

Comparison and Critique review of Durability Provisions and Design Requirements of Various International Design Codes and Standards.

دراسة متطلبات التصميم لديمومة المباني ومقارنة بين بنود تصميم ديمومة المباني في مختلف معايير ومراجع التصميم الدولية

by

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ABSTRACT

Codes and standards establish a standardized language and set of rules for building design, construction, and operation. Such codes and standards have long been the primary mechanism used by governments to establish agreed-upon norms within a territory. These codes are under continual development and update to respond to the outcomes of proven search and the ongoing evolvement of technology and construction processes.

Building codes are primarily concerned with establishing a framework for structural capacity and serviceability; nevertheless, many do not effectively consider durability design. In the absence of clear standard guidelines for design engineers, insufficient design and failures or an expensive over-design to provide for the worst-case scenario may occur. Failures in durability design endanger public safety and put a strain on the government's budget.

The ACI 318 code is the most widely used code for the design of new concrete structures. Adapting this code will result in a cost-effective concrete structure that is sufficient to withstand the applied loads, however, the provisions about durability are not well understood or thoroughly documented.

The goal of this study is to compare the development of the ACI 318 durability design approach to international codes and to suggest improvements to the provisions in light of this comparison. The proposed upgrade may be a beneficial start for the ACI code committee to begin updating the following ACI code generation.

The study revealed that the provisions of the ACI 318 code are not comprehensive and well documented, the requirements are prescriptive and dispersed throughout the code chapters, the terminology lacks crucial terms related to durability, and that complex structures and a highly aggressive environment are not included. On the other hand, in the European code and British standards, provisions are more detailed, harmonized, and comprehensive.

Additionally, the investigation uncovered inconsistencies in the way ACI publications provided durability criteria for corrosion caused by chlorides, resistance to freezing and thawing, and chemical sulphate attack.

Inadequate durability design and implementation can lead to structural failures; as a result, design codes need to be improved to enable code practitioners a coherent, understandable foundation for creating designs that can withstand the environment for their specified service lives.

ARABIC ABSTRACT

تحدد الكودات ومعايير البناء لغة موحدة ومجموعة من القواعد لتصميم المباني والتشييد والتشغيل. لطالما كانت هذه القواعد والمعايير هي الآلية الأساسية التي تستخدمها الحكومات لوضع معايير متفق عليها داخل الدول. تخضع هذه القواعد والمعايير للتطوير والتحديث المستمر استجابة لنتائج البحث المثبتة والتطور المستمر للتكنولوجيا وعمليات البناء.

تعنى الكودات و قوانين البناء في المقام الأول بوضع إطار لتصميم مباني متينه وامنه قادرة على مقاومه الاحمال التي تتعرض لها؛ ومع ذلك، لا يتضمن الكثير منها متطلبات التصميم لهذه المباني لتدوم للعمر الافتراضي التي صممت لأجله وتقاوم العوامل البيئية المحيطة بها وبالتالي فان انعدام وجود هذه الإرشادات بشكل واضح لمهندسي التصميم يؤدي الى انشاء تصميم غير فعال في مقاومه الظروف الجوية والبيئية او تصاميم بتكلفه عالية لضمان ديمومه المبنى حيث ان المصمم يأخذ بعين الاعتبار اسوا الاخطار المحتملة مما يعرض السلامة العامة للخطر ويؤثر على ميزانية الحكومات من اجل ترميم هذه المباني.

يعد الكود الأمريكي المرجع الأكثر استخدامًا لتصميم الهياكل الخرسانية الجديدة حيث انه يعنى بإنشاء بنية خرسانية متينه وامنه واقتصاديه ومع ذلك، فإن الأحكام المتعلقة بديمومة المباني ليست واضحة ومفهومة جيدا. كشفت هذه الدراسة أن أحكام الكود الأمريكي ليست شاملة وواضحة جيدًا، ومتطلبات التصميم مشتتة وموزعه في عده فصول من الكود الذي لم يشتمل على توضيح المصطلحات الأساسية المتعلقة بديمومة المباني، وأن الهياكل والمباني المعقدة وطرق مقاومه عوامل البيئة القاسية ليست مدرجة بالإضافة الى وجود تباين بهذه المتطلبات في عده مراجع أمريكية مترابطة. من ناحية أخرى، اثبتت الدراسة ان المرجع الأوروبي والمعايير البريطانية أكثر تفصيلاً وتنسيقاً وشمولية.

يهدف هذا البحث الى تقديم مقترح لتطوير مرجع التصميم الأمريكي من خلال دراسة نهج ومتطلبات التصميم لديمومه المباني في هذا المرجع الدولي بالمقارنة مع المراجع العالمية الأخرى وتحديدا الكود البريطاني والاوروبي والأيزو.

يمكن أن يؤدي التصميم والتنفيذ غير الفعال لديمومه المباني على إنتاج منشئات غير قادره على تحمل الظروف البيئية وبالتالي الى إخفاقات هيكلية؛ نتيجة لذلك، يجب تطوير احكام وبنود مراجع التصميم لتمكين مستخدمي هذه المراجع لإنشاء تصميمات يمكنها تحمل عوامل البيئة طوال مدة العمر الافتراضي لها دون الحاجة الى عمليات ترميم وإصلاح عالية الكلفة اثناء العمر التصميمي لهذه المباني.

DEDICATION

To my loving and caring husband, my backbone and army, Fadi

To my 7-year-old son, Andrew, who inspired and encouraged me to pursue my study when he said:

"Mommy, I feel very happy and proud when I see you studying and making your dreams come true"

To Jonathan, my 3-year-old son, who decorated my notebooks with his scribbles and stickers.

To my parents and family, who have always believed in me.

To every ambitious unstoppable mother in the world, I dedicate this work.

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"The God of heaven will prosper us. Therefore, we, his servants will arise and build" Nehemiah 2:20

Glory to God who strengthen me along the way and utilized my efforts to serve knowledge for others.

I would like to express my profound gratitude to my dissertation advisor, Prof Abid Abu-Tair, for his serious efforts, insightful commentary, and helpful guidance during the course of this research.

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CHAPTER 1: INTRODUCTION

1.1 Overview

Durability refers to both performance and time, and it indicates the extent to which a structure or infrastructure attains its intended goals over time. This concept encompasses all civil engineering structures and infrastructures. Furthermore, the ageing of structural materials in a structure causes time-dependent behaviours during its service life. Ageing processes can be inherent in structural materials or result from interactions between structural materials and service circumstances. This picture applies to all structures and the components that produce them.

Durability challenges in reinforced concrete (RC) constructions are a worldwide concern because they harm economic progress, natural resources, and human safety. As a result, efforts have been done in most countries' design codes and standards to include requirements for providing robust and durable RC structures.

These codes and standards establish a standardized language and set of rules for building design, construction, and operation. Such codes and standards have long been the primary mechanism used by governments to establish agreed-upon norms within a territory. They are frequently improved and developed upon the research, knowledge, and experience on a time cycle basis, this periodic exanimation is essential to maintain these codes updated and improved upon the technological fast-paced development to enhance the design process and include new methods for the design, implementation, and maintenance of structures.

Codes and standards could be international, adopted globally by multiple countries with the allowance of these countries to modify specific provisions or issue complimentary guidance for national requirements, such as the American and Eurocode, or national for the use of specific nations such as the Australian and Japanese codes.

The American Concrete Institute (ACI) is recognized as a leading developer and distributor of consensus-based standards, technical resources, and certification/educational programs for those involved in concrete design, construction, and materials. ACI's 120+ technical committees have made significant contributions by providing standards, specifications, reports, and guides that are extensively used worldwide. While maintaining consistency among documents is therefore a major responsibility, it's also a major challenge for the Institute.

The ACI 318 code is the most widely used and adopted code for the design of concrete structures; it specifies requirements for safe, serviceable, and cost-effective constructions. However, the code's durability design of concrete structures is not comprehensive or well understood. As a result, the goal of this study is to assess this subject and compare the ACI 318 code with other international design codes and standards to recognize their strategy and implementation of durability design and to establish proposals and recommendations to promote the successful international practice of the American code.

In this study, the ACI 318-19 code will be compared to equivalent international codes and standards: The Eurocode (EN1992 1.1), British standard (BS 8500-1), and ISO standard ISO13823. Moreover, the durability requirement across ACI 350, ACI201.2R and ACI 318 are examined.

Generally, the current strategy in the studied documents for dealing with concrete durability is the prescriptive approach, which sets requirements for material compositions and quantities, techniques, and test methods that are assigned according to the environmental exposure category. Although such strategies may include minimum compressive strength, maximum water/cement (w/c) ratio, minimum supplementary cementitious materials (SCMs) content, and cover depth limitations, the desired concrete performance is not easy always achieved. Furthermore, maximum w/c and minimum cement content are difficult or pricey to monitor in practice and might frequently hinder innovation. Recent research has concentrated on performance techniques that quantify relevant concrete qualities, particularly transport-related variables for durability. Ideally, these techniques should be entirely performance-based, but in fact, an intermediate blended approach referred to as a 'hybrid' approach is frequently more helpful.

The ISO 13823 International Standard has a different approach from the other three studied documents, even though it does not identify design procedures for durability, it establishes a sturdy framework by defining a process that begins with the structure's environment and progresses through mechanisms that convert this environment into environmental actions on component materials that result in action effects such as damage. This cause-and-effect mechanism must be considered while designing methodologies for predicting service life.

To supplement this research on the international codes and standards, a literature review about durability terminology, factors affecting it, and its specification are addressed. Following that, durability provisions in each document are specified and compared. Finally, an understanding of the development areas needed in the ACI 318 code will be concluded and a recommendation will be proposed upon that. Additionally, the outcomes of other ACI documents comparison for durability aspects will be discussed as these documents are not unified which will confuse the code practitioners.

Attention to concrete durability design of structures has increased and the awareness of its importance is reflected in the growing number of studies and research. The outcomes of these studies should be considered by the code and standard committees to update the design codes accordingly.

1.2 Research Significance

To sustain ACI's position as the global leader in the creation and distribution of concrete knowledge, the next generation of ACI Codes and standards will require to place more emphasis on "comprehensive structural design" not only "structural design" to include and satisfy structural, durability, and other requirements for ordinary structures in a nonaggressive environment, as well as structures that can be more complex or require an extended service life in aggressive environments.

To do so, this research will analyze and compare multiple equivalent international codes and standards, their approach, provisions, and design parameters and propose improvements to serve

as a beneficial foundation for a future ACI durability Code or Code requirements adjustments in existing Codes.

1.3 Research objective

The ACI 318 code doesn't address durability design effectively, its provisions are basic and not comprehensive, some limited values are not harmonized among the code itself or other ACI-related documents, other related conditions are fragmented, multiple critical durability issues are not addressed, and the approach is prescriptive.

This study examines the shortcomings in the ACI 318 code and compares this code with other international codes and standards to understand where ACI 318 is standing. As it is essential to have consistent standards for code practitioners, this research also examines the uniformity of durability related ACI documents and investigates potential development areas in the internationally recognized design codes.

The following goals should be attained to fulfil the study's principal objective:

- Examine the international codes' provisions for durable design (ACI 318, EC2, BS 8500-1, ISO 13823).
- 2. After reviewing the codes, compare and analyze the listed provisions to identify commonalities, discrepancies, and potential development areas.
- Assess the consistency of the ACI documents' durability-related requirements. (ACI 350, ACI 201.2R, and ACI 318)
- 4. Investigate the challenges in improving the durability design for every ACI 318.
- 5. Propose amendment suggestions to assist develop the upcoming generation of ACI 318 standards.

1.4 Research approach and methodology

The study begins with gathering critical information related to durability, its definition, factors that affect structure durability, design for durability principles and a comparison between performance and prescriptive specifications. The situation of structural durability in the Arab Gulf is also investigated.

Following that, a comprehensive overview of the codes and standards development backgrounds, their concepts and usage are addressed.

The study gets more focused after that on four global codes and standards at which durability design provisions and requirements are listed and compared, this comparison will reveal the similarities and differences among these documents and in combination with the literature review, a critique review of the four documents can be done to outline all the strengths and cons in each document. Additionally, further ACI codes are examined to verify their uniformity.

Finally, a discussion and conclusion based on the acquired results will assist to offer modifications to the ACI 318 code and other codes and standards in mind. A proposal for future exposure classes as well as a basis for terminology standardization is presented as a beneficial framework for refining the soon-to-be-published ACI 318 code.

1.5 Research challenge

Comparable codes and standards must be allocated for the study to provide a good basis for the ACI committee to build and improve the ACI 318 code. A careful selection is made from a wide range of available, well-defined codes after examining these codes to ensure they will bring value on an international level. Each standard comprises several documents, some of which may be related to the same issue, making selections more difficult. EC2 and BS8500-1 approximately have the same approach as the ACI 318 however they are more comprehensive and detailed in an integrated matter. ISO 13823 has a different approach, nevertheless, it will assist the ACI 318 code to establish processes and recommendations for durability issues mechanisms and failures of structures due to materials and most importantly is the basis for durability planning.

Aside from selecting the appropriate codes, another challenge is the limitation of critique evaluation for the values of durability criteria such as water-cement ratio, strength, and so on. The fact is that each country has its environment, geographical challenges, and availability of raw materials or exported commodities, making measuring the difference in values complicated. Furthermore, while presenting a proposal for the ACI 318, it is critical to preserve clear and easy understanding; the detailed description will be confusing and may lead to overdesign, removing a crucial element from the ACI code; simplicity of interpretation.

Lastly, it was not possible to analyze and assign the optimum specific numeric values for the design parameters as this should be done upon testing which is out of the scope of this study. However, the current design code values are accepted.

CHAPTER 2: LITERATURE REVIEW

2.1 Durability of Concrete

Concrete is a widely used construction material, coming in second only to water in terms of consumption (Gagg 2014) with a yearly usage anticipated to be around 30 billion tonnes (Monteiro, Miller & Horvath 2017). See figure 1.



Figure 1. Historical graph for construction material (Kelly, T. et al. 2018), (FAOSTAT 2017)

Historical concrete structures are a testimony to the incredible long-time performance of this material, such as the Pantheons in Rome, Italy (see figure 2), and the Ponte de Gard in France.

Concrete, like masonry, has a high resistance to compression forces but is weak in tension. Concrete performed exceptionally well for load-bearing structures with rounded shapes, such as domes and arches, and this old concept is being revived today with modern 3D-printing technology, such as Zaha Hadid-designed Striatus 3D-printed bridge in Venice, Rome. See figure 3.



Figure 3. Ponte de Rome. (Panini 1734)



Figure 2. Zaha Hadid Architects creates unreinforced 3Dprinted concrete bridge at Venice

Steel reinforcement in concrete allowed for the design of a wide range of structural components that can withstand compression and tension stresses. This integrated material met the need for a fire-resistant and cost-effective construction (Moussard, Garibaldi & Curbach 2017). However, if R.C is not managed properly from proportioning, casting into curing, the service life of the structure will be shortened during its exposure to the environment, and steel members may corrode and severely damage the R.C concrete structure which will result in costly repairs.

