RILEM Technical Letters (2024) 9: 36-49
https://doi.org/10.21809/rilemtechlett.2024.191

Concrete Infrastructure: Recent Advancements and Needs with a Focus on North America

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Received: 06 December 2023 / Accepted: 17 October 2024 / Published online: 15 November 2024

Abstract

This letter provides an overview of the continent's diversity in geography and climatic exposure and the impact of chlorides on reinforced concrete structures in North America. Several research needs are identified, including those that arise as specifications begin to change from prescriptive to performance-based approaches. Further, the widespread changes in material compositions or chloride exposures, require important changes to specifications, design practices, or maintenance procedures. Related to reducing carbon emissions, there is a need to reduce clinker content in concrete mixtures, increase the use of novel cementitious and supplementary cementitious materials (SCM), and to understand the durability of such concretes. The following research efforts from a North American context are warranted: (i) investigating the long-term durability of novel cement and SCM systems, including non-Portland cement-based materials and those made with CO_2 mineralization used to meet carbon emission targets; (ii) understanding climate change impacts of temperature and sea levels, including flood impact, on chloride exposure and chloride-induced corrosion; (iii) developing rapid and reliable tests to estimate durability in practice, particularly for scaling, freeze-thaw, salt damage, and chloride-induced corrosion; and (v) developing better understanding of the short and long-term implications of changes in constituent materials and exposure.

Keywords: Low carbon concrete; Chlorides; Corrosion; Climate impacts; Codes/standards.

1 Introduction

North America is the third largest continent, spreading over 24 million sq. km and covering a latitude range from 15N to 90N [1]. North America has a variety of climates, from the dry and cold of the Arctic to the hot-humid marine exposures of the tropics, as shown in Figure 1. Other than the far north, with sub-zero temperatures and icecap coverings, and the far south, with hot and rainy low-lying areas, most parts of North America are cold in the winter and warm in the summer, with moderate precipitation levels that are favorable to human settlement [1]. Nevertheless, some areas possess short and mild winters with long and hot summers, while the opposite is true for other areas, resulting in distinct durability challenges and a need for measures for existing and new infrastructure that can resist varying local climates. North America is the fourth most populated continent with ~7.2% of the world's population and it is a high consumer of construction materials [2]. The latter is, in part, due to the distance between cities being considerably larger than, for example in Europe, requiring greater transportation facilities. Rapid urbanization is being experienced in North American countries; at the same time, infrastructure is aging and is vulnerable to climate related impacts (e.g., increased flooding, changes in water level, and fires) [2–7]. These changes have implications towards structural safety, but also to the cost associated with the repair and maintenance of these structures. Many structures are affected by chlorides from marine exposure, airborne chlorides along the coasts, and/or from de-icing salts used as snow and ice accumulate during the winter. Chloride exposure causes a variety of damage to the concrete, and/or to the reinforcing steel resulting in a reduced structural integrity. A compounding effect to this vulnerability is extreme weather events. Each year, the strong impact of meteorological phenomena, such as hurricanes and storms, is realized. These impacts affect parts of Mexico, USA, and Canada from both, the Atlantic and Pacific Ocean. The coupled and complex action of structural loads and environmental conditions, including chloride and carbonation, play a critical role on the durability and life of concrete infrastructure.

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6 Regions and 4 Seasons

Northern Hemisphere = Greenland, Canada, and most of United States have 4 distinct seasons:
- **Spring**: March, April, May
- **Summer**: June, July, August
- **Autumn**: September, October, November
- **Winter**: December, January, February

Southern Hemisphere = Mexico, Central America, Caribbean, southern United States have more constant temperature:
- **Wet season**: May to October
- **Dry season**: November to April.

Climate types

Coniferous Forest: Cold and dry with snowy winters and warmer summers

Deciduous Forest: 4 distinct seasons (cold winters, wet spring, warm summers, trees shedding autumn)

Alpine/Mountain: Cold, windy & snowy. Winter from October to May, Summer from June to September

Mediterranean: Warm to high temperatures with rainfall in the autumn and winter months.

Rainforest: High temperature and high rainfall all year

Grassland: Hot summers, cold winters, >50% rainfall

Tundra: layer of permafrost (soil that remained below freezing). Very cold winters, warm summers, some rainfall

Desert: Warm to high temp. with very little rainfall

Global Biomes data were obtained from the World Wildlife Fund (WWF) Terrestrial Ecoregions of the World dataset, in February, 2006. The data depict global terrestrial vegetation biodiversity patterns for the worlds' 825 ecoregions and 14 biomes. The data are distributed in vector format, which were created to be used at the scale of 1:1 million. CIESIN converted the data to raster grid format at a 30 arc-second resolution and clipped to match the extent of GRUMPv1.

Figure 1. North American map showing different regions, seasons, and climate types [reproduced from [1]].

Along with the rest of the world, the concrete industry in North America is also implementing technologies, guidelines, and specifications aimed to reduce carbon footprint associated with design, processes, systems etc. [8–10]. Recent action plans and roadmaps identify several drivers over the concrete products life cycle, for example, to: reduce the cement and clinker content in concrete, increase the service life of reinforced concrete infrastructure, (re)-carbonate construction and demolition waste for use as aggregate or sub-base, and implementation of direct and indirect carbon sequestration technologies within the concrete industry. These efforts are confounded by other concurrent changes in the industry such as: (i) prescriptive approaches, which largely dominated construction practices decades ago, are giving way to performance-based approaches, (ii) ordinary Portland cement (OPC) or general use cement (GU) are being replaced with Portland limestone cement (PLC) or general use limestone (GUL) cement, respectively, (iii) demands for reducing clinker in mixtures are resulting in a substantial increase in conventional and novel supplementary cementitious materials (SCMs), generally replacing the cement during concrete mixing (interground) at the ready mix or precast plant, and (iv) the availability, variety and variability of novel materials are highly affected by the vast geography of North America.

