Review of Deemed-to-Satisfy Provisions in Australian Standards by Using Fully Probabilistic Model: Durability of Reinforced Concrete Structures Exposed to Chlorides

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Abstract: The current system in Australian Standards for specifying and ensuring the durability of new concrete structures is a prescriptive type. In prescriptive specifications, adequate durability is assumed to be guaranteed indirectly by ensuring compliance with limiting values for minimum characteristic compressive strength, concrete composition (i.e. minimum cement content, maximum water/cement ratio, cement type, maximum chemical content in concrete) and construction details (i.e. minimum initial curing requirement and minimum concrete cover). These parameters define the resistance of a concrete and construction element to withstand different actions from the surrounding environment. The environmental action is characterized through exposure classes (i.e. A, B1, B2, C1 and C2). The purpose of this paper is to review the prescription given in Australian Standards in relation to the reliability ranges regarding the chloride-induced depassivation of rebar. The reliability analysis is carried out using the full probabilistic model for chloride-induced corrosion presented in *fib* Bulletin 34, *fib* Model Code for Concrete Structures 2010 and ISO Code 16204.

Keywords: chloride, full probabilistic model, Australian Standards, concrete structures, reliability.

1. Introduction

The current system in Australian Standards for specifying and ensuring the durability of new structures is prescriptive. In prescriptive specifications, adequate durability is assumed to be guaranteed indirectly by ensuring compliance with limiting values for concrete characteristics and construction details. However, there is a significant move for durability design to follow structural design and incorporate reliability based principles. This requires a comprehensive reliability and engineering analysis of durability (CREAD).

In BCRC's CREAD utilized in this study, AS 5100.5:2017 Deemed to Satisfy (DtS) requirements are reviewed using fully probabilistic analysis (FPA) based on the *fib* Bulletin 76 chloride model. In AS 5100.5:2017 Section 4, the concrete characteristics to be limited are minimum characteristic strength, minimum cement content, maximum water/cement ratio, cement type and maximum chemical content in concrete. The construction details to be limited are minimum initial curing requirement and nominal concrete cover required. The limited values are designed to ensure the durability of new concrete structures exposed to the specific exposure class based on past experience.

FPA chloride model as recommended in *fib* Bulletin 76 is used to review the prescriptive specifications described in AS 5100.5:2017. The minimum reliability of 1.3 is selected for Serviceability Limit State as recommended by CIA Z7/01 and Z7/05. This applies to the limit state of depassivation which is considered in this paper. The reliability of 1.3 provides the probability of failure of 10%.

The following sections of this paper will describe some key parameters which dependent on concrete characteristics limited in AS 5100.5:2017.

2. Chloride Migration Coefficient and Aging Factor

2.1 Chloride Migration Coefficient D_{RCM}

The apparent chloride diffusion coefficient $D_{app}(t)$ is used to describe the diffusivity of the concrete. $D_{app}(t)$ is usually determined through the 'chloride profiling method'. This method is described in NT Build 443:1995. Chloride profiles can either be taken from existing structures or from test specimens stored under conditions which are similar to those expected in practice. The determination of $D_{app}(t_0)$ on test specimens (for the design of new structures) is very time consuming. Therefore, alternative method (NT Build 492:1999) provides chloride diffusion coefficients by means of accelerated test under different experimental conditions.

$D_{RCM}(t_0)$ is simply determined by the Rapid Chloride Migration (RCM) test method by accelerating chloride transport through the application of an electric field through the water saturated concrete specimens.

For reliability analyses, the mean values for chloride migration coefficient, $D_{RCM}(t_0)$ at t_0 = 28 days, are dependent on the type of binder and the water/binder ratio. The relationship between chloride migration coefficient at t_0 = 28 days and water/binder ratio for various type of binder or cement are presented on Figure 1 below. The data are obtained from specific studies presented in references [1 – 4] and BCRC consultation works. The data will be used in the reliability analyses to review of deemed-to-satisfy provisions in AS 5100.5:2017. However, the data only represent indicative values. For design in an individual case, the chloride migration coefficient of the concrete mix being considered can be measured if it is significant, for example if the reliability shown by calculation is well in excess of that required for a conservative assumption of the concrete performance project tests would not be required. This is a consistent extension of the Levels of Approximation approach whereby more sophisticated analysis is only undertaken when a more accurate assessment is required.