R.C design professionals focus most of their design time and effort on the structure's strength and serviceability, with little or no thought given to the structure's durability. Structures' durability, defined as their capacity to sustain their designed features in a service environment for a specific amount of time with limited or no maintenance, is as significant as their strength and serviceability.

To achieve long-term performance and sustainable structures, the three factors of strength, serviceability, and durability should be successfully harmonized and integrated. See figure 4.



Figure 4. Significant correlated factors must be considered in the structural design.

In recent years, there has been an increase in the awareness and understanding of durability. Between 1970 and 1990, an extensive study on this topic was undertaken, resulting in a vast knowledge (Noyce & Crevello 2016). This is owing to the budgetary impact of shorter life spans of structures on a country's budget due to costly repairs, disruption of vital daily activities, and a reduction in sustainability.

Starting with the design process, the owner must first establish the structure's service life based on its requirements; design specialists should take this into account and proceed from there; high strength does not imply endurance. Contractors should follow procedures for mix design, casting, and curing during the execution phase, especially with major technological advancements and the use of additives, accelerators, retarders, supplemental cementitious materials, and other materials, depending on the project. Inspection and maintenance at regular intervals are also required to detect any deterioration early.

To integrate durability in their designs, design experts must adhere to acceptable references, which are codes and standards. Contractors require performance specifications to use the most up-to-date and effective methods for building a long-lasting R.C construction. The following chapter will go over this issue in depth.

2.2 Factors affecting the durability of concrete

To achieve a structure that can retain its design characteristics while exposed to the environment for a specified life span, several factors must be considered carefully. These factors can be grouped into two categories: The concrete system, and the service environment. See figure 5.



Figure 5. Factors affecting durability of concrete

2.2.1 concrete system – Materials

Concrete material selection is a critical component in the processing of concrete to minimize durability issues. The goal of owners and engineers is to provide long-lasting concrete at a reasonable cost. This can be accomplished by recognizing the deterioration mechanisms that must be avoided. The first stage should be to assess the environmental and service conditions that the concrete will face during its manufacturing and service life. Because protecting against environmental acts to which the concrete will not be exposed may be uneconomical, recognizing those mechanisms that can be ignored may improve project engineering. Furthermore, understanding the characteristics of the different constituent materials accessible for use is a basic

responsibility of the materials engineer. Certain issues can develop when engineers make poor material choices.

2.2.1.1 Binder type and content

Cement is a broad term that encompasses all binder materials. Binders have been used in conjunction with rock and stone to produce more sturdy structures since ancient times. Mud was used as a binder, and it is being used in some regions of the world today (Gagg 2014). During the early civilisations of Egypt, Greece, and Rome, lime cement was manufactured by 'burning limestone' to produce Quicklime (Davidovits 2022). Following that, the Greeks and Romans invented hydraulic cement, which, unlike lime, reacts with water and does not get impacted with it once hardened.

In 1824, Portland cement was invented by Joseph Aspdin, an English mason. He received a patent for his product, which he termed Portland cement because it generated a product that matched an oolite limestone found on the Island in Dorset, on England's channel coast. (Aspdin 1824).

The word 'Portland Cement' is now widely used over the world, with many producers adding their trade or brand names. The proportions of lime, silica-alumina and iron in the materials used to make Portland cement must be precise.

Concrete used to be a simple substance composed of Portland cement, water, and aggregate before the 1930s. To obtain the required compressive strength and workability, these materials were proportioned and combined according to the project requirements and exposure conditions.

After that, in North America, additives such as air-entrained, water-reducers, and fly ash were introduced and employed in the mix to enhance concrete performance. Slag cement was also used throughout Europe. Chemical admixtures did not become popular until 1930. Nowadays, a wide range of additives is being used and adapted to obtain unique characteristics in concrete mixes.

These same materials can be utilized for both durable and non-durable designs; the key to longlasting structures is to choose the right material in the right proportions while considering the exposure conditions.(Alexander, Bentur & Mindess 2017). Thereby, design codes such as the reviewed ones in this research recommend the quantities and types of such materials that are appropriate to the environment and durability demands.

A wide variety of experiments were conducted to study and compare various types of binders and their durability parameter response. To begin with, Jee & Pradhan (2019) investigated and correlated durability parameters in concrete that has been exposed to external chloride using three types of the binder: Ordinary Portland cement (OPC), Portland pozzolana cement (PPC) and OPC + fly ash, the results showed that ordinary Portland cement (OPC) had a 4.82 and 2.02 times higher apparent chloride diffusion coefficient than Portland pozzolana cement (PPC) and OPC + fly ash, respectively, thus PPC-reinforced concrete specimens outperformed OPC + fly ash and OPC-reinforced concrete specimens in terms of corrosion resistance. Adding to that, Chen et al.(2021) confirmed that Geopolymer concrete has higher durability than OPC concrete in many circumstances. It shows up as less strength loss and minimal erosion in acid, sulphate, and chloride solutions, as well as modest surface cracklings following high-temperature exposure. However, due to a higher Ca/Si ratio of the C-S-H gel of OPC concrete, geopolymer concrete after carbonation has a lower extent of reaction and weaker mechanical characteristics.

Furthermore, Ribeiro et al.(2021) looked at how the cement's properties and the concrete's dosing parameters affect chloride diffusion in both single and combination situations. Several concretes were dosed with various water/cement and water/binder ratios, types of cement, mortar content, and mineral additives, and their specific diffusion coefficients were determined using the chloride migration test for each. The scholars discovered that the water/cement ratio is not the most important factor in limiting chloride diffusion in concrete. Chloride diffusion is influenced more by the aluminate content, the fineness of the cement utilized, and the water/binder ratio. Medjigbodo et al.(2018) suggested the partial replacement of cement with latent hydraulic or pozzolanic materials due to environmental and technical considerations. Even though such substitution is still limited to a small percentage of the population (less than 30 percent by mass of cementitious materials), they tried to achieve 45 percent total replacement. the experimental research study was conducted on mortars produced with binary and ternary binders (Portland cement; metakaolin; limestone filler) along with two sets of mixes with W/C of 0.42 and 0.5. The

tests were carried out to see how their relative strength (activity index) and durability criteria (shrinkage, porosity, carbonation) changed over time. Metakaolin properties, such as manufacturing method and particle size distribution influence the strength development of ternary binders' mortars. By lowering the W/C ratio, the pozzolanic reaction was expedited, and early-age strength and durability metrics were improved.

To sum up, as per some of the conducted investigations, different binder types perform differently regarding durability parameters, proper type, and dosage of biner must be chosen to guarantee long life performance. Codes and standards contribute to helping design professionals to choose the correct type of cement in accordance with the exposed environment. For example, Portland cement must fulfil the requirement for ASTM C150 or AASHTO M 85 ASTM C150. ASTM C150/C150M-21 provides 10 types of Portland cement of which each has a specific function. (See table 1 below).

Portland Cement Type	Description	Function	Uses
Туре І	Normal	General-purpose cement when no special requirement is needed.	Pavements,Slabs,reinforcedconcretebuildings, bridges, dams,precast concrete
Туре ІА	Normal, air- entraining	General purpose cement when no special requirement is needed but air-entrained is required.	Same as Type I
Туре II	Moderate sulphate resistance	For general use, particularly when a modest level of sulphate resistance is desired.	Marinestructures.Buildings are exposed toseawaterduetotheir

Table 1*. Summary of Portland cement types and uses*

Туре ША	Moderate sulphate resistance, air entraining	For general use, particularly when a modest level of sulphate resistance is needed but air- entrained is required.	availability, mostly used even no sulphate resistance is required. Same as Type II
Type II (MH)	Moderate heat of hydration and moderate sulphate resistance	Used to reduce temperature rise, peak temperature, and temperature-related cracking, pouring concrete in hot weather, and when thermal control is very crucial.	Mass structures such as massive piers, large foundations, and thick retaining walls.
Type II (MH)A	Moderate heat of hydration and moderate sulphate resistance, air entraining	Used to reduce temperature rise, peak temperature, and temperature-related cracking, pouring concrete in hot weather, and when thermal control is very crucial with the need for air entrained.	Same as Type II (MH)A
Type III	High early strength	For use when high early strength is desired.	When forms must be removed as soon as feasible, or the construction must be put into operation quickly. In cold weather areas.

	High early	For use when high early strength	
Type IIIA	strength, air-	is desired together with air	Same as Type IIIA
	entraining	entrained.	
			Used in large concrete
			buildings, such as huge
Type IV	Low heat of	When a low heat of hydration is	gravity dams, where
1 ype 1 v	hydration	needed.	temperature rise from
			hardening heat must be
			kept to a minimum.
			Utilized in concrete
			exposed to high sulphate
Type V	High sulphate	High sulphate resistance is	conditions - primarily
Type v	resistance	desired.	when soils or
			groundwaters contain a
			large amount of sulphate

*Info. based on ASTM C150/C150M-21 and AASHTO M 85 requirements. Information gathered from (Kosmatka & Wilson 2016) (Kelechava 2021).

2.2.1.2 Aggregate

Aggregate, which is a mixture of rocks and minerals that makes up 60 to 80 percent of the concrete mix matrix, has a considerable impact on the properties of both fresh and cured concrete, as well as on cost.

Changes in gradation, maximum size, unit weight, and moisture content might impact the properties and performance of the concrete mix. Because aggregate makes up the body of concrete, it's vital to utilize the right type of aggregate to ensure the long-term performance of concrete structures.

Furthermore, some aggregates, such as extremely expansive or reactive, have a negative impact on the durability of concrete. As a result, international design requirements prohibit their usage or allow it with authorized consent on a mitigation strategy for their effect.

Below is a review of different categories of aggregate and their effect on concrete.

Aggregate Size

Aggregate can be classified according to its source, shape, size, and unit weight. Aggregate size can be coarse or fine. See table 2.

Aggregate Type	Aggregate Size	Source	Usage	Example
Coarse	>5mm, usually in the range of (9.5mm - 37.5 mm)	Gravel, Crushed Stone, or a combination of both.	Form rigid body of concrete, main factor for determining the strength and durability of concrete.	
Fine	< 5mm	Sand or Crushed stone.	Improvetheworkabilityofconcrete.	

Table 2*. Types of aggregate size.

*Information gathered from (Hilton 2020) (Kosmatka & Wilson 2016)

Aggregate Shape

Coarse aggregate has different shapes, aggregate shape has a direct effect on the concrete performance and durability, classification of aggregate shape can be summarized in table 3.

Aggregate shape effect on concrete features and durability has been investigated by multiple researchers, for example, De Larrard et al. (2013) investigated the effects of aggregate shapes on

drying and carbonation phenomena using 3D finite element models. The results showed that the influence of coarse aggregate forms on the drying and carbonation phenomena appears to be insignificant (low for flat shapes) when compared to their volume fractions. If more exact numbers are required, the aggregate shape should be considered if its aspect ratio exceeds roughly 2, since it may have a significant impact on the results. Another study explored the impact of aggregate shape on permeability. The Aggregate shape is an important factor that affects porosity and permeability, Jain, Chouhan & Goliya (2011) confirmed that the permeability of pervious concrete varies depending on the number of particles used and their angularity.

For all sizes of course aggregates utilized in the study, it was also discovered that aggregates with a lower angularity number form a mix with lower permeability. Moreover, Li, Xu & Chen (2016) proved that Concrete's permeability will be reduced if almost impermeable aggregates are present. ITZ with higher porosity, on the other hand, will increase the permeability of concrete. With the combined effects of aggregates and ITZ, the overall permeability of concrete reduces.

Aggregate Shape	Features	Application	Example
	Offers fewer voids and more	Lintel concrete	
Rounded	workability. Poor	and as a filler	
Aggregate	interlocking characteristics.	material	
	Offers high-strength		
	concrete, lower voids, and		
	hence more durability. Good	High-strength	
Angular	interlock but low	concrete	
Aggregate	workability.	members.	生物的度

 Table 3. Aggregate Classification by shape. (Mahajan 2022)

	Offers less compressive		
	strength and bonding		
Irregular	strength than the angular	Rarely used in	
Aggregate	aggregate.	mix design.	CHAN
	Thickness is less than width	Not suitable for	
	and length, or the least	concrete mix.	
	dimension is <60% of the	Resulting from	-
Flaky	average aggregate	poorly crushed	
Aggregate	dimension.	rocks.	
	The length of the aggregate	Not suitable for	
	is larger than its width and	concrete mix.	
	thickness. L> 180% of the	Resulting from	
Elongated	average aggregate	poorly crushed	
Aggregate	dimensions.	rocks.	
	Flaky and elongated	Not suitable for	
	aggregates have a length that	concrete mix.	
Flaky and	is greater than their width	Resulting from	
Elongated	and a width that is greater	poorly crushed	
Aggregate	than their thickness.	rocks.	

Aggregate Weight

Aggregate can be classified according to its weight as summarized in table 4 below.

Lightweight concrete (LWC) is preferred in the construction industry due to multiple reasons, the reduced self-weight of the structure because of the smaller structural elements that consequently reduce cement and reinforcing steel consumption, lower transportation and lifting equipment costs,

and exceptional heat and sound insulating properties. To benefit from these features, a good quality LWA must be utilized to not compromise on mechanical properties and durability.

Aggregate type	Bulk Density	Sources	Application
Normal Weight	1200 kg/m3 to 1750 kg/m3	Sand, gravel, and crushed stone.	In most construction applications, the main concrete members
Lightweight	560 kg/m3 to 1120 kg/m3	Expanded shale, clay, slate, cinder, blast- furnace slag, volcanic pumice.	For lightweight members, modern structures, and small cross-section foundations. Also, enhance insulation and fire resistance.
Heavyweight	> 2100 kg/m3	Barite,limonite,magnetite,ilmenite,hematite,iron,steel punching or shot.	Heavyweight concrete and as a radiation shield.

Table 4*. Aggregate classification by weight

Info. Based on (TeamCivil 2017) (Kosmatka & Wilson 2016).

(Ibrahim et al. 2020; Lu et al. 2022) investigated the suitability of multiple lightweight aggregates to be used in construction achieving the required mechanical properties along with durability. Lu et al.(2022) research aimed to develop a new lightweight ultra-high-performance concrete (L-UHPC) with low density and great performance using a mathematical approach because of the conventional lightweight concrete's mechanical qualities and endurance that make it unsuitable for a wider range of applications. The L-UHPC mix design included two lightweight components (micro-sized glass microspheres and expanded shale aggregates). They also compared it with a normal-weight UHPC. The developed L-UHPC had functional and durability attributes that were comparable to, if not

better than, normal-weight UHPC and high-performance cement mortar. The adoption of specific lightweight materials was critical in ensuring L-UHPC's characteristics. The high microhardness of the paste matrix, as well as the internal curing of lightweight particles, led to L-UHPC's long life. Scholars suggested that L- UHPC's could pave the way for new ways to build high-performance lightweight structures and composites.

