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STATE-OF-THE-ART ON THE COMBINED EFFECTS OF FREEZE/THAW EXPOSURE AND REINFORCEMENT CORROSION ON THE STRUCTURAL PERFORMANCE OF RC STRUCTURES

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Abstract: Freezing and thawing cycles (FTC) on reinforced concrete (RC) structures is a significant problem for vulnerable infrastructure exposed to extreme climate conditions. This problem is exacerbated by the presence of de-icing agents that lead to reinforcement corrosion and overall concrete deterioration. Current research has mainly focused on studying the mechanical properties of concrete when exposed to cyclic conditions of freeze and thaw. Few studies have analyzed the influence of FTC on the structural performance of RC structures or the dual action of FTC and reinforcement corrosion on the structural performance of RC structural members. This paper surveys available literature on the synergistic effects of one or multiple environmental exposures on the durability and structural performance of RC structures subjected to service loads. It also provides a summary comparison between adopted test methodologies according to current national and international standards. The literature survey is organized as follows: the 1) effect of FTC on: i) mechanical properties; and ii) structural performance; 2) the effect of dual action of FTC and corrosion on the mechanical properties and structural performance of concrete; and, 3) a comparison summary of the methodologies implemented by previous studies according to current international standards. Finally, this paper draws a series of conclusions and recommendations for future work based on the reviewed literature.

1 INTRODUCTION

Due to climate change as a result of the increase in greenhouse gas emissions, adaptive measures and green alternatives become necessary to increase the resiliency and service life of reinforced concrete (RC) infrastructure. One of the major concerns of the engineering community is to mitigate existing and deteriorated structures affected by global warming and to design new resilient ones. This is in order to lengthen their service life by ensuring that they are durable, adaptable and resilient to extreme climate conditions. In effect, this will significantly reduce carbon dioxide emissions associated with the production and construction of new concrete structures. In Canada, it is expected that the frequency of freeze-thaw cycles (FTC) will increase as a result of temperature rise due to climate change. In turn, it will have adverse effects on Canada's vulnerable concrete infrastructure leading to serious and premature deteriorations (International Institute for Sustainable Development (IISD) 2013).

This problem is exacerbated in the presence of de-icing agents that lead to reinforcement corrosion and overall concrete deterioration. Premature deterioration of RC infrastructure due to the combined environmental exposure of reinforcement corrosion and FTC while subjected to static loads leads to loss of bond between reinforcement and concrete, and reduction in the structural capacity, ductility and stiffness. When detailing and strength requirements are compromised, RC infrastructure subject to static loads are no longer capable of performing within their intended elastic range of deformation or of withstanding large inelastic deformations under earthquake loads, for example, leading to devastating results. Therefore, it is very crucial to understand the impact of the combined action of FTC and reinforcement corrosion on the structural performance of RC infrastructure, especially since the combined effect of these two phenomena on the structural performance of RC columns is not fully investigated, Figure 1.

Available research is mainly focused on evaluating material deterioration and the mechanical properties of concrete exposed to FTC conditions by conducting experimental testing (Hasan et al. 2004; Shang and Song 2006; Petersen et al. 2007; Hassanzadeh & Fagerlund 2007; Hanjari et al. 2011; Duan et al. 2011). Others have extended this work to study the effect of FTC on steel corrosion and the mechanical properties of concrete, while few researchers have assessed the seismic performance of RC columns exposed to FTC by conducting experimental tests and numerical simulations (Xu et al. 2016; Qin et al. 2017). Oldershaw (2008) and Mitchell (2010) invistigated the effects of FTC and sustained load on FRP strengthened structures. Diao et al. (2012) assessed the structural performance of small-scale columns immersed in seawater and subjected to the combined action of FTC and sustained load.

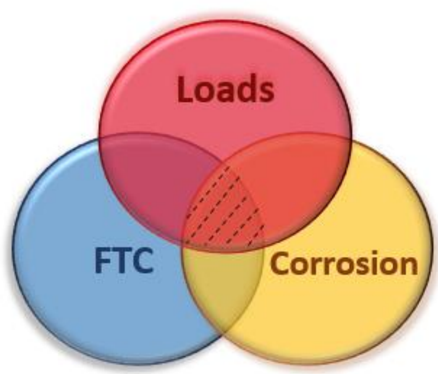


Figure 1: Synergistic effect of combined environmental exposure and structural loads

This paper presents a review of the current state-of-the-art and is organized as follows: effect of FTC on: 1) mechanical properties; and 2) structural performance; 3) the effect of dual action of FTC and corrosion on the mechanical properties of concrete. This is followed by 4) a comparison summary of the methodologies implemented according to current international standards.

