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Current Trends of Durability Design and Government Support in South Korea: Chloride Attack

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Abstract: Concrete is considered to be a construction material with high durability and excellent fire resistance. However, degradation occurs, leading to structural safety problems and expensive maintenance costs. Currently, durability design and its concepts are provided in the concrete specifications and structural design codes in many countries, but they vary in terms of the design methodologies and users' demands. Reinforced concrete (RC) structures based on a reasonable durability design with a quantitative procedure can prevent unnecessary maintenance expenses and reduce environmental loads. This paper presents the current trends of durability design in South Korea and government support for infrastructure. In this work, the two representative durability design philosophies (deterministic and probabilistic approaches) are briefly summarized, and the current guidelines and related requirements for durability design in several countries are investigated. Durability design is now changing from simple material requirement control to performance-based design with quantitative parameters considering various exposure classifications and evaluation processes. RC structures based on reasonable durability design can make a great contribution to reducing maintenance costs and environmental effects like CO_2 emissions.

Keywords: durability design; design code; deterministic approach; probabilistic approach

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1. Introduction

Concrete is an attractive construction material whose engineering advantages have been known for a long time. The engineering properties of concrete such as strength and stable material behavior in the curing process make it suitable for use and provide designers with the freedom of geometry, a short construction period, and cost-effectiveness. In reinforced concrete (RC) or pre-stressed concrete (PS) structures, an important assumption for design is the perfect integration between concrete and the embedded steel [1,2]. The durability problems caused by steel corrosion begin with rust stains but can also include the degradation of serviceability and the reduction of structural safety [3]. Durability is the capacity to withstand the influence of actions in the course of time, such as chloride attack, carbonation, and freezing/thawing cycles. Among the parameters affecting durability, chloride attack is considered one of the most severe as it affects steel corrosion directly, leading to cracking, reduction of steel area, delamination of the concrete cover, and breakdown of structures [3,4]. Several critical disasters due to steel corrosion have been reported, including the collapse example of the I35W bridge in Minneapolis [5]. The total estimated direct cost for repairing or preventing corrosion is reported to be $276 billion, which is approximately 3.0% of the gross domestic product in the United States of America (USA) [6]. The reasons for the increasing consideration of durability design can be summarized as follows:

(1) The determination of the intended service life of the infrastructure: Concrete is considered an economical and durable construction material. In small structures, durability problems can be

controlled by simple measures such as sufficient concrete cover depth and a low water/cement (w/c) ratio. However, structures are constructed on a large scale with various types; therefore, the significance of the life cycle costs (LCC) for maintenance increases accordingly [7,8]. In order to secure cost benefits and the required performance at the same time, an intended service life should be determined in the planning stage. Several important structures are planned to maintain performance for 100 years or longer without active repairing or retrofitting [1,9]. LCC analysis for infrastructure covers the costs from initial construction to the dismantling process, and plays an important role in cost savings and optimization of maintenance processes [7,8]. The determination of intended service life, considering the significance of the structure, the maintenance costs, and the difficulties of repairing, is the first step of durability design.

(2) Increasing users' needs for maintenance: Before 1990, the serviceability of a structure was simply achieved through satisfying the requirements regarding structural safety. However, the user needs as well as maintenance expenses are increasing owing to an expectation of more safe and convenient usage of the structures. Corrosion control and the related repairs in the USA are reported to require \$3.6 trillion [6,10]. User needs can be another expense since citizens are users and reporters of corrosion detection at the same time [11]. The increasing repair costs in South Korea are shown in Figure 1 for different structure types [12].

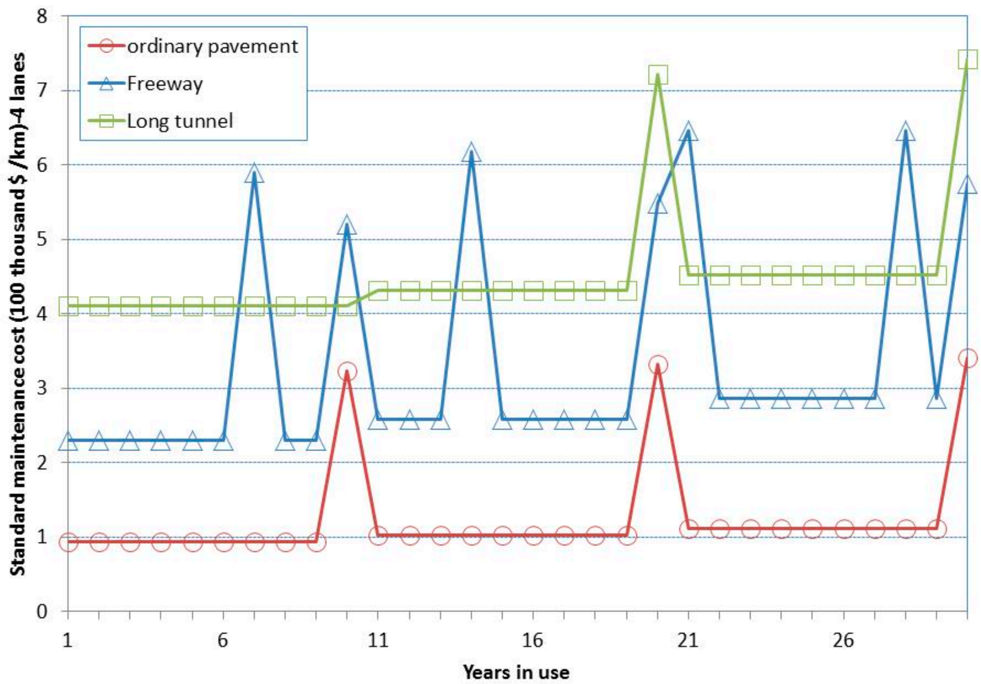


Figure 1. Increasing maintenance costs in South Korea (standard maintenance cost).

