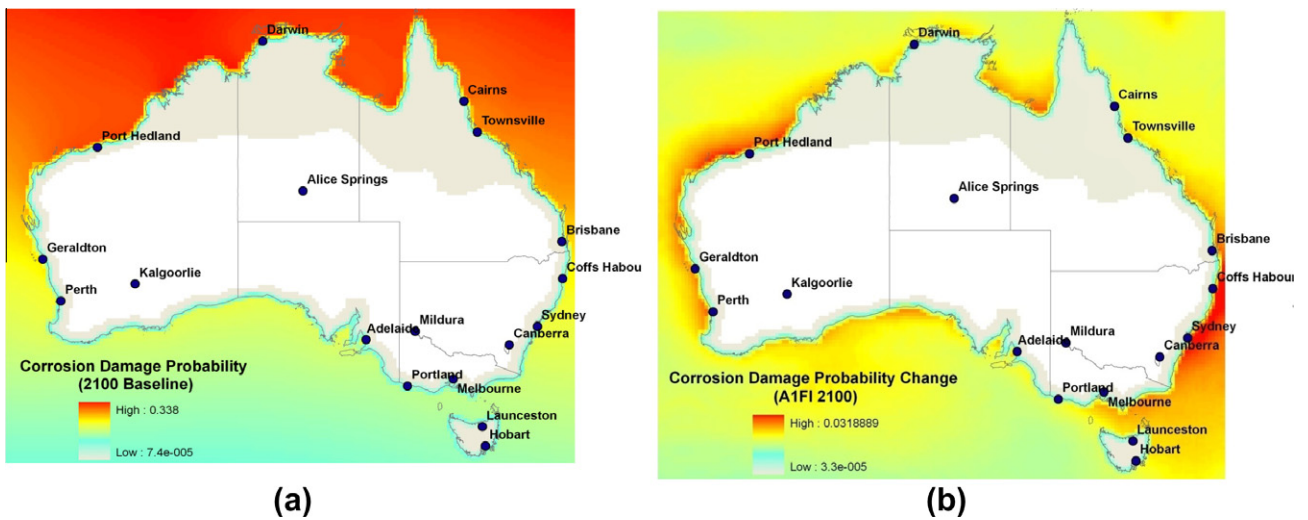


Fig. 6. Probability of chloride-induced corrosion damage of concrete structures by 2100: (a) Probability of corrosion damage without consideration of climate change (baseline), (b) change in probability of corrosion damage considering A1FI emission scenario [34].

In addition, a full scale spatial assessment of chloride-induced corrosion shows that corrosion mostly occurs around coastal regions and inland areas where salinity and water exposure are high. As shown in Fig. 6, for the A1FI emission scenario, the probability

of chloride induced corrosion initiation varies widely by region, from 0% in southern Australia to 34% in the north by 2100. Chloride induced corrosion initiation is much less sensitive to climate change than carbonation induced corrosion. In response to climate

change the additional risk of chloride induced corrosion is 0–3.2%, depending on the region. However, the proportional increase in damage risks can easily exceed 10%. This lower change in risk profile may be due to the fact that under climate change temperature rises in coastal areas are likely to be much less marked than those occurring inland. 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.

3. Adaptation measures

The present paper will focus on adaptation strategies that are implemented during design and construction rather than in-service (e.g., when corrosion damage occurs) as the latter will be much more costly in terms of direct costs and inconvenience/user delays and other indirect costs; namely (i) increasing design cover, (ii) increasing strength grade, and (iii) applications of protective surface coatings. The Program CIRCAA-RC assumes that all adaptation strategies are applied during construction and that any coatings are adequately maintained during the life of the structure (i.e. coating will not deteriorate with time). Nine urban centres are considered: Darwin (DAR), Townsville (TOW), Brisbane (BRN), Sydney (SYD), Adelaide (ADE), Perth (PER), Melbourne (MEL), Canberra (CAN) and Hobart (HOB), see [Fig. 4](#).

