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COUPLED EFFECTS OF ENVIRONMENTAL LOADS ON CONCRETE NUCLEAR STRUCTURES: A REVIEW

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ABSTRACT

Identification of age-related degradation mechanisms based on destructive, non-destructive and visual inspection of nuclear concrete structures can be complex. There are many sources of uncertainty that add to the complexity, some of which are: (i) concrete is exposed to several environmental parameters simultaneously; (ii) structural concrete is reinforced or prestressed; and (iii) in-service concrete has applied loads. Typically, fundamental degradation mechanisms, effects, and symptoms are reflected by the action and reaction of a single mechanism at a time. However, to ensure long term performance of the structures in nuclear industry, the effects of interactions of various stressors should also be considered.

In the Canadian climate, damage of structural concrete may be attributed to a specific degradation mechanism however, the role of additional exposure (i.e., freeze-thaw, natural carbonation) as well as composite materials (i.e., reinforcement (pre-stressing)), and specimen size need also be considered. There is a need to examine the effect of relevant coupled degradation mechanisms to understand the visual manifestation as well as fundamental combined mechanisms which can have competing effects.

The paper includes discussion on the performed critical literature review to study the degradation and coupled degradation of existing concrete structures including those in nuclear industry.

INTRODUCTION

Concrete structures are known to degrade with age due to degradation mechanisms. The identification of the impact of these deterioration mechanisms offers valuable insights into aging management and longevity prognosis for the concrete structures. Interestingly current standards and codes typically consider the effects of single degradation mechanisms on concrete structures while in reality combinations of these degradation mechanisms could occur in concrete structures. Understanding the effects of these combinations of age-related degradation mechanisms is necessary to accurately assess the health of structures in nuclear industry.

CODES AND STANDARDS ON SINGLE DEGRADATION MECHANISMS

Early in the review of the literature it became clear that it is challenging to compare current reports in the literature due to differences in code and standard protocol. Differences can range from test specimen geometry, mix design, system type (mortar or concrete), curing regime, preconditioning, external conditions (i.e., temperature, relative humidity, concentration of ion exposure, duration of exposure and cycle frequency and corresponding conditions). For example, Tables 1 and 2 present sample comparison of the key variables and differences between codes intended to investigate freeze-thaw (FT) resistance (Table 1) and sulfate resistance (Table 2).

Table 1: Key parameters of ASTM and RILEM standards for FT exposure in concrete

Code	ASTM C666 (2015)	RILEM TC 176 IDC* (2004)
Specimen size	75 - 125 mm width or depth or diameter 275 - 405 mm length	110 x 150 x 70 mm
Measure of resistance	Relative dynamic modulus of elasticity	Relative dynamic modulus of elasticity
Maximum temperature	4 ± 2 °C	20 ± 1 °C
Minimum temperature	-18 ± 2 °C	-20 ± 0.5 °C
Cycle duration	2 h to 5 h	12 h
Test termination	300 cycles or 60% of relative dynamic modulus	Demineralized water – 56 cycles De-icing agent – 28 cycles

*IDC= internal damage of concrete

Table 2: ASTM and CSA standards on the sulfate attack

Code	ASTM C1012 (2018b)	CSA A3004-C8 (2018)
Specimen size	25.4 x 25.4 x 285 mm	Adapted from ASTM
Temperature	23 ± 2 °C	23 °C (ettringite formation) and 5 °C (thaumasite attack)
Reagent	Na_2SO_4 – 50 g/L	Adapted from ASTM
Duration	365 days	
Measure of resistance	Length change	Length change

The variations in specified parameters across the standards range from small to large. For example, the minimum temperature of RILEM IDC differs ASTM C666 by 11% while maximum temperature by 400%. The higher maximum temperature in RILEM could allow the concrete specimens to regain the depleted mechanical properties. However, this comparison is moot since both standards are developed based on different theories. Thus, comparison of studies addressing the same problem, following different standards may yield erroneous conclusions which hinders development of comprehensive understanding of the deterioration mechanisms.

COUPLED DEGRADATION MECHANISMS IN CONCRETE

The scope of this study involves a review of coupled degradation mechanisms in concrete arising only due to external environmental exposure. The following combinations of exposure degradation mechanisms have been reviewed for their design of experiments exposure combinations, and damage indication:

- FT and chloride exposure
- FT and carbonation
- FT and sulfate exposure
- Alkali-silica reaction (ASR) and FT
- ASR and chloride exposure
- ASR and carbonation
- Sulfate exposure and chloride exposure
- Delayed ettringite formation and FT

Trends in The Literature on Coupled Degradation Mechanisms of Concrete

Despite the differences in the concrete specifications and the exposure conditions, the following trends are observed (Table 3).