(3) Long service life for sustainability: With the extension of service life of RC structures without large-scale repairs, concrete usage can be reduced. During clinker manufacturing, 0.9 tons of CO_2 emissions are reported per 1.0 ton of cement [13]. The maintenance-free period is currently recognized as a critical period since other construction efforts, and repairs on a large-scale cause additional environmental impacts. Previous research on life cycle CO_2 ($LCCO_2$), i.e., the evaluation of total CO_2 emissions, reported that an initial investment into construction materials and design details for reducing CO_2 was the most sustainable solution when compared with the total CO_2 considering frequent repairs and small CO_2 uptake in use [14].

(4) Reduction in social impact: Social impact is defined as "the consequences to human populations of any public or private actions that alter the ways in which people live, work, play, relate to one

another, organize to meet their needs, and generally cope as members of society" [15] (p. 1436). Several reports have shown that construction projects affect human population, communities, and social relationships [15,16]. For example, human health and a reasonable quality of life cannot be achieved when living near a construction site owing to noise issues and traffic obstructions. The extension of the service life of a structure can contribute to the members of a community feeling settled.

This paper investigates the durability design trend for chloride attacks. Additionally, the recommendations and requirements from concrete specifications in the USA, the European Union (EU), Japan, and South Korea are investigated.

2. Deterministic and Probabilistic Durability Design for Chloride Attack

2.1. Overview of Durability Design in Specifications and Design Codes

Before 1990, the significance of durability was not yet a concrete issue and only conceptual durability designs were proposed [1,17,18], as shown in Figure 2. During that period, durability design was performed based on specifications such as maximum w/c ratio and minimum cover depth. If structural safety was satisfied, the durability performance was thought to be satisfied accordingly. With the increasing use of mineral admixtures and problems due to steel corrosion, durability design was upgraded to deterministic design from the 1990s onwards. Several institutes, such as the Japan Society of Civil Engineers (JSCE) [19] and the Architectural Institute of Japan (AIJ) [20], proposed unique techniques for service life evaluation; however, they could not be developed to meet concrete specifications or international codes.

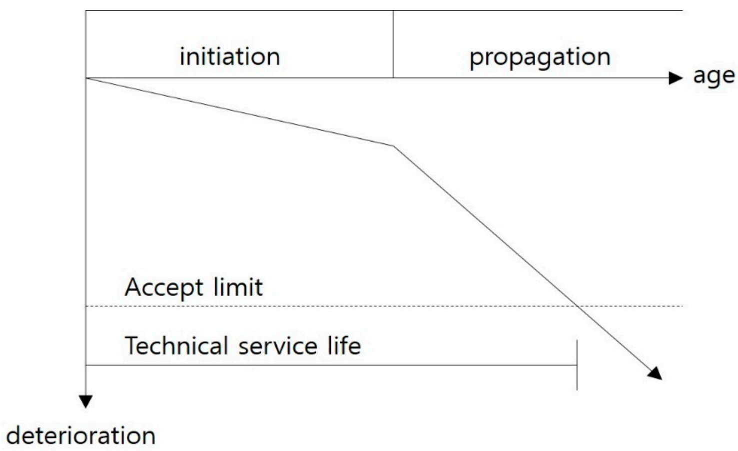


Figure 2. Service life concept in durability design [18].

2.2. Durability Design Based on the Deterministic Method

Durability design based on a deterministic approach is a method that ensures the induced chloride content does not reach the critical threshold initiating corrosion in the outer steel during the intended service life. Similar to structural safety design, the induced chloride and critical chloride content are regarded as external loads due to design loads and internal strength due to nominal strength from the designed material, respectively. The governing equations can be classified into two equations. The first is Fick's second law of diffusion [21,22] and the second is the Nernst-Einstein equation. Conventional design is based on Fick's second law of diffusion, and is rendered in Equation (1)

$$C(x,t) = C_s[1 - erf(\frac{x}{2\sqrt{Dt}})], \quad (1)$$

where D is the chloride diffusion coefficient at time t, Cs is the surface chloride content, and erf is the error function.

Several parameters for reasonable diffusion coefficient have been studied considering time effect [21–23], temperature effect [21,24], humidity effect [25], surface chloride build-up [17,21,26], and the mineral admixture effect on diffusion [27,28]. The diffusion coefficient in Fick's second law is an apparent diffusion coefficient that assumes steady-state chloride diffusion, where chloride transport is explained only by the diffusion coefficient. The apparent diffusion mechanism is improved using a multi-layer theory for concrete with different surface conditions. The apparent diffusion coefficient is usually obtained from a long-term submerged test and field investigations. The chloride profiles along the concrete depth are regressed based on a non-linear line (error function). Surface chloride content and the diffusion coefficient are then obtained from the best fit line based on the chloride profile [29–31]. In order to evaluate corrosion initiation, the critical chloride content is very important. Many research efforts have been carried out to determine the chloride content accurately. However, it varies depending on local conditions, including the cement type and mixture proportions. The previous results regarding critical chloride content are summarized in Figure 3 [32–39].