In this study, climate adaptation for concrete structures is achieved through the selection of design options for RC structures under a changing climate. This is done in order to retain the durability and serviceability for their service life (i.e. to meet the same envisaged performance by specifications defined in AS 3600 and AS 5100) as if climate change was not considered. In this regard, the criteria for the selection of design adaptation measures is that its *corrosion damage probability* $p_s(t)$ is no less than for the standard structure subject to carbon concentration and local climate conditions at 2000 calendar year conditions. In another words, the selection of a design option can lead to the durability and serviceability that will not be compromised at any circumstance as a result of climate change in the design service life of concrete structures.

The following sections reviews a selection of results that show the effectiveness of adaptation measures in concrete design in relation to corrosion damage risks $p_s(t)$. Since there are nine urban locations, three emission scenarios (A1FI, A1B and 550 ppm stabilisation), and nine exposures (A1 to C2) it is not possible to show all results for all these combinations. Full results are described in Wang et al. [34].

3.1. Increase in cover thickness

The increase in cover thickness can increase the time of carbonation and chloride ingress to reach concrete reinforcement and in turn delay carbonation and chloride-induced corrosion. It is therefore one of the most obvious and simplest adaptation options in

the design of concrete infrastructure under a changing climate to maintain structural durability and serviceability.

3.1.1. Carbonation-induced corrosion

As discussed previously, concrete structures that are designed for exposure A1 and A2 (20–30 mm design cover) are more vulnerable to carbonation under the impact of changing climate. Therefore, the discussion on how the cover should be changed to meet the challenge will be carried out in relation to these two exposures, as well as exposure B1 (40 mm design cover). The probability of corrosion damage for other exposures is negligible.

Table 2 gives the minimum cover increase required for concrete structures designed for exposure A1, A2 and B1 and expected service until 2100, to counteract the impact of climate change on corrosion damage, for A1FI, A1B and 550 ppm emission scenarios and for nine urban centres in Australia. For the A1FI emission scenario and exposures A1, A2 and B1 the required cover increase of the urban centres is 5–6 mm, 4–7 mm, and 5–6 mm, respectively. If the criterion for selecting minimum cover is maintaining the current level of probability of corrosion initiation, then the minimum cover increases to 10 mm, 9 mm and 7 mm for exposures A1, A2 and B1 respectively, for A1FI emission scenario.

A reduction of carbon emissions will reduce the requirement of cover increase. Considering A1 exposure, the cover increase is in the range of 4–5 mm for structures to 2100 for A1B emission scenario, and 3–4 mm for 550 ppm stabilisation emission scenario (almost 50% drop in comparison with the A1FI emission scenario). In the circumstance of concrete structures at exposure A2, the cover increase is within 4–5 mm for structures to 2100 for A1B, and 3 mm for the 550 ppm stabilisation scenario.

In addition, if the mean urban CO₂ concentration factor is considered as 1.15 (or 15% increase) to account for elevated CO₂ levels in urban environments [27], then this increases cover requirements by up to 3 mm for structures designed to 2100. Hence, if the A1FI emission scenario is considered the most likely, then a 10 mm increase in design concrete cover might be recommended to offset the effects of a changing climate in circumstances where durability is governed by carbonation. The eventuality of a less severe emission scenario might result in lower additional covers, perhaps as low as 5 mm.

3.1.2. Chloride-induced corrosion

Unlike carbonation-induced corrosion, climate change has the most impact on chloride-induced corrosion of concrete structures designed for high environmental exposure, which is categorised as C, C1 and C2. The increase in cover that is required to counteract the impact of climate change to maintain the current level of damage risks designed for exposure C, C1 and C2 is only 4–6 mm and 2–3 mm for A1FI and 550 ppm emission scenarios, respectively (see Table 3). Concrete structures designed for Sydney and Canberra shows more sensitivity to a changing climate over time with a higher cover change requirement. This may be caused by the fact that temperatures in these areas are projected by the most GCM

Table 2
Minimum cover (mm) required to counteract the impact of climate change on carbonation-induced corrosion damage risks by 2100.

[illegible]

Table 3

Minimum cover (mm) required to counteract the impact of climate change on chloride-induced corrosion damage risks by 2100.