On the other hand, Ibrahim et al. (2020) focused on the production of long-lasting structural lightweight concrete (LWC) with expanded perlite aggregate (EPA) ranging from 0% to 20% by weight. Concrete was made with a low water-to-cement ratio and ordinary Portland cement (OPC) was replaced with 50% and 7% ground granulated blast furnace slag (GGBFS) and silica fume (SF), respectively, to ensure its longevity in a chloride environment. Because it was made with a low water-to-cement ratio and extra cementitious components, the durability of concrete created with 0 percent EPA was outstanding, as expected. The durability of EPA-prepared concrete was generally satisfactory. Water absorption, chloride permeability, and chloride migration coefficient ranged from 4.10 percent to 7.22 percent, 354 to 844 coulombs, and 11.90 to 17.07 (1012) m2 /s, respectively. The drying shrinkage in the 20% EPA-modified concrete was larger, but it was comparable to the NWC in the 10% and 15% EPA-modified concrete mixes. In most of the mixes prepared for this study, the resistivity of EPA-modified concrete was moderate. Because the concrete's initial compressive strength was good, it could be employed as cast-in-place concrete or in the precast sector. The research team concluded that the material is appropriate for structural elements including slabs, beams, and walls.

Aggregate source

Aggregate can be found from different resources, they might be natural, manufactured, recycled or marine-dredged.

Recently, many governments across the world are advocating recycled aggregate concrete as means to alleviate the problem of aggregate shortages while also encouraging waste recycling and material reuse. Natural aggregates are reconstituted into recycled aggregate at different rates, which is used to replace natural concrete (Naouaoui, Azzeddine & Cherradi 2021), Nevertheless, the durability of such RA is limited, leading to a wide range of studies and research.

The cyclic usage of waste concrete is a significant issue that must be addressed for the environment's and resources' long-term sustainability. Currently, the overall usage rate of waste concrete in many nations is inadequate, and the primary disposal techniques for abandoned structures are stacking and landfilling, both of which degrade the environment significantly.(Revilla-Cuesta et al. 2020)

Naouaoui, Azzeddine & Cherradi (2021) Compared different rates of replacement of natural aggregate with RA and its effect on the mechanical properties and durability. They concluded that mechanical properties diminish above a rate of 30%, however, admixtures boost this rate, and concrete with a 50% restitution rate can be utilized instead of natural concrete. The durability of this concrete for various restitution percentages was tested by determining the porosity of hardened concrete. For all the compensation percentages, the results were between 13 and 14 percent. According to the findings, this concrete meets the durability standards in common buildings. Other, more in-depth investigations will be required for projects with specific criteria.

Carbonation of RA has been studied and different outcomes were given, De Brito et al.(2016) tested high-quality RA, and the results showed that despite a potential for RA inclusion to slightly increase the carbonation depth, the differences in carbonation depths between mixes with and without superplasticizer(SP) are minor. When compared to normal concrete, RAC has a higher tendency for chloride ingress because it is more permeable. Supporting this finding, Silva et al. (2015) stated that If all other elements are equal, increasing the amount of RA in the mix results in deeper carbonation. The use of 100 percent coarse RCA in concrete can result in carbonation depths that are up to two times higher than those of similar NAC mixtures. Moreover, Xiao et al.(2012) argued that With greater RCA replacement ratios, RAC's carbonation resistance and chloride penetration both decline because of the higher amount of mortar that has to suffer carbonation and

the higher chloride porosity. Adding to that are the results obtained by Revilla-Cuesta et al. (2020) who concluded that the use of RCA worsens permeability and carbonation resistance.

(Zheng, Zhuo & Zhang 2021) studied the effect of the old mortar component in the recycled aggregate on durability. There are four interface transition zones formed including the old interface transition zone (recycled aggregate-old mortar), the new interfacial transition zone (old mortar-new mortar), the natural aggregate-new mortar interface transition zone, and the regenerated aggregate-new mortar interface transition zone. Lee & Choi (2013) stated that this ITZ connects the mortar matrix to the coarse aggregate particles and acts as a bridge, if any cracks or fractures occur in this area, RA will have high porosity and high-water absorption and hence durability issues.

Scholars have tried to study approaches to improve the mechanical and durability performance of RA, Zheng, Zhuo & Zhang (2021) studied the effects of the addition of Nano-SiO2 (NS), Basalt fibre (BF), and composite addition of NS and BF are put forward. The addition of BF reduces the generation and development of early primary microcracks in RAC and prevents the generation and propagation of microcracks in the mortar. The addition of NS fills the micro-cracks in the concrete, which reduces the porosity, and facilitates the densification of the structure on the microscopic scale. By mixing NS and BF in experiments, NS can promote the adhesion between the fibre and matrix through the coupling effect, and effectively improve the fibre reinforcement effect. NS, BF, and a combination of NS and BF can significantly improve the interface structure and durability of recycled concrete. However, because of the flaws in recycled concrete and the complexity of the interface structure more research is required.

Another study by Dimitriou, Savva & Petrou (2018) supports the previous findings by demonstrating that RA has a detrimental influence on mechanical properties and durability and that the higher the RA replacement ratio, the more negative it has on the concrete. The combined effect of mineral admixtures (fly ash and silica fume) was quite strong and increased the durability qualities significantly. The usage of silica fume had a significant impact on sorptivity and chloride permeability values. Another finding is that RAC is less expensive than NA, resulting in a little less expensive concrete.

From these studies we can state that RA can be used to replace NA with different proportions, however, it has a negative impact on durability and mechanical properties. This can be mitigated using admixtures.

Overall, aggregates must be clean, hard, robust, and long-lasting particles that are inactive, free of absorbed chemicals, clay coatings, and other fine pollutants in proportions that could affect the hydration and binding of the cement paste. The use of friable aggregate particles or those that can be split is not recommended. Some siltstones, clay stones, mudstones, shale, and shaley rocks, as well as some siltstone, claystone, mudstone, shale, and shaley rocks variants, should be avoided. Certain chert kinds should be avoided since they are vulnerable to weathering and can cause surface flaws such as pop-outs. It's expected that aggregate properties including sort, quality, cleanliness, grading, moisture content, and other characteristics will vary.

2.2.1.3 Admixtures

Admixtures are materials that are added to concrete in addition to the basic ingredients (cement, aggregate, water, and sand) to obtain specific characteristics in both fresh and cured concrete. These admixtures lower the cost of concrete while also improving the fresh concrete process, mechanical properties, and hard concrete durability.

The use of proper batching and concreting procedures is critical to the successful usage of admixtures. Most admixtures are delivered in liquid form and are mixed into the concrete at the factory or on the job site. Pigments, expanding agents, and pumping aids, for example, are used in very small amounts and are typically batched by hand from premeasured containers.

The efficiency of an admixture is determined by several elements, including the type and amount of cement used, water content, mixing time, slump, and concrete and air temperatures. (*Chemical Admixtures* 2019)

According to the China Building Material Federation, superplasticizers accounted for roughly 75% of all admixtures manufactured in China in 2013. Figure 6 depicts the production distribution of Chinese admixtures.



Figure 6. Production distribution of Chinese admixtures. (Cheung, Roberts & Liu 2018)

Admixtures are of two types: mineral and chemical admixtures.

Mineral admixtures such as silica fume and fly ash impact the properties of hardened concrete (Kanamarlapudi et al. 2020). They reduce structure permeability and continue to react for a long time, they react with some cement constituents and fill gaps in the concrete matrix, moreover, they produce denser structures and reduce the heat of hydration.

Chemical admixtures are divided into five categories: air-entraining, water-reducing, retarding, accelerating, and plasticizers (superplasticizers). All other admixtures are classified as a speciality, with functions such as corrosion inhibition, shrinkage reduction, alkali-silica reactivity reduction, workability enhancement, bonding, damp proofing, and colouring.

Cheung, Roberts & Liu (2018) discussed that Cement additives and concrete admixtures can increase the long-term performance of a wide range of cement-based systems. Enhancing durability and strength through water reduction, as well as accelerating the cement hydration process to allow extra cementitious materials to replace clinker, can all contribute to this improvement. Using current best practices, a clinker replacement of roughly 20% by weight can be achieved by using these strong compounds at a fraction of a percent of the total concrete mix. With proper mix proportioning, this replacement amount can be more than doubled. Pre-test tools and smart concrete management systems are examples of innovative technologies that improve the efficacy of admixtures used in both existing and new cementitious materials. Further CO₂ emissions reductions are possible if longer set times, which are a result of SCM inclusion, can be tolerated. Making trade-offs like this will be critical to cement-based materials' long-term viability.
Adding to that, Chong et al.(2019) studied the resistance of magnesium potassium phosphate cement (MKPC) incorporating limestone (LS) and silica fume (SF) to freezing and thawing when exposed to water. The findings revealed that the rate of deterioration in MKPC was considerably influenced by the solution types. After 400 freeze-thaw cycles, MKPC paste without any admixture demonstrated the most violent corrosion when exposed to a 5 percent salt sulphate solution. The inclusion of limestone powder and silica fume, on the other hand, significantly improved MKPC paste resistance to combined solution attack and freezing and thawing, particularly in a sulphate solution.

What is more, Kapoor, Singh & Singh (2016) and Dimitriou, Savva & Petrou (2018) findings agreed on the vital effect of admixtures to compensate for the deterioration effect of replacing natural aggregate with recycled aggregate. Kapoor, Singh & Singh (2016) stated that when 50 percent of the NCA was replaced with RCA, the addition of Silica Fume (SF) or Metakaolin (MK) at 10% by weight of PC was able to compensate for the loss of durability qualities, with MK being more successful than SF. The pozzolans were ineffective in fully compensating for the loss of durability qualities due to the substitution of NCA with RCA for a 100 percent replacement of NCA with RCA.

Adding to that, Velandia et al. (2018) studied different mixes, including Na2SO4-activated highvolume fly ash concretes, and the results showed that the water permeability and chloride ingress of 50% fly ash and sodium sulphate reduce when an activator is employed. The water permeability reduces as the fly ash level rises for the same compressive strength. This is not the same for carbonation, tests revealed higher carbonation depths. When the compressive strength and fly ash % were raised, and an effective curing technique was used, the concrete behaviour improved in general. Lower water permeability, chloride penetration, and diffusion coefficient values were detected for samples with the greatest fly ash levels among concretes with the same compressive strength, varied fly ash percentages, and the same curing. When sodium sulphate is added to concrete, its performance improves when compared to concrete that does not have an activator. These admixtures are recommended for seawater structures.

2.2.1.4 Concrete Mix design

Mix design is the process of selecting suitable concrete materials and determining their relative proportions to produce concrete with the minimum strength and durability required criteria while being cost-effective. Mix design plays a vital role in concrete strength as well as durability, thereby it must be designed and handled properly.

Mix design of concrete has been studied widely, Balakrishna et al. (2020) discussed that to preserve desirable engineering qualities, concrete must withstand harsh climatic weather conditions. Depending on the exposure scenario, different concretes require varying levels of durability. Concrete's mechanical qualities are determined by its density, which results in stronger strength and fewer voids and porosity. The number of spaces in concrete is reduced, making it less permeable to water and soluble elements. As a result, this form of concrete is projected to last longer. Durability qualities, as well as concrete mixture designs, must be considered during the design criteria, as they affect the performance of concrete structures.

Butler et al.(2013) stated that the physical attributes of the concrete (such as strength) required for a given structure are determined by the building methods and intended use of the concrete, the exposure circumstances, the size and shape of concrete elements, and the physical properties of the concrete. Concrete durability qualities such as resistance to freezing and thawing, as well as resistance to chloride penetration, should be verifiable using the stipulated test procedures. It is no longer appropriate to use a basic proportion specification in the hopes of meeting the objectives of a modern building project in terms of placing rate, strength gain, and durability. Following the selection of characteristics, the mixture can be proportioned using aggregate parameters determined in the field or the laboratory. Because the quality of the cementitious paste has a significant impact on the qualities of hardened concrete, the first stage in proportioning a concrete mixture is to choose the suitable water-to-cementitious materials ratio (w/cm) for the required durability and strength. Concrete mixtures should be as basic as possible, as having too many elements might make them difficult to regulate. Modern concrete technology, on the other hand, should not be overlooked. For durable concrete, mix design should have the lowest possible water-cement ratio, this will satisfy workability, strength, and compaction requirements and reduce permeability. Materials must be sound, well-graded, appropriate and contamination free. Proper handling of the mix and high-quality curing will also have a positive impact on long-lasting structures. For long-lasting concrete, the lowest possible water-cement ratio should be used in the mix design. This will improve workability, strength, and compaction, and reduce permeability. Sound, well-graded, acceptable, and contamination-free materials are required. Long-lasting constructions will also benefit from proper handling of the mix and high-quality curing.

Mix design requirement is included in the American, British, and European codes as a prescriptive specification for concrete durability, more precisely, w/c ratio, minimum cement content, SCM limitations and types. A detailed review of this in the coming chapters.

2.2.2 The service environment effect on durability

Understanding and evaluating the environment wherein the structure will be erected and function for the desired life span is critical to achieving durability and designing for it. Environment detrimental factors can be physical (abrasion, erosion, cavitation, freezing and thawing) because of temperature, moisture, wetting and drying (splash zones) or chemical (dissolution, leaching, expansion, and alteration) due to the presence of some chemicals, such as sulphate, chloride, alkaline or acids.

These physical and chemical environmental factors can be regrouped into 1) major durability issues such as alkali-aggregate action, sulphate attack, steel corrosion, and freeze-thaw; 2) concrete durability in the marine environment; and 3) the effects of both mechanical load and environmental factors on concrete durability. (Shekarchi et al. 2015).

2.2.2.1 Alkali Silica reaction

The alkali-silica reaction in concrete is caused by the chemical interaction of the strongly basic and alkali-rich solution contained in the matrix pores with the reactive phases of certain aggregates. For the process to start, there must be high relative humidity and a high concentration of total

alkalis. This reaction causes the structure to expand, crack, exude, and lose mechanical performance, thus, depending on the severity of the phenomenon, the structure may disintegrate. (See figures7)



Figure 7. Alkali Silica reaction mechanism

This phenomenon, which is mostly seen in pavements, bridges, walls, dams and hydraulic structures, barriers, and nuclear/power plant structures (see Figure 8) has been recognized from the work of Stanton who figured out the relation between the severity of ASR and alkali cement content, humidity, and pozzolans (Rogers 1999).



Figure 8. Du Vallon–Charest highway interchange viaduct, in Quebec City, Canada, was recently demolished because of ASR. (Fernandes & Broekmans 2013)

Stanton also developed a test procedure that eventually became known as the mortar bar test. Since the 1940s, the primary focus of the study has been on understanding response processes, creating test procedures to identify reactive minerals and aggregates, estimating the long-term performance of concrete mixtures in service, and proposing and assessing viable solutions to prevent ASR in new and existing structures. (Stanton 1943) (Rajabipour et al. 2015) had explained this deleterious factor comprehensively and developed an illustration for the reaction mechanism clarifying that the ASR is the outcome of a chain of actions that occur in order: silica dissolution, sol formation, gel formation, and gel swelling.



To offer solutions that can successfully mitigate such deterioration, Moreira et al.(2021) & Rajabipour et al. (2015) agreed that understanding the ASR process is key. Moreira et al.(2021) mentioned that the use of extra cementitious elements in concrete is one of the most investigated measures.