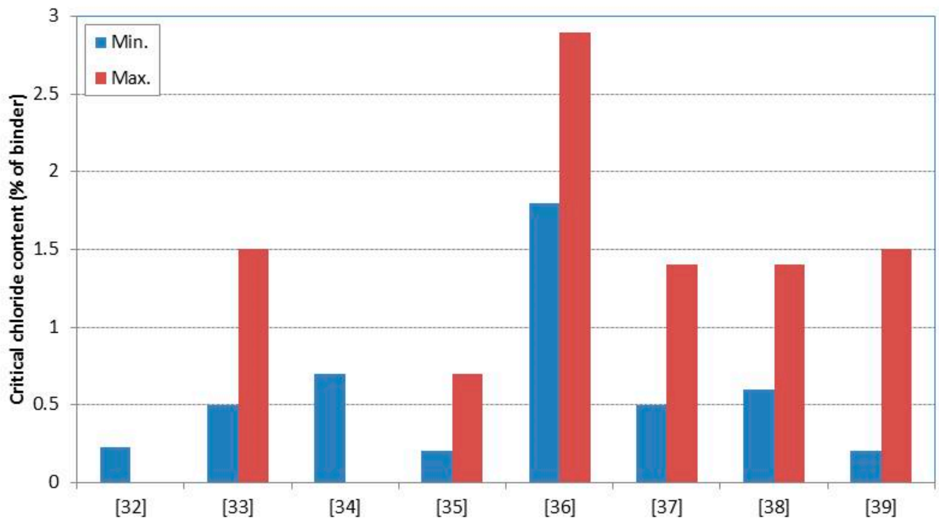


Figure 3. Previous results on critical chloride contents that can initiate steel corrosion [32–39].

In the Nernst-Einstein equation, the behaviors of chloride ions in a non-steady state condition are represented considering diffusion of free chloride ions, convection due to moisture pressure, and kinetic reaction with cement hydrates. In the system, free and bound chloride ions are calculated separately and the total chloride ions are considered as their summation based on isotherm equations [40–42]. Recently, the models using the Nernst-Einstein equation adopted behaviors such as porosity and saturation, which vary with time and local conditions, in early-aged concrete. The models typically include cement hydration, moisture transport, and pore structure formation theories [43–46]. The strong points of these models are: (1) consideration of the varying external conditions (e.g., relative humidity, temperature, and surface chloride content); (2) evaluation of the material characteristics that are affected by external conditions; and (3) determination of the free chloride content, which directly affects corrosion initiation. The models have been applied to the combined deterioration with carbonation and locally unsound concrete with cracks [47]. The representative analysis frame for the model is presented in Figure 4 [48].

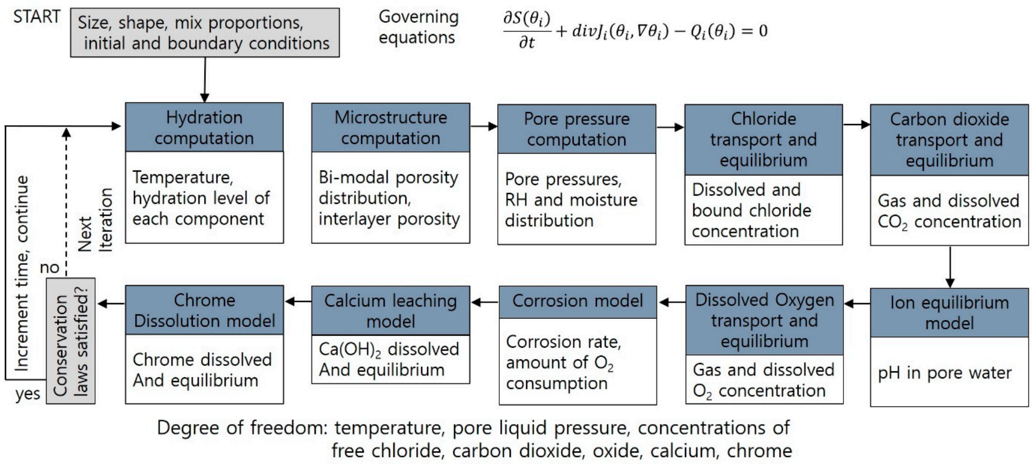


Figure 4. System dynamics for chloride behavior evaluation [48].

2.3. Durability Design Based on the Probabilistic Method

Durability design using a probabilistic approach began in the 1990s and was applied to actual durability designs in the 2000s. The deterministic models are reported to have several limitations since they cannot consider engineering uncertainties such as physical and statistical determination, and the model itself. The uncertainties are summarized in Table 1 [49,50].

Table 1. Engineering uncertainties in durability design [50].