The scope of this letter has particular emphasis on the role of chlorides and how they affect concrete infrastructure in Mexico, USA, and Canada from the perspectives of: (i) external sources of chloride particularly related to cold weather exposure (deicing materials) and tropical marine exposure, (ii) internal sources of chlorides, such as admixed seawater and brines, (iii) consequences of internal and/or external sources of chloride on reinforcement corrosion, and (iv) the role of specification and performance-based mixes in driving advancement.

2 Some Key Fundamental Mechanisms – State-of-the-Art

2.1 Deicing Salt on Concrete Pavements and Flatwork (Focusing on $CaCl_2$ and $MgCl_2$)

During the last two decades, jointed plain concrete pavements, sidewalks, and flatwork began to display distress at the longitudinal and transverse joints previously not observed [11]. The reason for this damage was not immediately understood. This damage is a concern for agencies and owners due to the size and value of the concrete pavement network and the shortened service life before repair (e.g., substantial repairs being required at 10-15 years rather than 35 to 50 years). Further, the damage was concerning as it appeared in well-built concrete pavements that had received national quality awards (i.e., low variability, all specifications met or exceeded). It appeared that these concerns were occurring primarily in North America and, it was unclear as to whether this was related to materials, climate, or deicing practices. In response, guidance documents detailing methods to reduce deicing salt were prepared to guide practitioners and owners of infrastructure [12]. It was found over time that when the joint sealants fail or are not propertly drained they have higher salt concentration and degree of saturation values [13]. Further, deicing salt practices changed with the addition of the application of salt ahead of winter events without full consideration of how this may impact pavement design.

While it is well known that deicing salts contribute to scaling damage [14] due to changes in the ice formation and cracking processes [15], chemical reactions between deicing salts and the concrete matrix were less recognized despite some papers reporting such damage [16]. In response to pavement distress being observed in the field, research [17,18] linked $MgCl_2$ and $CaCl_2$ deicers to expansive cracking and loss in mechanical performance. Over the last 15 years, these chemical reactions have become more commonly recognized [19–28]. Eq. 1 outlines a reaction mechanism, in which deicing salt ($CaCl_2$) reacts with the calcium hydroxide ($Ca(OH)_2$) in the paste matrix to form calcium oxychloride ($3Ca(OH)_2.CaCl_2.12H_2O$, CAOXY). The formation of CAOXY is linked to a volume change, that potentially explains the observed damage.

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \text{ --> } 3Ca(OH)_2.CaCl_2.12H_2O \qquad (1)$$

Similar reactions occur for $MgCl_2$; however, the magnesium appears to form brucite or replace the calcium in the calcium silicate hydrate to form a magnesium silicate hydrate. This reaction also results in the formation of $CaCl_2$, which can react following Eq. 1, or possibly form magnesium oxychloride [29]. While many laboratory studies focus on a single deicing salt, in practice, deicing salt blends are used. The performance and damage caused by these blends can be predicted based on the proportion of the various salt species [30].

Studies have exposed concrete samples made with different cementitious systems to deicing salt solutions and measured mass loss, length change, visual damage, or strength loss [31]. Farnam et al. [29,32–35] used a longitudinal guarded comparative calorimeter with acoustic emission to assess effects of salt concentration, the degree of saturation, and temperature for a wide range of salts. Oxychloride and ice formation were quantified by measuring the electrical properties during thermal changes. It was shown CAOXY formed at temperatures above freezing, and that the formation temperature was linked to the salt concentration (Figure 2a). Monical et al. [26] developed a procedure using low temperature differential scanning calorimetry (LT-DSC) to quantify the volume of ice and CAOXY that formed for mixtures with various blends of cement and SCMs. This method (of CAOXY quantification) was standardized as AASHTO T365, which is a part of the transportation departments' effort towards moving to performance specifications (AASHTO R101). Qiao et al. [36] built on the use of the LT-DSC to develop phase diagrams, outlining the phases that form and temperatures at which they form for varying $Ca(OH)_2/CaCl_2$ concentrations (Figure 2b). It was shown that the conventional water-$CaCl_2$ or water-$MgCl_2$ phase diagrams were not sufficient to describe the behaviour of these materials in concrete. Qiao et al. [36] showed that as the temperature reduced, the phase change associated with CAOXY formation resulted in a volume reduction that was reversed on heating. Suraneni et al. [37] demonstrated how the solution concentration needed to be adjusted when the test was extended from paste to concrete. $Ca(OH)_2$ can also be measured using thermogravimetric analysis as an indicator of CAOXY; however, this may overestimate the amount of $Ca(OH)_2$ that is capable of reacting due to its potentially limited availability and access to solution [38]. This may be due to the $Ca(OH)_2$ being surrounded by other hydration products or a carbonation 'shell' [38]. Reductions in clinker content with the use of higher volumes of SCM that limit the $Ca(OH)_2$ in a mixture could have a theoretical downside for reinforced concrete if this is reduced to low values (i.e., to near zero). Removing the $Ca(OH)_2$ removes the buffering capacity of the mixture and increases the risk of reinforcing steel corrosion. It has been shown that SCM type, chemical composition, replacement level, and reactivity impact the SCM level where low $Ca(OH)_2$ values become a concern. For example, for fly ash degree of reaction lower than 40%, this potential increases sharply for greater than 50% Class F fly replacement, and 60% for Class C fly ash replacment [39]. Ongoing research continues to explore the development of more rapid test procedures to assess CAOXY using electrical resistivity [24] and other methods [40].