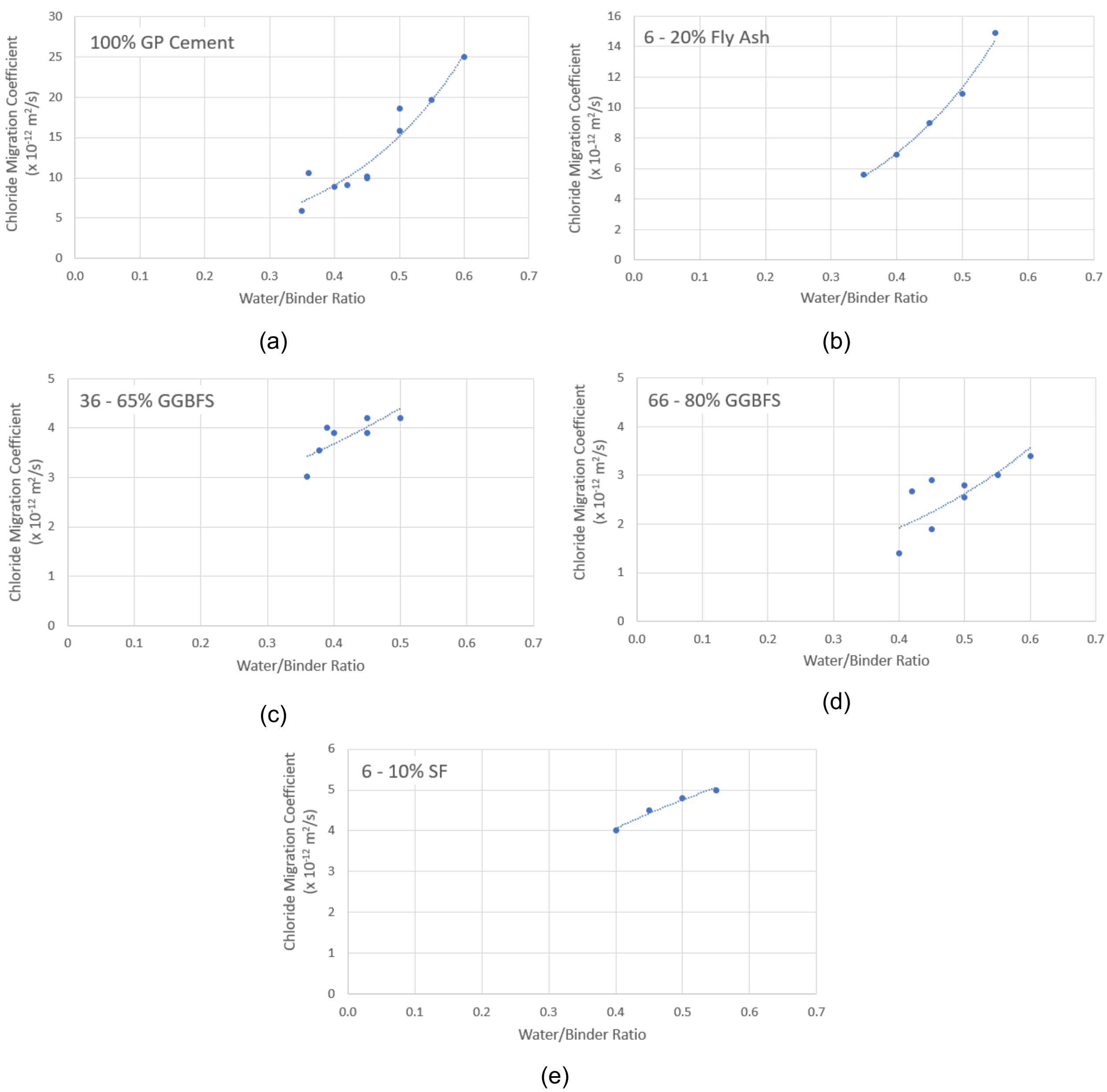

Figure 1. Effect of water/binder ratio on chloride migration coefficient of concrete with various cement types

For the purpose of reviewing of deemed-to-satisfy provisions in Australian Standards, in particular AS 5100.5:2017, the chloride migration coefficients presented in Table 1 are used.