Table 3: Coupled degradation mechanisms and their effect on the damage to concrete.

Coupled degradation mechanism	Damage to concrete (based on measure of resistance)	Positive and negative effects to the concrete durability	Additional comments	Citations
FT and Chloride Exposure	Increase	Negative: Micro cracks from FT enhanced the permeability of concrete to chloride ions. Positive: Chloride ions can lower the freezing point of water	• Usage of multiple measure of resistances resulted in % increase in damage from less then 10% to over 200% • Scarce SCM studies • Lack of air entrainment	Chung et al., 2010 Zhao et al., 2014
FT and Carbonation	Increase	Negative: Microcracks can increase the carbonation depth. Positive: Critical saturation of pores may hinder the carbonation	• Effect of carbonation on FT is not investigated. • Lack of SCM studies • Lack of air entrainment	Whittman et al., 2006
FT and Sulfate Exposure	Increase (except in the case of $MgSO_4$ exposure)	Negative: The sulfate salts can reduce the freezing point of water Positive: In case of $MgSO_4$ exposure, formation of brucite can increase the mechanical properties	• Lack of SCM studies	Miao et al., 2002 Jiang et al., 2015
ASR and FT	Increase	Positive: Low temperatures delay the progression of ASR in the early stages Negative: Cracks formed due to FT can increase the ASR transport and expansion in late stages	• Lack of air entrainment • Lack of SCM studies	Bérubé et al., 2002 Deschenes et al., 2018
ASR and Chloride exposure	Increase (Long term)	Positive: ASR gel could lower the rate of chloride ingress Negative: Higher rates of chloride ingress can be found at later stages	• Lack of studies detailing the effects of chlorides on ASR • Lack of short-term vs long term studies	Heisig et al., 2016 Kawamura and Ichise, 1990
ASR and Carbonation	No consensus	Negative: Carbonation depth could rapidly increase due to ASR	• Dependent on the age, extent of carbonation and chemical	Thomas and

		induced cracks Positive: Formation of calcite due to carbonation could prevent the substitution of alkali in the ASR with Ca thereby hindering the formation of ASR capable of severe damage.	composition of concrete.	Monkman, S., 2019, Wang et al., 2022
Sulfate and Chloride exposure	Increase	Negative: The cracks generated by sulfate attack can increase the chloride penetration Positive: The competition for reaction sites between sulfates and chlorides causes the penetration of ions to slow down	• Lack of studies with SCM usage	Maes and De Belie., 2014
DEF and FT	Increase	Negative: Filling of cracks and air voids with ettringite can reduce the air void system performance	• Lack of studies with SCM usage	Aqel and Panesar., 2018

KEY OBSERVATIONS FOR COUPLED DEGRADATION MECHANISMS IN CONCRETE

Codes and Standards

Across standards of CSA, RILEM, and ASTM standards, there are considerable differences in the investigation of single deterioration mechanisms. For example, within ASTM, multiple test methods are available for the testing of different materials (such as ordinary Portland cement (OPC) and blended systems) and systems (such as mortars and concrete), for single deterioration mechanisms like ASR. These diverse testing methods tailor the exposure conditioning and severity relevant to the local/regional infrastructure. Thus, a comparison of existing literature for building a database of concrete behaviour or obtaining a consensus on concrete resistance to degradation mechanisms is difficult due to these diverse testing methods.

Interpretation/Understanding of Pass/Fail or Good/Bad Performance

Current standard test methods also do not convey the probabilistic or definitive quantitative estimation of the field performance of the concrete mix designs. As the test methods clearly state that the tests are an indication analogous to field exposure, thus, the results of the concrete field tests will quantitively vary. However, the current standards can guide the comparative performance of different mixes, helping in gauging the performance of mix designs against known thresholds. For example, in ASR affected 100% OPC concrete, 0.04% length change is taken as a threshold beyond which the probability of aggregates exhibiting the ASR is significant.

Lack of Standardization Across Studies

Studies investigating the single deterioration mechanism use different mix designs and parameters relevant to local climatic conditions and building practices. For example, usage of air entrainment in chloride studies may become necessary in cold climates while it may be unnecessary for hot and arid environments. The lack of standardization across the studies will hinder the accurate comparison of studies to build a comprehensive knowledge repository. Such knowledge repositories not only eliminate the need for repeated experiments but also can help in modelling and prediction of concrete damage.

