Cement & Concrete Composites 34 (2012) 931–935

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Carbonation in concrete infrastructure in the context of global climate change: Part 2 – Canadian urban simulations

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ARTICLE INFO

Article history:
Received 18 October 2011
Received in revised form 21 April 2012
Accepted 24 April 2012
Available online 11 May 2012

Keywords:
Concrete
Carbonation
Degradation
Climate change
Durability

ABSTRACT

In Part 1 of this paper, a carbonation model was developed and experimentally verified which was able to forecast carbonation depth of a concrete specimen considering varying ambient temperature, humidity and CO_2 concentrations.

Part 2 of the paper applies the carbonation diffusion/reaction model developed in Part 1 to predict the effects of global climate change on the carbonation of concrete. Climate scenarios were formulated and combined with the model for two major Canadian cities, Toronto and Vancouver. Results show that for undamaged and unstressed concrete, climate change will significantly affect carbonation progress. The model showed that for unloaded, non-pozzolanic concrete, ultimate carbonation depths in Toronto and Vancouver could be up to 45% higher. For in-service structures under load, the rates of deterioration are likely to be even faster. This is a cause for concern, and much further effort must be devoted to fully understand these phenomena.

1. Introduction

One of the more significant effects of global climate change may be to increase rates of deterioration of reinforced concrete structures due to carbonation-induced corrosion. A model was developed in Part 1 [1] which addressed the shortcomings mentioned with previous carbonation models [2,3]. This model is used in this paper to evaluate possible future climate scenarios. Further details about the model and its development can be found in Part 1 [1].

Limited work has been carried out on the effects global climate change may have on the structural integrity of our concrete infrastructure, mainly because the problem has only been recently recognized. The work done by Yoon et al. [2] and Stewart and Ping [3] was summarized in Part 1 of this paper. Additionally, Bastidas-Arteaga et al. [4] have looked at the influence global warming may have on chloride ingress into concrete. A stochastic model of chloride penetration, and corrosion initiation was developed and evaluated. Of particular interest was their approach to model future weather conditions, recognizing that temperatures will fluctuate not only over the century, but also during a given year, and that the duration of the hot season throughout most of the world is expected to increase with time. In this paper, the improved carbonation model developed in Part 1 was coupled to the climate model proposed by Bastidas-Arteaga et al. [4] to provide insights into what may happen to concrete infrastructure in the future.

2. Climate scenarios and results

In developing the climate model for this study, temperature changes, CO_2 concentrations, and relative humidity levels were accounted for, as these are likely to have the most direct effect on concrete deterioration. Rainfall amounts would affect erosion/abrasion of concrete surfaces, as well as diffusion of pollutants into the subsurface. However the actual effects of rainfall on a concrete structure are highly site specific, as rainfall, surface temperatures, and surface impact depend on the orientation of the site, as well as any shelter provided to the surface. Therefore, for simplicity, the effect of rainfall is ignored in the climate model of this paper. The Canadian cities of Vancouver and Toronto are chosen for analysis. These are both major Canadian urban centers, but they have different climates. Vancouver is located on the west coast of the country and has a coastal climate, whereas Toronto lies in the eastern portion of the country, and has a more continental climate.

2.1. CO_2 concentrations

The two locations being considered, Vancouver and Toronto, as urban centers, will have higher than average CO_2 concentrations.

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http://dx.doi.org/10.1016/j.cemconcomp.2012.04.012

Idso et al. [5] reported urban CO_2 concentrations of approximately 67% higher in the urban city center of Phoenix, AZ, compared to the outlying rural areas, and noted the presence of an urban CO_2 dome. George et al. [6] also reported atmospheric CO_2 as being consistently and significantly increased on average by 66 ppm (approximately 15%) from rural to urban areas in and around the city of Baltimore, MD. George et al. [6] also reported on a variety of urban centers, where the average concentration was 5–30% higher than in nearby rural environments. Therefore, in their models, they employed an 'Urban Environment Factor' of 1.15, thereby increasing concentrations in urban centers by 15%. Based on CO_2 concentration data provided by the Special Report on Emissions Scenarios (SRES) (storylines A1FI, A2, B1, B2) [7], as well as including the original Intergovernmental Panel on Climate Change (IPCC) data for IS92a [7], projected CO_2 increases based on the data after applying the Urban Environment Factor of 1.15 are provided in Fig. 1 for the BERN carbon cycle model starting from the year 2000:

The worst case scenario to consider, therefore, is Scenario A1FI (Scenario α) which shows the highest projected increase in CO_2 concentrations over 100 years. The best case scenario is Scenario B1 (Scenario β) which projects the lowest increase in CO_2 concentrations over 100 years. In addition, we will consider a third control scenario in which CO_2 concentrations are held constant at present day concentrations (Scenario γ). Concentrations in ppm can be converted into molar concentrations considering ambient temperatures and assuming Ideal Gas Behavior. Regression equations can then be developed to describe how CO_2 levels will increase over time.

2.2. Temperature predictions

Originally, local temperatures were to be predicted using data generated from the Canadian Center for Climate Modelling and Analysis (CCCma), and their third generation coupled climate model (CGCM3.1) [8] for each of the SRES and IS92a emissions scenarios. However, this approach was abandoned, as the surface resolution for this model was insufficient, and the results would not be representative for Vancouver or Toronto. Sufficient resolution is important, as carbonation is highly dependent on site conditions. Rather, the change of temperature produced by global warming for coming years is modeled using a simplified approach which considers changes in mean global temperature and seasonal variations of weather parameters which are down-scaled and localized to a particular city through a linear time-variant function, based on work of Bastidas-Arteaga et al. [4]. The local mean yearly temperature is expected to increase at the same rate as the global yearly mean does due to global warming, while the seasonal temperature fluctuates yearly around this increasing mean, with a peak during the annual hot season (period when temperatures exceed the yearly mean), and a trough during the annual cold season (when temperatures fall below the yearly mean). In addition, it is recognized that over time, the duration of the hot season is expected to increase, while that of the cold season decreases.

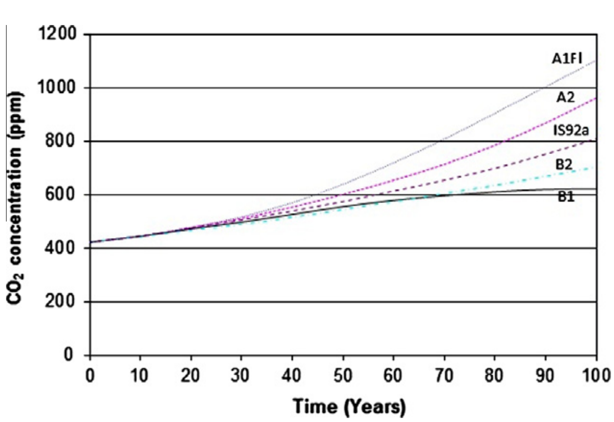

Fig. 1. Projected global CO_2 concentrations for urban centers.

The IPCC Third Assessment Report [9] provides the results of expected global mean increases in temperature for a Simplified Climate Model (SCM). Based on these SCM results, equations were developed to predict the mean yearly temperature for the cities of Vancouver and Toronto, starting from the year 2000, over the next 100 years (Fig. 2).

We define the equations for mean yearly temperatures in Vancouver and Toronto by the function:

$T(t)$

Vancouver:

$$\text{Scenario } \alpha \quad T(t) = -5E - 06t^3 + 0.0009t^2 + 0.0045t + 283.3 \tag{1}$$

$$\text{Scenario } \beta \quad T(t) = -7E - 07t^3 + 2E - 05t^2 + 0.0248t + 283.3 \tag{2}$$

$$\text{Scenario } \gamma \quad T(t) = 283.3 \tag{3}$$

Toronto:

$$\text{Scenario } \alpha \quad T(t) = -4E - 06t^3 + 0.0008t^2 - 0.0066t + 282.4 \tag{4}$$

$$\text{Scenario } \beta \quad T(t) = -1E - 06t^3 + 0.0002t^2 + 0.0132t + 282.4 \tag{5}$$

$$\text{Scenario } \gamma \quad T(t) = 282.4 \tag{6}$$

where t is time in years, and T is in °K. To model seasonal fluctuations, a sinusoidal function can be used with an amplitude ϕ corresponding to the yearly deviation of the maximum and minimum temperature from the mean. Based on historical annual temperature data from Environment Canada [10], the following yearly amplitudes were determined

