Predicting service life extension and cost due to different repairs on concrete structures under marine environment

Aruz PETCHERDCHOO [1], Koonnamas PUNTHUTAECHA [2]

[1] King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

[2] Department of Rural Roads, Ministry of Transport, Bangkok, Thailand

Contact e-mail: aruz.p@eng.kmutnb.ac.th

ABSTRACT: In this study, the service life of repaired concrete structures under marine environment is predicted by considering the mechanism of chloride ion diffusion based on the partial differential equation (PDE) of the Fick's second law. The one-dimensional PDE cannot simply be solved, when those concrete structures are cyclically repaired with two repair strategies; cover replacement or silane treatment. The difficulty is encountered in solving nonlinear chloride ion concentration and space-dependent diffusion coefficient after repairs. In order to remedy the difficulty, the finite difference method is used. By virtue of numerical computation, the nonlinear chloride ion concentration can be treated point-wise. And, based on the Crank-Nicolson scheme, a proper formulation embedded with space-dependent diffusion coefficient can be derived. By using the aforementioned idea, space- and time-dependent chloride ion concentration profiles for concrete structures under diffeent repairs can be determined, and their service life can be predicted in addition to their associated cost. Finally, numerical examples are presented for comparison.

1 INTRODUCTION

Chloride attack is considered as one of the important factors in the deterioration process of concrete structures. When the threshold amount of chloride ions at the surface of reinforcement is reached in combination with enough oxygen and moisture, steel corrosion may take place probably resulting in concrete cracking and decreasing the bond strength between concrete and reinforcement. And, the debonding would subsequently reduce the flexural or shear strength of structures. As a result, the corrosion of reinforcement adversely affects the safety and serviceability, and shortens the service life of concrete structures.

To prevent the structural deterioration, an appropriate maintenance strategy is desired (Petcherdchoo 2015). In this study, the strategy to slow down the rate of corrosion by applying cyclic repairs is considered, i.e., either concrete cover replacement or silane treatment.

In predicting the service life of repaired concrete structures, a quantitative assessment of chloride transport is preferable (REHABCON. 2004). Here, the chloride transport by diffusion based on the Fick's second law is considered. There are two principal mechanisms of interest; chloride ion penetration in concrete without repair, and that with repairs. These two mechanisms have widely been studied by researchers (e.g., Vaysburd and Emmons 2004, Petcherdchoo 2018). In the first mechanism, the initial surface chloride ion concentration and the diffusion coefficient were assumed constant. By these two assumptions, 1-D PDE was analytically solved. However, the two assumptions cannot be held, when the second mechanism is faced after either replacing concrete cover or treating concrete surface with silane. In order to break

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down these difficulties, the Crank-Nicolson based finite difference method is introduced as explained below.

2 CHLORIDE IONS IN REPAIRED CONCRETE STRUCTURES

2.1 With concrete cover repairs (CR)

From REHABCON (2004), concrete cover replacement is defined as an action causing removal of original concrete cover and replacement by new materials, e.g., concrete, polymer-based material etc. For this, there are two main steps for chloride ion penetration over the lifetime of concrete structures:

2.1.1 Chloride ion penetration through the original concrete

The fundamental 1-D PDE for chloride ion diffusion from the outer surface through the original concrete (Crank 1975) can be written as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial C}{\partial x} \tag{1}$$

where C is the chloride ion concentration as a function of position x and time t, and D is the diffusion coefficient. With proper initial and boundary conditions, Eq. (1) can be solved analytically (Saetta et al. 1993).

A Crank-Nicholson numerical scheme for Eq. (1) can be written (von Rosenberg 1969) as

$$\frac{c_{i,j+1} - c_{i,j}}{\Delta t} = \frac{D}{2}\left[\frac{\left(c_{i+1,j+1} - 2c_{i,j+1} + c_{i-1,j+1}\right)}{(\Delta x)^2} + \frac{\left(c_{i+1,j} - 2c_{i,j} + c_{i-1,j}\right)}{(\Delta x)^2}\right] \tag{2}$$

where $c_{x,t}$ is, in a general form, the chloride ion concentration at a mesh point x and time t. And, Δx and Δt are the size of the mesh point (2 mm) and incremental time step (1 week), respectively.