Exposure	Emission scenario	DAR	TOW	BRN	SYD	ADE	PER	MEL	CAN	HOB
C	A1FI	4.7	4.8	4.6	5.2	5.0	5.0	5.8	6.2	4.8
	A1B	4.0	4.2	4.0	4.5	4.5	4.5	4.5	5.6	4.0
	550 ppm	3.0	3.0	3.0	3.2	3.0	3.1	3.8	4.2	3.0
C1	A1FI	3.8	7.0	6.3	6.3	6.0	6.0	6.0	6.1	5.5
	A1B	5.8	5.6	5.0	4.8	4.7	4.5	4.7	4.8	4.4
	550 ppm	3.5	3.4	3.2	3.2	3.0	3.1	3.0	3.1	3.0
C2	A1FI	6.0	6.0	5.7	5.8	5.6	5.5	5.7	5.7	5.6
	A1B	4.7	4.8	4.5	4.5	4.5	4.5	4.5	4.8	4.6
	550 ppm	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.0

models to experience higher increases than other coastal urban centres. Meanwhile, the tropical climate in Darwin and Townsville also leads to higher covers than most of the coastal urban centres against the increasing risk of corrosion damage, especially for exposure C1. In Hobart, there is the lowest cover increase requirement among the urban centres (less than 2 mm), not only because of its cold climate but also due to the least sensitivity to climate change. Hence, if the A1FI emission scenario is considered the most likely, a 5 mm increase in design concrete cover will offset the effects of a changing climate in circumstances where durability is governed by chlorides.

3.2. Reducing diffusion coefficient and increasing strength grade

While the change of cover is considered as the most straightforward design approach to reduce the impact of changing climate, other options may also include the selection or design of concrete materials to reduce the diffusion coefficient of deleterious substances – i.e. slow the ingress of those substances, and hence delay corrosion of concrete reinforcement. Rather than giving details on the mix of cement or water/cement ratio, change of diffusion coefficient is taken as a proxy for the design of concrete materials to counteract a changing climate. In practice, selection of a higher strength grade of concrete is one approach to reduce the diffusion coefficient, in addition to enhancing its mechanical properties.

The use of a higher grade concrete in terms of high strength can slow down the penetration of carbon dioxide and chlorides as result of its reduced diffusivity. It therefore extends the time to corrosion initiation, and subsequently reduces the probability of corrosion damage. In fact, any measure to reduce the diffusion coefficient of carbon dioxide and chlorides will increase the adaptive capacity of concrete structures against a changing climate. One example would be the use of a high cement/water ratio and the increase of cement content. The use of the various cementitious materials, such as fly ash, ground granulated blastfurnace cement (ggbs), and silica fume, may also reduce the transport of deleterious agents in concrete due to reduced diffusion coefficient thus increasing the durability of concrete materials. However, fly ash and ggbs may increase the rate of carbonation [19].

3.2.1. Carbonation-induced corrosion

Fig. 7 shows the diffusion coefficient reduction required to maintain the current (no climate change) level of probability of carbonation-induced corrosion damage of concrete structures at three exposures for the A1FI emission scenario. The difference among the nine urban centres is moderate, so Fig. 7 shows results for Sydney and Darwin. As indicated in Fig. 7, the effect of emission scenario on diffusion coefficient reduction requirement is significant, with the highest emission scenario (A1FI) requiring an additional diffusion coefficient reduction of approximately 0.15 when compared to the low emission scenario (550 ppm) for three exposures indicating the significance of the impact of climate change.