Table 1. Chloride migration coefficient used for various water/binder ratios

Cement Type	Water/Binder Ratio	Mean and Std. Deviation Normal Dist. (μ / σ)
100% GP [No. 1]	0.45	11.7 / 2.34
80 – 94% GP & 6 – 20% FA [No. 2]	0.45	8.9 / 1.78
	0.40	7.0 / 1.4
	0.36	5.8 / 1.16
35 – 64% GP & 36 – 65% GGBFS [No. 3]	0.45	4.0 / 0.8
	0.40	3.7 / 0.74
	0.36	3.4 / 0.68
20 – 34% GP & 66 – 80% GGBFS [No. 4]	0.45	2.2 / 0.44
	0.40	1.9 / 0.39
	0.36	1.7 / 0.34
90 – 94% GP & 6 – 10% SF [No. 5]	0.45	4.4 / 0.88
	0.40	4.1 / 0.81
	0.36	3.7 / 0.75

In the early 1990s it was observed that chloride diffusion coefficient or chloride migration coefficient decrease with time. There are several factors which may contribute to a decrease of the chloride diffusion coefficient or chloride migration coefficient with increasing exposure time as described in *fib* Bulletin 76.

- *The development of a denser pore structure due to the ongoing hydration process after reference age t_0*
- *A pore-blocking effect due to chloride ingress*
- *Concentration dependence of the binding capacity inherently included in the apparent chloride diffusion coefficient or chloride migration coefficient*
- *The degree of water saturation and therefore the chloride diffusion coefficient or chloride migration coefficient is depth dependent (e.g. due to self-dessication in the inner concrete)*

The time dependent chloride migration coefficient is described in the following equation.

$$D_{RCM}(t) = D_{RCM}(t_0) \times (t_0/t)_{\alpha} \quad (1)$$

where α is the aging factor which dependent on cement type and exposure class.

2.2 Aging Factor α

It is widely accepted that the chloride migration coefficient will decrease with increasing exposure time. There are two schools of thought over the length of time that aging factors should apply for (*as described in CIA Z7/05*):

- *Hypothesis A: Aging factors can be used only to predict the chloride penetration within the exposure period during which measurements were taken, as it is unknown how the aging factor will continue over extended periods. Some have suggested that aging factor application should be limited to 20-30 years.*
- *Hypothesis B: There is no reason to suppose that the factors causing the chloride ingress rate reduction will not continue. For example, pore blocking due to chemical reactions such as carbonation and magnesium hydroxide (Brucite) formation could continue until pores are completely blocked for chloride ingress. However, this is not sustainable indefinitely as the availability of chemical reactants is finite.*

In *fib* Bulletin 76 and related documents *fib* Bulletin 34 and the *fib* Model code 2010, the aging factor is applied over the entire design life. This practice is followed when using the factors set out in Table 2.

Table 2. Aging factor used for various exposure classes

Exposure Class	Cement Type 0.40 ≤ w/b ≤ 0.60	Aging Factor α [-] BetaD (μ / σ) with a = 0.0 & b = 1.0
C1 and C2	100% GP [No. 1]	0.30 / 0.12
	80 – 94% GP & 6 – 20% FA [No. 2]	0.60 / 0.15
	35 – 64% GP & 36 – 65% GGBFS [No. 3]	0.40 / 0.18
	20 – 34% GP & 66 – 80% GGBFS [No. 4]	0.45 / 0.20
	90 – 94% GP & 6 – 10% SF [No. 5]	0.40 / 0.16
B1 and B2	All cement types and mix proportions	0.65 / 0.12

3. Surface Chloride Content C_S

The chloride content at the exposed concrete surface C_S are variables that mostly depend on environmental conditions. CIA Z7/02 Table 5.6 and *fib* Bulletin 76 Table 2.6 provide guidelines to determine surface chloride content for each exposure class. By considering these guidelines, the proposed surface chloride content for various exposure class used in this study is presented in Table 3.

Table 3. Surface chloride content dependent on exposure class

Exposure Class	C_S [wt.%/b] LND (μ / σ)
B1	1.0 / 0.45
B2	2.0 / 0.90
C1	2.0 / 0.90
C2	3.5 / 1.58

This takes the C_S values given in CIA Z7/02 as being mean values rather than upper limits. In Papworth 2021 [9] the view is expressed that they were intended as upper bounds, but this is not explicitly stated and considering them as means makes them coincident with *fib* Bulletin 76.