2.1.2 Chloride ion penetration and redistribution after cover replacement.

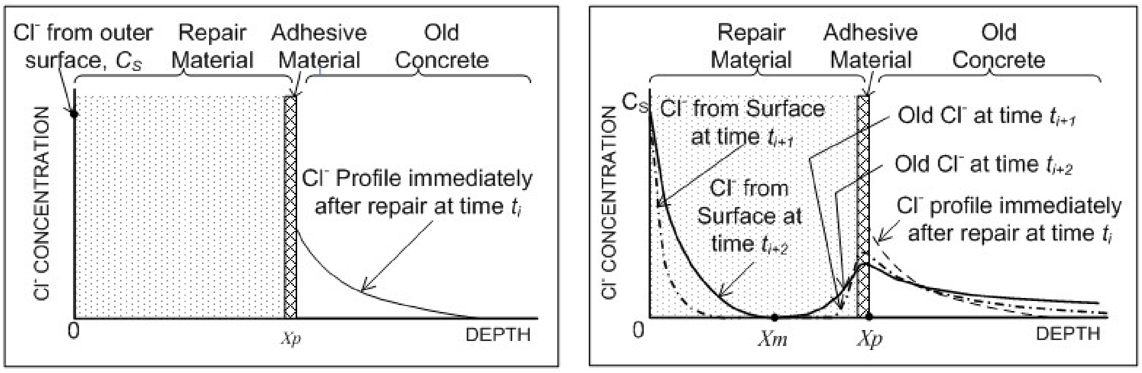
Let consider Figure 1a. At time t_i, concrete cover is initially taken off as deep as the distance of x_p (or repair depth), and consequently the chloride ions inside the cover are also taken off. Then, a repair material and an adhesive material are replaced for the taken-off concrete.

After that, there are three principle stages as shown in Figure 1b. First, when the chloride ions in the original concrete are about to redistribute through the repair material and the adhesive material, the problem will involve in solving the PDE with nonlinear initial chloride ion profile at time t_i, or C(x,t).

Secondly, when the redistributing chloride ions penetrate from the original (old) concrete to the repair material and the adhesive material, the problem involving space-dependent diffusion coefficient, or D(x), will be encountered due to the difference of diffusion coefficients among the original concrete, repair material, and adhesive material. Mathematically, the PDE based on the Fick’s second law for this problem can be written as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D(x) \frac{\partial C}{\partial x} \tag{3}$$

Thirdly, when the penetrating surface chloride ions merge with the redistributing chloride ions at the point x_m, the problem in solving the PDE will again be faced. It will be even more complicated, if the number of repairs is more than one.



(a) Immediately after repair

(b) After repair

Figure 1. Chloride Profile after Concrete Repair (REHABCON 2004).

In order to avoid all the aforementioned difficulties, the Crank-Nicolson based numerical scheme is proposed for computation. Let consider the three stages as a whole. The problem only involves the diffusion of chloride ions through the materials having different diffusion coefficients. Hence, the numerical solution for Eq. (3) can be formulated (Press et al. 1996) as

$$\frac{c_{i,j+1}-c_{i,j}}{\Delta t}=\frac{1}{2}\left[\frac{\left\lfloor D_{i+1/2}\left(c_{i+1}-c_i\right)_{,j+1}-D_{i-1/2}\left(c_i-c_{i-1}\right)_{,j+1}\right\rfloor}{(\Delta x)^2}+\frac{\left\lfloor D_{i+1/2}\left(c_{i+1}-c_i\right)_{,j}-D_{i-1/2}\left(c_i-c_{i-1}\right)_{,j}\right\rfloor}{(\Delta x)^2}\right] \quad (4)$$

where $D_{i+1/2} = (D_i + D_{i+1})/2$ and $D_{i-1/2} = (D_{i-1} + D_i)/2$. It is noted that if the diffusion coefficients are constant, Eqs. (3) and (4) will reduce to Eqs. (1) and (2), respectively.

In numerical computation, when the concrete cover is replaced over the depth x, its diffusion coefficient will be updated, e.g., $(D_x)_0 = (D_x)_{CR}$. It is noted that $(D_x)_0$ and $(D_x)_{CR}$ are defined as the diffusion coefficient of original concrete and repair material, respectively, at the depth x. By making use of the finite difference method, nonlinear chloride profile can be treated point-wise, so the problem involving nonlinear chloride ion profile can be solved.