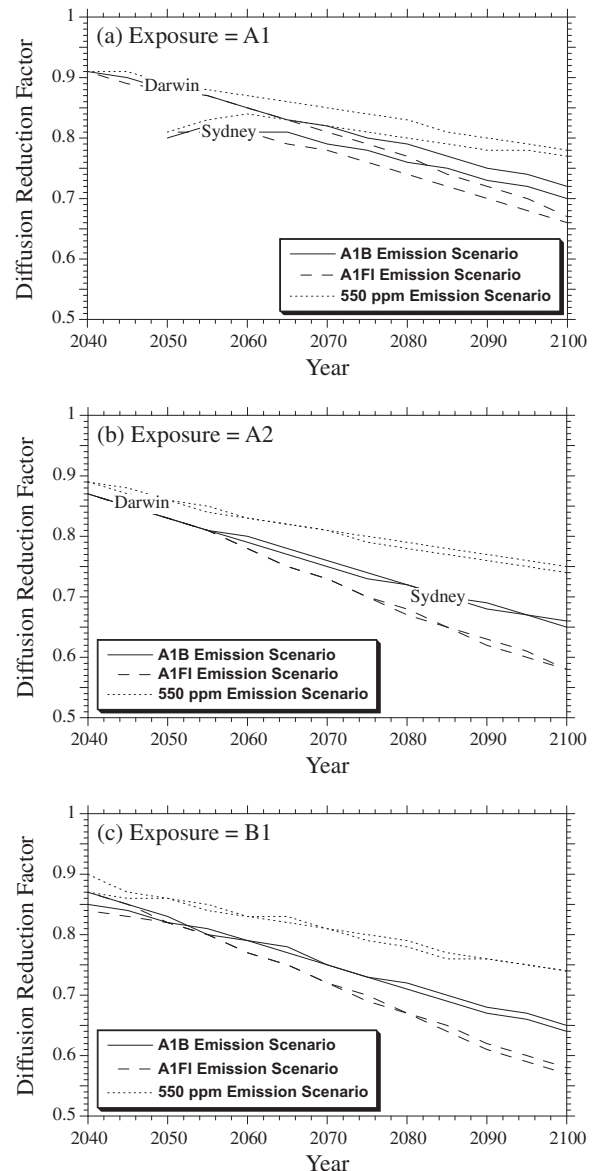


Fig. 7. Diffusion coefficient reduction factor for concrete structures to maintain the same probability of carbonation-induced corrosion damage at a given year for concrete structures that meet the requirement of AS3600 for exposures A1, A2 and B1 without consideration of climate change, for Sydney and Darwin.

In addition to the reduction of water/cement ratio and increase of cement content, selection of a high strength grade of concrete is a practical option that can meet the reduction requirement of diffusion coefficient. For example, concrete currently designed to

exposure A2 ($F'_c = 25$ MPa) might require 32 MPa strength concrete (as specified for B1) to reduce the effects of climate change. As shown in Fig. 8, the selection of a strength grade of concrete higher than the design required reduces the probability of carbonation-induced corrosion damage in Darwin under a changing climate (A1FI emission scenario). For example, the use of higher strength grade of concrete (exposure B1) will reduced the corrosion damage risk at exposure A2 from 3.4% to 1.1% by 2040, from 12.4% to 5.1% by 2070, and from 29.1% to 13.3% by 2100. Clearly, Fig. 8 shows that

increasing the strength grade by one grade for exposures A1, A2 and B1 significantly reduces damage risks to below current levels.

For all nine urban locations the probability of corrosion damage is significantly reduced when increasing one level of strength grade of concrete structures. Hence, the minimum strength grade required to counteract the impact of climate change is not sensitive to the location. Moreover, the recommended increase in concrete strength grade is not affected by the emission scenarios. Table 4 shows the minimum exposure level on which concrete structures should be currently designed to counteract the changing climate in the future. Similar results are obtained when the criterion is probability of corrosion initiation.

3.2.2. Chloride-induced corrosion

For concrete structures designed to service by 2040 at exposure C, a minimum 2–3% reduction in diffusion coefficient is required. For structures designed to service by 2070 and 2100, the minimum reduction will be in the range of 4–8% and 5–10%, respectively. For concrete structures at exposure C1, the reduction of the diffusion coefficient is 4–5% for structures designed to service by 2040, 5–8% for structures to service by 2070, and 6–12% for structure to service by 2100. For exposure C2, it is 3–5% for structures to service by 2040, 5–7% for structures to service by 2070, and 6–12% for structures to service by 2100. The reductions in diffusion coefficient are significantly less than that reported above for carbonated concrete.