Technical laws exist in Brazil that encourage the use of certain cementitious materials. Although the Northeast part of the country produces a lot of fly ash and granulated blast furnace slag, not all of it is used in other sectors. Rajabipour et al. (2015) concluded that mitigation strategies should aim at removing one or more of the ASR four main prerequisites: a source of reactive silica, alkalis or, more precisely, OH ions in concrete pore solution to attack silica, a source of soluble Ca (e.g., portlandite) to react with dissolved silica and form a deleterious gel, and access to moisture to allow gel expansion.

Guo, Dai & Si (2019), Rajabipour et al. (2015), Souza, Polder & Çopuroğlu (2017)explored the effects of lithium and calcium on the alkali-silica reaction kinetics and phase formation processes at atomic scales, thus both the alkali-silica interaction and the reaction between dissolved silica and Ca (OH)² were restrained. On the other hand, the main disadvantages of these admixtures, according to Rajabipour et al. (2015) are their relatively high cost and lithium scarcity. Li is a rare and significant element that makes up less than 0.002% of the earth's crust (20 ppm). Another solution proposed by the team is to replace the reactive aggregate with a non-reactive one, although this too faces the same problem as Li, namely a scarcity of such resources. Furthermore, using low-alkalinity Portland cement in conjunction with low-alkalinity aggregate will considerably reduce

this reaction. In comparison, another study by Wang, Noguchi & Maruyama (2022) revealed that the lithium nitrate reduced the expansion of AAS mortars, but the reduction was restricted, and the expansion did not decrease further when the lithium nitrate concentration was increased from 1.11 mol/L to 1.48 mol/L.

Even though ASR is common, only lithium-based chemical admixtures are effective in reducing its negative effects, Oey et al. (2020), Kaladharan et al.(2021) performed further investigations on other materials. Oey et al. (2020) study has shown, for the first time, that calcium nitrate additives efficiently prevent aggregate dissolution and, as a result, mortar bar expansion, using highly reactive sodium borosilicate (NBS) glass as a model ASR-reactive aggregate. Furthermore, this research implies that any chemical additive capable of preventing reactive silicate dissolution, independent of its mechanism of action, can be used to mitigate ASR. From another aspect, Kaladharan et al.(2021) tested the performance of multiple salts in reducing ASR, Calcium acetate, Magnesium acetate, 1H2O Calcium format, calcium bromide, 4H2O Magnesium bromide, 2H2O Calcium nitrate, 6H2O Magnesium nitrate with 4H2O 6H2O and /or blends of the aforementioned salts, these salts are very promising in suppressing ASR due to their effect on regulating the pH of concrete without affecting other important features including workability, setting, and strength development.

The above-mentioned approach works for new structures, for already existing structures, the methods are more limited, due to the poor penetration depth of Li (10 to 20 mm), lithium treatment has had limited effectiveness, limiting concrete's access to external moisture by enhanced drainage, penetrating sealers, and cladding is currently the most viable mitigation approach for existing structures. Restraint and confinement techniques have had some success (e.g., FRP wrapping of columns, enclosing affected concrete with fresh prestressed concrete). Crack filling (to lessen the likelihood of further damage from freeze–thaw or corrosion), and slot cutting (e.g., in dams) to relieve ASR caused compressive pressures are two more approaches for addressing the symptoms (not the cause) of ASR.(Rajabipour et al. 2015)

More research and methods are needed to better understand the process behind this and find more effective strategies to improve the mitigating impact.

2.2.2.2 Sulphate attack

Sulphate attack is a decomposition mechanism in which sulphate ions attack the elements of cement paste. Water-soluble sulphate-containing salts such as alkali-earth (calcium, magnesium) and alkali (sodium, potassium) sulphates, which are prone to chemically interact with concrete components, induce sulphate attack on concrete. Sulphate attack on concrete can take a variety of forms, depending on the chemical type of sulphate and the concrete's exposure to the environment. (See figure 9)



Figure 9. Structure affected by sulphate attack. (Suryakanta 2015)

According to ACI's Guide to Durable Concrete (201.2R), the creation of ettringite and the formation of gypsum are the two principal processes of sulfate attack. However, more forms can be identified because of Sulphate chemical interactions with cement hydration products. This includes Thaumasite form (TSA), a Physical sulphate attack associated with the crystallization of sulphate containing salts at or near an evaporative surface.

In the case of chemical sulphate attack, macroscopic studies are defined by expansion, cracking, and/or spalling. Expansion is the most prevalent method of measuring sulfate attack. Damage is

also indicated by a loss of strength, a change in dynamic modulus, and a change in mass. Softening and decohesion are also possible outcomes. Physical sulfate attack has received a lot of attention recently. However, there is still no conventional test for this type of exposure. (Whittaker & Black 2015)

Scholars from early times investigated the factors that affect this detrimental process, for example, Dhole et al. (2019), Qiang Yuan et al. (2021) and Liu et al. (2020) stated that Sulphate attack on concrete is influenced by several elements, including the type and concentration of sulphate solution, temperature, pH value, cement composition, admixtures, and erosion form. The most essential elements in sulphate attack are the temperature, concentration, and kind of sulphate solution.

Jiang et al.(2015) examined concrete subjected to freeze-thaw cycles, sulphate solution has both beneficial and negative effects. The benefit is that sulphate solution lowers the freezing point of concrete pore solution, preventing sulphate assault during freeze-thaw cycles. The negative effect is that the sulphate solution's chemical reaction produces expansion products, which cause microcracks in concrete and speed up the deterioration process

Sulphate attack causes billions of dollars in damage to concrete wastewater collection and treatment facilities all over the world (Pan et al. 2017), thus this phenomenon's mechanism, mitigation, and protection of structures during their lifetime are critical.

Multiple recent research was applied to control this type of structural damage, Shi et al.(2019) studied the effect of calcined clay-Limestone-Portland cement on sulphate resistance. In comparison to the reference mortars, all the examined mortars containing calcined clays (either metakaolin or calcined montmorillonite) have excellent sulphate resistance, regardless of compressive strength or pore structures, as a result, the team findings propose that clay-limestone – Portland cement be classified as a new form of sulphate-resistant Portland pozzolana cement and Portland composite cement in standards. Another study, by Chen et al. (2017) aimed to compare the sulphate attack effect on partially and fully exposed samples for sulphate, when it comes to enhancing the resistance of cement mortars with fly ash and ground blast furnace slag to being

partially immersed in sulphate solution, fly ash (FA) outperforms grounded blast furnace slag (GBFS). Supporting this finding about the effect of fly ash is the study by Dhole et al. (2019) with controlling the water-cement ratio (w/c) and mixing with Class F fly ash, and silica fume a better sulphate resistance to the fly ash concrete was provided.

Additionally, Pan et al. (2017) studied the effect of surface coating on sulphate resistance, the results showed that polyurethane proved to be efficient and cost-effective treatment option. Organic coatings are often more resistant to physical sulphate attack than silane-based hydrophobic and sodium silicate

coatings, however, acrylic coatings cannot protect concrete against physical sulphate assault due to their brittleness.

From the above, we can understand the effect of such factors to the concrete, the newly formed reaction products can be detrimental and mitigation approaches must be followed to achieve resistance to the sulphate attack impact.

2.2.2.3 Steel corrosion

Harsimran, Santosh & Rakesh (2021) defined corrosion as the irreversible damage to a metal surface caused by chemical processes that result in the conversion of a pure metal to a chemically more stable form such as sulphides, oxides, hydroxides, and other compounds in a corrosive environment, that can be solid, liquid, or gaseous in nature. This applies to the steel embedded in reinforced concrete, Jin et al.(2014) stated that steel corrosion is considered the most important durability problem in building engineering, and determining ways to reduce the degree of steel corrosion is a significant difficulty in practical engineering.

Chloride ions can invade the concrete covering that shields the reinforcing steel by capillary absorption, hydrostatic pressure, and diffusion. Diffusion, or the movement of chloride ions along a concentration gradient, is the most prevalent mechanism. For this to happen, the concrete is often exposed to a continuous liquid phase that is chloride-bearing, creating a gradient in the concentration of chloride ions. Permeation, which is propelled by pressure gradients, is a second

method for chloride invasion. Chlorides may permeate inward, as in underwater tunnels, if there is an applied hydraulic head on one face of the concrete. Capillary absorption into unsaturated surfaces is a frequent and quick form of transfer. A concrete surface will go through wetting and drying cycles when it is exposed to the environment. Chloride-containing water will be pulled into the pore structure by capillary suction when it comes into contact with a dry surface; the pace will depend on the amount of moisture on the concrete surface.

The main sources of exposure to external chloride are de-icing salts, brackish water, salty soils, and seawater. Because marine exposure is a more complex combined exposure, it is considered separately in the ACI code than other chloride exposures. While reinforcing corrosion due to chloride penetration is the primary risk in marine exposures, sulphates, and magnesium in saltwater, combined with freezing and thawing in particular seasons, as well as abrasion/erosion due to wave action, are additional factors to consider. Even though the sulfate concentration would ordinarily be considered a severe exposure, the impact of the sulfates in saltwater is rather small, hence in ACI standards seawater is only regarded as a moderate sulfate exposure. This is assumed to be caused, at least in part, by the seawater's Cl and SO4 ions competing to combine with the hydrated aluminate phases of cement and several more cementitious components. Some of the chlorides in saltwater are incorporated into mono chloroaluminate complexes. Because high C3A cement promotes chloride binding in seawater exposures, its use is advantageous. Portland cements with up to 10% C3A are permitted by ACI because less residual monosulfoaluminate will be present as a result of the creation of chloroaluminate, there will be less chance that it will be converted into potentially harmful secondary ettringite. (Douglas Hooton 2019)

There are many salts used for de-icing, such as sodium chloride, or calcium and magnesium chlorides used in locations with very cold weather. These salts are another source of exposure to external chlorides. In recent years, some nations have adopted spraying liquid brines with 30 percent chloride before winter storms. This causes the brine to penetrate the concrete, causing joint rot, which is an early sign of concrete deterioration at the joints of the pavement. (Sutter 2008)

Chen & Leung (2015) explained that the passive coating on the steel surface is damaged when corrosion-inducing substances (such as chlorides) reach a threshold concentration on the steel

surface, and reinforcement corrosion begins. Corrosion products form and grow as steel depletes in the presence of water, this expansion of corrosion products causes internal pressure in the surrounding concrete, causing tensile stress in the concrete cover. A crack will emerge as the tension meets the concrete's tensile strength. Its spread due to further corrosion will finally result in the cover spalling or delamination that considerably impact the structural serviceability because water, oxygen, and other contaminants can easily contact the steel surface due to cover spalling or delamination thus the rate of corrosion will dramatically rise. (See figure 10)



Figure 10. Corrosion-induced damage on a concrete bridge in Cape Town that was exposed to airborne chlorides. (Alexander & Beushausen 2019b)

Bezuidenhout & van Zijl (2019) studied the relation between cracks and chloride ingress corrosion. They tested three reinforcement samples with single or two transverse cracks in flexure that are kept at the same crack width. the findings show that crack width, and reinforcement quantity have an impact on the corrosion rate of RC components. Corrosion initiation is currently used to mark the end of a service life. In fractured areas, however, rusting starts quickly. The residual structural service life is proposed here to be based on the propagation rate of corrosion and a limit condition

of reinforcing steel loss. Furthermore, crack spacing and reinforcing density must be considered. Supporting this result of the effect of cracks on corrosion is the research done by Yang et al. (2019) who concluded that corrosion crack in concrete is determined to be a more dominant factor than corroded rebar shape and rust build-up. In addition, rust accumulation helps to improve bond weakening caused by corroded rebar form.

There are a variety of methods for steel corrosion protection, because the most important characteristic that affects the rate of chloride infiltration appears to be the combination of concrete quality and concrete cover thickness, improving the quality of concrete has been deemed the key protection measure. Nossoni & Harichandran (2014) said that the amount of concrete cover over the rebar can have a substantial impact on the time to corrosion of the embedded reinforcing steel, However, The rebar becomes less effective as the cover grows, and the risk for cracking owing to tensile stress, shrinkage, and temperature impacts increases. Therefore, Asamoto et al. (2021) studied the effect of cover depth on penetration, the outcome revealed that an acceptable cover depth of higher than 40 mm was found to limit moisture and oxygen penetration at the steel, which confirmed the survey findings of cover depth effect on high resistance to corrosion-induced deterioration despite an increase in service life. In confirmation with the above studies about the significant effect of concrete cover is the findings from the Norwegian Public Roads Administration's Bridge Management System and field investigations on corrosion damage in pretensioned Norwegian standard I-beam (NIB) girders in 227 coastal climate bridges, Yang et al. (2019) discovered girder corrosion problems on 51% of the bridges. The proportion is highest for bridges constructed when the necessary cover thickness was the smallest. Corrosion damage was generated by 74 percent of the time when the cover thickness was less than what was required due to manufacture flaws.

Coating is another way for steel protection; there are many different coating materials and application procedures, each with its own set of advantages and disadvantages. Al-Tholaia et al. (2014) compared the effect and efficiency of three types of coating : epoxy-coating, red-oxide and zinc primer coating, when compared to red-oxide and zinc primer coatings, epoxy has a far better performance against steel corrosion. Nevertheless, epoxy coating application is critical to perform

properly, Vakili, Ramezanzadeh & Amini (2015) concluded that any damage in the epoxy coating before concrete casting will considerably affect its efficiency, and that some conversion coating is beneficial, the Ce–Zn chemical treatments improved the corrosion protection properties of the epoxy coating on the steel surface by restricting the cathodic reaction occurrence at the coating/metal interface and preventing the coating detachment from the steel surface when exposed to the corrosive electrolyte. Another coating approach is the hot dip galvanizing, even though it acts as a very good barrier Pernicova, Dobias & Pokorny (2017) study revealed that despite the benefits of hot-dip coating, the viability of zinced rebar is questioned, as the circumstances of fresh concrete mixture cause zinc coating deterioration and, more significantly, its bond strength with cement.

Usage of inhibitors also another way of steel corrosion protection, but the use of such methods has to be carefully applied, Topçu & Uzunömeroğlu (2020) concluded that for field implementation, they are simple to use and cost-effective. on the other hand, when the concentration of corrosion inhibitor is increased, the strength of concrete decreases. Mixed type inhibitors demonstrated higher cracking time, reduced permeability, higher compressive strength, and lower corrosion rate. An example of corrosion inhibitor hat is proportioned and added according to chloride limits stated in the ACI 318 code is the DCI inhibitor, it is an liquid with a calcium nitrite base that chemically restrains the corrosive effects of chloride salts. It is incorporated into a concrete mixture either at the job site or during batching, and it disperses evenly throughout the concrete. DCI® stabilizes the passivating oxide layer that is often present on the reinforcing steel in concrete after the concrete has been laid. By making it more difficult for chlorides to permeate the passivating layer, this greatly lowers the corrosion rate (GCP 2019).

Steel corrosion, which is caused mainly by chloride ingress and carbonation of concrete, is a critical detrimental factor for the concrete, thus, lots of research has been done to monitor and suppress this cause from limiting the structure durability.

2.2.2.3 Freezing and thawing of concrete

One of the most typical physical deteriorations of concrete in cold conditions is the action of freezing/thawing, which causes major damage and cracks in concrete structures. (See figure 11).