Vancouver: ϕ = 7.2°
Toronto: ϕ = 13.2°

where ϕ is the temperature amplitude in °K. Thereafter, temperature fluctuations are represented graphically in Fig. 3:

Additionally, the change in the duration of the seasons is assumed to be linear [4], so that:

$$R(t) = R_0 + \left(\frac{\Delta R}{t_a}\right)\lfloor t \rfloor \tag{7}$$

where $R(t)$ is the duration of a season at a point in time (years), R_o is the duration of the season in the year 2000 (0.5 years), ΔR is the change in duration of the season over 100 years, t_a is the time over which climate change is considered (100 years), and $\lfloor t \rfloor$ is the floor function of time.

The change in duration is generically illustrated in Fig. 4:

Notice that towards the end of the time duration, the length of the cold season has decreased ($R_0 > R_{100}$), while that of the hot season has increased. Additionally, the mean temperature has now increased at the end of the time span compared to the initial time.

For the worst case scenario, the expected change in duration of the hot season (ΔR) was an increase between 0.16–0.22 years [4] while for the best case scenario, the expected increase was between 0.06–0.14 years [4]. Based on these values, the expected change in the duration of the hot season to be used in this model for the worst case scenario was taken as +0.2 years while that for

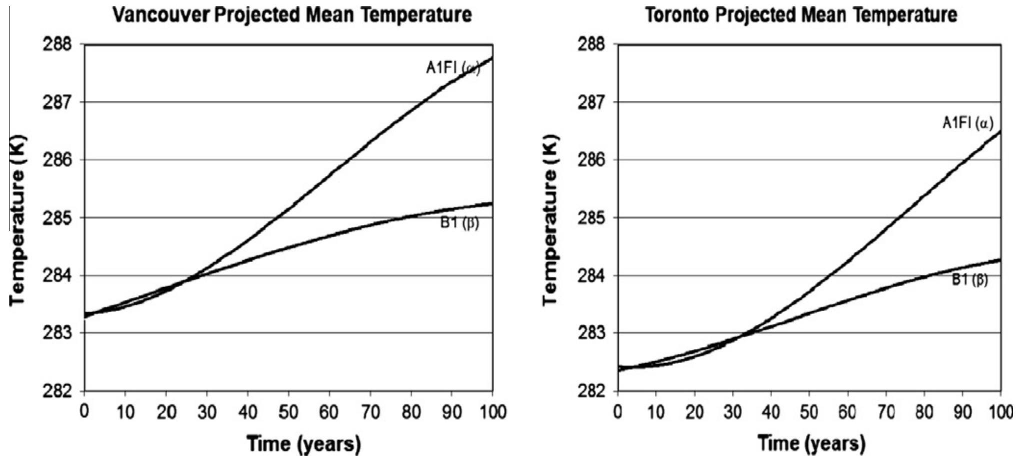

Fig. 2. Projected mean annual temperature increases for Vancouver and Toronto.

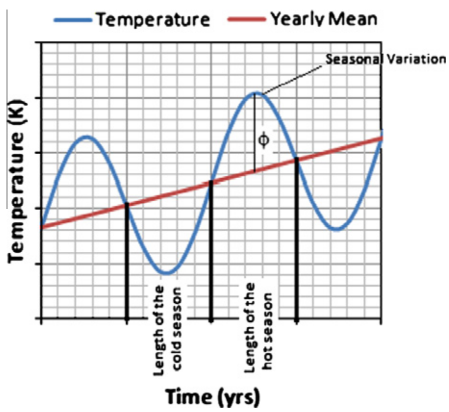

Fig. 3. Projected temperature fluctuations for an urban center.

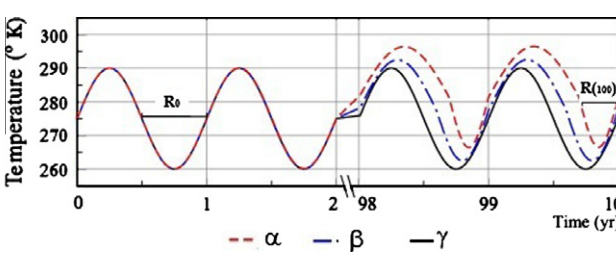

Fig. 4. Change in seasonal duration over time [4].

the best case scenario was assumed to be +0.1 years. For the control, there will be no change in durations.