2.2 With silane treatments (SL)

From NCHRP-558 (2006), silane treatment is categorized as a kind of penetrating sealers which react with the pore structure within hardened concrete to create a nonwettable or hydrophobic surface (Petcherdchoo 2019). There are two steps over the service life of silane-treated concrete structures as follows

2.2.1 Chloride ion penetration through the original concrete

For chloride ion penetration from the outer surface through the original concrete, Eqs. (1) and (2) can be used.

2.2.2 Chloride ion penetration through silane treated and original concrete

Let consider Figure 2 At time t_i, silane treatment is applied at the surface of concrete. Hence, silane will react with the pore structure as deep as the distance x_p (or repair depth). This will result in the problem involving space-dependent diffusion coefficient, or D(x), due to the difference of the diffusion coefficient of the silane-treated concrete and the original concrete. So, the PDE for this diffusion problem is similar to Eq. (3). Hence, Eq. (4) can be used, and the diffusion coefficient of silane-treated concrete can be updated after repair. However, the remaining chloride ions in the silane-treated concrete are not updated, because they are not removed during silane treatment.

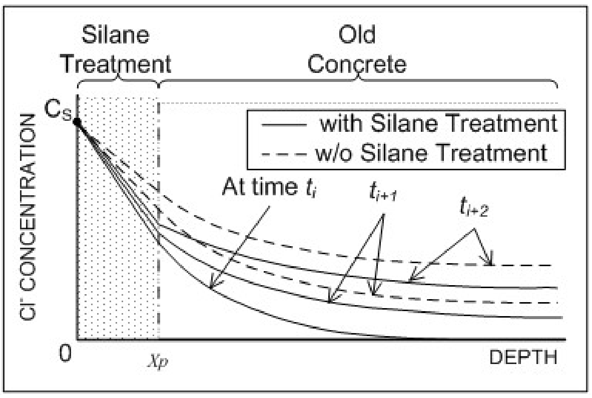


Figure 2. Chloride Profile without and with Silane Treatment (NCHRP-558 2006).

3 PARAMETERS AND NUMERICAL EXAMPLES

3.1 Surface chloride ion concentration

The surface chloride ion concentration, which is a boundary condition in computation, depends on many factors, for example, the distance of structures from the sea, the region of structures or exposure condition (i.e., atmospheric, tidal, splash, or submerged zones), and concrete mix or properties (Costa and Appleton 1999). According to these factors, several forms of surface chloride functions were proposed (see Uji et al. 1990, Petcherdchoo 2017). In this study, the constant surface chloride ion concentration is chosen as 7.89 kg/m^3 according to obtained from field tests on concrete structures located at the sea (Yokota and Iwanami 2006).

3.2 Diffusion coefficient of materials

The corrosion of concrete structures is directly related to the resistance or diffusion coefficient of concrete. The diffusion coefficient depends on material types, e.g., concrete, polymer-based material, silane treated concrete etc.

In this study, the diffusion coefficient of the original concrete and concrete cover repair material is chosen as 2.19×10^{-8} cm^2/s (from field tests by Yokota and Iwanami 2006) and 80% of the original concrete, respectively, while that of silane-treated concrete is adopted form Shimomura (2005) as shown in Table 1. It is noted that the diffusion coefficient of silane treated concrete in Table 1 is compatible to the test results of Medeiros and Helene (2009) which stated that treating concrete by silanes could reduce the diffusion coefficient by 9% to 86%.