Type	Source of Uncertainty
Physical	Inherent random nature of basic variables
Model	Governing mechanism and equation
Statistical	Assumption for probability density function—limited sample size
Decision	Definition of durability failure criteria

In probabilistic durability design, the design parameters are considered as random variables with a specific distribution. The cover depth, diffusion coefficient, and critical chloride content with each random variable (i.e., mean, Coefficient of Variation COV) are usually adopted for the evaluation of failure probability [51–54]. Currently, several actual durability designs have been attempted for large RC structures; however, this process has not been widely performed [55,56].

The critical condition—determined as the probability that can cause steel corrosion—does not exceed the intended durability probability within the intended service life. The governing equation can be rendered as Equation (2)

$$P\left\{C_\sigma(\mu,\sigma) < C_o(\mu,\sigma)\left[1 - erf\left(\frac{x(\mu,\sigma)}{D(\mu,\sigma)t}\right)\right]\right\} < P_{\max} \tag{2}$$

where $C_\sigma(\mu,\sigma)$ and $C_0(\mu,\sigma)$ are the random variables for the critical chloride and surface chloride content. P_{max} is the intended durability failure probability within the intended service life. In Equation (2), random variables for the diffusion coefficient ($D(\mu,\sigma)$) and cover depth ($x(\mu,\sigma)$) are highly dependent on field investigations and test results. In the design concept as presented in Figure 5, the resistance distribution, $R(t)$, and deteriorating distribution, $S(t)$, are usually calculated in terms of time (t). The design concept for the upper graph with two distributions represents the service life period design concept, while the lower graph with one distribution represents the lifetime design concept [1].

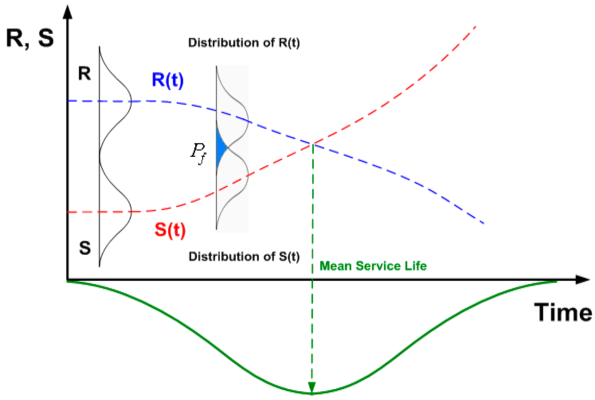


Figure 5. Design concept of probabilistic approach [55].

Recently, many research approaches have been proposed that include spatial variation through random field generation of design parameters such as the diffusion coefficient and surface chloride content [57–60]; however, these techniques have not been attempted for actual durability design.

2.4. Engineering Limitations of the Two Methods

From an engineering perspective, the proposed design methods have both strong and weak points. The strength of the deterministic method is its design simplicity. That is, the solution can be obtained as the chloride content, and the calculation process is relatively easier than the probabilistic manner; hence, the remaining service life can be easily estimated when the design technique is applied to the existing structure. The solution from the deterministic method is a physical value and the estimated service life can provide a reasonable service period, thereby avoiding an overestimation of the cover depth and binder content. The weakness of the design is the adaptation of the fixed critical chloride content, which can vary with local conditions.

The design parameters can reflect actual situations such as the level of construction and material quality. The strength of the probabilistic method is based on conservative design and higher reliability; however, the weakness of the design is the complexity of the calculation frame and the low intended probability of durability failure, which is proposed to have a range from 7.0% to 10.0% [61–63]. The design limitations of the two methods can be summarized in Table 2.

Table 2. Design limitations of the two approaches.

Deterministic	• Determination of diffusion coefficient at the reference time • Time-dependent diffusion behavior considering binder type • Diffusion due to local conditions such as cracks or joints • Design parameters for curing and aging • Environmental parameters for temperature and humidity • Critical chloride content causing corrosion initiation • Determination of the surface chloride content considering the binder type and exterior conditions
Probabilistic	• Appropriate random variables and probabilistic distributions for design parameters (cover depth, diffusion coefficient, critical content, construction level) • Determination of intended durability failure and intended service life • Variations of environmental conditions • Accuracy of the analysis/evaluation system for chloride behavior • Significant dependence on field investigation results or long-term exposure data

3. Current Durability Design Methodology

3.1. Durability Design of Concrete Specifications and Structural Design Codes

With the increasing engineering and social significance of durability and durability design, the related requirements are prepared in structural design codes and concrete specifications in many countries. Durability design based on specific requirements such as maximum w/c ratio, minimum cover depth, and critical chloride content is still prevalent. Several classifications for harsh environment are prepared by considering the distance from the seashore line and the required performance. The current section examines durability design methods in the Structural Codes and Concrete Specifications of Japan, the USA, the EU, and South Korea; as well as governmental support for durability and maintenance in South Korea.