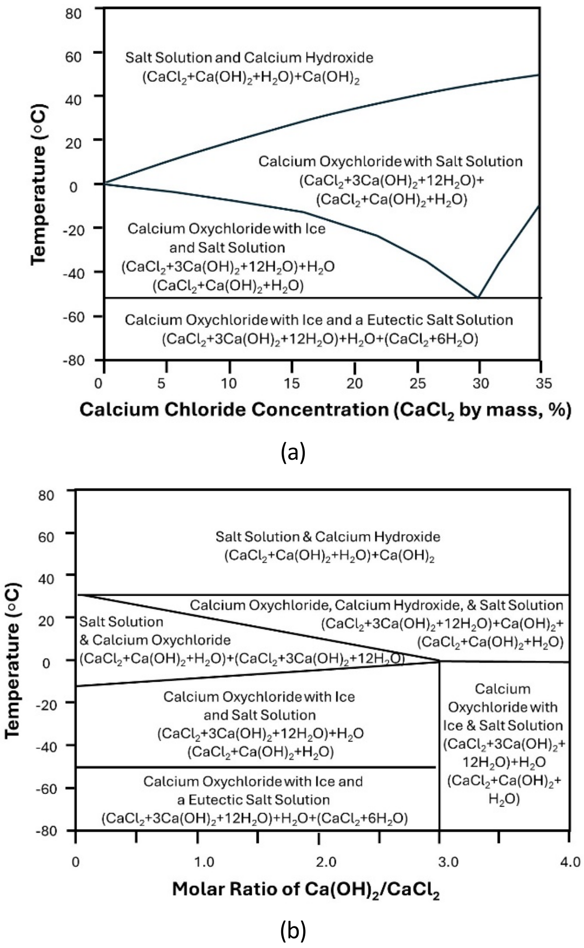

Figure 2. a) Phase isopleth for a $Ca(OH)_2$-$CaCl_2$-H_2O system with varying $CaCl_2$ concentration ($Ca(OH)_2/CaCl_2 = 1$) (after [21]) and b) phase isopleth with varying molar ratios of ($Ca(OH)_2/CaCl_2$) for a 20% $CaCl_2$ solution concentration (after [36]).

Given the reaction in Eq. 1, most OPCs or PLCs result in the formation of a similar amount of CAOXY [11,26]. In general, fillers (such as limestone in PLC/GUL) improve resistance to deicing salt due to dilution [23,30]. However, SCMs further reduce CAOXY formation due to their pozzolanic reaction as $Ca(OH)_2$ is consumed. The reactivity of SCMs has been linked to $Ca(OH)_2$ consumption and CAOXY amounts [23,30]; the damage level was found to be directly related to SCM replacement in pastes [21]. The CAOXY that forms for a wide range of fly ashes was measured and compared well to predictions using thermodynamic modelling [23], providing the ranges of CAOXY based on statistical probability. Field examinations from several studies suggest that CAOXY amounts be limited to either 10 g/100 g or 15 g/100 g cement paste to limit damage [13]. Theoretically this would correspond to $Ca(OH)_2$ contents of 4 to 6 g/100 g paste. This range may be due to factors like mild carbonation, inaccessible $Ca(OH)_2$ [23] or air voids that permit some CAOXY to form without visible damage as described in the following section [42].

Air entrainment can reduce CAOXY damage [20,24,41]. Ghantous et al. [42] quantified how concrete with higher air content is less susceptible to damage as the voids, provide space for fluid absorption, and accommodate ice and CAOXY formation. This beneficial impact of air only occurs for mixtures with moderate levels CAOXY formation as low levels did not result in sufficient damage and at high levels the damage could not be controlled for the volume of air typically used (i.e., 5 to 7% of the concrete volume). Ghantous et al. [42] reported a reduction in CAOXY volume (both due to a coefficient of thermal expansion and formation) with a decrease in temperature, is associated fluid absorption during the cooling process. The absorbed fluid filled-in the space created when the CAOXY formed, and with an increase in temperature, expansion results creating damage.

The timing and depth of the saw-cutting on concrete can play a role in the resulting deicer damage. Many joints did not open after cutting, the joint sealant was failing, and the joints were holding salt-rich solutions that became more concentrated due to evaporative drying and additional salt application [43]. The degree of saturation of the concrete around the saw cut could be quite high resulting in the critical degree of saturation being exceeded [44,45]. Some saw cutting practices (e.g., when the saw cut was applied too late) can cause microcracking at the tip of the saw cut, that increases both the rate and degree of saturation resulting in damage [46]. Further changes in the surface tension and viscosity of deicing salt solutions were shown to impact the rate of diffusion and fluid absorption by the concrete [47], while the hygroscopic nature of the salts alters the drying degree of saturation in the concrete [48]. Esmaeeli et al. [49] developed a model to predict the volume of ice that would form for concrete containing deicing salt of various concentrations using the lever rule to account for the decrease in temperature at which ice forms.

Four primary potential solutions to reduce CAOXY damage are increasing SCM replacement which consumes $Ca(OH)_2$, air entrainment that reduces degree of saturation and provides space to accommodate expansion [24,40,42], carbonating the cement paste reducing the availability of the $Ca(OH)_2$, and placing a barrier between the salt solution and the $Ca(OH)_2$ by using a topical treatment [38,50,51]. Deicing salt types and application procedures are also important for damage. For example, the application of deicing salt has changed from after weather events begin (thereby applying the salt to a wetted surface) to before the events occurred (thereby enabling a more rapid absorption of the salt solution). In addition, the use of salt blends has become more common than use of NaCl or anti-skid materials alone.

Concrete testing and long-term laboratory evaluation is limited [52,53] however, few recent studies have involved long-term concrete testing [19,24,42,54]. These studies confirmed that (increasing) SCMs and entrained air reduce damage in concrete, validating the cement paste and mortar results. These results held true under multiple, varied exposure conditions. The effects of concrete exposure to NaCl, $CaCl_2$, $MgCl_2$, and a mixture of the three on concrete was studied for 8 years. Van Niejenhuis and Hansson [55] reported on the first 5 years, showing a significant decrease in compressive strength for $CaCl_2$, $MgCl_2$ and multi-chloride mixture in comparison with NaCl, consistent with 1-2 year results from prior studies [19,24,42]. Further, thermodynamic modelling has been used to predict the performance of concrete pavements using samples obtained from long-term pavement performance (LTPP) sites throughout the US over the last three decades [54].