Table 1. Diffusion coefficient of materials

Material	Diffusion coefficient (cm^2/s)
Original concrete	2.19×10^{-8}
Repair material	1.752×10^{-8}
Silane treated concrete	0.6351×10^{-8}

3.3 *Application time and lifetime of repairs*

Concrete cover replacement is applied whenever the chloride ion concentration at a threshold depth reaches a critical value (threshold based), while silane treatment is applied according to a specific cyclic time (time based). For concrete cover replacement, JSCE (2002) defined the critical value of 1.2 kg/m^3 as a value to initiate reinforcement corrosion. Moriwake (1996) defined the critical value of 2.0 kg/m^3 as a value to initiate concrete cracking. Here, the critical value is chosen as 1.2 kg/m^3 for corrosion control (CR1) and 2.0 kg/m^3 for crack control (CR2) as shown in Table 2. For silane treatment, NCHRP-558 (2006) stated that its service life depends on exposure conditions, e.g., ultraviolet light, moisture, and surface wear. And, it ranges from 5 to 7 years before reapplication. Accordingly, the application time of silane treatment is chosen as every 7 years (SL1) or every 5 years (SL2), while its lifetime is chosen as 5 years after application as shown in Table 2. It is noted that silane treatment in SL2 is applied every 5 years or at the end of the lifetime of the previous application to keep its effect active continuously.

Table 2. Application times and lifetime of repairs

Repair actions	Type	Time of repair application	Lifetime
Cover replacements	CR1	whenever $Cl_{TH,T}$ = 1.2 kg/m^3	whenever $Cl_{TH,T}$ = 1.2 kg/m^3 again
	CR2	whenever $Cl_{TH,T}$ = 2.0 kg/m^3	whenever $Cl_{TH,T}$ = 2.0 kg/m^3 again
Silane Treatments	SL1	every 7 years	5 years after the application
	SL2	every 5 years	5 years after the application

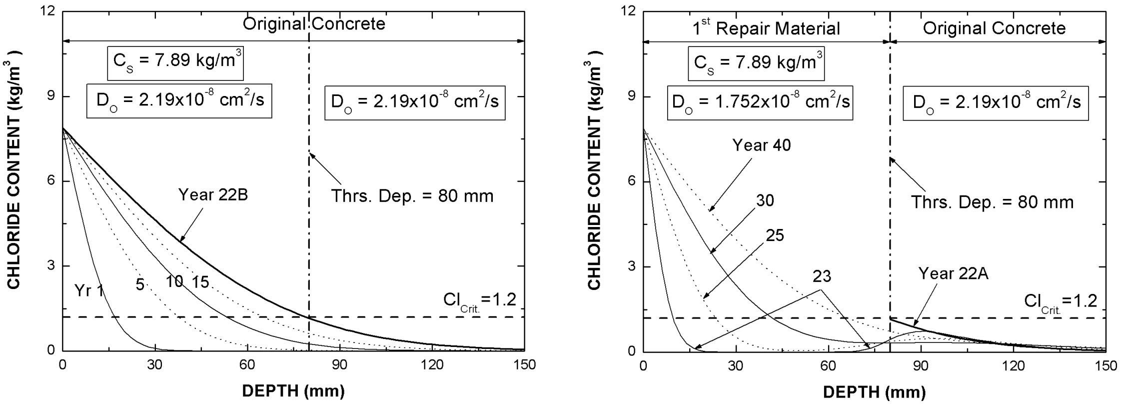
Note: $Cl_{TH,T}$ means chloride ion concentration at the threshold depth TH and at the time of repair application T.

3.4 *Numerical Examples*

There are two numerical examples; (1) concrete structures with concrete cover replacement, and (2) those with silane treatment. And, the threshold depth is selected as 80 mm for concrete structures in the marine environment (JSCE 2002). Moreover, the adhesive material and the effect of interfacial zone between the original concrete and repair material are neglected.

3.4.1 Concrete Cover Replacement (CR)

With all the aforementioned data, the chloride ion diffusion through the depth of the concrete structure can be predicted as shown in Figures 3a and b. From Figure 3a, the chloride ions penetrate through the original concrete with the surface chloride of 7.89 kg/m^3, after the time passes by. In the 31st week after 22 years, the chloride profile reaches the critical value at the threshold depth as shown by the profile at year 22B (B : before repair). With concrete cover replacement, the chloride profile will become the profile at year 22A (A : after repair) in Figure 3b. At year 23, the chloride ions from the surface will penetrate through the concrete (as shown by the profile near the surface), and the remaining chloride ions in the original concrete will both redistribute through the repair material and penetrate through the original concrete (as shown by the profile near the threshold depth). After that, the process of chloride ion diffusion still continues. Whenever, the profile reaches the critical value again, the same repair process will be repeated till the end of the consideration time.