This phenomenon is visible in European countries where temperatures fall below 0°C and ice begins to form. The freezing of water inside the capillary pore structure generates a 9 percent increase in volume, resulting in significant concrete cracking and disruption, especially if the pores in the concrete are close to saturation. (Isabirye et al. 2012)





Figure 11. Buildings damaged due to freeze and thaw effect. (Paul 2014)

There are various factors that affect the concrete's potential to freeze/thaw damage, including composition, permeability, porosity, type, moisture level, age, air-entraining admixtures, workability, exposure environment, and aggregate type. The most critical criteria impacting freeze/thaw endurance, especially when admixtures are used, are air void qualities.

According to Etman & Ahmed (2018) study on the effect of freezing and thawing on concrete behaviour, the results showed that 0.15 percent air entrained in cement weight improves freezing-thawing durability, with a durability factor of 85 percent for mixes exposed to freezing-thawing cycles in the range of 0-200. Moreover, the compressive strength of the mixes and the durability

of the mortar and concrete were not affected by up to 200 freezing-thawing cycles. More than 300 freezing-thawing cycles should be avoided.

Despite the positive impact of another mitigation method studied by (Behfarnia & Salemi 2013; Duan et al. 2013; Wang et al. 2017; Liu et al. 2021) of the use of nanoparticles and supplementary cementitious materials to improve the resistance of concrete to freezing and thawing, and the use of superabsorbent polymer examined by (Laustsen, Hasholt & Jensen 2015; Schröfl et al. 2022) that showed its impact to improve such phenomenon, these methods suggests approaches to cure the effect of F &T rather than prohibiting the ice crystallization, hence, other studies were introduced, Frazier et al.(2020) whose investigation was inspired by nature, they demonstrated that a soluble biomimetic antifreeze polymer with ice recrystallization inhibition (IRI) and dynamic ice shaping (DIS) activities may prevent ice crystal formation in cement paste and concrete. Moreover, Laustsen, Hasholt & Jensen (2015) study on another antifreeze (urea and calcium nitrate) found that in comparison to urea and the control sample, calcium nitrate samples showed a more compact and denser microstructure that has less water absorption.

The usage of de-icers is another factor that affects concrete longevity and is linked to freezing and thawing. Salts may penetrate the concrete cover if there is insufficient drainage, causing steel corrosion when it reaches the embedded steel. Another result is that the chemical interaction of the de-icing solution with cementitious hydration products produces a range of compounds, all of which induce physical deterioration in the form of scaling and a loss of compressive strength. As a result, the most frequent therapy for preventing de-icer-induced concrete deterioration is to change the microstructure and porosity of the concrete, which focuses on reducing the size and volume of voids in concrete to prevent harmful de-icing chemical ions from penetrating.

Freezing and thawing is a damaging environmental element harming concrete prolongation in cold places. There are a range of measures to restrict its influence on structures, however it is recommended to inhibit the ice crystallization rather than treating its effect.

2.3 Design for durability

Design for durability is the process of designing and constructing buildings and/or infrastructure to meet design lifetime and needed requirements in harsh environments. Design for durability is not an easy task. In fact, durability design is a multilevel process that includes multiple criteria: design for the entire structure, structural parts, and structural materials. The durability design for a structure strives to assure the most rational structural element configuration and worldwide pattern for a certain service life, considering environmental conditions and financial restrictions. This will guarantee that the transient performance may always be maintained to an expected level. Furthermore, a reasonable division of initial building budget and later maintenance expenditure should be addressed.

The expense of maintenance work owing to deterioration caused by environmental acts was claimed to have reached an alarming level, putting a huge financial strain on structure owners. Because of this, decisionmakers, structural designers, and material suppliers around the world are concerned about durability. As a result, huge efforts have been dedicated over the last three decades to rigorous study on the deterioration processes of structural elements and concretes, as well as the durability standards for concrete structures at the design level.(Li 2016)

The service life of the project must be specified at the project's initiation stage, then the design phase must outline the exposure conditions, member characteristics, such as concrete cover, materials, mix design, and curing approaches, as well as develop a plan for monitoring and maintenance. Finally, at the project's execution stage, workmanship and material quality must be taken into consideration. To achieve that, clear standards must be available for design professionals to guid their design process toward durable structures. Even though some codes included durability design standards, other codes lack that.

Douglas Hooton (2019) stated that current building codes have generally focused on structural capacity and serviceability for life safety considerations, but many do not fully address durability design. It should be emphasized that concrete durability criteria are often stricter than those for structural capacity, and structural designers are concerned about the additional expenses of

"overdesign," as many people term it. It should be noted, however, that most structural elements in buildings are not generally exposed to harsh environments.

Supporting that, Grković & Folić (2015) stated that durability design is challenging to quantify because it depends on a variety of factors during the design phase, from actual performance during construction to maintenance. The majority of the current national rules for concrete structures design lack detailed instructions for planning the durability of structures with SL of more than 50 years, particularly if exposed to more hostile environments than those defined in these codes.

Rostam (2000) proposed two categories for durability design: based on the principles of complete protection of concrete structures, Strategy A ("Avoidance of deterioration") offers three potential options: altering the microenvironment (A1), selecting materials that do not react to harmful impacts (A2), and preventing reactions (A3). Four different approaches to Strategy B, which minimizes deterioration through the best design and material selection, are possible : B1-"Deemed-to-satisfy"; B2-resistance based on the application of one (B2.1) or multiple phases of protection (B2.2); B3-Factor method in accordance with ISO 15686); and B4-"Performance based design", based on probability and reliability, which can be of "Full (B4.2) Meeting standards outlined in codes and putting them into practice are both part of the B.1 method.

Furthermore, Beushausen et al.(2016) explained that the aggressiveness of the environment, which needs to be carefully assessed and categorized, affects design durability. The aggressiveness of the environment and the capabilities of the hardened concrete affect the potential penetration and transport mechanisms of chemicals in the concrete during the interaction between the environment and the material. Hence, Grković & Folić (2015) explained that these functional specifications for hardened concrete and eligibility requirements serve as the foundation for performance-based durability design (PBDD) for the needed service life. Typically, indicators of concrete's permeability (such as capillary absorption, gas permeability, water permeability, and porosity) are used for durability for the designer sets the DI values that the hardened concrete must meet when building durability for the desired service life based on the type, function, and aggressiveness of the environment. DIs are examined utilizing accepted techniques and/or techniques that have been used for a long time and whose accuracy has been confirmed. Additionally, the testing phase

is completed before to the commencement of the project, whereas the acceptance phase is completed on the job site. After construction is complete, the DI values, which are updated in the structure's "Birth certificate," are examined to see if they are in compliance with the functional requirements for the quality of concrete. See figure 12 below summarizing performance-based durability design.



Figure 12. Performance based Durability Design PBDD. (Mayer & Schießl 2009)

2.4Types of Specification for durable concrete design

Each project is unique and is created to meet a specific requirement in a particular region. To do this, different standards must be established and followed by project stakeholders, including designers, contractors, and craftsmen. Construction specifications are known as a set of instructions supplied by a state agency to a contractor/producer that outlines the qualities of the materials to be utilized and/or a procedure for doing work on a project. (Weiss et al. 2017)

There are two types of specifications: prescriptive and performance specifications. Prescriptive specifications include sections for means and methods of concrete mixture proportions and building processes rather than outlining end product criteria, in contrast, performance specs lay out the concrete requirements in measurable terms for proper in-place servicing to satisfy the owner's objectives.(NRMCA 2021)

Looking at these specifications and approaches, Andrade C.(2006) advises that four different levels of approach be considered when specifying concrete in order to achieve the desired service life. This methodology, depicted in Fig. 13, is similar to that proposed in fib Model Code and has been explored by a number of publications, such as (Alexander & Thomas 2015).

Wally, Magalhães & Pinto da Silva Filho (2022) explained that the levels in Figure 13 can be classified into two categories: prescriptive and performance-based. The single entirely prescriptive level is Level 1 (deemed-to-satisfy), whereas the others steadily add concrete performance analysis, environmental harshness that can be provided by the exposure environment, and service life modelling. When a hybrid technique (Level 2) is utilized, durability indicators such as chloride

Specification of durable concretes

Level 1 – Deemed to satisfy: minimum compressive strength, maximum water/binder ratio, minimum cement content, and minimum cover depth Level 2 – Hybrid approach: introduction of limiting values app

and

for durability-related parameters,

such as water absorption,

chloride penetrability,

carbonation rate

Level 3 – Performance-based approach (deterministic): service life modeling based on deterministic service life prediction models and using data from appropriate test methods Level 4 – Performance-based approach (probabilistic): introduces probabilistic assessments, considering the variability of parameters involved in the deterioration process

Service life predictions refinement

Figure 13. Levels of approach for the specification of durable concretes. (Wally, Magalhães & Pinto da Silva Filho 2022)

diffusivity, electrical resistivity, carbonation rate, and permeability are used to assess the concrete's resistance to aggressive agent penetration. It should be noted, however, that prescriptive specifications are still necessary at Level 2, with durability indications being used as a supplement to other assessment methods. Service life prediction models are utilized at Levels 3 and 4. These models, whether deterministic or probabilistic, require data from at least one concrete durability indicator, as well as, in most situations, external conditions, cover depth, and structure specified service life.

2.4.1 Performance vs Perspective Specification

There have been several studies and examinations into which requirements should be followed in order to achieve the target project durability. Alexander, Santhanam & Ballim (2011) stated that structural concrete is made to meet certain workability and strength requirements. Traditionally, durability requirements have been incorporated into the design process as specific material requirements, such as the maximum water to cement ratio, minimum cement content, minimum concrete grade, amount of air entrainment, and so on, as appropriate for a particular service environment. which means that the design approach is prescriptive in terms of mix and material parameters or attributes that are thought to assure long-term concrete durability. Only the compressive strength of the concrete is measured after it has been mixed and installed to confirm that it meets the design requirements and standards. However, it is now widely understood that prospective durability should be assessed on the concrete system, considering not only the concrete material but also the concrete's processing during construction.

Agreeing with that, Beushausen, Torrent & Alexander (2019) said that concrete was created without many chemical or mineral admixtures in previous decades, its durability could be related to its strength and microstructure, hence to the binder concentration. Nonetheless, admixtures are in considerable demand these days, and they appear to have an impact on concrete durability. The qualities of permeability, diffusion, and absorption can be minimized by utilizing a low cement content. The lower water-to-cement ratio results in better strength and durability and the strength test of the specimen prepared on site is proven to be less realistic than the quality measurement of cover concrete.

Moreover, Jilty M Varghese (2021) stated that specifications for raw material qualities and construction techniques are part of the prescriptive approach. Concrete strength, as well as the water-cement ratio, are used to assess the quality and durability of the material. Due to the exposure condition, these values are limited and for the same exposure condition, the limiting values of water-cement ratio and minimum cement content vary by country. The team declared that traditional prescriptive specifications are unsuccessful in predicting service life since they are based on limited values of mix design parameters. Performance specification, on the other hand, entails the measurement of relevant durability that can be utilized as input parameters in a service life model to estimate the structure's durability.

From the above scholar conclusions, we can see that perspective specifications have to be combined partially – if not completely for some projects -substituted by performance specifications.

2.4.2 Performance related specifications

Multiple research projects in different countries were carried out outlining directions for performance specifications. In the late 1990s, Goodspeed, Vanikar & Cook (1996) created a high-performance concrete performance specs by developing performance grades based on eight standard tests. Celik Ozyildirim (1993) studied the establishment of quantitative links between testing and performance was examined. Furthermore, Buenfeld et al. (2000), Dhir et al.(2004), Kolias & Georgiou (2005) and Yiğiter, Yazici & Aydin (2007) created Performance Related Specifications (PRS) for pavements, which relate tests, performance, and repair costs. The National Ready Mix Concrete Association (NRMCA) created performance-based guidelines that link hardened concrete needs to established testing criteria.

Others have established estimates for a variety of durability-related distresses such as (Wassermann, Katz & Bentur 2009), (Harrison et al. 2015) and (Angelucci et al. 2017). The results of these investigations generally demonstrated that lowering the cement quantity while maintaining the water/cement ratio improved concrete quality. This can be attributed to a decrease in paste volume, resulting in an increase in relatively impermeable aggregate phases in the concrete matrix

and less paste with higher porosity. In many cases, the change in the relatively impermeable aggregate phase for more permeable paste phases resulted in a greater improvement in microstructural characteristics than would be expected. This additional benefit could be attributed to the different amounts of chemical admixtures employed in the various mixes, as well as the different consistence levels, which could alter plastic qualities like bleed and settlement. In order to implement that, they recommended to follow performance specifications.

Even though it is not a code by itself, FIB model 2010 & 2020 has established estimates that provide various equations that relate 'penetrability' variables to concrete compressive strength (water and gas permeability coefficients, water, gas, and chloride diffusion coefficients, and water absorption coefficients). Adding to that, Obla & Lobo (2017) issued a recommendation to engineers to reduce prescriptive requirements for concrete mixtures in project specifications and examine performance alternatives, this included alternative performance requirement for freeze thaw exposure, water exposure, sulphate exposure, alkali silica exposure and corrosion protection for steel reinforcement.

All of these approaches had a positive impact on concrete durability; nevertheless, due to the wide range of environmental conditions and project characteristics, these and other studies, particularly the test methods used, need to be reviewed and combined to provide clear and consistent specifications for project stakeholders to follow in order to achieve the required service life.

2.4.3 Worldwide Applications for performance-based approaches

Performance-based techniques for concrete durability have explicit and well-understood principles. However, the general use of appropriate methodologies for all phases of the in-situ concrete manufacturing process, from initial mix design to quality control and compliance evaluation, has been limited to a few countries, with South Africa and Switzerland topping the list (Beushausen, Torrent & Alexande2019). This is because of the numerous deterioration mechanisms impacting reinforced concrete structures are still not entirely known in all important features, and the association between performance test results and actual durability performance of concrete structures has not been fully established. Concrete strength standards had shifted gradually from prescriptive to performance approaches very early, this is probably due to the rapid development of appropriate and widely accepted testing methodologies. According to history, the first systematic concrete tensile strength tests were done in Germany in 1836 (Kindij 2008) and the Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM C39, was first developed in 1921. Counter that, only in the 1970s did test procedures for determining a concrete's probable durability in a reasonable amount of time become available, such as the RILEM-Cembureau method to measure oxygen permeability (Kollek 1989), the chloride migration test method, adapted in (ASTM C1202 2012), and chloride diffusion (NT Build 492 1999).

Efforts have been made toward the creation of service life prediction models based on durability indicators testing for several years now. Among these, the European DuraCrete project (DuraCrete 2000) aimed at probability-based modelling of the service life of structures vulnerable to carbonation and chloride penetration deserves special mention. This project was simplified and refined over time as more practical experience was obtained, and in 2004 the Norwegian Association for Harbour Engineers recognized it as the foundation for recommendations for the construction of concrete infrastructure in Norwegian ports. Hooton, Hover & Bickley (2005) outline the end result specification system (ERS) used in Canada, where the obligation for producing durable concrete is shared by the concrete supplier and producer; the quick chloride penetration test (ASTM 1202-05) is used to ensure compliance with performance standards. Adding to that, In the Netherlands , Polder & R.B. (2006) offer an approach that involves verifying the diffusion coefficient obtained using the DuraCrete model and cover depth. Furthermore, in France, Baroghel-Bouny (2006) a French researcher, proposed the use of universal durability indicators that take into account various transport systems that govern aggressive chemical absorption.