2.2 Marine Exposure

Researchers have generally confirmed the finding of Mather from the 1960s that damage as a result of rebar corrosion, freeze-thaw, or wetting-drying, was more common in concrete exposed to seawater than direct seawater attack on the concrete [56,57]. The limited sulfate ingress, presumably due to the numerous other ions and relatively low levels of sulfate, generally leads seawater ingress to cause sulfur enrichment, instead of sulfate attack [58]. Long-term studies of concrete exposed to marine environment have shown evidence of chemical and mineralogical zonation: (i) the first ~1-3 mm zone is decalcified but enriched in magnesium, largely in the form of M-S-H; (ii) the next zone, typically ~1-7 mm, is enriched in sulfur, largely in form of ettringite; and then (iii) a chlorine-rich zone, typically ~10-80 mm, of C-S-H and Friedel's salt phases [58]. Other studies also note leaching, including the loss of $Ca(OH)_2$ from the first 20 mm [59], and the effects of magnesium and sulfur [60].

Studies on the effect of the tropical marine environment in Mexico, have examined chloride profiles (shape, intensity, trajectories) and their interaction with environmental conditions, (namely, thermal cycles, relative humidity, rainfall, wetting time etc.). These results have been compared with the Intergovernmental Panel on Climate Change (IPCC) data and predictions [61,62]. Figure 3 illustrates the maximum temperature cycle data (referred to as macrocycles) and an increase in temperature is observed from ~1974 to 2020 [61,63]. Figure 4 presents the chloride content of concrete cylinders (w/c of 0.46 and 0.76) exposed to the tropical marine environment of the Yucatan Peninsula [61]. In Figure 3, the total chloride content in the bulk of concrete is shown on the vertical axis (chlorides as a function of % by weight of cement in the concrete) at a given age and along 10 years (120 months in horizontal axis). The interpretation and trends of the measured data in conjunction to environmental and climate impacts, fluctuations, and meteorological phenomena in the Yucatan Peninsula are presented in [61]. Broadly, due to seasonal and geographic variability of environmental parameters and the trajectory of climate impacts, chloride concentrations have potential to exhibit cyclic measurements and/or fluctuations of concentrations which has potential to lead to conflicting structural assessment outcomes. Assessment during periods of relatively high chloride concentrations could lead to conservative (safe) outcomes, and, conversely, assessment at low chloride concentration periods could lead to unconservative/over-optimistic service-life projections. Ongoing work on this topic is that of references [61] and [64], however, no new results appear in the consulted literature yet.

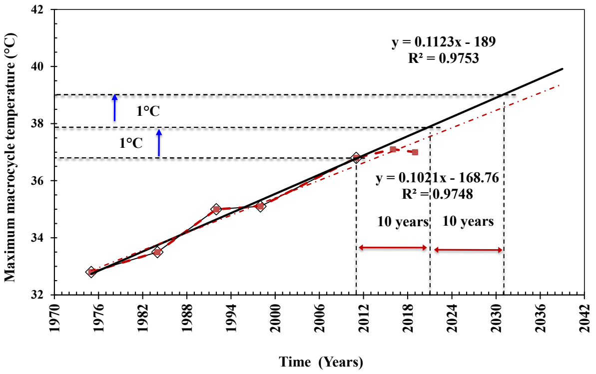

Figure 3. Increase and projection of maximum macrocycle temperature in station at 780 m from the seashore of the Yucatán Peninsula.

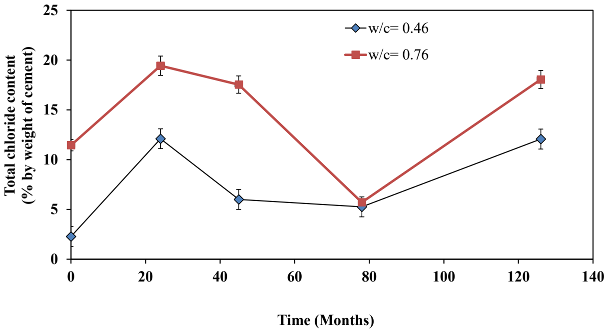

Figure 4. Behavior of the total chloride content (% by weight of cement) in cylindrical specimens (w/c ratio 0.46 and 0.76) from the Yucatán Peninsula.

Several test methods are commonly used to quantify transport processes in concrete. The rapid chloride permeability test (RCPT, ASTM C1202) is often used in North American specifications where chloride transport is a concern (i.e., seawater or deicing salts) [65,66]. Electrical properties of concrete have been studied in the past [67–70]; however, only recently has it been adopted into construction specifications. This began in AASHTO (T358 and T402) and has been adopted by ASTM (ASTM C1876). Bulk electrical measurements are relatively simple and rapid; however, sample geometry [71,72], sample conditioning (which can impact leaching [72] and saturation [73,74]), and sample temperature can impact test results [75]. Further, resistivity measurements can be considered as the product of pore volume, pore connectivity, and pore solution resistivity [74]. As such, the formation factor can be used as a material property since it accounts for the pore solution, though a standardized approach does not yet exist to measure pore solution resistivity. Often the resistivity of the paste can be scaled to mortar or concrete [19]; however, the interfacial transition zone (ITZ) and/or alkali absorption or release from the aggregate may complicate this measure [76]. Fundamentally, the resistivity test can be related to the RCPT (neglecting the temperature effects in RCPT testing) [77–79]. The formation factor has been combined with binding and transport to predict chloride ingress profiles [80,81].

Some groups have used the NT Build 492 or ASTM C1556 to determine the surface chloride concentration and the apparent diffusion coefficient [82]. While popular, these values are dependent on the type and concentration of the salt used and co-present ions [83]. The use of a migration cell [84,85] has been proposed, and adopted for naval construction. This has been coupled with transport software for use in service life modelling [86]. A mini-migration test has recently been used for cement pastes [87]. The authors show a relationship between the effective chloride diffusion as measured by the mini-migration test and bulk resistivity. One advantage of migration cell testing is that fundamental studies of the microstructure can be carried out before, during, and after the testing [87]. Another advantage is that the ingress and binding of chloride can be quantified on the same specimen.