2 FTC EFFECTS ON THE MECHANICAL PROPERTIES OF CONCRETE

Several researchers have studied the effects of frost damage on the physical and mechanical properties of concrete (Hasan et al. 2004; Shang and Song 2006; Petersen et al. 2007; Hassanzadeh & Fagerlund 2007; Hanjari et al. 2011; Duan et al. 2011). All of these studies relied on damage indicators, such as compressive strength, tension strength, modulus of elasticity, and bond-slip response, to give a detailed description of the changes that occur to the specimens upon cyclic exposure to FT. Shang and Song (2006) and Hasan et al. (2004; 2008) found that the static strength of concrete is reduced as the number of FTC is increased (according to ASTM C666). Hasan et al. (2004) found a linear relation between the reduction in the tensile strength and the reduction of both the relative dynamic modulus of elasticity (RDME) and stiffness as the number of FTC, expressed in terms of equivalent plastic strain, was increased after a strain value of 0.24 (Figure 2). A Comparison with FTC damaged specimens response in compression, illustrated in Figure 3, shows that a reduction in RDME, compression strength and stiffness values occur almost immediately.

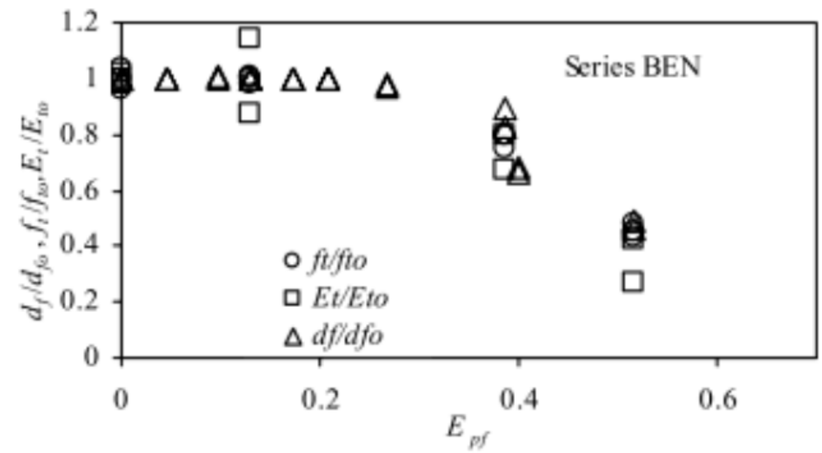


Figure 2: RDME, tensile strength and stiffness reduction with the increase of FTC equivalent plastic strain (Hasan et al. 2004)

Hasan et al. (2004) concluded that the response of FTC damaged specimens subjected to static loads is different in compression and tension. This was attributed to the fact that reduction in compression strength is linearly dependant on the increase of the equivalent plastic strain developed during FTC, whereas reduction in tensile strength is associated with the development of cracks (Figure 3). Tests results, in which FTC testing was conducted according to RILEM TC-176IDC, led to conclude that there is 25-50% reduction in compressive strength for damaged concrete cylinders, in addition to stiffness loss (Hanjari et al. 2011).