4. Depth of Convection Zone Δx

For structures subject to the cyclic exposure of chlorides the transport mechanisms in the near-surface layer will significantly differ from Fick's law of diffusion. It will undergo a process of capillary suction during any subsequent re-wetting. In contrast to diffusion process, capillary action leads to a rapid transport of chlorides into the concrete up to a depth Δx where the chlorides can accumulate with time until a steady-state chloride content $C_{S,\Delta x} = C_{S,0}$ is reached. The variable Δx can be described by a Beta distribution. *fib* Bulletin 76 states that under splash conditions the average depth Δx up to which chlorides can rapidly penetrate will be limited to 6.0mm ≤ Δx ≤ 11.0mm. Under exposure classes B1 and B2, the formation of a convection zone cannot be detected anymore (Δx = 0). Therefore, *fib* Bulletin 76 recommends the depth of convection zone Δx as shown in Table 4.

Table 4. Depth of convection zone dependent on exposure class

Exposure Class	Δx [mm]
B1	Constant (0)
B2	
C1	BetaD (μ = 10 / σ = 5 / a = 0 / b = 50)
C2	

However, El Farissi [5] propose the equation to estimate depth of convection zone Δx which is dependent on porosity and chloride migration coefficient. The study concludes that negligible values of the convection zone depth (Δx < 2.5mm) are observed for high performance concretes exposed to marine tidal condition. A threshold of water porosity (φ = 11.5%), under which we have not a convection zone, is observed. AS 5100.5:2017 specifies maximum water/binder ratio of 0.40 and 0.36 for exposure classes C1 and C2. Negligible values of the convection zone depth (Δx < 2.5mm) are applicable to concrete with maximum water/binder ratio of 0.40 and lower. Therefore, in this paper, negligible values of the convection zone depth are taken for all exposure classes.

5. Other Parameters Required for Full Probabilistic Model of Chloride Ingress in Concrete

The other parameters used in fully probabilistic chloride model are presented in Table 5. The values are adopted for concrete bridge structures in Western Australia.

Table 5. Other Parameters used in Full Probabilistic Model

Parameter	Unit	Distribution Type	Mean	Std. Dev.	Beta a	Beta b	Source / Note
Concrete Age at Test, t_0	year	Constant	0.0767				Assumed 28 days
Design Life, t	year	Constant	100				
Ref. Temp., T_{ref}	K	Constant	293				20°C (standard temp. in the RCM test)
Actual Temp., T_{real}	K	Normal	292	5			Assumed 19°C (average temp. in Perth Metro)
Temp. Coeff., b_e	K	Normal	4800	700			*fib* Bulletin 76
Initial Chloride Content, C_0	wt.%/c	Approx. 0.1					Assumed 0.4 kg/m^3 (MRWA Spec 820)
Critical Chloride Content, C_{crit}	wt.%/c	Beta	0.60	0.15	0.2	2.0	*fib* Bulletin 76

Nominal Concrete Cover, C_{nom}	mm	Normal	45 (B1) 60 (B2) 70 (C1) 80 (C2)	3			Table 4.14.3.2 and Section 17.7.3 of AS 5100.5:2017

Notes:

1. Concrete grade 40 MPa is used for exposure classes B1 and B2, 50 MPa for C1 and 55 MPa for C2.
2. Nominal concrete covers are based on standard formwork and compaction.

6. Results

From full probabilistic chloride model results, the prescriptive specifications described in AS 5100.5:2017 give reliability index ≥ 1.3 for 100 year design life except for silica fume concrete in C1 and C2 exposure classes. The silica fume concrete prescribed in AS 5100.5:2017 is not adequate to ensure durability of new concrete structures exposed to C1 and C2 exposure classes. It is due to its unfavourable estimated chloride migration coefficient and aging factor. From this study, the maximum chloride migration coefficients of 2.4 x 10^{-12} and 2.0 x 10^{-12} m^2/s are required for silica fume concrete exposed to C1 and C2 exposure classes respectively to provide minimum reliability of 1.3. This can be achieved with water/binder ratio ≤ 0.34 and ternary blended cement (i.e. 60%GP/34%GGBFS/6%SF).