Chloride binding behaviour from chloride ingress tests [88,89] is generally well researched, with the possible exception of the sorption of the chlorides on the C-S-H. A recent study showed that the chloride sorption is not linked to alkalis, but rather to the calcium amounts in the pore solution [90]. While it is commonly thought the difference between physical and chemical binding is permanent, it appears that at least some portion of the physically bound chloride in the C-S-H is reversible [90,91]. When $CaCl_2$ or $MgCl_2$ are used, the binding curve may depend strongly on temperature as a portion of the binding be attributed to CAOXY formation [30].

Modelling transport of ionic species in concrete has been widely studied by several researchers over the past three decades [92–94]. Less comprehensive transport models focus on the uncoupled or loosely coupled transport of individual species (e.g., chloride, hydroxide, oxygen) by approximating the multi-mechanism phenomena with diffusion-based (Fickian) processes. Comprehensive transport models include the numerical solution of the extended Nernst Plank equation for various ionic species in concrete. These models treat the transport phenomenon as a coupled process that involve advection, diffusion, and electrical migration. A disadvantage of these models is their dependence on a large number of input parameters, some of which cannot easily be determined. However, in recent years, progress has been made to determine these input parameters (e.g., porosity, electrical resistivity, formation factor, and diffusion coefficients) from thermodynamic calculations [95–97].

A major challenge in modelling transport processes in concrete is the inclusion of reactions as the species move within the cementitious matrix. In recent years, a new approach to reactive-transport modelling combines the solution of the transport problem using finite element analysis and the simulation of reactive processes through thermodynamic calculations, as demonstrated by Jafari Azad et al. [98], and more recently, by Tran et al. [99]. Since these thermodynamic calculations can be performed for any cementitious mixture, regardless of the chemical composition of the materials and deteriorative processes that might be present, they are highly versatile and do not require empirical relationships (e.g., chloride binding isotherms) to model reactions. These thermodynamic/kinetic models allow seamless integration of reactive processes into transport modelling and in recent years, significant progress has been made to use thermodynamic calculations to study new binders. Despite this progress, since validated kinetic models are needed for properly incorporating thermodynamic calculations in reactive-transport models, there is still work to be done on developing better kinetic models for various cementitious processes such as chloride binding and alkali update.

It should also be noted that while substantial work has gone into measuring the properties of concrete (resistivity, formation factor, apparent diffusion coefficient, etc.), substantially less work has focused on the variation in cover thickness, concrete curing quality, or temperature effects. In addition, there is a great deal of uncertainty, due to these less researched areas, on the critical chloride threshold to initiate corrosion or the best way to represent this number in practice. Converting some of these values to codes and standards is challenging as normalizing these values by cement content, cementitious content, powder content, or concrete content requires certain assumptions that need to be clearly understood and conveyed as the binders used change.

2.3 Admixed Seawater and Brines

In North America, there has been some interest in the use of seawater replacing potable water in concrete. Largely owing to the scarcity of freshwater, this topic has gained attention in the Middle East and China [100–103]. Generally, seawater cannot be used in concrete due to concerns regarding the corrosion of the reinforcement, however, this concern can be alleviated when using non-corrosive reinforcement (such as fiber reinforced polymers) or when using unreinforced concrete. Overwhelmingly, data shows that there is an initial acceleration of the hydration reaction (in terms of ‘peak heights’ and ‘peak times’) in the first 3 days, which is also accompanied by increased strengths, due to accelerating effects of the chloride ions [100]. Later-age strengths show relatively minor effects with the exact nature of the effects depending on the mixture and exposure conditions. While a few papers show notable long-term strength reductions, most show strengths comparable to control concretes [100,102]. Studies on the long-term durability (sulfate attack, alkali-silica reaction, etc.) of seawater-mixed concrete are limited and further work is needed. Exact effects of seawater on dissolution, nucleation, and growth processes have only recently started to be decoupled using pure phase systems [104]. Although, actual structures have been constructed using seawater-mixed concrete, practical challenges (such as preventing the seawater from corroding mixing and batching equipment during transport and uniformity of seawater composition) and lack of codes and guidelines mean that, at least for now, seawater-mixed concrete will mostly only be used for niche applications (e.g., after natural disasters, in the Middle East, on isolated islands, etc).

2.4 Corrosion

It is well known that steel reinforcing bar (rebar) in concrete forms nanometre thin passive oxide or hydroxide film that allows for a relatively low corrosion rate [105–107]. In the last few decades, some passivity breakdown models have been proposed: (i) diffusion model, resulting from anion (i.e. chloride ions) penetration to the metal/film interface or cation (i.e. iron ion) ejection to the film/electrolyte interface; (ii) adsorption model, resulting from anion (i.e. chloride ions) attachment to the film surface to compete with hydroxide ions [108–110]; and (iii) point defect model, in which chlorides at film surface induce iron vacancies that penetrate into the film and create defects at the film-metal interface [111]. It was initially assumed that the passive film grows relatively uniformly and homogeneously on metal surfaces [108–112]. More recently, passive films have been revealed to be a multi-layered crystalline structure, usually with an inner compact protective oxide region and an outer loose and less protective (hydro)oxide region, with several local defective sites acting as depassivation path [113] and the basis of new passivity models [114–117]. A gap in these studies is a lack of predictive tools that can determine passive film properties (such as film defect density, thickness, depassivation path number) using these mechanistic models. Since film breakdown is an integral part of rebar corrosion, and depassivation is influenced by a range of parameters (e.g. concrete systems, rebar grade and surface conditions, and exposures), a predictive tool is essential. Recent work has translated scientific corrosion properties [106,107] into engineering parameters, such as critical chloride threshold (CCT) used in service life models [118,119].