In addition to the prescriptive requirements that are still in practice, several national standards have begun to include performance requirements. For specific exposure and service life conditions, Canadian Standard provides requirements for maximum Coulomb values (CSA A23.1-14/A23.2-14 2009) . Maximum values of water permeability or chloride diffusivity depending on the

exposure classes for cast specimens, as well as air permeability tested on site, are specified in Swiss Standards (SIA262/1 2019). Standards for durability design in South Africa are still mostly prescriptive, while performance-based specifications and quality control for concrete durability were established on a significant, industry-wide scale around 10 years ago. Furthermore, the South African Durability Index test techniques have recently been included into South African National Standards, and standardized limitation values for the respective durability indicators will most likely follow soon. (Nganga, Alexander & Beushausen 2013) (Nganga, Beuhausen & Alexander 2017).

Performance techniques are still primarily at the research stage in many countries, with only limited practical use. The two approaches developed in Switzerland and South Africa have already been effectively deployed in practice.

The next sections go into the principles and applications of these techniques.

2.4.3.1 South African Performance Approach - Durability Index

Durability Index (DI) tests were created to analyze concrete's near-surface characteristics and to assess its resistance to fluid and ionic transport mechanisms. The tests determine the permeability of a concrete specimen representing the cover layer in terms of gas permeability (Oxygen Permeability Index, OPI), sorptivity and porosity (Water Sorptivity Index, WSI), and conductivity (Chloride Conductivity Index, CCI).

Mackechnie & Alexander (2002), Torrent & Fernandez Luco (2007) and Alexander, Ballim & Mackechnie (2018) and others explained the equipment and procedure for OPI test. They explained that the OPI is equal to the negative log of the permeability coefficient. OPI values for South African concretes typically range from 8.5 to 10.5, with a higher number suggesting less permeability and thus a potentially higher-quality concrete. Because the oxygen permeability index is calculated on a log scale, the difference between 8.5 and 10.5 is significant, with the former being 100 times more permeable.

The findings of the OPI test can be used to characterize concretes for factors such concrete grade, binder type, compaction, and curing. The carbonation resistance of concrete can be related to the early age (28 days) OPI value based on fundamental and empirical correlations, allowing OPI to be employed in a carbonation-type service life mode.(Bjegović et al. 2015)

For the prediction of carbonation depth development, a recently revised version of the South African carbonation prediction model includes components of binder chemistry, mix composition, ambient variables, and the concrete's diffusivity as measured by the OPI value. The permeability coefficient determined by the OPI test can be linked to the carbonation coefficient using this model. (Salvoldi, Beushausen & Alexander 2015). Based on these relations, durability estimates are produced only based on the concrete's permeability, in this case based on the forecasted time to reinforcement corrosion beginning due to carbonation, as carbonation rates are influenced by the chemistry of the hardened cement paste as well as the physical pore structure as determined by permeability studies.

Another performance approach considered in South Africa is curing and quality control. Quality control requires test samples to be taken from the real structure and samples from mock-up panels that re-present the genuine structure. Panels are fabricated and cured using the same formwork and processes as the real structure in this case.

2.4.3.2 Swiss Performance Approach – Torrent Test

The Swiss Federal Highway Administration has been sponsoring research and development programs aimed at creating an appropriate technique for determining and controlling the quality of the cover concrete on site since the early 1990s. This experiment, combined with previous investigations, resulted in the establishment of a non-destructive test method created by Torrent (Torrent 1992) to measure the air-permeability of the cover concrete on site in 2003. That same year, a new Swiss Concrete Construction Code was published (Olivier Burdet, Lausanne et Albin Kenel & Rapperswil 2003), based on Eurocode 2. The importance of the impermeability of the cover concrete is acknowledged in this Code, which states that "the impermeability of the cover

concrete shall be checked, by means of permeability tests on the structure or by extracted cones from it. (Torrent 2012)

Neves (2016) explained that the Torrent method relies on establishing a vacuum on the concrete's surface and measuring the rate at which the pressure in the test chamber rises once the vacuum pump is turned off. A double-chamber cell and a pressure regulator that balances the pressure in both chambers during the test are the method's distinguishing features. The inner chamber receives a controlled, unidirectional flow of air from the concrete pores, while the outer chamber serves as a guard-ring. It is feasible to compute the concrete's coefficient of permeability to air, or kT, under these conditions. Several studies have found that the coefficient of air permeability kT relates well with other standardized durability tests including water sorptivity and chlorine migration.

The defined limited values of kTs were established based on laboratory investigations and site testing of over 100 new and ancient construction elements. In terms of composition and conformity testing, the air permeability was measured on concrete elements and specimens that met the real requirements of the Swiss concrete standard (SIA 262, SN EN 206). Then, based on these findings, the kTs limiting values for on-site measurements are determined as a function of the exposure classes of the Swiss version of Standard EN206.

Nganga, Beuhausen & Alexander (2017) summarized the outcomes of a research conducted to assess the applicability of Durability Index (DI) performance-based specifications that have been applied on a broad scale in a major infrastructure project in Gauteng Province, South Africa, involving bridges and other structures. The approach's practicality was assessed by looking at the magnitude and variability of DI test values (Oxygen Permeability Index, OPI, and water sorptivity) and cover depths; the DI tests' applicability in laboratories to determine if proper test procedures are being followed, as well as its application on site where samples are obtained; and the industry's response to this recently implemented approach, which was assessed by looking at responses to a survey. The average values of durability parameters (OPI, sorptivity, and cover depth) in all cases met the limiting minimum values, according to the statistical analysis. However, a large percentage of individual DI test results for several structures did not meet the limitation limits. The coefficient of permeability (k) and sorptivity values have a lot of variation. The variability measured for

structures cast in situ for cover depth readings was significantly larger than for prefabricated elements. Engineers had a mixed opinion on the impact of this method; some thought it had no influence on construction practices, while others thought it had resulted in tougher controls in the execution of construction techniques as a result of the performance-based project specifications.

2.4.3.3 Combination of South Africa and Swiss Performance Approach

The Torrent method and the Oxygen Permeability Index (OPI) test are the two most commonly used durability performance measures in practice that leverage transport qualities as durability indicators. Both procedures are based on determining a concrete's gas permeability and comparing the results to a general quality rating. Furthermore, both methodologies are linked to building specifications for restricting test variables in response to a variety of environmental exposure situations. (Beushausen, Torrent & Alexander 2019)

(Starck et al. 2017) conducted a comparison of the two methodologies based on extensive experimental investigations. Both permeability tests were found to be sensitive to common external and internal concrete parameters, such as the w/c ratio, cement type, and curing environment. The tested concrete specimens were frequently classified in the same acceptability groups by permeability-related performance ratings defined in South Africa and Switzerland. This was viewed as an affirmation of their validity because it demonstrated the complementary nature of the two techniques. Incorporating in situ and laboratory-based permeability test methodologies is advised as part of an integrated approach.

2.5 Durability in the Arab Gulf

Construction, where reinforced concrete is mostly employed, has grown significantly in the Gulf region. The environment of the Gulf region affects concrete structures because it is one of the world's most aggressive exposure conditions for the durability of reinforced concrete structures, which tend to degrade more quickly unless special precautions are taken because of high ambient temperature, low relative humidity, salt-contaminated dust, sea water, and underground salts.

2.5.1 Effects of Arabian Gulf Weather and Environment on Concrete Structures

Since the climate and environments of the countries in the Arabian Gulf region differ greatly from one region to the next, no single country can generalize the climate features for the entire region. In the Arabian Gulf region, there are observable changes in temperature, humidity, rain, wind, soil geology, and raw materials. The "Hot-Dry" and "Hot-Humid" climate zones can be used to distinguish the location. Al-Samarai (2015) explained that since the climate and environments of the countries in the Arabian Gulf region differ greatly from one region to another, no single country can generalize the climate features for the entire region. In the Arabian Gulf region, there are observable variations in temperature, humidity, rain, wind, soil geology, and raw materials. The "Hot-Dry" and "Hot-Dry" and "Hot-Dry" and "Hot-Humid" climate 2015.

He also stated that despite the harsh environmental conditions in the Gulf Region, not all structures decay or lose their usefulness after a brief period of use. Many structures have lasted for thirty to forty years or longer without requiring significant upkeep or repairs. Instead of basing the design of concrete structures on the overall environmental conditions of a large area, designers should consider the local environmental factors and the impact of a hot climate on the structure. Weather, topography, geography, and other factors specific to the immediate area must be considered during design.



Figure 14. Hot-Dry and Hot Humid zones in the Arab Gulf Source: (Ahmed, Hamouda & Gadala 2010)

Mehta (2003) also explained that environments which are hot, humid, hot, dry, and salty are the biggest difficulties for reinforced concrete building in the Gulf region. High ambient temperatures in warm climates have an impact on concrete structures because heat is a driving energy source that quickens the deterioration mechanisms' progression. According to the traditional law relating heat to the rate of chemical reactions, the rate of chemical reactions doubles for every ten-degrees increases in temperature.

Another challenging factor for the structure durability is the shortage of water. Raouf (2012) mentioned that this is justified by the variable low rainfall, high evaporation rates, and frequent droughts that characterize the region. Despite the GCC countries' limited water resources, demand for water is rising because of population expansion, fast urbanization, as well as excessive consumption habits in the residential and agricultural sectors. To overcome this challenge, the use of high-performance concrete and self-curing concrete should be considered.

Al-Samarai (2015) studied the effect of hot weathering concrete on the tendency of tensile specimen cracking. According to test results, hot weather concreting increased the width of cracks in tensile specimens by 20–40% for mixes with low water/cement ratios and low slump, while crack widths dropped by 30–40% for mixes with high water/cement ratios and high slump. On the crack spacing, there was no substantial difference. The findings brought to light the significant interaction between the technique of casting in hot weather and the bond strength and susceptibility of concrete to crack. Any cracking that occurs prior to applying a load has an impact on both the orientation of the cracks and the level of stress after application.

2.5.2 Solutions to Reinforced Concrete Durability under Harsh Climate of Arabian Gulf

To overcome the harsh environement effect on the concrete durability, multiple studies took place in different gulf countries. To begin with, Ghous Sohail et al. (2020) examined how well newly created high performance concretes (HPC) and ultra-high performance concretes (UHPC) withstand over time. Without applying any new techniques, the HPC and UHPC were made in Qatar from materials that were readily available there. Scholars examined how long-lasting properties of HPC and UHPC compared to a normal strength concrete (NSC) from existing structures built in 1970,1980 and 1990. In comparison to NSC, HPC and UHPC had electrical resistivities that were 11 and 20 times higher, respectively. For HPC and UHPC, respectively, the sorptivity was two and three times lower than NSC. While HPC and UHPC had porosities of 2.45 and 1.43 percent, respectively. In durability tests, these freshly manufactured concretes performed better than concrete from actual structures. With these qualities, the UHPC will be an effective instrument for slowing down the rapid deterioration of RC structures, particularly in the harsh environmental conditions of the Arabian Gulf.

Another study examined the effect of strengthening concrete beams using carbon fibre-reinforced polymer (CFRP). Al Nuaimi et al. (2021) assessed the durability performance of RC beams reinforced with CFRP composites performance after being exposed to sunshine and salt water for 6, 12, and 24 months. The results of the four-point bending tests after each exposure were compared to the specimens tested at 28 days, to the control specimens that hadn't been strengthened but had undergone a similar amount of exposure, and to the strengthened specimens that had spent the same amount of time in the lab. After 28 days, the CFRP-strengthened specimens showed a 67 percent greater ultimate load capacity than control specimens, and after two years of exposure to direct sunshine and saline water, respectively, they showed up to 51 percent and 71 percent higher load capacities than control specimens. No obvious degradation of stiffness or strength, or harm to the epoxy, was found. Saline water exposure changed the failure modes from cohesive to adhesive, however samples exposed to sunshine showed no change in the failure-pattern and the failure types remained cohesive or interfacial. Environmental strength reduction criteria are suggested for design and analysis and contrasted with current industry standards. Thus, laminates strengthened with CFRP can withstand harsh environments with high salinity, temperature, and humidity and yet perform well.

Even though the previous study showed that CFRP performs better in terms of durability and strength in harsh environment compared to normal concrete, Helbling et al. (2006); Choi et al. (2012); Chotickai & Somana(2018) stated that this must be further investigated and three important issues need to be addressed: how fiber-reinforced polymers (FRPs) react, how well FRP composites

adhere to the surface of concrete, and how durable the overall strengthened element will be under harsh service circumstances.

Moreover, Abd El Fattah et al. (2018) performed a study on the west coast of the Gulf where marine exposure site was built to identify the effects of SCMs and chemical admixtures on corrosion activities in reinforced concrete. Eight mixes of cement Type I and Type V with various SCMs and corrosion inhibitors (Migrating Corrosion Inhibitors (MCI), Calcium Nitrite Inhibitor (CNI), and Calcite) were used to make plain and reinforced concrete blocks, which were then exposed for a year to the tidal, splash, and atmospheric weathering processes. Each mix yielded eight blocks: four plain and four reinforced with four black steel bars of varying cover depths. The blocks were observed, and their performance was assessed in terms of steel corrosion activity and chloride ingress. The findings showed that the increased cover depth improved the efficiency of corrosion inhibitors. The best performance for preventing corrosion was demonstrated by fly ash and slag cement. When compared to control blocks, calcite demonstrated only small decreases in chloride concentrations and a slight improvement in corrosion rates. Unlike the samples exposed to tides, the samples exposed to the atmosphere very slightly increased the surface concentration of chloride. The outcomes highlight the significance of making sure there is a suitable cover depth for a lengthy service life in a tough environment. Supporting this study, (Cheewaket, Jaturapitakkul & Chalee 2010; Boa & Topu 2012; Kim et al. 2016) tested the effect of replacing cement with fly ash to the mix, the results showed that fly can be used against chloride ingress and works well against corrosion.

Adding to the above-mentioned studies, a wide variety of studies focused on the effect of supplementary cementitious materials SCM on concrete durability and examined diffusion and track corrosion activity. Firstly, Ganjian & Pouya (2009) who explored the effectiveness of cement paste and concrete mixes using silica fume (SF) as a cement replacement at 7 percent and 10 percent was examined under three exposure scenarios. The outcomes demonstrated that under cyclic wetting and drying circumstances, plain type II Portland cement outperformed blended SF cement. When exposed to repeated cycles of soaking and drying in simulated seawater, silica fume specimens lost more strength than normal type II Portland cement did when it was cured in potable

water. Additionally, the capillary water absorption under tidal zone exposure or/and under wetting and drying simulation increased according to the amount of silica fume utilized in the mixes. Additionally, the ground granulated blast furnace slag (GGBS) mix that was ternary blended had the weakest performance overall. Secondly, Lizarazo-Marriaga & Yépez (2012) studied the effect of silica fume (SF) addition on the chloride-related transport properties of high-performance concrete, The findings indicated that silica fume in concrete increases strength and decreases chloride ion permeability, however there were noticeable variations between the findings of the long diffusion and quick electrical tests.