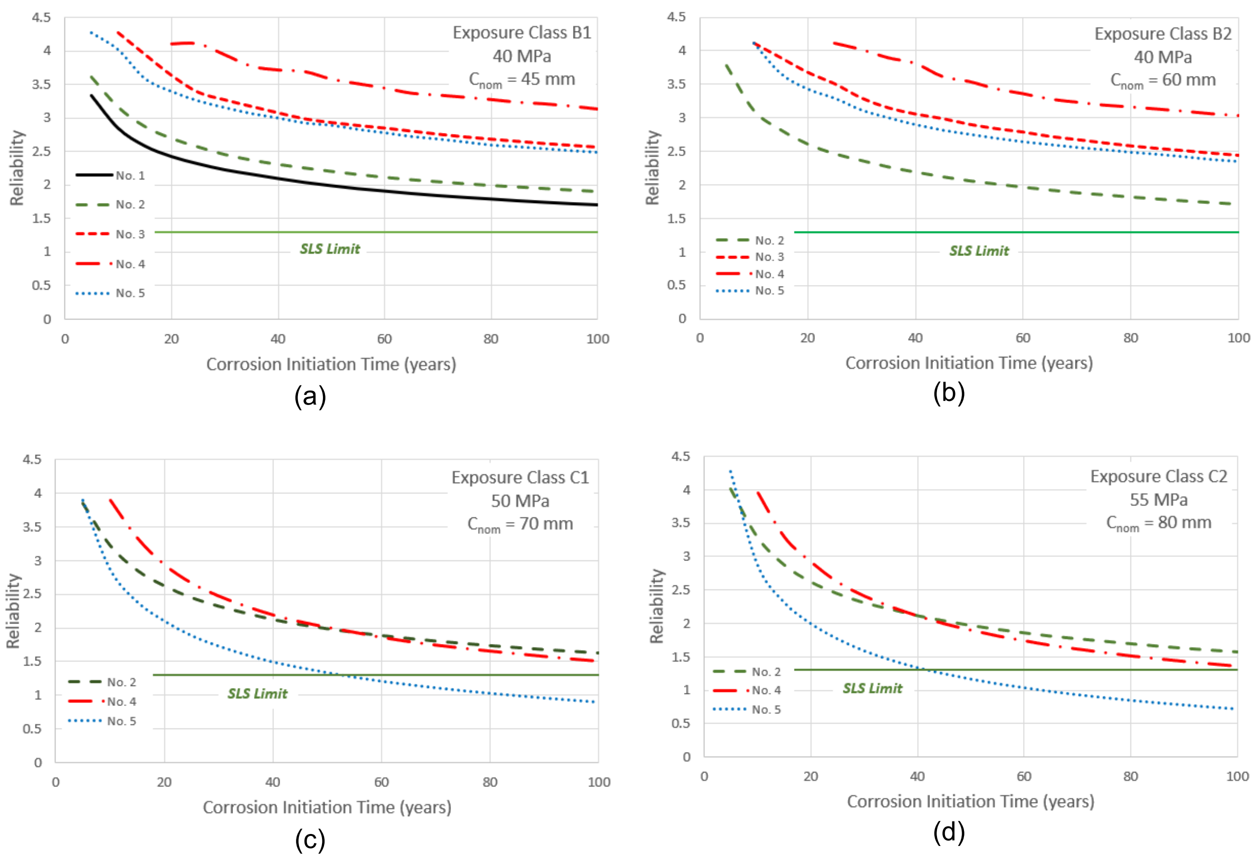

Figure 2. Development of reliability index over time

7. Conclusions and Recommendations

Full probabilistic analysis for chloride model has been done to review the prescriptive specifications described in AS 5100.5:2017. The following conclusions and recommendations can be drawn.

- For exposure class B1 and B2, the prescriptive specifications described in AS 5100.5:2017 are adequate to give minimum reliability of 1.3 for 100 year design life.
- For exposure class C1 and C2, the prescriptive specifications for Fly Ash and GGBFS concretes are adequate to give minimum reliability of 1.3 for 100 year design life. However, the prescriptive specifications for Silica Fume concrete are unfavourable.

- The maximum chloride migration coefficients of 2.4×10^{-12} and 2.0×10^{-12} m^2/s are recommended for silica fume concrete under C1 and C2 exposure classes, respectively. This can be achieved with water/binder ratio ≤ 0.34 and ternary blended cement (i.e. 60%GP/34%GGBFS/6%SF).
- The full probabilistic analysis can be done to review the prescriptive specifications described in other Australian Standards (i.e. AS 3600:2018, AS 4997:2005 and AS 3735:2001)
- This exercise can be extended to concrete using ternary blended cement when sufficient information will become available.

8. Acknowledgement

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9. References

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