Specimen Size

In addition to mix designs, specimen size also plays a role in the assessment of degradation mechanisms. For example, in sulfate exposure tests shown Table 2, the specimen sizes are the same. However, in FT test methods, the ASTM test allows for a 25% change in all the dimensions, while RILEM suggests a fixed dimension. Even in the same test method, unless the effect of specimen size is clearly established and accounted for, the errors arising due to specimen sizes can lead to misinterpretation.

Exposure (Concentration, Temperature, Relative Humidity)

Concrete specimens are largely resistant to deterioration mechanisms as it takes days to years to see the visible damage due to degradation mechanisms. Laboratory standards on the other hand, use more aggressive temperature, concentration, and humidity ranges to control and optimize the time and accuracy of the test to suit the needs of the project. As these parameters are time bound as well as variable, it presents the same problem of unique data points that are incomparable with each other.

Test Set Up and Orientation

The effect of concrete deterioration mechanisms can be isotropic or anisotropic (directional). In some cases, such as ASR, the damage of concrete without loading conditions can be non-directional, while under loading, damage mechanism develops a favourable direction. Thus, test set up and orientation adds to the list of parameters needed to be understood for their effect on damage.

Frequency and Duration of Testing

Standard test methods employ assessing concrete mixes at a specific age of hardened concrete while strength and microstructural changes in concrete continue to change beyond the testing age.

Coupled Mechanisms

Compounding behaviour of coupled mechanisms is not always twice as bad as one mechanism! Combined deterioration mechanisms have both positive and negative impacts on the health of concrete. Nearly all combined deterioration mechanisms depend on the availability of moisture, which tends to increase the damage. However, due to competition of reaction sites, varying temperatures, and water stable reaction products, the damage from the coupled degradation mechanisms is not a linear addition of individual mechanisms.

Lack of studies

The major hurdle for the coupled degradation mechanisms so far is the lack of experimental and modelling studies that can be comparable between each other and that can shed light on mechanisms. The lack of research in the coupled degradation mechanisms contribute to inaccurate estimation of concrete durability, leading to premature failures.

Highly Dependent on Exposure Conditions

The exposure conditions of concrete can affect the reaction kinetics of single degradation mechanisms, thereby affecting the coupled degradation mechanisms. As the exposure increases in severity, the compounding effect of coupled degradation mechanisms also increase.

Quality of Concrete

Quality of concrete in single deterioration mechanisms is indicated by the ability of concrete to resist the damage. However, combined deterioration mechanisms may cause damage in higher quantities beyond the levels of single deterioration mechanisms. Thus, an adequately good quality concrete, incurring less or no damage can be severely affected by combined deterioration mechanism and need to be evaluated for both single and combined deterioration mechanisms.

Measure of Resistance

Measure of resistances for one degradation mechanism may not be suitable for other. For example, length change is taken as a prominent measure of resistance for ASR, while fundamental transverse frequency is taken as a primary measure of resistance for FT damage.

Pessimum Exposure Conditions and Pessimum Testing Protocol

Pessimum conditions for maximum damage (reactive aggregate proportion and size in ASR in Ichikawa, 2009) and mitigation techniques (LiOH in ASR treatment in Diamond, 1999) are determined based on the single degradation mechanisms in the absence of any interactions between mechanisms. These limits and testing protocols may not hold true as coupled degradation mechanisms create complex interactions.

Series or Parallel Testing

Some combinations of degradation mechanisms can only occur in series (such as ASR combined with FT or carbonation combined with FT) while other combinations can occur in parallel (such as sulfate and chloride exposure). This key distinction can shape the damage in concrete and must be understood to evaluate the coupled degradation mechanisms.

Other Observations

FT degradation combinations were tested on non-air entrained concrete. Omission of air entrainment can be observed in majority of the studies involving FT, rendering the test results, shorthanded in truly understanding of coupled degradation mechanisms.

Much of the literature available on the coupled degradation mechanisms involves examinations of 100% OPC concrete. The usage of 100% OPC enabled the researchers to establish a basis for coupled degradation mechanisms. However, the new construction guidelines, with a focus on environmental impact and sustainability, shift from 100% OPC to blended cements. Thus, adaptation of SCMs in coupled degradation studies is needed to bridge the gap between laboratory standard test methods and field concrete.