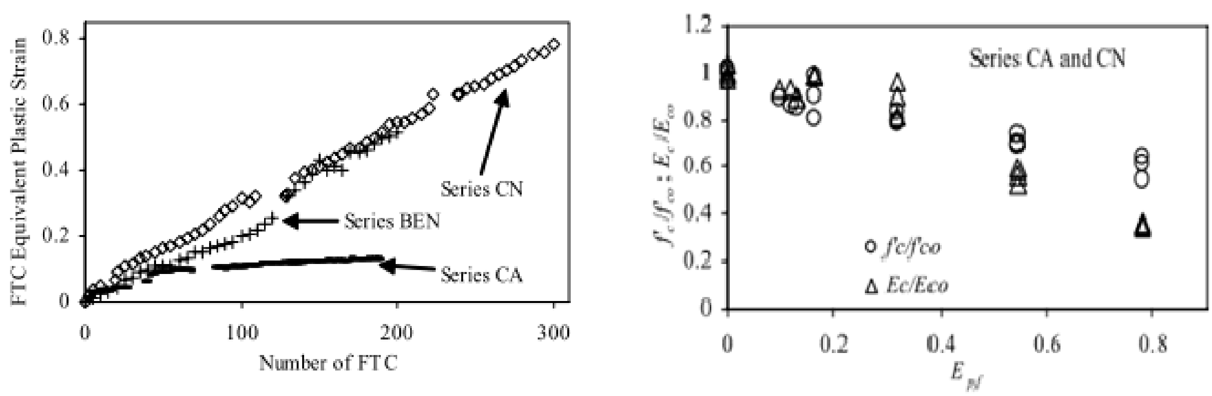


Figure 3: Left: Increase in plastic tensile strain as FTC are increased, Right: Compressive strength and stiffness reduction with the increase of FTC equivalent plastic strain (Hasan et al. 2004)

More damage has been observed for concrete in tension compared to compression (Hanjari et al. 2011). However, there is not enough information for the tensile softening behaviour of concrete, which is essential for modelling (Hanjari et al. 2011). Therefore, Hanjari et al. (2011) proposed a bi-linear relation between tensile stress and crack opening (σ–w) using inverse analysis with results from splitting wedge tests, and then the relation was inputted into finite element analysis for frost damaged specimens. In this analysis, it was observed that at zero tensile stress, the fracture energy and critical crack opening notably increased for damaged specimens (Hanjari et al. 2011). Hanjari et al. (2011) results showed 29% decrease in the tensile strength along with crack opening and an increased in the fracture energy as the number of FTC is increased. Shang and Song (2006) found that increasing the FTC results in reduction in the modulus of elasticity for both uniaxial and biaxial compression loading at a particular stress ratio value, as shown in Figure 4. It was estimated that there is a 62% reduction in the elastic modulus under uniaxial compression, whereas there is a 59% reduction under biaxial compression at the same stress value after 50 FTC.

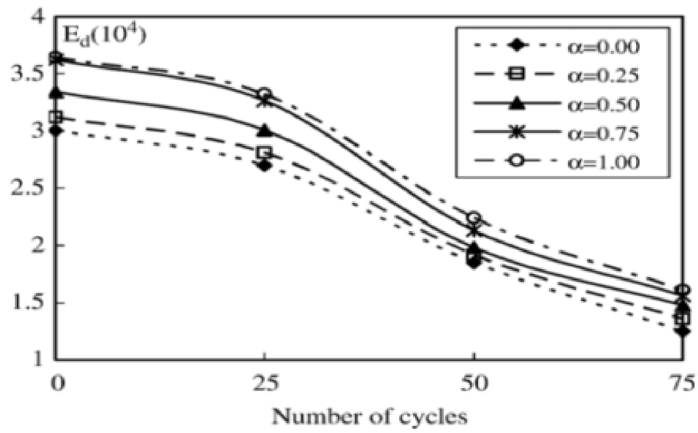


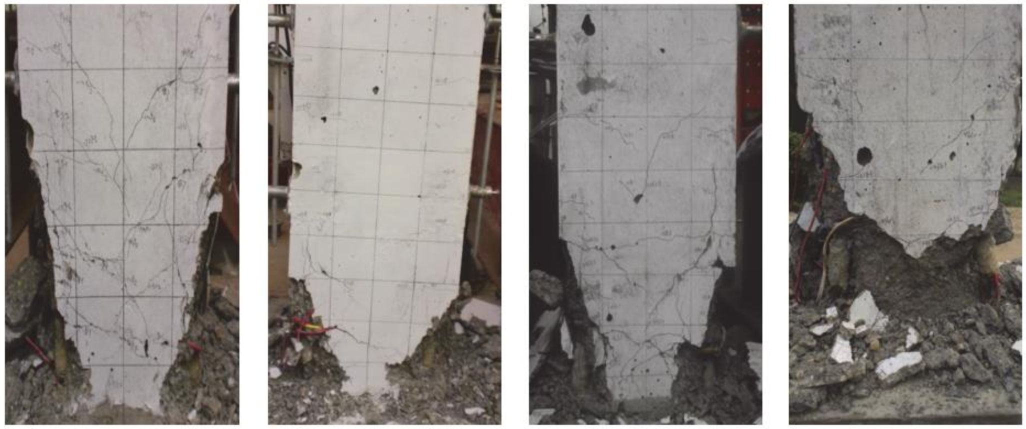
Figure 4: Reduction in the elastic modulus of elasticity as a function of FTC (Shang & Song 2006)