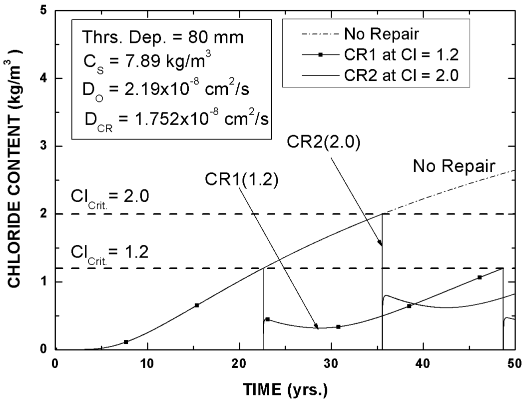


(a) Profiles: Yrs. 1 to 22B

(b) Profiles: Yrs. 22A to 40

Figure 3. Space dependent chloride profile with 80 mm concrete cover replacement.

The time-dependent chloride profiles with concrete cover replacement can be plotted at 80 mm cover depth as shown in Figure 4. With no repair, the chloride ions will cause corrosion initiation in the concrete structure. If the service life of the concrete structure is defined as the time which the chloride ion concentration at the 80-mm cover depth reaches 1.2 kg/m^3 (CR1) or 2.0 kg/m^3 (CR2), the service life is approximately equal to 22 years for corrosion control or 36 years for crack control, respectively.



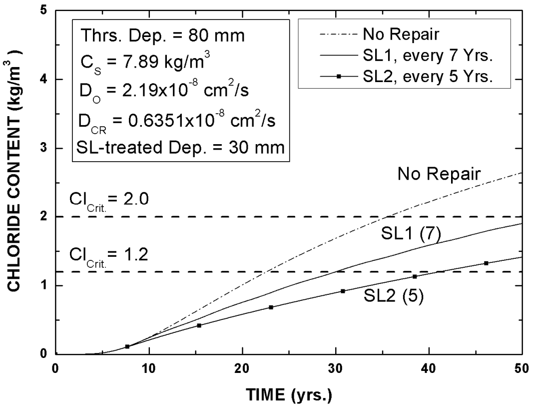


Figure 4. Time-dependent chloride profile with cover replacement.

Figure 5. Time-dependent chloride profile with silane treatment.

But if concrete cover replacement is applied for corrosion control or at the time which the chloride profile reaches 1.2 kg/m^3 in year 22, the service life can be prolonged by 26 years before reaching the critical value again at year 48 as shown in Figure 4. It is noted that at the repair time, the chloride ion concentration decreases to zero due to removing the chloride ions with concrete. However, the chloride ion concentration suddenly increases, because of immediate redistribution of chloride ions from the original concrete. At year 48, the chloride profile reaches the critical value again, the same kind of repair as the first repair is reapplied. It is observed that two cover replacements result in prolonging the service life of the structure over 50 years. It is also noted that the diffusion of chloride ions in concrete structures with corrosion control (CR1) is different from that with crack control (CR2) in spite of the same kind of repair. On the other hand, the concrete structure with crack control need fewer repairs leading to lower repair cost, but allows more deterioration which need more attention and higher cost in the future due to risk of failure.

3.4.2 Silane Treatment (SL)

In the second example, silane treatment is used instead of concrete cover replacement. The space-dependent chloride profile can be shown as similar to Figure 2, so not depicted here The time-dependent chloride profile at the 80-mm cover depth can be drawn as shown in Figure 5. With silane treatment applied every 7 or 5 years (denoted as SL1 and SL2, respectively), the service life of corrosion control concrete structures can be prolonged by about 8 or 19 years, respectively, while that of crack control can be extended more than 50 years. Thus, the concrete structure is free of crack for 50 years.

3.4.3 Comparison

From the previous sections, it is noted that the effect of cover replacement result in eliminating the chloride ions in concrete cover, while that of silane treatment result in retarding the penetration of chloride ions. However, the question is which one is more cost-effective. Based on the opinion of structural repair experts, e.g., Frangopol et.al. (2004), the cost of concrete repair is found to be as high as 15 times that of silane treatment. For consideration, let the cost of one concrete cover replacement be 150 unit, and that of one silane treatment be 10 unit. As a result, during 100 years, the cost of CR1 and CR2 is equal to 300 (applied twice) and 150 (once), respectively. However, the cost of SL1 and SL2 is equal to 70 (7 times) and 100 (10 times), respectively. Therefore, if the cost and corrosion control is needed, the optimum one is CR1. But if the cost and crack control is needed, the optimum one is SL1.