One indirect option to reduce the diffusion coefficient is to select a higher concrete strength grade. Considering concrete structures designed for exposure B1, the chloride-induced corrosion damage probability is reduced from 0.14% to 0.08% by 2100 when concrete strength grade for exposure B2 is applied, for the A1FI emissions scenario for Darwin. It is similar for concrete designed for exposure B2 where the probability of corrosion damage drops from 0.8% to 0.45% when the strength grade for exposure C is selected.

In general, 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 to counteract the impact of changing climate, especially for concrete infrastructure with a long service life. These conclusions prevail for concrete structures in all discussed nine urban centres considering the three emission scenarios.

3.3. Surface coatings

Creating a surface barrier by a coating may be more appropriate for reducing the exposure of concrete structures to external stimuli. Meanwhile, chloride extraction and cathodic protection is more commonly carried out during service life to reduce the ingress of deleterious agents.

Table 4

Exposure indicator for the minimum strength grade required to counteract the impact of climate change on carbonation-induced corrosion damage.

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

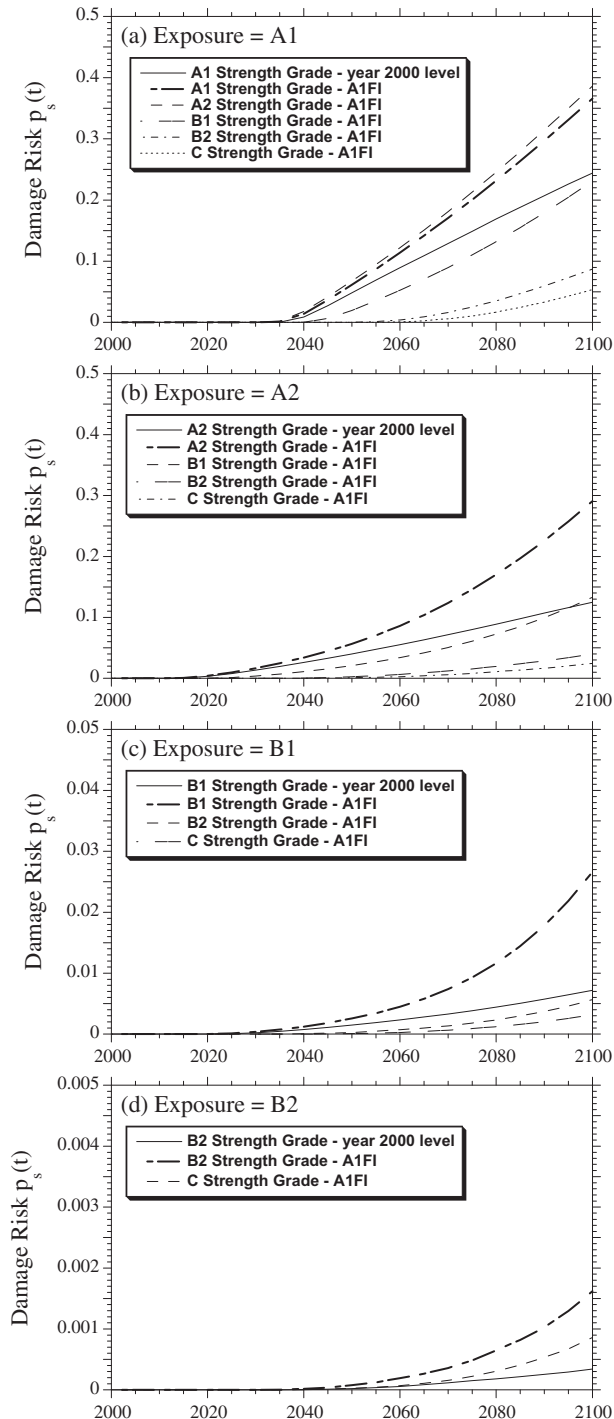


Fig. 8. Probability of carbonation-induced corrosion damage of concrete structures in exposure A1, A2, B1 and B2 in Darwin under climate change (A1FI emission Scenario), with a given strength grade of concrete that meets the requirement for higher exposure in AS3600 (The probability is represented by decimal numbers).