Shih et al. (1988) found that frost damage on the concrete cover significantly decreases the bond strength between concrete and reinforcement as the number of FTC increased. There is an observed 15% to 50% reduction in bond strength between concrete and reinforcement (Hanjari et al. 2011). Fagerlund (1994) suggested a 30% to 70% reduction. Hassanzadeh & Fagerlund (2006) conducted experimental work on beams with different cross sections and reinforcement ratios. Results showed that frost effects reduced the bond strength, stiffness and strength capacity of the beams. Beams had a reduced compressive strength and as a result had a brittle type of failure, the beams failing due to compression fracture instead of reinforcement yield-typical failure. Also, it was observed that there is an overall reduction in the load carrying capacity due to FT damage.

3 FTC EFFECTS ON STRUCTURAL PERFORMANCE

Few researchers have investigated the effects of FTC on the structural performance of RC beams and columns, most of them following the protocol outlined in ASTM C666 for small specimens (Oldershaw 2008; Xu et al. 2016; Qin et al. 2017). Results of the experimental tests have showed that cyclic conditions have definitely a major impact on the structural performance of RC columns. Incremental exposure of FTC resulted in 19% decrease in the ultimate bearing capacity after 300 cycles compared to a 10% decrease following 100 cycles (Qin et al. 2017). Failure was characterized by an early yielding of the longitudinal reinforcement and premature concrete crushing at the column base, as shown in Figure *5*. Material ductility increased up to 200 cycles due to the increase in the yield and ultimate displacement as a result of microcracks formation. Then, at 300 cycles the ductility decreased due to a drop in the ultimate displacement (Qin et al. 2017).

Furthermore, from the hysteresis loops generated for this study (Figure 6), it is observed that FTC exposure has a significant effect on the structural performance of the RC columns. At the elastic stage, the loading/unloading curve was linear. Once yielded, the curve reduced gradually at the elastic-plastic stage. However, once the specimens reached the peak load, there is a significant degradation in stiffness and strength at the same displacement level compared to specimens not exposed to FTC. Also, there is an increase in the displacement value with the increase of number of FTC (100 to 300) due to the increase in ductility value and decrease in ultimate strength (Qin et al. 2017).



(a) 0 cycles (b) 100 cycles (c) 200 cycles (d) 300 cycles

Figure 5: Significant crushing of the concrete at the base of the column at 300 cycles (Qin et al. 2017)