3.2. Foreign Trends in Durability Design

3.2.1. Japan

In Japan, quantitative design procedures are introduced based on deterministic approaches (Fick's second law of diffusion) where performance-based durability design is partially suggested. Regarding durability design, in the Japanese concrete specifications [64], the determination of the diffusion coefficient is based on field investigations and lab-scale tests. In order to evaluate the service life of RC structures, a safety factor of 1.0–1.3 is considered, and design parameters are provided for concrete with normal and slag cement. Surface chloride contents based on a specified distance from the seashore are determined from field investigations. In order to achieve a 100-year service life, the maximum w/c ratio, required cover depth, and construction levels are determined for several concrete members like columns, girders, slabs, and piers. For the durability design, the required diffusion coefficient from the tests discussed in JSCE 571 [65] and JSCE 572 [66] is proposed. The design diffusion coefficients and the related cover depths are proposed for an intended service life ranging from 20 to 100 years by considering the critical chloride content (1.2 kg/m^3) and a safety factor of 1.3. Design parameters for actual crack width and allowable crack width are considered in the design diffusion coefficient. Surface chloride content from the coastline is prepared for durability design based on the specific cities listed in Table 3. It is very informative to enlist the regional conditions in concrete specifications for reasonable durability design.

Table 3. Chloride ion concentration at concrete surface (kg/m^3) according to Japanese concrete specifications [64].

		Splash Zone	Distance from Coast (km)				
			Near Shoreline	0.1	0.25	0.5	1.0
Region with high airborne chloride concentration	Hokkaido, Tohoku, Hokuriku, Okinawa	13.0	9.0	4.5	3.0	2.0	1.5
Region with low airborne chloride concentration	Kanto, Tokai, Kinki, Chugoku, Shikoku, Kyushu		4.5	2.5	2.0	1.5	1.0

Regarding materials and construction, Japanese concrete specifications [67] propose maximum w/c ratios and minimum binder content for specified external conditions, as shown in Tables 4 and 5. In the specifications, the requirements are provided for concrete mix proportions with several external conditions.

Table 4. Maximum water/cement ratios determined from durability (%) in the Japanese concrete specifications [67].

		Construction Conditions	
		Ordinary Construction	**Concrete Products, or the Quality Equal to or Higher than Concrete Products**
Environmental classifications	Offshore air	45	50
	Splash zone	45	45
	Undersea	50	50

Table 5. Minimum cement content of concrete determined to ensure durability (kg/m^3) the Japanese concrete specifications [67].

		Maximum Size Coarse Aggregate (mm)	
		20 or 25	**40**
Environmental Classifications	Offshore air, Splash zone	330	300
	Undersea	300	280

In Japan, quantitative procedures are provided for durability design based on deterministic manner using Fick's second law. Additionally, the Japanese concrete specifications determine several material requirements for mixture. The criteria of acceptance for the cover depth and diffusion coefficient is shown in Figure 6, and the diffusion coefficients with required cover depth for durability design are listed in Table 6 [64]. In Figure 6, γ_{cl} and γ_i are noted as the material and structure factor, and C_0 and C_{lim} represent the surface chloride and critical chloride content, respectively. C_d and D_d represent the design cover depth and diffusion coefficient based on the intended service life (t).

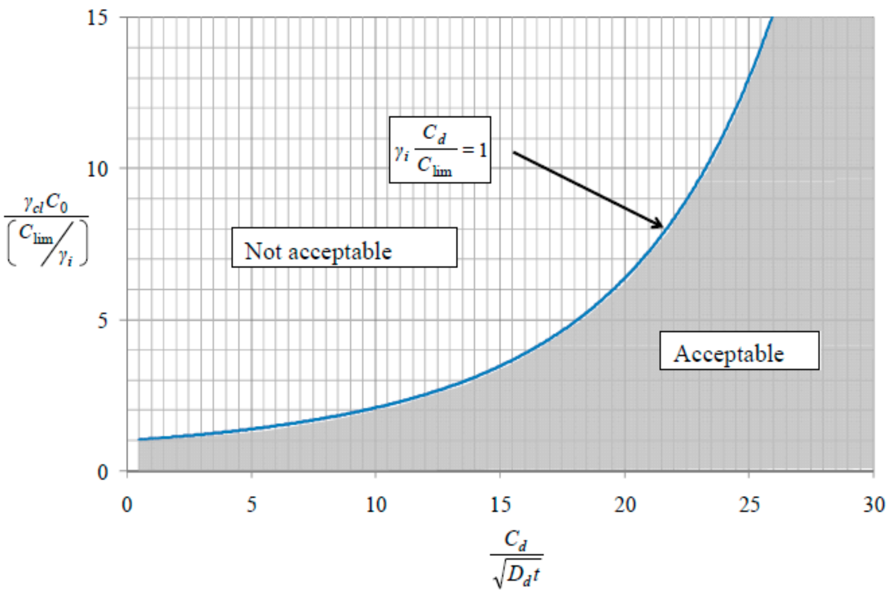


Figure 6. The combination of design concrete cover and diffusion coefficient that passes the examinant for chloride attack according to the Japanese concrete specifications [64].

Table 6. Maximum diffusion coefficients for passing the examinations for chloride ingress (D_d) (only 1 km from coast) according to the Japanese concrete specifications [64].