For structures exposed to marine environments or deicers, diffused chloride must reach a critical value (i.e. CCT) near the rebar surface before active corrosion is initiated [120]. While it is generally agreed that a unique CCT value should theoretically exist for each rebar grade, it has not been practical to have a single, agreed upon, value because it is dependent on a large number of variables and factors that has been summarized in recent work [121,122]. Recent study using machine learning based models has also shown the dependency of CCT on several material and testing variables [123]. Table 1 shows the variations in CCT value of various grades of stainless steel rebar exposed to synthetic concrete pore solution. Although, Table 1 is based on sodium chloride, recent work has shown the CCT value to in fact be lower in solution containing Mg- and Ca-chloride salts [119]. Figure 5 shows varying surface chloride build-up rate, which influences time to rebar corrosion, on structures in Canada and the USA. The data was collected for NaCl “rock salt” deicers, and not the more recent locally used anti-icing brines that are generally more destructive to both concrete and rebar. In Figure 5, the average annual surface chloride build-up content of concrete in some parts of North American structures only provides an indication of the magnitude of the potential infrastructure chloride corrosion concerns. The source from which the damage occurs (i.e. melting salts, splash zones, subsoil chlorides, etc.), as well as the environmental conditions and the intensity of climate change effects, will dictate damage kinetics. Just as Figure 5 shows a wide variety of chloride build up rate in concrete with respect to the diverse geography, a recent study [124], shows the inhomogeneity of natural carbonation rates and CO_2 uptake of concrete corresponding to twelve locations in Canada (including four urban, four rural, and four Indigenous communities) owing to differences in ranges of environmental temperatures, relative humidity, and CO_2 concentration. The impact of regional variations in surface chloride build-up and carbonation must be accounted for when generating rebar corrosion parameters (such as time to corrosion, which embodies CCT), for use in service life analysis and when choosing reinforcement type for concrete in different locations.

There is still a need for the long-term corrosion durability analysis of economically viable corrosion resistant bars and/or corrosion resistant coatings (e.g. clad stainless steel [118], continuously galvanized steel [125], epoxy-coated steel [126,127], and other emerging coats such as basalt-fibre and graphene-coated rebar [128]). Two- and five-years long study on continuously galvanized and clad stainless steels in concrete exposed to North American climate and anti-icers has shown that they can be used in mild to highly aggressive environment, respectively [118,125]. However, it was noted that the quality of production of these less-costly bars must be improved for them to be as effective as their traditional expensive counterparts.

In addition to generating corrosion parameters for different rebar and concrete systems in the presence of chloride or carbonation, on-going research work are accounting for the effect of multi-degradation mechanisms on rebar corrosion. Some North American reinforced structures may be under freeze-thaw and deicer exposures during winter season, alkali- carbonate or silicate reaction attacks when cast with reactive aggregates during summer season, and carbonation all year round. Therefore, it is essential to determine the effect of combined chloride and carbonation action or either chloride or carbonation in combination with other concrete-related problems such as freeze-thaw and ASR, on rebar corrosion properties and parameters needed for service life predictions. Initial results of studying the effect of ASR and chloride attack showed that ASR gel may block chloride ingress, which is beneficial for rebar corrosion, but may also reduce pH at ITZ, which is detrimental to passive film formed on rebar surface and CCT [129,130]. The overall long-term impact of this combined effect on rebar passive film properties and corrosion performance requires further study. To account for the large variations influencing rebar corrosion, recent research is developing a corrosion model that incorporates different mixture proportions and exposures as input parameters to predict pitting corrosion behaviour [131–133] and generate parameters such as CCT [64,134,135]. However, recent study [123] model based on machine learning identified that extensive effort is still needed to unify test methodologies used for generating rebar corrosion parameters needed for this model to avoid erroneous and inaccurate output [131].

Current research is taking advantage of corrosion microscopy techniques using scanning probe electrochemical systems that characterizes corrosion behaviour at local regions and maps the global corrosion parameters across the metal surface [136,137]. While these microscopy techniques are a significant advancement to circumventing the inhomogeneity of pitting corrosion behaviour across rebar surface either due to the rebar itself (i.e. as-received surface roughness or composition) or their local attack at microscale level, it further widens the range of methodology used to generate rebar corrosion parameters such as CCT. Therefore, guidelines will eventually be needed to aid comparison of corrosion results from conventional macroscale and new microscale corrosion techniques.

A major assumption of many service life models, following Tuutti’s work from 1982 [138], is that the corrosion propagation period contributes very little to the overall service life of the structure, and so is ignored (ACI365.1R-17 2017). Therefore, most research has focused on CCT value and time to corrosion initiation of rebar alloys, rather than their corrosion propagation rate [120,139,140]. However, ongoing research is showing increased contribution of corrosion propagation period, particularly from stainless steel rebar, to service life of structures and the importance of combining the initiation and propagation stages of corrosion during modelling [122].

Table 1. Critical chloride threshold (CCT) values in wt.% for stainless steel rebar alloys tested in simulated pore solutions containing sodium chloride [141].

Stainless steel grade	[139]	[105]	[140]	[141]	[120]
pH (after test)	12.8 – 13.3	12.6	12.6	12.6	12.5 – 13.5
304L	2.8 – 10.6	5.0	6.5 – 10.0	-	18.8 – 24.0
316L	5.7 – 6.8	5.5	>10.0	2.8 – 11.3	20.7 – 23.5
LDX 2101	5.7 – 10.6	-	3.5 – 6.0	1.1 – 1.4	-
2304	4.6 – 10.6	>10.0	7.5 – 8.0	-	20.0 – 23.0
2205	-	-	-	-	23.7 – 27.0
24100	-	-	-	-	18.5 – 21.0

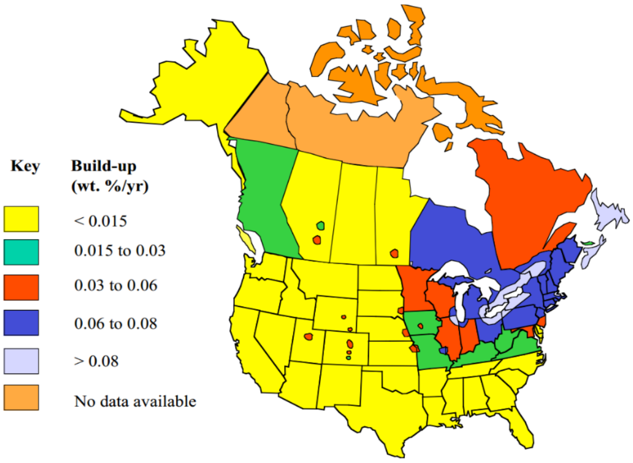

Figure 5. Canada and USA: Surface chloride build-up rate in concrete structures [144].