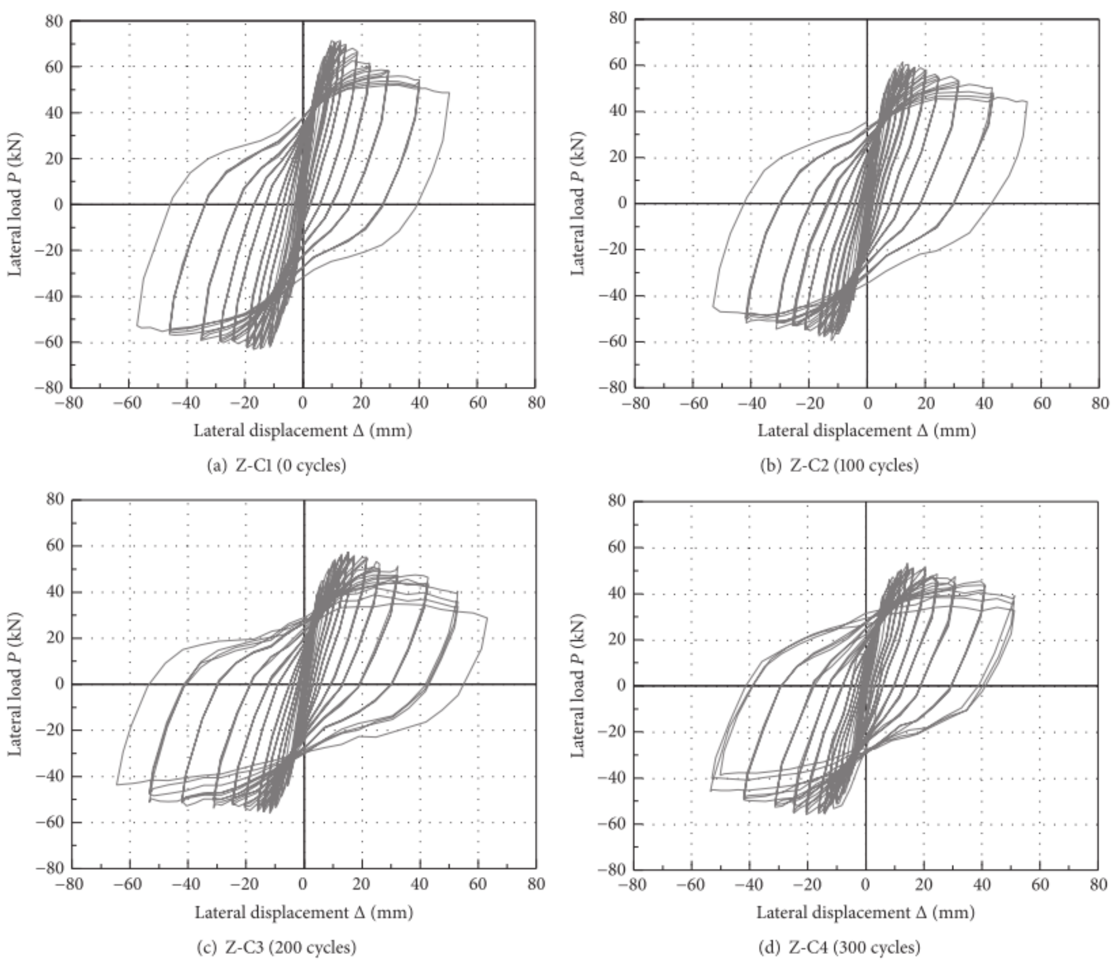


Figure 6: Lateral-displacement hysteresis of both columns: (a) undamaged, (b), (c) and (d) damaged after 100, 200 and 300 FTC, respectively (Qin et al. 2017)

Xu et al. (2016) found that there is a continuous reduction in the value of the ductility factor (ratio of the ultimate displacement to the yield displacement) as the load ratios and FTC are increased, Figure 7. In addition, results indicate that the displacement capacity of the columns was reduced following FTC due to decrease in the bond strength and an increase in the slip between the concrete and the reinforcement. Xu et al. (2016) found that the higher the applied compression ratio along with FTC exposure, the higher the reduction in the stiffness of the columns. From the lateral load-displacement hysteresis, it was prominent that as the number of FTC increased, strength and stiffness degraded at a fast and abrupt rate compared to those not exposed to FTC, as shown in Figure 8. In addition, Figure 8 illustrates that as the number of FTC increased, the number of hysteresis loops decreased at 300 FTC.

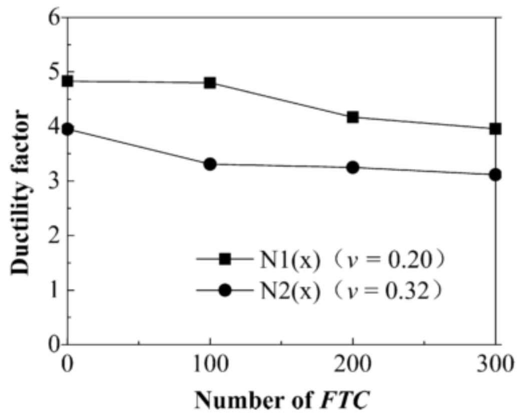


Figure 7: Lateral-displacement hysteresis of columns exposed to FTC (Xu et al. 2016)