Life Time (Years)	Design Concrete Cover (mm)									
	25	30	35	40	50	60	70	100	150	200
20	0.62	0.893	1.22	1.59	2.45	3.57	4.86	9.92	22.3	39.7
30	0.413	0.595	0.81	1.06	1.65	2.38	3.24	6.61	14.9	26.4
50	0.248	0.357	0.486	0.635	0.992	1.43	1.94	3.97	8.93	15.9
100	0.124	0.179	0.243	0.317	0.496	0.714	0.972	1.98	4.46	7.93

3.2.2. United States of America (USA)

In the USA, American Concrete Institute (ACI)'s 318-11 Code [68], durability design is considered a part of structural design. The specification provides minimum requirements for concrete considering exposure classifications. In ACI 318-11, there are four major classifications and the durability requirements are provided with each classification. Compared with the JSCE classification, the ACI 318-11 code has more detailed exposure classes such as F (freezing and thawing), S (sulfate), P (permeability), and C (corrosion). For each exposure class, the durability requirements are proposed including maximum w/c ratios, minimum strength, binder types, and maximum water-soluble chloride ion content. Among the classifications, the corrosion category is shown in Table 7 for the exposure class and Table 8 gives requirements for the concrete.

Table 7. Exposure categories and classes in the US American Concrete Institute (ACI) 318-11 Code [68].

Category	Severity	Class	Condition
C Corrosion protection of reinforcement	Not applicable	C0	Concrete dry or protected from moisture
	Moderate	C1	Concrete exposed to moisture but not to external sources of chlorides
	Severe	C2	Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources

Table 8. Requirements for concrete by exposure class in the US ACI 318-11 Code [68].

Exposure Class	Max. w/c	Min. f'_C psi	Additional Minimum Requirements	
			Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement (%)	
			RC	PS
C0	N/A	2500	1.00	0.06
C1	N/A	2500	0.30	0.06
C2	0.40	5000	0.15	0.06

w/c, water/cement; f'c, compressive strength; RC, reinforced concrete; PS, pre-stressed concrete.

In Table 8, lower criteria for water-soluble chloride ions are recommended for PS since the tendons inside the concrete are subject to tensile stress, which causes more rapid corrosion propagation. The actual concept and quantitative procedures for durability design are not introduced. Several committee reports handle specific deterioration and the related countermeasures. The guidelines from the respective ACI committees can be summarized as in Table 9.

Table 9. Guidelines and contents the ACI committee related to concrete durability.

Committee	Contents and Guidelines
ACI 201R [69]	• Overall mechanism for freezing/thawing, chemical attack, erosion, alkali-silica reaction • Repairing corrosion and local damage • Protection and enhancement for durability
ACI 210 [70]	• Control of erosion, cavitation, abrasion • Overall explanation on mechanism, causes, and control for hydraulic structures subjected to erosion
ACI 362 [71]	• Control of steel corrosion, freezing/thawing, cracking, spalling, and delamination in parking structures • Special considerations for deicing salt and concrete joint • Suggestions for requirements such as cover depth, w/c ratios, anti-corrosive agents, and coatings for concrete/steel
ACI 357 [72]	• Classification of sea water conditions (splash, tidal, submerged) • Material requirements to meet greater than 40 years of service life (mix proportions, aggregates, low w/c ratios)

The ACI's requirements for durability seem to be more demanding when compared with the JSCE standards [64,67], where specific durability design requirements are not yet codified and the concept of intended service life is not clearly determined. The suggestions from ACI 201 contain durability design based on Fick's second law of diffusion [69].

3.2.3. European Union (EU)

The EU's concrete specifications, e.g., EN 1992-1-1 (2004) [73], do not consider the service life design and quantitative design procedures. However, exterior classifications are determined in detail with six grades. Major deteriorating environments are as follows: normal condition (X0), carbonation (XC), chloride attack (XD and XS), freezing and thawing (XF), and chemical attack (XA). In particular, special attention is paid to the determination of minimum cover depth. For a 100-year service life, additional severe exterior conditions are assumed. Moreover, quality control and strength grades are roughly proposed to ensure meeting the required performance levels (composition limits and compressive strength). The minimum cover depth for embedded steels and tendons are also proposed, but the related service life is not determined.

In the European and British codes [73,74], very detailed conditions are provided for considering strength grade, maximum w/c ratios, binder type, and nominal cover depth. Exterior conditions are classified into four groups, and unit content of binder and minimum w/c ratio are proposed in each category. The exposure classes regarding steel corrosion are listed in Table 10. The recommended minimum cover depth and the required performance are listed in Tables 11 and 12, respectively. The cover depth in Table 11 should be increased by the additive safety element over 10 mm.

Table 10. Exposure classes related to environmental conditions in accordance with EN 206 [73].

Class Designation	Description of the Environment	Informative Examples Where Exposure Classes May Occur
No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze/thaw, abrasion or chemical attack For concrete with reinforcement or embedded metal: very dry	Concrete inside buildings with very low air humidity
Corrosion induced by carbonation		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
Corrosion induced by chlorides		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools Concrete components exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements Car park slabs
Corrosion induced by chlorides from sea water		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures

XO, normal condition; XC, carbonation; XD/XS, chloride attack; XF, freezing and thawing; XA, chemical attack.

Table 11. Minimum cover requirements with regard to durability for reinforced steel in accordance with EN 10080 [73].