According to the above scholars' conclusions, the adaptation of supplementary cementitious materials in the concrete mix, chosen at precise amounts and suitable to the exposure, together with correct curing, can overcome durability limiting factors in the Gulf's severe environment.

2.5.3 Design for Durability in the Arab Gulf

The varied climatic conditions of the Arabian Gulf represent a significant challenge for the durability of reinforced concrete structures there. Beyond the constraints of the conventional Deemed-to-satisfy method, it is obvious that a systematic durability design process is required. Such specifics on the durability design of RC structures are included in the guide "Guide for the Design of Concrete Structures on the Arabian Peninsula" established by the Concrete Society. In this regard, the structure's service life is a direct design parameter, and assessment of this parameter is advocated for "special" constructions. According to the fib principles (Demis & Papadakis 2019), a four-step durability design approach for RC structures has been established. This design process will occur at the conceptual design phase. See Figure 15.



Figure 15.Service life design procedure of an RC structure. (Fib Bulletin 53 2010)

Designing a significant reinforced concrete infrastructure project in the Gulf region in accordance with these recently implemented laws resulted in a disagreement between the project's stakeholders on the specifications for concrete mix proportions and concrete cover, consequently, Demis & Papadakis (2021) conducted their own durability study with the use of a physicochemical deterministic (in accordance with performance-related methodologies) service life assessment tool and they stated that the outcomes supported the initial probabilistic durability study while also recommending additional changes in terms of mix design and preventive measures to increase the durability of the structural parts for the required service life of 120 years. Thereby, an appropriate (for the exposure environment) physicochemical verified deterministic model on service life estimation, if properly configured, can produce accurate estimates (compared to those probabilistically derived), under a highly aggressive environment on concrete structures as such be

further tested and enhanced considering known differences across (other) deterministic techniques. Therefore, the development and validation of physicochemical deterministic computations employing calibrated reduction safety factors, or in other words, semi-probabilistic estimations, should be the focus for the estimation of concrete service life under chloride exposure.

Because the climate and environment in the Arabian Gulf are harsh and harmful to structures, it is crucial to have a design approach for the durability taking diverse exposure situations and elements affecting durability into consideration.

CHAPTER 3: INTERNATIONAL DESIGN CODES AND STANDARDS

3.1 Development of codes and standards

Since people have had houses, a certain level of codified common sense has been required. Apparently, despite humans' endless ingenuity and proclivity to push boundaries, they are also prone to make poor decisions when it comes to building safety and aesthetics. Building codes were first developed by Hammurabi (about 1772 BCE), who established a performance-based code with severe penalties for violation. An interesting fact is that according to Deuteronomy, which is part of the Torah and the Old Testament of the Bible, all residences must have parapets on the flat roof to protect people from falling off (Deut. 22:8). These old principles were later evolved and transported to the new globe and became the framework for countries code.(Inc. 2020)

These codes are developed in response to the environment they are applied in. Building codes developed in response to the environment in which they are implemented. Their primary goal is to establish basic health, safety, and general well-being benchmarks (structural integrity, mechanical integrity, such as lighting, water, and ventilation; enough exits, fire-safety provisions, including prevention and control, and more recently energy conservation), climate change, natural disasters, and aesthetics.

Building codes and standards provide a common language and set of rules for the design, construction, and operation of structures. Historically, governments have used such codes and standards to establish agreed-upon practices within their territories. As a result of the rapid revolution and technical and industrial development, codes have been amended to take advantage of these advancements to better adapt design and construction methods. The principal philosophy of codes is to set minimal requirements to ensure building safety and serviceability; nevertheless, one additional crucial component, durability, has proven to be necessary to be considered.

International codes and standards are deemed to have achieved consensus in basic durability design ideas for small structures and options for more complex structures, from initial design to monitoring durability during construction to ensure requirements are satisfied. Nonetheless, within ACI standards, there is no unified approach to design and construction methodologies of durability for a particular service life in new or existing structure.(ACI Foundation agreement 7-18-18 2020).

The International Code Council (ICC) Codes are the most extensively used general building codes in the United States. Different general building codes, such as the International Building Code (IBC), International Existing Building Code (IEBC), International Fire Code (IFC), and International Mechanical Code (IMC), are developed for different areas of practice, addressing various aspects associated with distinct areas of practice and whether the structure is new or existing. However, these Codes primarily outline broad requirements, and they rely on associated technical standards bodies to supply precise material-specific design requirements for structural construction materials such as steel or concrete. The American Institute of Steel Construction (AISC), for example, specifies steel requirements, whereas the American Concrete Institute (ACI) specifies concrete requirements.

3.2 Concepts for Codes, Standards, Reports, and guidelines

Below table shows a comparison between codes, standards, reports, and guidelines.

Document	Definition	Features
Code	A building code is a set of regulations governing the design, construction, and modification of commercial buildings, houses, and other structures in a jurisdiction, created by city or county	Code language is mandatory and indicates industry standard practice and care, and it becomes legislation if adopted and enforced by a competent government or private institution. Design professionals, contractors, and

Table 5. Comparison between Codes, Standards, Reports, and guidelines
officials with the assistance of regulators are the primary users of codes (Code officials). construction professionals.

A technical standard is an established norm or requirement for technical is systems that usually produced through a consensus process by a standards group. It is a formal document targeted to a technical reader that defines standard engineering or technical criteria. methodologies, processes, and practices. When compared to a building code, a standard is more technical.

Standard

Guidelines

Technical standards are written in mandatory language with merely references to mandatory-language publications to limit the scope of interpretation. Testing methods. material specifications, instruction manuals. and practices are all established by standards. Standards are used to define quality and are frequently used to develop performance and safety criteria.

A technical guide outlines and recommends several parts of a such project, as analysis, design, assessment, and testing. **Report and** Technical guides are frequently written in nonmandatory language and include relevant examples or case studies.

A technical report is a document that contains technical information on a topic. certain То convey current knowledge about a topic, reports can incorporate research findings or a discussion of best-practice procedures. Reports are written in non-binding language and may include action recommendations, although they are rarely enforced.

3.3 International and national design documents

3.3.1 International Codes

International codes are those that are produced and adopted in more than one country or region around the world. The structure of these codes can be complicated and might require constructing further technical standards in other language and refer to them for more information on appropriate regional loads and load combinations, materials, production requirements, and conformity.

A model building Code for concrete is produced and maintained by an independent standards agency from the jurisdiction responsible for implementing the building code. A general building code or enforcement agency can adopt a model building code as their own and it becomes operational, allowing enforcement agencies to enforce a technically sound Code without incurring the costs and expertise associated with developing their own. ACI 318, ACI 562, EUROCODE, and the Code developed by the International Federation for Structural Concrete (fib) are examples of model Codes for concrete; however, fib's Code remains a model Code, whereas the formers have been approved in many counties.

ACI 318 & ACI 562

ACI 318 and ACI 562 are model codes that can operate individually or be incorporated into a general building code. They were created to give design professionals and building code inspectors clear, easy-to-understand requirements.

ACI 318 and ACI 562 are standards of care for the design and repair of concrete structures that are legally enforceable when adopted. The use of these documents has been expanded globally due to formal translations into languages other than English. The two documents have different approaches to durability. ACI 318 principally provides a prescriptive framework for addressing the consequences of defined "exposure classes," which are defined by the predicted degree of exposure. On the other side, ACI 562 provisions are performance-oriented, most of the durability requirements are without specific solutions due to the wide range of conditions faced with existing

structures. Referenced standards are either maintained (e.g., ASTM) or other local standards can be replaced when used outside of the United States.

Eurocode

The Eurocode is a collection of Codes (or umbrella Codes) established and adopted as distinct national Codes by members of the European Union (EU) and other non-EU countries.

This unified strategy aims to promote commerce and free markets both within and beyond the European Union, as well as common engineering and design principles. Nations customize these broad EU Codes by adding annexes that detail specific criteria for their region or country. The major target audience is practicing engineers, and its framework prioritizes usability. Prescriptive ("deemed-to-satisfy") and performance-based techniques are both acceptable. Environmental interventions are classified into classes and levels of intensity based on the likelihood of deterioration. Working life, or "design service life," is contained in Eurocodes, and durability requirements must be incorporated into structural design. To offer technical detail, EN or ISO standards are referred to.

FIB Model Code

The goal of the fib Code for Concrete Structures is to represent the state-of-the-art in theory and practice. It was created to not only supply countries with the current knowledge base for designing concrete structures, but also to share ideas for new design criteria and obtaining optimal structural and material behaviour. It's an international model Code that gets updated every ten years, with a greater emphasis on the "importance of design standards for durability and sustainability." This Code is not intended to be legally implemented by building code authorities or design professionals, but rather to give background material for operational Codes for regions and nations in the form of best practices and recommendations (i.e., not written in mandatory language with interpretation guidance).

3.3.2 International Standards

International standards are technical standards created by professionals from international organizations under the supervision of entities. Many technical standards are developed in the United States in compliance with the American National Standards Institute's requirements (ANSI). Other countries have similar standards bodies that manage their standardization processes, but they do not necessarily produce standards for internal use. They might instead adopt or alter other national standards for usage in their own country.

<u>ASTM</u>

ASTM International (previously the American Society for Testing and Materials) develops consensus technical standards, including testing and specification standards for cementitious materials. Codes refer to ASTM tests for multiple design provisions.

<u>CEN</u>

The European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC), and European Telecommunications Standards Institute all retain EN standards, which give consistent instructions for testing of materials and specifications.

<u>ISO</u>

The International Organization for Standardization (ISO) publishes a number of technical standards for testing and specifications, including specifications for cementitious material testing and standards, service life estimation, new concrete design, and concrete structure maintenance and repair.

British Standards

It provides standards for concrete constituents, fresh and hardened concrete qualities and their validation, concrete mixture constraints, concrete specification, fresh concrete supply, production control processes, and conformity criteria and evaluation of compliance.(BSI 2019b)

3.3.3 National Codes & Standards

<u>Japan</u>

The Japan Society of Civil Engineers (JSCE) created a set of standard specifications (English translation) to handle the material and construction (JSCE 16), design (JSCE 15), and maintenance (JSCE 17) of civil concrete structures. These guidelines do not consider designs made of plain concrete.

China

This standard was created to ensure that concrete structures are durable enough to last the stipulated design working life and that engineering structures have a suitable working life. This standard applies to the durability design of conventional concrete structures and their members in residential buildings, bridges, tunnels, and other infrastructures, as well as general constructions in a variety of natural settings.

It overlooks the degradation of structural performance caused by low-cyclic reversed load and sustained load, and thus is inapplicable to structures made of light aggregate concrete, fibre concrete, and other special concrete types, as well as the design of concrete structure durability throughout special aggressive conditions such as high heat and high humidity, and microbial corrosive environment. The durability provisions are the bare minimums that must be met for the structure to meet the design working life with the stated assurance rate. According to the project's individual qualities, local environmental circumstances, and practical experience, as well as specific construction requirements, the design may be enhanced properly. In addition to this norm, the design of concrete structure durability must meet the requirements of China's current relevant standards. (GB/T 50476 2019)

Australia (Standards Australia)

AS 3600 is an Australian standard that contains unified prescriptive requirements for the design of plain, reinforced, and prestressed concrete structures, as well as performance standards for the

structures. Standards Australia and ISO are also developing testing standards to support AS 3600. (AS 3600 2018)

Canada (CSA Group)

The CSA A23 series, published by the CSA Group (previously the Canadian Standards Association), specifies design and strength requirements for plain, reinforced, and prestressed concrete elements used in building structures and special structures, such as blast-resistant structures. The scope of the standard A23 includes requirements for materials and construction procedures (A23.1), standardized testing methods (A23.2), and design provisions (A23.3 and A23.4). CSA S413 addresses requirements specific to parking buildings. CSA S448.1 covers building and parking structure repair, while CSA S478 handles building durability from a structural (design) standpoint.

3.3.4 National or Regional Guidelines, Reports, and Specifications

ACI, AS, CIA, ISO, and other general companion papers

Additional, more detailed guidance documents are developed to provide information to the design engineer, producer, or user on a variety of topics, including concrete specification. These might stand alone or be linked to a certain Code or standard.

PIANC

A Maritime Navigation Commission working group's Advice for Increased Durability and Service Life of New Marine Concrete Infrastructure gives recommendations on best practices for owners and design professionals of marine concrete infrastructure. The scope of this publication includes advice on condition evaluation, preventative maintenance, and repairs of marine concrete structures.

The United Facilities Guide UFGS-03 31 29

The Naval Facilities Engineering Command (NAVFAC) of the United States Navy specifies criteria for reinforced concrete structures subjected to marine, chloride environments with a predetermined service life.

The United States Bureau of Reclamation

The US Bureau of Reclamation has established a guidebook that covers concrete fundamentals as well as improvements in concrete technology and construction to make construction administration and concrete operations easier.

CHAPTER 4: DURABILITY PROVISIONS DEVELOPMENT IN INTERNATIONAL CODES AND STANDARDS

4.1 Durability development in the ACI 318 Code

The American Concrete Institute created the ACI 318 building code to control the quality, safety, and durability of reinforced concrete structures. Since its original publication in 1910, the code has evolved tremendously. Changes to the code are made because of a better understanding of concrete behavior gained via ongoing research and experience. As a result, the design criteria and constraints on concrete strength and durability in the code are constantly evaluated and revised.

This Building Code in the USA specifies the criteria that the licensed design professional must conform to. Multiple city and state building codes in the United States as well as the International Building Code (IBC), and as many countries in Central and South America and some regions of the Middle East, have adopted this Code in whole or in part. The ACI 201.2R Guide to Durable Concrete serves as the basis for the durability criteria in the ACI 318 Code, which are generally restricted to the determination of exposure categories and the providing of minimum standards for each exposure class, it also permits the use of fly ash and natural pozzolans, Portland cements, blended hydraulic cements, crushed granulated slag, and silica fume.(ACI Committee 201 2016; ACI Committee 318 2019)

Although the 318 Code does not apply to pavements, water-retaining structures, or transportation structures, ACI has other Code publications, such as the ACI 350 Code for Environmental Structures and the new ACI 562 Code, which deals with structural repair and restoration. The specifier may then incorporate the requirements for concrete submittals, testing, inspection, acceptance, placing, protection, and curing from the ACI 301 Specifications for Structural Concrete into contract documents. (ACI Committee 562 2019; ACI Committee 350 2020)

It has recently been approved for the ACI 201 durability committee to create a code for durability in design that may be adopted by the 318-building code as well as other codes. Additionally,

Committee 201 has started work on a durability specification that might be used in construction implementation. (Douglas Hooton 2019)

Many research efforts that analyze modifications in the ACI318 code simply discuss changes from previous codes and do not address how the changes may affect the structural members' capacity or durability. Yehia et al. (2013) summarized the change of the code during the period (1999-2011). For the durability, the requirements for different exposure circumstances have evolved over time; the codes provided detailed requirements for various exposure scenarios. Furthermore, the criteria of newer codes are generally more conservative than those of previous codes. Although the 2011 code covers additional exposure circumstances than the 1999 code, there are no notable differences between the two versions. Adding to that, since 1989, durability requirements have been included in addition to desired compressive strength when proportioning concrete mixes. In 2008, an addendum was introduced that allowed the ASTM C1012 specification to be used to evaluate the sulphate resistance of concrete mixtures using different cementitious materials listed in table 4.3.1 of the code which defines the maximum expansion due to sulphate exposure (as measured by ASTM C1012), if different cementitious materials specified in the code are employed.