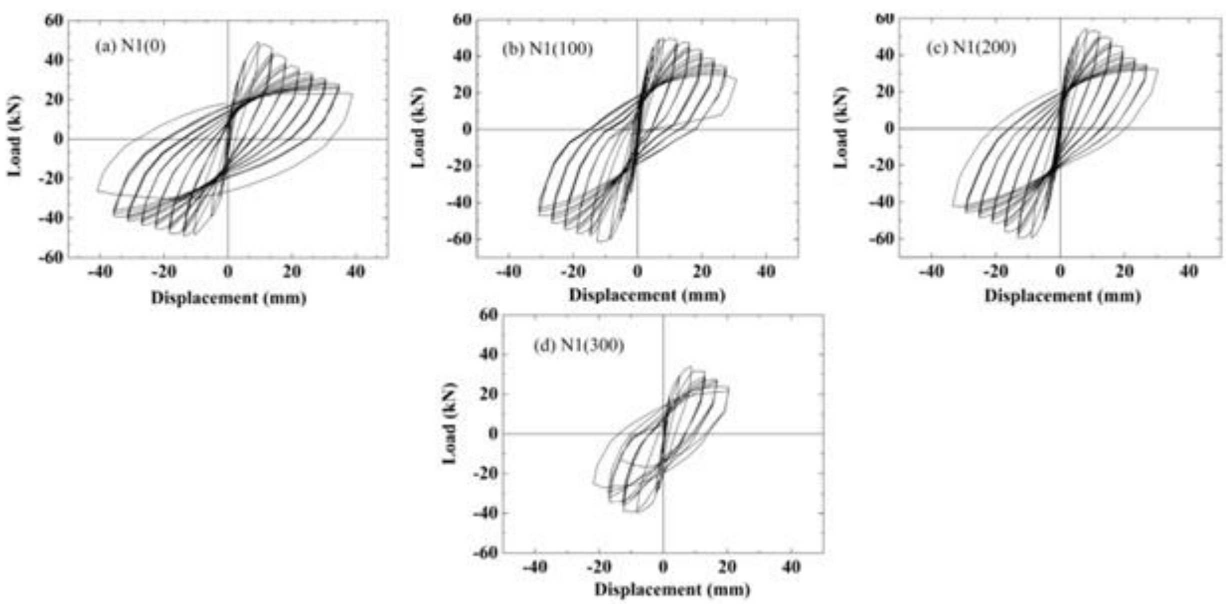


Figure 8: Lateral-displacement hysteresis of both columns: (a) undamaged, (b), (c) and (d) damaged after 100, 200 and 300 FTC, respectively (Xu et al. 2016)

On the other hand, Mitchell (2010) and Oldershaw (2008) investigated the combined effect of FTC and sustained load of FRP-reinforced beams and slab strips, respectively. These studies showed no-to-minor reduction in ultimate strength and ultimate strain capacity, concluding the beneficial effect (strength increase due to confinement effect) of FRP wraps in containing the damage induced by FTC.

4 THE EFFECT OF THE COMBINED ACTION OF FTC & CORROSION ON THE MECHANICAL PROPERTIES AND STRUCTURAL BEHAVIOUR OF CONCRETE

Diao et al. (2012) studied the synergistic effects of environmental conditions inducing reinforcement corrosion and FTC on both the mechanical properties and structural behaviour of RC columns, using the GB/T 50082 standard and sustained loads. The author found that the compressive strength is reduced by 33% after 300 FTC. Furthermore, the ultimate capacity is reduced by 11.5% when the RC columns are subjected to the combined action of corrosion and FTC. This decrease in ultimate capacity is aggravated from a 15% to 26.9% drop when the environmental conditions are coupled with incremental sustained load (52 to 130 kN) applied eccentrically, Figure 9 and Figure 10.