COUPLED DEGRADATION MECHANISMS IN NUCLEAR STRUCTURES

Concrete nuclear structures may be susceptible to various types of concrete degradation mechanisms. For example, FT, elevated temperatures, salt crystallization, leaching, efflorescence, alkali-aggregate reactions, sulfate attack, acid attack, DEF, carbonation, corrosion, abrasion and erosion, and irradiation are presented in both review papers (Arel et al., 2017; Basu et al., 2013; Busby et al., 2008; Le Pape et al., 2022; Marquié et al., 2019; Naus 2009; Naus et al., 1991; Scott and Chen, 2019; Tripathi 2015) and experimental investigations (Ciampoli and Ellingwood, 2002; Ferreira et al., 2015; Ichikawa and Koizumi, 2002; Jóźwiak-Niedźwiedzka et al., 2022; Kang and Cho 2017; Kojima et al., 2021; Králik 2013; Maruyama et al., 2017; Mitsugi et al., 2021; Qiao et al. 2021; Vazquez and Duffó, 2018).

The combinations arising from these degradation mechanisms may adversely affect performance of concrete structures in nuclear industry; thus, the effects of coupled degradation mechanisms need to be well understood. Le Pape et al. (2022) noted an increase in the dissolution of alkalis in irradiated concrete. Ichikawa and Koizumi, (2002) reported the enhanced reactivity of supposedly non-reactive aggregates in irradiated concrete, indicating the exacerbated damage due to coupled degradation of irradiation and ASR. Thus, irradiation, a common degradation of the nuclear industry can be observed to assist the ASR progression in concrete exacerbating the damage in concrete.

Naus (2009) noted the presence of multiple degradation mechanisms in nuclear structures such as elevated temperatures, irradiation, and fatigue effects in combination with corrosion. Although combined mechanisms can result in different symptoms in concrete, Naus (2009) reports that the predominant manifestation in the study is reinforcement corrosion.

Jóźwiak-Niedźwiedzka et al., (2022) found a proportional relation between the carbonation depth and the radiation dose in mortar specimens. Jóźwiak-Niedźwiedzka et al., 2022 also reported an increase in calcite hardness using nanoindentation. Mitsugi et al. (2021) examined the role of elevated temperature (60 °C) in carbonation induced corrosion. Elevated temperature resulted in high carbonation levels, while resulting in low corrosion for a given relative humidity in Mitsugi et al. (2021).

Qiao et al. 2021 compared the performance of laboratory specimens against single degradations and field samples of below grade concrete samples of nuclear power plants exposed to coupled degradation due to acid and sulfate attacks. Qiao et al. 2021 noted the exacerbation of damage in laboratory specimens due to high concentration exposure solutions and the need for reducing the gap in results of laboratory and field examinations. However, as per Maes and De Belie. (2014) the competition of different ions in coupled degradation may also contribute to the low damage in field structures.

The studies on the coupled degradation of the concrete in nuclear industry indicate alternate outcomes than single degradation (Ciampoli and Ellingwood, 2002; Ferreira et al., 2015; Ichikawa and Koizumi, 2002; Jóźwiak-Niedźwiedzka et al., 2022; Kang and Cho 2017; Kojima et al., 2021; Králik 2013; Maruyama et al., 2017; Mitsugi et al., 2021; Qiao et al. 2021; Vazquez and Duffó, 2018). These studies suggest the higher levels of complexity in damage due to coupled degradation mechanisms as opposed to single degradation mechanisms. Thus, further investigations on concrete used in nuclear industry exposed to coupled degradation mechanisms can assist in bridging the gap in laboratory and field performance of concrete.

CONCLUSIONS AND FUTURE OUTLOOK

Concrete elements in the nuclear industry can be exposed to coupled degradation mechanisms. The coupled degradation mechanisms can adversely affect the properties of the concrete. A careful observation of the parameters influencing the damage in studies investigating coupled degradation revealed interesting takeaways.

1. Concrete test standards across used across associations such as ASTM and RILEM can differ in specimen type and size, temperature, exposure duration, and measure of resistances. The differences across the standards make the assimilation of test results related to single degradation mechanisms difficult.
2. Eight coupled degradation mechanisms were discussed for their effect on the concrete damage and different parameters that influenced the damage. These mechanisms indicate a general trend of increased damage due to cracks from one mechanism increasing the permeability to enhance the progression of another mechanism.
3. Coupled degradation studies of nuclear industry reveal a trend of accelerated damage similar to concrete studies. However, a systematic testing related to the coupled degradation is needed to enhance the understanding of the age-related degradation in concrete structures in the nuclear industry.
4. The literature review forms the basis of a multi-year project that has been initiated aiming at evaluating the effects of coupled degradation mechanisms on performance of nuclear concrete structures, which is essential to enable the safe and reliable prognosis of in-service nuclear concrete structures and their elements that is critical for knowledge-based decisions regarding repair, maintenance, life extension and decommissioning.

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