3 Specifications, Performance Based Mixtures, and Modelling

In general, North American concretes have historically been cement rich. This occurs for three primary reasons. First, minimum cement contents were used as a safety measure in many prescriptive standards to increase the probability that strength was achieved. Second, the risk of the producer not meeting specified strength and incurring financial penalty or the need for repairs or removal) was mitigated/reduced with additional cement. Third, prescriptive mixtures were used with a wide variety of constituent materials (cement reactivity and aggregate gradations) resulting in a very forgiving mixture design. In general, three primary concepts for approaching sustainable mixture design for conventional concretes include: 1) reducing the cementitious content, 2) reducing the clinker content, and 3) extending the service life.

Efforts have focused on improving aggregate gradation to minimize clinker content in concrete [145]. SCM usage has also increased to help reduce clinker content. Blended cements of clinker and SCMs are permitted, although are not the most widely used products in the US. Frequently in the US the cement and SCM are not blended at the cement manufacturer but are done at the concrete production facility. As a result, optimizing the size distribution of the powders or the sulfate content may be more difficult [146]. The geography of North America results in differing SCMs with different compositions and reactivity being used in different locations [147–149]. Tests are being used more frequently to assess the reactivity of the SCM and to use this in mixture proportioning.

In North America, the switch from conventional OPC began two decades ago allowing up to 5% limestone addition in 2004 in ASTM (ASTM C150/AASHTO M85 OPC [150]) and more recently the shift to PLC (ASTM C595M/AASHTO M240 [151]) which incorporate up to 15% limestone. In general, PLCs are ground finer than OPC to achieve similar early strength. The additional limestone in cement can react with alumina-rich reactive phases from SCMs and affect the chemical composition, porosity, and the microstructure of the end product [152].

AASHTO R101, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures [153], provides State Highway Agencies (SHAs) with an alternative to prescriptive specifications for concrete mixtures with mechanical and durability performance criteria. This has allowed many SHAs to start the process of comparing how their current mixtures compare to mixtures made with different proportions or constituent materials.

The development of performance-based mixture proportioning methods that can incorporate the chemical composition and reactivity of cementitious materials, as well as extensive use of limestone and other inert materials, requires tools. In recent years, predictive tools using thermodynamic modelling of the cementitious systems including pozzolanic reactivity of binders have been developed, such as the Pore Partitioning Model (PPM) [95–97,154].

The ability to predict microstructural and transport properties of performance-based concrete mixtures produced with new cementitious materials allows for service life predictions of structures made from these concretes in various environments, without relying on expensive and time-consuming testing. Reactive processes such as chloride binding, sulfate attack, or carbonation pose a major challenge in modelling transport processes in concrete, especially when new and unconventional cementitious materials are used. As discussed earlier, the ability to model these systems through coupling the transport problem with thermodynamic/kinetic [98,99] is a major advance that allows for rapid implementation of new systems. This implementation becomes critical in North America due to material variability, the use of extensive deicing and anti-icing chemicals, and extreme exposure conditions.

Corrosion of steel in concrete has unique challenges that are specific to North America. One critical challenge with respect to reinforcement corrosion is related to the allowable admixed chloride limits (amount of chloride allowed in new concrete, from aggregates, mixing water, or binders) in concrete. Until recently, ACI specified these limits as a mass percentage of cement, which limited extensive use of SCMs in new concrete. In the most recent ACI documents, allowable admixed chloride limits have been updated to be as mass percentage of cementitious materials, which allowed more flexibility in incorporating SCMs. While this may seem a small change, it can result in easier adoption of more sustainable structural design and construction.

There is still conflicting guidance in documents on the allowable admixed chloride limits. For example, ACI 318 [155] (often legally adopted in the building code) requires a maximum of 1.00% allowable admixed (water-soluble) chloride in concrete containing conventional reinforcing steel in dry conditions. On the other hand, ACI PRC 222R [156] provides the same limit as 0.25% by mass of cementitious material content. Currently efforts are underway to synchronize the ACI requirements. These efforts are pursued in parallel with an initiative by the ACI 222 Committee on Corrosion of Metals to develop a standardized CCT testing method for concrete. Currently, this method is in its round-robin testing stage, and it is expected to be finalized in the upcoming years [157].

Finally, it should be noted that the selection of rebar type in aggressive environments is still a controversial topic in North America. For example, while some jurisdictions (e.g., SHAs in the US or Provincial Departments of Transportation in Canada) support the use of epoxy-coated reinforcement in concrete, others do not allow its use in many applications as it has been reported that preexisting defects and deterioration of epoxy exposed to moisture could accelerate steel corrosion [156]. Similarly, the use of stainless steel rebars, despite their demonstrated success in delaying corrosion, in some cases by decades, still has not found widespread adoption due to the political/economic reluctance to base new designs on life cycle analysis of the systems. Even though the application of non-metallic reinforcement in bridge decks has increased over the years, for the foreseeable future, it is expected that conventional carbon steel rebar will remain to be the main reinforcement used in concrete structures across North America due to current knowledge gap of non-metallic reinforcement in critical structures.

4 Summarized Research Needs

Five key research needs are identified, from the North American perspective, dealing with experimental and modelling efforts pertaining to concrete durability of existing structures, as well as, projections towards a low carbon future.

