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Urban scale mapping of concrete degradation from projected climate change

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ABSTRACT

Anthropogenic increases in atmospheric greenhouse gas (GHG) concentrations and resultant changes in climate will have significant detrimental effects to urban infrastructure, from both extreme events and longer-term processes. Here we investigate impacts to concrete structures due to enhanced corrosion through increases in carbonation and chlorination rates. High and low emission scenarios (IPCC A1FI and B1) are used in combination with downscaled temperature projections and code-recommended material specifications are used to model carbonation and chloride-induced corrosion of concrete structures in the Northeast United States. The results suggest that current concrete construction projects will experience carbonation and chlorination depths that exceed the current code-recommended cover thickness by 2077 and 2055, respectively, well within the lifetimes of these buildings, potentially requiring extensive repairs. Geospatial modeling in the Boston metropolitan area is used to project building and block-level vulnerability of urban concrete structures to future corrosion, and related maintenance needs, and to project cover thickness degradation for the existing building stock. The methods described here can be used for city-specific modeling of long-term climate impacts on concrete infrastructure and provide a scientific basis for future-oriented construction codes.

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1. Introduction

Understanding the implications of climatic variation has become a critical issue for infrastructure maintenance planning. The Earth's average temperature has been increased by 0.6 °C since the 1900s and is expected to increase by approximately 1.4–5.8 °C by the end of this century (McMichael et al., 2006). Many of the effects of climate change, including changes in temperature, pollutant concentrations, relative humidity, precipitation, and wind patterns, as well as increased frequency of severe events could have significant impacts on the operations and lifespan of critical and non-critical infrastructure (Rosenzweig et al., 2011). Infrastructure capacity could be acutely overwhelmed (e.g., sea walls failing due to storm surge) or degraded gradually. Assessing the potential impacts of climate change on the built environment is difficult, as the relationship between material degradation and climate is complex (Cole and Paterson, 2010). The Northeastern United States is likely to see an increase in extreme precipitation events as well as overall increases in temperature and relative humidity (Stocker et al., 2013).

Climate-induced damages to urban infrastructures are of particular concern. Urban areas in the United States currently include approximately 250 million residents, projected to grow to ~365 million by 2050 (U.S Census Bureau, 2010). While the urban share of population and economic output in the US has grown in the past decades, much of the existing urban infrastructure has become increasingly susceptible to failures (Solecki and Marcotullio, 2013; Wilbanks, 2012). Aging buildings and transportation, energy, water, and sanitation infrastructure are all expected to become more stressed in their ability to support existing services for urban residents in the coming decades, especially when the impacts of climate change are added as stressors (McCrea et al., 2011). Climate change will also contribute directly to physical degradation of infrastructure and building materials (Nijland et al., 2009).

While much research on climate change impacts has focused on infrastructure susceptibility to extreme events and flooding from long-term sea level rise (Anderson and Boesch, 2009), relatively few studies have been carried out on the direct effects of climate change on the structural deterioration of infrastructure. One direct mechanism is acidic attack of cementitious materials. Concrete degradation due to acid rain has been extensively studied (Zivica and Bajza, 2001), and elevated levels of atmospheric CO_2 will increase the formation of carbonic acid in precipitation. Similarly, uptake of CO_2 by the oceans and the resulting decrease in pH will amplify degradation of structures in urban coastal areas that are exposed to seawater (Greaver et al., 2012).

Another mechanism for climate-induced concrete degradation is through early failure of the protective concrete cover over reinforcing steel, leading to corrosion and spalling, due to changes in CO_2 and temperature (Talukdar et al., 2012a; Mehta and Monteriro, 2006), which has only recently been analyzed. Yoon et al. (2007) was among the first to consider the effects of climate change on concrete performance and lifetime, in particular the effect on carbonation rates; however, this model does not account for the influence of temperature change, which can significantly affect the diffusion coefficient of CO_2 into concrete, the rate of reaction between CO_2 and $Ca(OH)_2$, and the rate of dissolution of CO_2 and $Ca(OH)_2$ in pore water. The model is also a time-independent predictive model that assumes CO_2 concentrations to be constant up to a given time, thereby underestimating carbonation depths under changing atmospheric conditions (Stewart and Peng, 2010). Stewart et al. (2011) built on the work by Yoon et al. (2007) by taking into account the effect of temperature on the diffusion coefficient, but they did not consider the influence of temperature on the other aforementioned parameters. Their work looked not only at carbonation and chlorination, but also at the time to crack initiation, crack propagation, and failure due to reinforcement corrosion. Similar carbonation and chlorination models were used by Stewart et al. (2011) in their work, who noted that there is a need for an improved model that considers the time-dependent effect of CO_2 concentration and other parameters such as temperature and relative humidity.

Recently, Talukdar et al. (2012a) estimated carbonation (but not chlorination) penetration depths in concrete due to projected climate change. Several deterministic model parameters were experimentally verified using unloaded/undamaged concrete. They reported 25–35 mm increase in penetration depth due to carbonation alone. Separately, Bastidas-Arteaga et al. (2010) investigated the influence of