Finally, the equations for temperature for the cities of Vancouver and Toronto taking into account seasonal fluctuations varying around a mean yearly temperature, with a linear decrease in the length of the cold season over time can be represented [4] by:

$$K(t) = T(t) + \phi \sin\left(\frac{t - \lfloor t \rfloor}{1 - R(t)}\pi\right) \quad (8)$$

where K is in °K. The final equations $K(t)$ for the A1FI (α) and Control (γ) scenario for Vancouver are shown in Figs. 5 and 6:

Fig. 5 clearly shows that as yearly temperatures fluctuate around the mean, the mean yearly temperature gradually increases over the course of the century. The same result occurs for the Toronto scenarios.

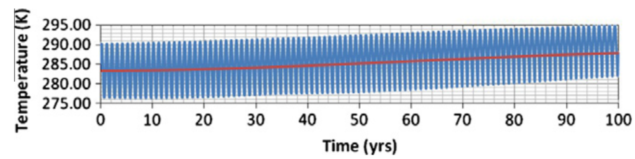

Fig. 5. Vancouver: scenario α. $T(t) = -5E - 06t^3 + 0.0009t^2 + 0.0045t + 283.3$, $\phi = 7.2°$, $\Delta R = 0.2$.

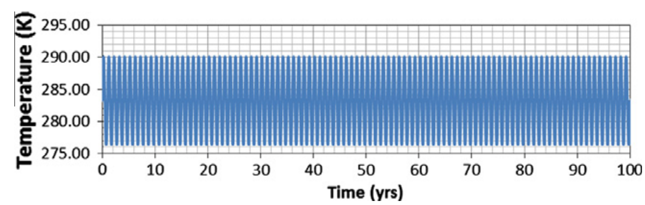

Fig. 6. Vancouver: scenario γ. $T(t) = 283.3$, $\phi = 7.2°$, $\Delta R = 0$.

2.3. Relative humidity predictions

Trends in relative humidity over the next hundred years have been a source of contention amongst climate researchers for many years. Global warming increases the evaporation from the ocean and from many land areas, leading to an increase in atmospheric water vapor content. As the global climate has warmed during the last several decades, constant global relative humidity has been observed, so within global climate modeling of future scenarios of climate change, constant relative humidity is generally assumed [9,11]. However, not all researchers agree with this assumption. Vuille et al. [12] and Sperling et al. [13] have predicted increases in relative humidity of between 0% and 2.5% per decade. An analysis of historical trends in relative humidity in Canada, however, shows that between 1950 and 2000 there was an overall decrease in average relative humidity across the country of 6% [14].

Ultimately, given that the current generation of climate model projections make the assumption of constant relative humidity, and that they are used as the basis for all major climate change studies including the IPCC Assessment Reports [9,11], we have adopted this assumption for our study, with the relative humidity remaining constant at the mean values from the year 2000. Based on local weather data, the mean relative humidity in Vancouver is taken as 78.5% and in Toronto is taken as 73.2%.

3. Results

The equations for CO_2 concentrations, Temperature and Humidity for the Scenarios labeled α, β, γ were input into the carbonation model developed in Part 1 for Vancouver and Toronto. Predictions starting from the year 2000 are shown in Figs. 7 and 8.

From these figures, climate change is predicted to have a noticeable effect on carbonation occurring in non-pozzolanic, unloaded concrete structures. Results showed that for Vancouver, for the worst case scenario, carbonation depths would be approximately 5 mm greater after 100 years, increasing by ~45% from 11 mm to 16 mm. For Toronto the results are even more severe, with depths increasing from 16 to 23 mm. As Toronto has a slightly less humid environment, penetration of CO_2 into the concrete pore space is easier. The effects of climate change are predicted to become noticeable after about 30 years. At approximately 30 years, we notice that the climate change effects of scenarios α and γ begin to cause carbonation depths to noticeably divert from the control case. This is to be expected, as, over time, the magnitude of the temperature increase becomes greater, and the hot seasons become longer.