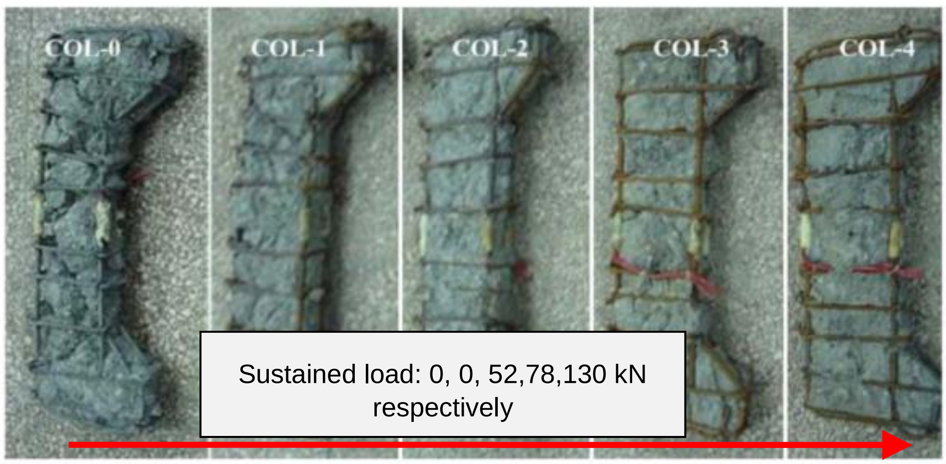


Figure 9: Significant reinforcement corrosion as the load ratio is increased (Diao et al. 2012)

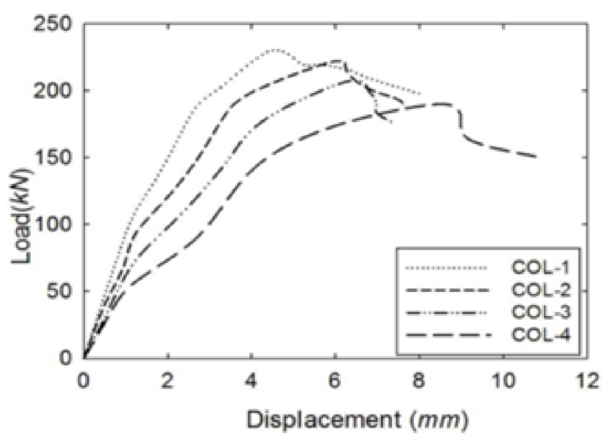


Figure 10: Load-displacement curve of columns exposed to FTC and immersed in seawater subjected to incremental sustained load (Diao et al. 2012)

Diao et al. (2011) investigated the degradation of concrete material properties in prisms and the structural performance of RC beams when exposed to both FTC and steel corrosion. Results show a reduction in the compressive strength and RDME as the number of FTC increases. In addition, results show a 4% increase in the reduction of the strength of RC beams under a 4-point bending load and an increase in the deformation capacity as the number of FTC was increased. The beams' mode of failure changed from a ductile failure characterized by flexural cracks and crushing of the concrete at the compression zone to a brittle failure. Failure was characterized by loss of bond between the longitudinal rebar and concrete. Zhu et al. (2016) found that as the number of FTC is increased, there is a significant reduction in the bond strength of corroded RC. Results also show that exposure to FTC accelerates the corrosion process of RC specimens (increases the corrosion rate). Also, the RDME was decreased between 24% and 80% depending on the water/cement ratio. In addition, sustained loading resulted in reducing the resistance to pull-out load and increasing the rebar slip for the same number of FTC.

5 CURRENT STANDARDS TEST METHODS FOR THE EVALUATION OF FTC DAMAGE

Currently in Canada there is no available standard on evaluating FTC damage on RC structural members. As discussed previously, several researchers have relied on different international standards to assess the FTC damage on the concrete. These standards differ in the testing method used and in the methodology carried out for evaluating damage in concrete specimens. RILEM TC 117-CDF and CEN/TS 12390:9, 2006 evaluate the external damage, while ASTM C666, CEN/TS 15177, GB/T 50082-2009, RILEM TC 176-IDC assess the internal damage. Both ASTM C666 and GB/T 50082-2009 have a 5-hr cycle period, while others have a 24-hrs cycle. RILEM TC 117-CDF and CEN/TS 12390:9, 2006 and CEN/TS 15177 specify a testing procedure for de-icing agent exposure in addition to FTC. Both ASTM C666 and GB/T 50082-2009 require water immersion during thawing and dry freezing, while CEN/TS 12390:9, 2006 and CEN/TS 15177 specify no water immersion. It is worth to note that these standards propose testing procedures for small-scale unreinforced concrete specimens and not for large-scale RC specimens. Hence, researchers mentioned previously have applied some modifications to standards procedures to render the experiments feasible according to their specimens' size and type and size of their environmental chamber. Therefore, the number of cycles (N) according to one standard must be converted to an equivalent number (N_{eq}) to provide the same FTC effects (Berto et al. 2015). A comparison of all current standards used to evaluate the damage induced in concrete by FTC is provided in Table 1.