Acrylic-based surface coatings can reduce carbonation depths by 10–65% [14], whereas Swamy et al. [29] reported a 60–83% reduction in carbonation depth after two and a half years of testing. Moreno et al. [17] found an 85% reduction in carbonation depth after 64 days for acrylic and ‘good quality’ vinyl-acrylic coatings, but that most vinyl-acrylic coatings had smaller reductions in carbonation depth. If the treatment is uniformly applied with the minimum number of defects then the reduction in carbonation depth can be considerable. Since a comprehensive model for the effect of surface coatings on carbonation is not available the present section will focus on surface coatings to mitigate chloride-induced corrosion.

Surface treatments are often applied to reduce the concrete deterioration, basically by creating a barrier to retard chloride penetration. Similar to a series impedance model, the equivalent diffusion coefficient of the surface barrier and concrete cover is [8]:

$$D_e = \frac{T_c + T_{ST}}{\left(\frac{T_c}{D_c} + \frac{T_{ST}}{D_{ST}}\right)} \quad (2)$$

where T_c is the concrete cover (mm), T_{ST} the thickness of surface treatment (mm), D_c the chloride diffusion coefficient without surface treatment, D_{ST} the chloride diffusion coefficient of surface treatment

Table 5 gives the parameters applied to simulate the effect of three types of coatings to impede chloride penetration.

It should be noted that the results based on this model are very much preliminary due to lack of sophisticated coating models. This may lead to inaccurate simulation of chloride penetration and corresponding corrosion initiation and damage. In reality, the effectiveness of surface coating not only depends on the diffusion coefficient and coating thickness, but also on the ageing factor. Therefore, rather than taking these results to be conclusive, they are considered to be a guide only. In fact, this requires further thorough investigation. In addition, it is assumed that the coating is always maintained intact over the discussed time period in the simulation.

Fig. 9 shows the chloride-induced corrosion damage probability in Adelaide for different coatings, for exposures C, C1 and C2 and A1FI emissions scenario. By applying a 2 mm thick silane coating to concrete structures for exposure C, the probability of chloride-induced corrosion damage drops from 27.9% to 13.0% by 2100, for emission scenario A1FI in Adelaide. For exposure C1, the probability of corrosion damage is reduced from 0.8% to 0.1% by 2100. For exposure C2, the probability of corrosion damage is reduced from 16.6% to 6.6% by 2100.

By applying a polyurethane sealer 0.02 mm thick on concrete structures for exposure C, the probability of chloride-induced corrosion damage drops from 27.9% to 6.9% by 2100, for emission scenario A1FI in Adelaide. For exposure C1, the probability of corrosion damage is reduced from 0.8% to 0.02% by 2100. For exposure C2, the probability of corrosion damage is reduced from 16.6% to 3.1% by 2100. For a polymer-modified cementitious coating with 1.5 mm thickness, the probability of corrosion damage is reduced to a negligible amount for all exposures. The results described herein are similar for A1B and 550 ppm stabilisation emission scenarios and for all urban centres.

Table 5

Parameters selected for the simulation of surface treatment for chloride penetration [8].

Surface treatment	T_{ST} (mm)	D_{ST} (10^{-12} m ² /s)
Polyurethane sealer	0.02	1.4×10^{-3}
Silane	2	2.5×10^{-1}
P-m (polymer modified) cementitious coating	1.5	6.3×10^{-3}