Structural Class	Exposure Class						
	X0	XC1	XC2/XC3	XC4	XD1/XS1	XD2/XS2	XD3/XS3
S1	10	10	10	15	20	25	30
S2	10	10	15	20	25	30	35
S3	10	10	20	25	30	35	40
S4	10	15	25	30	35	40	45
S5	15	20	30	35	40	45	50
S6	20	25	35	40	45	50	55

Table 12. Recommendation limiting values for composition and properties of concrete.

Types	Exposure Classes										
	No Risk of Corrosion or Attack	Carbonation-Induced Corrosion				Chloride-Induced Corrosion					
						Sea Water			Chloride Other Than from Sea Water		
	X0	XC1	XC2	XC3	XC4	XS1	XS2	XS3	XD1	XD2	XD3
Maximum w/c	—	0.65	0.60	0.55	0.50	0.50	0.45	0.45	0.55	0.55	0.45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C30/37	C30/37	C30/37	C35/45
Minimum cement content (kg/m^3)	—	260	280	280	300	300	320	340	300	300	320

As listed in Table 4 (JSCE) and Table 12 (EN), the required minimum w/c ratio level is 45%–50% for concrete exposed to chloride attack, in which the expected strength level is 30–35 MPa. The codes and concrete specification suggest a sufficient required strength since high strength with low w/c ratio usually leads low chloride diffusion coefficient. The guidelines in Table 11 show a higher cover depth with an increasing structural class and harsh exposure class. The penetrated chloride ion can be controlled by increasing the cover depth and low diffusion coefficient. In Table 12, the range for the cement binder in sea water is recommended to be 300–340 kg/m^3, which is slightly higher than for chloride other than from the sea (300–320 kg/m^3) as the exposure condition of sea water is considered to be harsh owing to the abundance of chloride ions. In Table 10, the carbonation depth may increase most rapidly in XC3; however, the corrosion in the carbonated concrete is more activated in XC4 due to abundant oxygen and moisture. Hence, it is determined that XC4 is the most critical condition for steel corrosion under carbonation. Chloride penetration under the actions of freezing and thawing is more severe than corrosion due to carbonation. With more harsh exposure classes, more conservative requirements on material design can be found like the higher cover depth in Table 11 and the lower w/c ratio in Table 12.

3.3. South Korea

3.3.1. Concrete Specifications

Unfortunately, original design codes and durability design procedures have not yet been developed for South Korea. In the Korean concrete structure design code [75], exposure classifications from ACI-318 are adopted and requirements such as minimum design strength, air content, and soluble chloride content are developed using the same ACI Code [68]. In the Korean concrete structure design code, the service life over 50 years is understood conceptually, but the intended service life considering structure type and significance is not determined. The design code for bridges in South Korea [76] adopts the same exterior classifications as the EN Code and suggests an allowable crack width. The minimum compressive strength and cover depth are also given for each exterior classification. In the concrete specifications on durability [63], durability design procedures based on JSCE [64,67] are adopted but several parts are modified to take regional conditions into consideration. The five major sources of deterioration are determined to be chloride attack, carbonation, freezing/thawing, chemical attack, and alkali silicate reaction (ASR). For each deteriorating agent, durability design procedures are provided for concrete material and structures with the same concept as JSCE [64,67]. Reliability indices like durability reduction factor and environmental factors are proposed; however, the deterministic method for durability design has been primarily adopted. The exposure conditions for temperature are listed for six representative districts in South Korea for freezing and thawing actions. Time dependent diffusion and mineral admixture effects (fly ash, slag, and silica fumes) are proposed based on Life365 (*Life365*, 1.0; Silica Fume Association (SFA): Lovettsville, VA, USA, 2002) [21] based on Fick's second law of diffusion. The durability design steps in Korea, comparable to the design procedure of the JSCE [64], are summarized as in Figure 7:

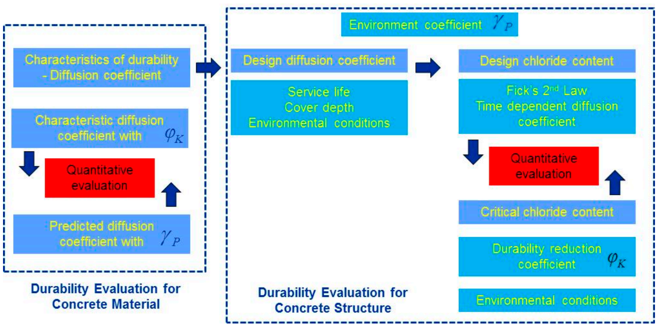
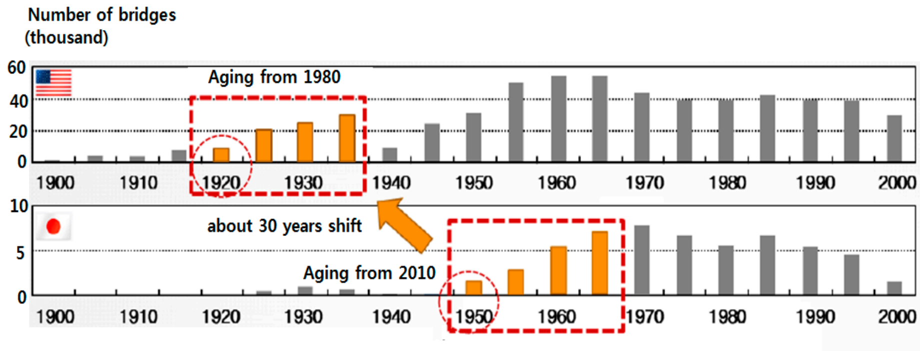


Figure 7. Durability design procedures in South Korea [63].