I. Freeze-thaw, deicers, and scaling: Currently, the use of SCM replacement levels is limited by ACI for some exposures. These limits are present to minimize surface scaling of concrete; however, scaling tests often do not correlate well with practice and these limits conflict with sustainability goals. There is a lack of a robust test to determine scaling performance of concrete as it relates to practice. Field exposure sites may be useful to provide databases of concretes with information on long-term scaling, freeze-thaw, and calcium oxychloride damage. This information should include concrete properties at the time of placement as well as the exposure conditions of the concrete throughout its life, as done with the LTPP sites in the US. Thermodynamic data for calcium oxychloride phases is not included in standard thermodynamic databases, which limits the ability to predict its formation. While a model has been developed for calcium oxychloride damage, there is an opportunity to improve this, including complexities associated with geometry, reactive transport and fracture as transport, chloride build up, and temperature profiles exist. Data is also needed from the field on the role of sealers and topical treatments. Additional documentation is needed on impact of changes to deicing and anti-icing procedures on the exposure conditions for concrete.

II. Transport properties and predictive models: Testing can more readily be used to indicate aspects of durability needs (e.g., resistivity or formation factor) and added to standard quality control/quality assurance testing. However, exposure conditions need to be more accurately defined to reflect the actual salt concentration, temperature, and moisture conditions. Tools to better predict chloride binding are needed. For instance, continuous efforts to evolve and validate thermodynamic reaction models and reactive-transport modelling approaches in concrete will allow for mixture optimization and service life predictions of novel cementitious mixtures, regardless of the chemical composition of the materials and present deteriorative processes.

III. Corrosion: While significant research efforts have been made to evaluate carbon steel rebar in NaCl deicers, future research must account for the use of economical corrosion resistant bars and exposures to local anti-icers of Ca and Mg. Set-ups used to study rebar corrosion and generate modelling parameters must consider field occurrences (e.g. combined degradation of chloride and freeze-thaw common in the winter) and provide sufficient details that aid repeatability, reduce differences in generated corrosion parameters, and aid urgently needed standardized methodology. Passivity and pitting corrosion predictive model are needed to: capture extensive variables affecting rebar corrosion; understand passive film breakdown, corrosion initiation time, and corrosion propagation rate and mechanism; and generate corrosion parameters needed for service life analysis. While physical tests are still needed, efficient use of corrosion models can reduce the extensive testing cost and time required to generate laboratory results and service life modelling parameters.

IV. Novel manufactured SCMs, non-Portland cements, and systems with CO_2 mineralization: As such materials become more common, more studies on chloride transport, chloride binding, and rebar chloride threshold are needed to build database for these materials.

V. Climate Impacts: Understanding and identifying the role that climate changes have in North America on environmental conditions and the corresponding chlorides exposure is needed. For example, changes in temperature, macrocycles, water line, flooding events, CO_2 concentration and relative humidity, have potential to vastly affect rates of material degradation in turn impacting the anticipated service life of concrete. The impact these changes, their characterization, their projections may have on exposures warrants attention.

5 Summarized Needs for Practice

The following are current and future needs pertaining to the evolution of codes, standards, and engineering practice in context with durable and sustainable concrete materials for application to reinforced concrete structures.

I. Performance-Based Alternatives: An opportunity exists to provide alternatives to prescriptive acceptance or prescriptive code-based requirements. A large portion of North American design is based on concrete strength and seemingly assumes that other properties improve with strength; however, this is not always true. In addition, ACI 318 currently limits the w/cm (and strength) of a mixture for specific exposure conditions, presumably due to the use of w/cm as an indicator of porosity and its use to limit the rate of fluid transport. While this approach worked well for systems composed primarily of OPC, this approach may not fully take advantage of the benefits of systems with SCM. Further, the w/cm has a slightly different interpretation for PLC systems due to the phases that form and a very different interpretation for carbonatable systems. Peformance Related Specifications were used in construction projects as early as 2001 in the US for concrete pavement construction [158,159]. This has developed over the years to include more durability related parameters which have been standardized in AASHTO R101. Additional information on performance standards can be adapeted from the CEB-FIP model code [160] or standards from other countries [161].

II. Mixture Proportioning: In large part, the mixture proportions used by transportation agencies in the US are based on historic prescriptive mixture proportions that were specified. Similar historical legacy exists in building mixtures. The industry is shifting from these prescriptive specifications to enable local materials optimization (e.g., aggregate optimization) or to allow performance-based mixture proportioning approaches. A major advancement, for example, has been eliminating minimum cement contents in many specifications [162] though many states still have standard cement minimum requirements [163]. As we move for more sustainable mixtures, it is important to allow a performance alternative that can be used to consider alternative cementitious material, SCMs, and alternative SCMs. Mixture proportioning tools have been developed that enable concrete mixture proportions to be optimized using mechanistic modelling to meet specific performance criteria through the minimization of a user-defined objective function that considers material cost and CO_2 cost [164].

III. Synchronization of Guideline Documents: Synchronization of guideline documents, specifications, standards, and codes provide consistence guidance to engineers, particularly with respect to chloride-induced rebar corrosion. One example for this is the need to have consistent guidelines for allowable admixed chloride limits for new concrete. Also, effort to be consistent in reporting methodological information from corrosion tests will aid development of accurate rebar corrosion models.

Acknowledgements

The authors are grateful to Professor Carolyn Hansson for her insights and review of the letter. P. Castro-Borges recognizes Mercedes G. Balancan Zapata for her technical assistance and data management. I.G. Ogunsanya acknowledges support from NSERC Discovery Grant on the topic of corrosion durability of reinforced concrete and Canada foundation for innovation (CFI). D.K. Panesar acknowledges support from NSERC Discovery Grant on concrete durability and from the Government of Canada, as part of an Environment and Climate Change Canada (ECCC) funding program. P. Suraneni acknowledges support from the Miami Engineering Endowment at the University of Miami. J. Weiss and B. Isgor acknowledge support from the Du-Re Transportation Center, ARA, and FHWA for portions of work that could be summarized here.

Authorship statement (CRediT)

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