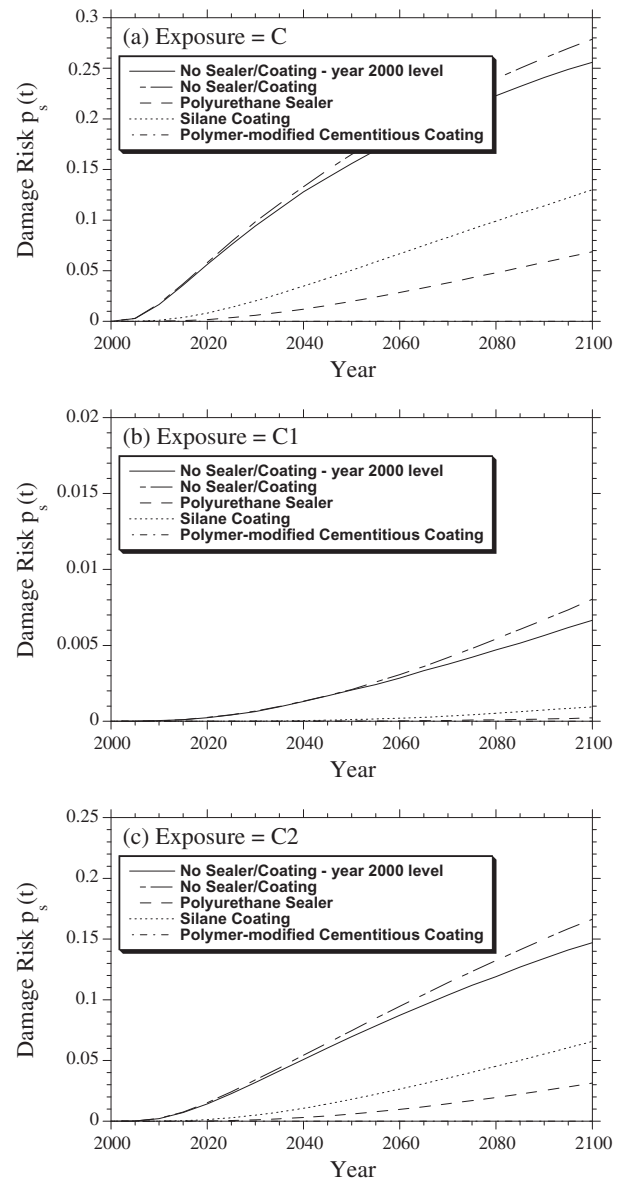


Fig. 9. Chloride-induced corrosion damage probability in Adelaide for different coatings, for exposures C, C1 and C2 and A1FI emissions scenario.

Clearly, all three kinds of coating specified in Table 5 are able to reduce the probability of chloride-induced corrosion to no more than the probability of corrosion damage without the effect of climate change. In other words, assuming that all three surface coatings are maintained in a good performance over the service period of concrete structures, they are capable of counteracting the impact of climate change.

3.4. Other adaptation measures

There are other adaptation measures that may be suitable to ameliorate the effects of a changing climate. This includes stainless steel and galvanised reinforcement, corrosion inhibitors, electrochemical chloride extraction, and cathodic protection. Their cost and effectiveness vary. For example, stainless steel bars are about six to nine times more expensive than carbon steel reinforcing bars, but a life-cycle cost analysis of deteriorating structures found that they may be cost-effective in some circumstances [30]. Moreover, it is also worth noting that the cost of reinforcing steel or

corrosion inhibitor is only a small fraction of overall initial construction costs, thus, the replacement of carbon steel reinforcement by stainless or galvanised steel or addition of corrosion inhibitors to concrete should result in a rather moderate increase in the overall initial costs. This also applies to other adaptation measures implemented during the design phase of a project. The effectiveness of typical adaptation measures is briefly reviewed; however, it is recognised that the effectiveness is often dependent on concrete material properties and the environment.

3.4.1. Carbonation-induced corrosion

The protective film which surrounds stainless steel is stable at alkaline to neutral environments, and so stainless steel will not corrode in carbonated concrete [20,25]. On the other hand, there is little quantitative information about the performance of galvanised steel in carbonated concrete. Sistonen et al. [25] found that corrosion rate of galvanised steel did not change in carbonated concrete when compared to carbon steel. However, Bentur et al. [6] observed that corrosion rate increased in non-carbonated concrete, but then decreased when concrete was carbonated. Corrosion inhibitors (calcium nitrite or organic based) appear to have no noticeable effect on CO₂ penetration or corrosion rate.

3.4.2. Chloride-induced corrosion

Since chloride-induced corrosion is typically more widespread and severe than carbonation-induced corrosion there is more research and field data for methods to mitigate chloride-induced corrosion. Stainless steel is an effective adaptation measure, with Williamson et al. [37] suggesting that the critical chloride concentration is 10–50 times higher than that for carbon steel. Corrosion rate is observed to be reduced by a factor of 50 [13,25]. Galvanised steel has a critical chloride concentration 2–3 times higher than that for carbon steel, and since corrosion products are less voluminous than carbon steel then concrete is also less likely to crack [37]. The corrosion rate for galvanised steel is also reduced by approximately 40% [25].