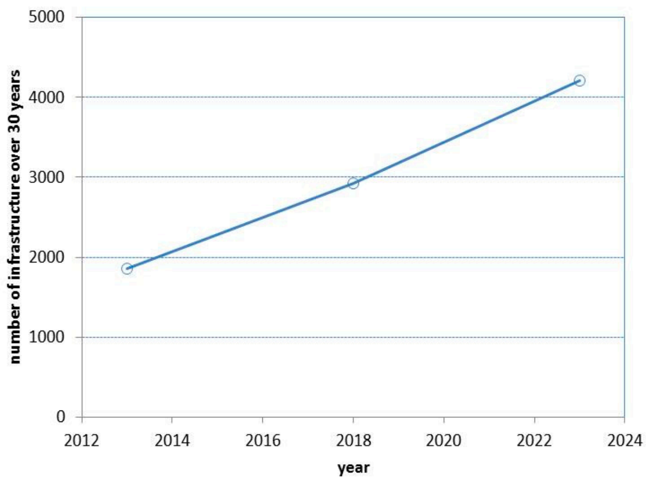
Currently, the Korean concrete specifications for harbor structures have proposed a roadmap for durability design [77], in which the required design level is improved from current specified material requirements to probabilistic durability design by 2025 through the deterministic design based on Fick's second law of diffusion by 2020.

3.3.2. South Korea's Governmental Support for Durability and Sustainability

Recently South Korea announced several major governmental plans. In South Korea, a significant amount of construction had been performed from the 1980s onwards, which now requires significant maintenance. In the USA and Japan, a number of structures from Social Overhead Capital (SOC) projects were constructed in the 1930s and 1950s, respectively. Thirty to 40 years later, these massive construction periods have now resulted in aged infrastructure that needs significant maintenance, as shown in Figure 8a [78]. Figure 8b plots the number of structures aged over 30 years [78], and shows that the number of structures used for over 30 years has increased by 2.23 times from 1860 (in 2013) to 4211 (in 2023). The structures without durability design usually incur significant maintenance costs, so durability design is strongly required here and now.



(**a**)



(**b**)

Figure 8. The aged Social Overhead Capital (SOC) structure distributions in the USA, Japan, and South Korea [76]: (**a**) SOC construction in US and Japan with time; (**b**) estimated SOC structures aged over 30 years in South Korea.

The major governmental plans are listed in Table 13 and they represent the increasing significance of durability and sustainability in infrastructure.

Table 13. Major governmental policy and plans in South Korea [10].

Policy and Plans	Agenda (2013–2017)
3rd Science-Technology Basic Plan	Safe City, New industry with ICT (Information and Communication Technology) convergence supported by Ministry of Science, ICT, and Future Planning
5th Civil Technique Promotion Basic Plan	Step-to-Step ability for Enhancement of require performance supported by Ministry of Land, Infrastructure and Transport
3rd SOC Safety and Maintenance Basic Plan	Active response safety maintenance and Needs for durability design supported by Ministry of Land, Infrastructure and Transport (Special law for city for maintenance)
Green Architecture Certification Plan	Eco building certification with performance grading and Durability introduction for structural design supported by Ministry of Land, Infrastructure and Transport, Ministry of Environment

4. Conclusions

Durability design in South Korea has not been widely pursued except for several major projects. The reasons for this can be found in the absence of a legal system for service life grading and design parameters without consideration of regional conditions. Sustainability for infrastructure can be achieved through reasonable durability design, which can cut CO_2 emissions and maintenance costs due to unnecessary construction or large-scale repairs. In the present study, the increasing significance of durability design and the related governmental supports in South Korea are described. The conclusions are as follows:

(1) Through a survey of several concrete specifications and design codes, durability design procedures that have been adopted in the USA, the EU, Japan, and South Korea were investigated. Durability design has been performed based on the specified requirements for material parameters; however, the exposure conditions and the related required performances are not quantitatively determined. The exposure classification is based on considering a specific deteriorating agent. In particular, the design code in Japan proposes a quantitative procedure for durability design similar to the procedures for structural safety design.

(2) Regarding chloride attack, two representative design methodologies are summarized. The current design trend is based on the deterministic design utilizing Fick's second law of diffusion. The probabilistic durability design is often attempted considering uncertainties in material, design, and the construction stage. The inherent strengths and weaknesses of the two methods are briefly discussed. In order to adopt the design method using the probabilistic technique, design parameters of random variables such as cover depth, diffusion coefficients, and surface chloride content should be determined quantitatively, considering regional conditions.

(3) Durability design in South Korea is still in the initial stages. Several durability requirements have been adopted from foreign structural codes and specifications. A legal system for service life grading and quantitative durability design procedure with reasonable design parameters are required for avoiding the costs for long-term maintenance, which has not yet been addressed but will come in the future. Durable structures can contribute to a reduction in maintenance costs and CO_2 emissions by eliminating unnecessary repairs or additional construction.

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