In order to check whether the predicted carbonation depths and diffusion coefficients were reasonable, the data were compared with data from previous studies. First, the diffusion coefficient simulated varied with temperature and humidity, and the simulated values of 10×10^{-4}–30×10^{-4} cm^2/s are in reasonable agreement with previous studies (5×10^{-4}–50×10^{-4} cm^2/s) for average quality concrete [15].

Secondly, the predictions from this simulation were compared to those from Yoon et al. [2]. It has been mentioned in Part 1 that there are some major differences in the carbonation model used in that study. However, as a basic reference when comparing the results of this study to their results for the city of Seoul, South Korea, the results appear to be reasonable, as for a *w*/*c* ratio of 0.5, for their climate change scenario, a carbonation depth of 16–17 mm was estimated after 100 years. The realistic values estimated for the diffusion coefficient, along with the reasonable values obtained for carbonation depths when compared to Yoon et al. [2] support the applicability of our model to the carbonation problem.

In terms of the practical effects of this simulation, it seems that at least in the short term, climate change will not affect the structural integrity of concrete via carbonation-induced corrosion, as rebar is usually covered by depths greater than 25 mm in concrete. However, it is important to remember that the simulation looked at unloaded/undamaged concrete. Diffusion coefficients of deleterious species into cracked concrete would be significantly higher, as demonstrated by Sappakittipakorn [16]. Therefore, the effects of loading and cracking need to be accounted for experimentally before the simulation is rerun to determine the full threat of climate change on accelerating carbonation-induced corrosion. Finally, it should be noted that the climate model utilized here is non-probabilistic. In fact, weather patterns will fluctuate over the next century on a yearly basis. Therefore, in order to account for extreme weather events, or years where weather conditions are more mild, a probabilistic approach would be warranted, similar to Stewart and Ping [3].

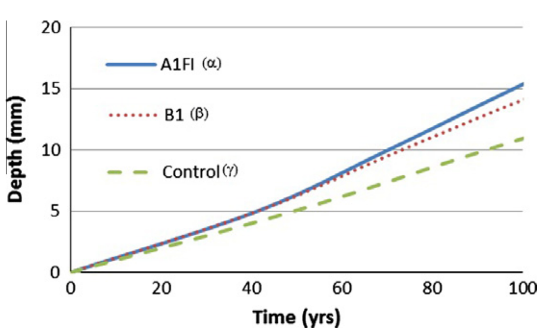

Fig. 7. Carbonation depth vs time for Vancouver.

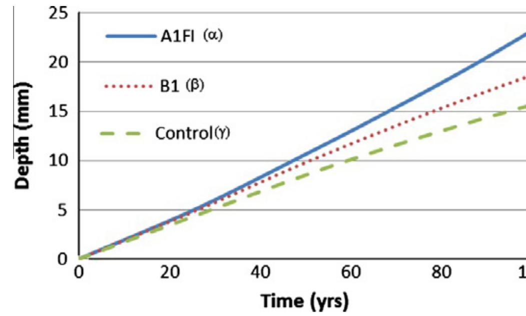

Fig. 8. Carbonation depth vs time for Toronto.

4. Conclusions and future work

Climate scenarios were developed for the cities of Vancouver and Toronto accounting for variations in atmospheric CO_2 concentrations, temperature and humidity to be combined with the carbonation model developed in Part 1. Seasonal fluctuations in temperature are included, along with a lengthening of the hot season over time. Simulations were then run for these two cities to predict the effect of global climate change on the progress of carbonation-induced corrosion in non-pozzolanic, unloaded concrete. The effects are predicted to be quite significant, with potential increases in carbonation depths over 100 years of approxi- mately 45%. Carbonation depths are predicted to be greater for Toronto than for Vancouver due to the higher relative humidity of the latter.

While the results show that there may not be any practical effect on short term structural integrity of concrete, structures which are cracked or under load are likely to show significantly less time to the onset of carbonation-induced corrosion. Therefore, the simulation model should be extended to account for the effect of loading and cracking before a final assessment can be made.

Ultimately, the goal is to produce a 'full-life model', which could be used with future weather scenarios of various cities around the world to predict the effects of global climate change on accelerating carbonation induced corrosion on damaged and undamaged concrete, from the initiation phase, through the propagation phase, and to cracking, spalling and ultimate failure.

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