Electrochemical chloride extraction removes some chlorides from the concrete cover. However, its effectiveness is variable, with reduction in chloride content varying from 20% to 90% [23,24,31]. Chloride extraction will also lower corrosion rate by 60–90% [31], and Broomfield [7] states ‘very low corrosion rates’ even if chloride levels are above the critical chloride content.

Calcium nitrite based corrosion inhibitors increase chloride threshold, reduce corrosion rate, but may increase chloride transport and slightly reduce strength (e.g., [2]). However, Ormellese et al. [21] found that nitrate and organic admixed inhibitors reduced diffusion coefficient by a factor of 2–4, with only a marginal (if any) increase in critical chloride level.

4. Discussion

The results presented are based on durability design specifications of AS3600-2009 and AS5100-2008, which relate to minimum concrete cover and concrete compressive strength only. It is important to note that, for a specific structure, accurate results in terms of climate change impact and damage risks can be obtained only by considering structural typology, structural detailing, structure orientation, and other structure specific information. It is also worth noting that even under an optimistic emission scenario (550 ppm stabilisation by 2100), the increase in damage risks will still be significant and cannot be ignored, particularly for carbonation-induced corrosion of structures with low cover or durability. This increase in damage risks is driven more by increases in CO₂ con-

centration in which there is high confidence, and less by the less accurate projections in temperature and relative humidity.

The results suggest that if concrete structures in non-coastal locations are designed with up to 10 mm extra concrete cover or use higher grade concrete then this will ameliorate the effects of climate change if the worst emission scenario (A1FI) is deemed likely to occur. The eventuality of a less severe emission scenario might result in lower additional covers, perhaps as low as 5 mm. In circumstances where durability is governed by chlorides, a 5 mm increase in design concrete cover is suitable for the A1FI emission scenario. Increasing design cover by up to 10 mm or increasing concrete compressive strength by one grade would increase construction costs by approximately 1–3% (e.g., [30]), but has the potential to save billions per year in damages. Protective surface coatings are also very efficient, but their cost may be prohibitive.

So far, climate change impact and adaptation have been discussed in the context of designing new concrete structures. Many existing concrete structures, for which design did not take into account the effect of a changing climate, are likely to suffer from decreased durability as a consequence of climate change. 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 maintenance of concrete structures would be wise. Clearly, the costs and benefits of such an approach, which will vary widely by location, and a cost-benefit assessment is essential for efficient practical implementation.

An economic assessment of design adaptation measures including increased cover, increased concrete mix durability, galvanised or stainless steel reinforcement, and coatings is essential in order to better manage concrete infrastructure over the next 100 years. In some cases, it may be optimal to ‘do nothing’, or to defer adaptation decisions to a later date when there is more certainty about emission and climate projections or if new materials or technologies become available. A preliminary cost-benefit assessment of adaptation measures is described by Stewart and Peng [26], but there is much scope for further research. The extent of required maintenance and repair to maintain current levels of existing concrete structure durability will be reported from our on-going research.

5. Conclusions

Increases in CO₂ concentration and changes in temperature and humidity associated with climate change will accelerate reinforcement corrosion that will affect the safety and serviceability of concrete infrastructure in Australia, US, Europe, China and elsewhere. A detailed spatial and time-dependent probabilistic analysis showed that additional carbonation-induced and chloride-induced damage risks may increase by 16% and 3%, respectively, by 2100. This suggests that up to one in six structures will experience additional and costly corrosion damage by 2100. We show that the impact of climate change on infrastructure deterioration cannot be ignored, but can be addressed by changes to design procedures including increases in cover thickness, improved quality of concrete, and coatings and barriers. It was found that an increase in design cover of 10 mm and 5 mm for structures where carbonation or chlorides govern durability, respectively, will ameliorate the effects of a changing climate. Moreover, increases in concrete strength grade or the application of coatings or barriers will reduce the diffusion coefficient significantly and improve the performance of concrete infrastructure to a changing climate.

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