Table 1: A comparison summary of available standards regarding FTC testing

Standard	**Canada**	**USA**	**China**	**International: International Union of Laboratories & Experts in Construction Materials, Systems & Structures**		**European Standard**	
		ASTM C666	**GB/T 50082-2009**	**RILEM TC 117-CDF**	**RILEM TC 176-IDC**	**CEN/TS 12390:9**	**CEN/TS 15177**
Objectives	None	Resistance of Concrete to Rapid Freezing &Thawing	Long-term performance & durability of concrete	FT test & deicing resistance of concrete	Internal Damage of Concrete due to frost action	Scaling resistance of concrete with water & salt	FT resistance of concrete with water & salt solution
Method		Procedure A & B	Not specified	Salt scaling	Frost Resistance	Scaling	Internal damage
Specimen Age		Young or mature concrete	28 days	24 days	24 days	Curing	
Conditions		In lime water	In water	In water for 7 days	In water for 7 days	65% RH for 7 days	
Temperature		(-18 to 4°C)	(-17 to 15°C)	Rates of 10/hr	(-20 to +20°C)	(-20 to +20°C)	(-18 to +5°C)
Cycles		5 hrs	5 hrs	12 hrs	12 hrs	Freezing: 16-18 hrs. Thawing: 6-8 hrs	
No. Cycles		0 to 300	0 to 300	28	DME <80%	25	
Environment		Chamber	Chamber	Suitable chamber	Suitable chamber	3% NaCl solution	
Water Immerse		Procedure A & B (thawing)	Yes, freezing	Yes, heating & cooling	Yes, heating & cooling	No	
Dry Freeze		Procedure B (freezing)	Yes, freezing	No	No	Yes	
Exposure		Full exposure air & water	Full exposure air & water	One surface in 3% NaCl solution	One surface in water	One surface	
Record		Durability Factor (DF) after 300 cycles & the initial one.		Scale mass	Procedure A: Length dialation & ultrasonic velocity. Procedure B: DME	Scaled mass every 5 cycles, max depth of damage.	
Damage		Internal Damage: 60% reduction in DME from intial. Visual: spalling, cracking, exposed rebars		Scaling	internal Damage: DME < 80%	Scaling	Internal damage

6 CONCLUSIONS AND GAP IN THE STATE-OF-ART

Authors, whose work has been reviewed, have used mechanical properties, such as compressive strength, tensile strength, elastic modulus of elasticity and bond-slip behaviour, as damage indicators to provide a good understanding of concrete deterioration and response in compression and tension following FTC exposure. It has been found that there is significant reduction in the compressive strength with the increase in the plastic tensile strain at the end of FTC exposure. Furthermore, the tensile strength and stiffness reduction is linearly related with the development of cracks. Also, the bond strength of different beams' cross sections and reinforcement ratios is also reduced.

Few authors investigated the seismic performance of FTC on small-scale RC columns and beams. They concluded that there is a reduction in the ultimate capacity and ductility along with premature and abrupt failure. Few authors investigated the dual effect of FTC and reinforcement corrosion by sea-water immersion on small-scale columns or beams; they found that there is a significant reduction of the ultimate capacity associated with the increase of the stress ratio value.

The discussed studies provide a good outline of the experimental program procedures and set-ups to test the structural performance of RC members exposed to FTC. This is especially valuable since there are no current standards or test methodologies in North America tailored for testing large-scale RC members exposed to FTC. Moreover, there is lack of publications on the effect of multi-deteriorating environmental mechanisms such as FTC and reinforcement corrosion on the structural performance of large-scale RC columns. This is significant because the combined effect of multi-deteriorating mechanisms in the presence of service loads could considerably accelerate the deterioration and degradation in structural performance of RC columns. Therefore, a comprehensive study of the structural performance of RC structures due to the combined environmental exposure in the presence of service load is necessary.

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