4 CONCLUSION

From the study, it is found that concrete cover replacement can be used for controlling the corrosion or crack in concrete structures by limiting the amount of chloride ion concentration at a threshold depth, while silane treatment is used for prolonging the time which the chloride ion at a specific threshold reaches the critical value.

According to this study, if the control of cost and corrosion controls are needed, the optimum one is CR1. But if the cost and crack controls are needed, the optimum one is SL1. It is recommended that more rigorous data of cost is required for study in order for more promising prediction of the total repair cost.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Petcherdchoo, A., 2015, Service life and environmental impact due to repairs by metakaolin concrete after chloride attack, *RILEM Bookseries*, 35-41.

REHABCON. 2004. *Final report on the evaluation of alternative repair and upgrading options: Strategy for maintenance and rehabilitation in concrete structures, EC Innovation and SME prog. project no. IPS-2000-0063, Dep. of Build. Mat.* LIT, Sweden.

Vaysburd, A.M., and Emmons P.H., 2004, Corrosion inhibitors and other protective systems in concrete repair: concepts or misconcepts, *Cement and Concrete Composites*, 255–63.

Petcherdchoo, A., 2018, Closed-form solutions for modeling chloride transport in unsaturated concrete under wet-dry cycles of chloride attack, *Construction and Building Materials*, 638–651.

Crank, J. 1975. *The mathematics of diffusion*. Oxford: The Clarendon Press.

von Rosenberg, DU. 1969. *Methods for the numerical solution of partial differential equations*. Elsevier Pub. Co.

Press, WH, Teukolsky, SA, Vetterling, WT, and Flannery, BP. 1996. *Numerical recipes in C: the art of scientific computing, 2nd Edition*. Cambridge University Press.

NCHRP-558. 2006. *Manual on Service life of corrosion-damaged reinforced concrete bridge superstructure elements*.

Petcherdchoo, A., 2019, Exponentially aging functions coupled with time-dependent chloride transport model for predicting service life of surface-treated concrete in tidal zone, *Cement and Concrete Research*, 1–12.

Costa, A., and Appleton, J., 1999, Chloride penetration into *concrete in marine environment – Part II: prediction of long term chloride penetration, Material* and Structures, 354–9.

Uji, K, Matsuoka, Y, and Maruya, T. 1990. *Formulation of an equation for surface chloride content of concrete due to permeation of chloride, corrosion of reinforcement in concrete*. Elsevier Applied Sci.

Petcherdchoo, A., 2017, Closed-form solutions for bilinear surface chloride functions applied to concrete exposed to deicing salts, *Cement and Concrete Research*, 136-148.

Yokota, H, and Iwanami, M. 2006. *Life-cycle management of degraded RC structures in ports and harbors*. Proc. of Int. workshop on Life Cycle Management of Coastal Concrete Structures, Japan.

Shimomura, T. 2005. *Evaluation of effectiveness of surface protecting materials for concrete by numerical analysis*. Proc. of Int. work. on dura. of rein. conc. under mech. and climatic loads, China.

Medeiros, M.H.F., and Helene P., 2009, Surface treatment of reinforced concrete in marine environment: Influence on chloride diffusion coefficient and capillary water absorption, *Constr. Build. Mater.*, 1476-84.

JSCE. 2002. *Standard specification for durability of concrete*. Concr. Lib. [in Japanese].

Moriwake, A. 1996. *Study on durability and maintenance of reinforced concrete jetty deck against chloride induced deterioration*. Ph.D. thesis, Tokyo Inst. of Tech., Tokyo, Japan.

Frangopol, DM, Neves, LC, and Petcherdchoo, A. 2004. *Health and safety of civil infrastructures: a unified approa*ch. Proc. of the 2nd int. workshop on structural health monitoring of innovative civil engineering structures, ISIS Canada Research Network, Fort Garry Hotel, Manitoba, Canada.