	Max. w/cm				Min. fc, psi			
Exposure	ACI	ACI	ACI	ACI	ACI	ACI	ACI	ACI
Class	318-71	318-83	318-99	318-11	318-71	318-83	318-99	318-11
F3	0.53	0.45	0.45	0.45	3000	4250	4500	4500
S3	0.44	0.45	0.45	0.45	4000	4250	4500	4500
P1	0.48	0.5	0.5	0.5	3750	3750	4000	4000
C2	NA	0.4	0.4	0.4	NA	4750	5000	5000

Table 6. Comparison of durability criteria for severe exposure circumstances since 1971. Yehia et al. (2013)

The scholars had also summarized the severe exposure standards in the 1999, 1983, and 1971 codes. The need for a minimum f'c under all exposure scenarios has been increased, indicating that the new standards are more conservative. See table 6

Following that, ACI 318-11 has gone into further changes seen in ACI 318-14, Ghosh (2016) highlights the significant changes between these two consecutive published codes as follows:

- 1. **Table 4.2.1** of ACI 318-11 Exposure Categories and Classes is changed to table 19.3.1.1 of ACI 318-14. This table has undergone a lot of revisions:
- The "Severity" column has been removed from the table.
- The exposure classes F1, F2, and F3 conditions have modified. "Limited exposure to water" has replaced "occasional exposure to moisture."
- "Frequent exposure to water" has substituted "continuous contact with moisture."
- Because permeability is no longer an exposure condition, Exposure Classes P0 and P1 (P for Permeability) have been renamed W0 and W1 (W for Water Contact).
- Table 4.3.1 of ACI 318-11 Concrete Requirements by Exposure Class is changed to table 19.3.2.1 of ACI 318-14 as follow:
 - For Exposure Classes F1 and F3, the maximum water-cementitious materials ratio and the minimum compressive strength criteria have changed.
 - Because ASTM C595 added standards for binary (IP and IS) and ternary (IT) blended cement since 2009, the cementitious material types that are authorized in concrete assigned to Exposure Classes S1, S2, and S3 have altered.
- 3. New commentary Section 19.3.3.2 specifies that the air content standards of ACI 318 apply to new concrete samples taken at the point of discharge from a mixer or a transportation unit when it arrives on site. If the licensed design expert specifies that fresh concrete air content be sampled and accepted at a different location, the construction documents must include the necessary provisions.

The technical work for "Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)" has been completed by ACI Committee 318, Structural Concrete Building Code, which includes responses to public comments on the finished text. This reflects the current committee members' successful completion of a 5-year cycle. The pervasive use of colour to highlight distinct areas of the document and improve the readability of figures is one of the most noticeable changes to the Code and Commentary.

Moehle (2019), the Chair of ACI 318 Building Code Committee summarizes the provisions modified as follows:

• Over multiple Code cycles, the IBC has introduced regulations for the use of shotcrete, although prior editions of ACI 318 have made no explicit reference of shotcrete. ACI Committee 318 has proposed and modified code sections to reflect current practice in collaboration with the American Shotcrete Association and ACI Committee 506, Shotcrete. The amended provisions can be found throughout the Code in multiple locations. In Commentary Section R4.2.1.1, there are cross-references.

Hanskat, Holland & Suprenant (2017) explained that shotcrete is cast-in-place concrete, and shotcrete is a construction placement method, both of which had to be applied in the context of the entire 318 Code in order for it to be included in the Code. Essentially, the subcommittees' main goal was to cast shotcrete in place, which necessitated that they consider and follow the following guidelines: integrate shotcrete provisions to be compatible with existing Code language; respect the objective of the IBC shotcrete provisions to reflect current ACI information; and use ASTM standards in the construction of the Code language.

- To account for the reduced mechanical properties of lightweight concrete, ACI 318-19 incorporated a new approach for determining the modification factor. This modification includes a method for determining based on the unit weight of lightweight concrete. This method makes it easier for a designer to specify a unit weight and calculate a value for throughout the design process. The method of determining splitting tensile strength by defining splitting tensile strength has been eliminated from the Code.
- The Code has been quiet on the alkali-aggregate reaction until now. ACI 318-19 includes new rules to prevent alkali-silica reactions (ASR). The strategy is to identify concrete that will be exposed to water during its service life. When this type of exposure is discovered, the Licensed Design Professional (LDP) is responsible for investigating and determining

the best course of action for aggregates that are vulnerable to ASR. The Code prohibits the use of aggregate that is prone to the alkali-carbonate reaction.

From the above stated changes of ACI 318 code, even though it adds and modifies durability provisions, durability design is not well understood or documented. The reliability of these provisions in designing structures that can resist harsh environments for a desired service life has been questioned by US practitioners. Compared to other codes, ACI code 318 approach to durability is prescriptive and limited to concrete materials and concrete cover based on exposure environment conditions.

4.2 Durability development in the British standards

The British Standard BS 8500 outlines concrete specifications and provides direction to designers. by providing requirements for concrete components, fresh and hardened concrete qualities and their verification, concrete composition constraints, concrete specification, fresh concrete delivery, production control processes, and compliance criteria and assessment of compatibility.

Annex A details the concrete quality that should be specified for various exposure classes, as well as the expected working life and minimum cover to normal reinforcement.BS EN 206 is supplemented by BS 8500-1. It includes UK national provisions when BS EN 206 requires or permits them. It also covers materials, testing methods, and procedures that aren't covered by BS EN 206 but are based on national experience. The newest alternatives and testing processes for constituent materials and concrete are included in BS 8500-2. It lays forth several fundamental standards for concrete and its constituent materials, as well as particular requirements for the concrete categories listed in BS 8500-1. (BSI 2019)

As the british standard institution clarified, (BSI 2019) the primary goal of the amendment is to broaden the scope of cementitious materials covered. Natural pozzolana, natural calcined pozzolana, or high reactivity natural calcined pozzolana as an addition, Portland pozzolana and pozzolanic cements, and a range of ternary cements with up to 20% limestone fines are now available. In addition, the choice to employ durability modeling or an equal durability process has

been explained, and small editorial adjustments, such as the change of stress terminology from N/mm2 to MPa, have been made. Part 2 has been updated with the same changes as Part 1. In addition, the equivalent concrete performance concept (ECPC) for demonstrating equivalence for the use of additions is explained, and further information on cube specimen preparation and transportation for strength testing is supplied.

It's worth noting that the 2018 amendments follow a thorough review of both standards in 2015 to align them with BS EN 206:2013. The revised standards are now officially referred to as: BS 8500-1:2015+A2:2019 Concrete, Complementary British Standard to BS EN 206, Method of Specifying and Guidance for the Specifier and BS 8500-2:2015+A2:2019 Concrete, Complementary British Standard to BS EN 206, Method of Specifying and Guidance for the Specifier and BS 8500-2:2015+A2:2019 Concrete, Complementary British Standard to BS EN 206, Method of Specifying and Guidance for the Specifier and BS 8500-2:2015+A2:2019 Concrete, Complementary British Standard to BS EN 206, Method of Specifying and Guidance for the Specifier and BS 8500-2:2015+A2:2019 Concrete, Complementary British Standard to BS EN 206 for concrete. Concrete and component materials specifications.

Kessy, Alexander & Beushausen (2015) stated that the specifier has five options for specifying concrete mixes in BS 8500-1: designated, designed, prescribed, standardized prescribed, and proprietary concrete mixes. Surprisingly, the first two and last categories are referred as performance approaches, but closer inspection reveals that they are prescriptive with maximum w/c, minimum cement content, and strength class requirements. They also discussed that BS 8500-1 allows for multiple binder types to be used depending on the exposure class. The maximum w/c and minimum cement content have been adjusted to suit the planned service life of 50 and 100 years, respectively, although EN 206-1 only assumes a 50-year service life. Tables A.4 and A.5 of BS 8500-1 contain cover depth criteria for several degradation methods, which are not included in EN 206-1. Nonetheless, the defined metrics (other than cover) cannot be quantified and so cannot be considered performance-based in the strictest sense.

Wang et al. (2019) compared the British and Chinese standards due to the similar environmental exposure along the long coastline between China and Britain, however, there are differences in exposure levels between Chinese and English standards for the same environmental categories. The Chinese standard classifies chloride-induced corrosion in seawater more precisely than the British standard, while the British standard classifies the environmental impacts of carbonation

corrosion and freeze-thaw erosion more precisely. The other environmental effects, on the other hand, are essentially the same. Although the concrete's exposure environment in China and the United Kingdom is similar, the durability of concrete structures is determined by the raw materials used and the mix design. The raw minerals in China and the United Kingdom differ due to geographical constraints. As a result, it is not only vital to recognize the parallels between the two standards in practical engineering, but also to accurately treat their variances as China's experience can't be applied for the UK.

We can conclude from the above findings that British standards are complementary to European standards. Furthermore, despite the fact that China and the United Kingdom share similar exposure of long coastline, exposure levels and environmental effects are not the same, and due to the differences in existing chemicals and available raw materials, one code cannot be applied to both territories.

4.3 Durability development in the Euro code

The EN Eurocodes are aimed to enable develop and operate the internal market for building products and engineering services by resolving discrepancies that restrict their free movement within the Community. They are intended to lead to more consistent levels of construction safety across Europe. After the publication of the National Standard transposing the Eurocodes and the National Annexes all conflicting standards must be eliminated. They are now in the maintenance and evolution stages, to keep up with the range of new technologies, materials, regulatory requirements, and societal needs that are emerging, as well as to expand harmonisation. There are five major concepts governed by EN Eurocode: Fundamental requirements (safety, serviceability, fire, and robustness), Reliability differentiation, Design working life, Durability and Quality assurance.(Europen Comission 2016)

EN 206-1 has seen very few changes since its initial publication in 2000, with most updates consisting of language corrections, clarifications, and updated references to new European standards. This was a deliberate policy of CEN/TC104/SC1: Concrete - Specification, performance, production, and compliance (the European standards body in charge of EN 206) since

they intended to gain some experience before making any significant adjustments. As a result, at the 2005 five-year review, it was determined that experience with EN 206-1 was still relatively limited, and it was extended for another five years. It was decided at the second five-year review in 2010 that a modification was now necessary, but that the changes should be kept to a minimum. A new Part of EN 206 (Part 9) on self-compacting concrete was released in 2010, however CEN/TC104/SC1 had decided that when EN 206-1 was amended, Part 9 and Part 1 would be integrated into a new EN 206. In addition, the test methods for self-compacting concrete that are used in practice would be examined to see if the range of tests defined at the European level needs to be expanded, and if more performance classes need to be added to EN 206 in the future. This review was deemed premature for the 2013 version of EN 206, and it is a work that should be completed before the next five-year review of EN 206. (ERMCO 2014)

Structure durability in the Europe code is defined as the one that meets serviceability, strength, and stability requirements throughout its life cycle without considerable loss of utility or excessive unanticipated maintenance. (Kansara 2012) compared this definition with the Indian code and concluded that they both have the same definition, however the Euro Code states that the required structure protection must be determined by considering the structure's intended use, design working life, maintenance program, and actions, as well as the potential significance of direct and indirect actions, environmental conditions, and consequential effects (e.g., deformations due to creep and shrinkage). Steel reinforcement corrosion protection is thought to be dependent on the density, quality, and thickness of the concrete cover, as well as cracking. The maximum w/c ratio and minimum cement content are controlled, and the cover density and quality may be tied to a minimum concrete strength class.

Today, the durability of new reinforced concrete structures in Europe is designed using a prescriptive approach (deem-to-satisfy). In EN 206, environmental impacts (called 'environmental actions' in the standard) are classified into exposure classes, and the structure's resistance to these impacts is defined by a set of requirements, such as concrete strength class, w/c ratio, cement content, cover depth, and crack width required to achieve the required service life without major repairs (for bridges, usually 100 years). Bertolini et al.(2013) stated that most forms of

deterioration, including corrosion, that are linked to faulty design, material composition, or construction technique can be eliminated if these limiting values are correctly used in construction.

It's important to note that European standards are complemented by national application documents, resulting in differences in requirements between nations despite similar environmental implications. According to Helland, Norge & Norway (2016), the accepted probability of failure, which, for example, for carbonation-induced de-passivation, results in different design service lives for a given structure or different cover thickness requirements for a given design service life, is a major explanation for the differences between national requirements in Europe.

A new durability design idea, analogous to the concept of strength classes, has been proposed to overcome the discrepancies of the present European prescriptive method by Von Greve-Dierfeld & Gehlen (2016c, 2016b, 2016a), they introduced and built on a system of exposure materials resistance classes for durability design. A probabilistic form of the limit state equation for concrete carbonation, which compares the concrete cover with the carbonation depth at the end of the design service life, was their starting point. Design charts showing values for the minimal concrete cover as a function of material resistance and exposure class are produced using a partial safety factor format.

In the next version of EN 1992–1, the idea of Exposure Resistance Classes (ERCs) is being introduced. Performance verification in the future is expected to be based on either deemed-to-satisfy criteria, as it is today, or performance testing and the ERC idea.

Geiker, Hendriks & <u>Elsener</u> (2021) stated that they believe that the proposed ERC approach will promote transparency in concrete performance classification and facilitate the unification of concrete standards across Europe. Furthermore, the performance-based approach will make it easier to introduce new materials. However, using the ERC idea demands the availability of accurate performance test techniques and standards, understanding of the impact of specific design parameters on long-term performance, or the use of conservative assumptions in the design. To some extent, this may hinder the use of creative solutions. The predicted limit state and the applied limit state function, which may be neither correct nor favourable to long-term solutions, is a second concern.

4.4 Durability development in the ISO standards

The International Organization for Standardization (ISO) is a global federation of national standard-setting organizations (ISO member bodies). ISO technical committees are often responsible for producing International Standards. Each member body with an interest in a topic for which a technical committee has been formed has the right to have a representative on that committee. International organizations, both governmental and non-governmental, collaborate with ISO on the project. On all aspects of electrotechnical standardization, ISO works closely with the International Electrotechnical Commission (IEC). Technical committees' primary responsibility is to prepare International Standards and they adopt draft International Standards, which are then sent to member bodies for vote. The approval of at least 75 percent of the voting member organizations is required for publication as an International Standard.

Durability design of structures is considered in ISO standards, the limit-state approach was adopted by ISO 2394, which is used to prepare and harmonize national and regional structural design standards and codes all around the world. Even though ISO 2394 includes durability in its standards, the limit-states method has not been developed to the same level for failures caused by material deterioration as it has for failures caused by gravity, wind, snow, and earthquake. Furthermore, numerous premature collapses have happened because of structural engineers' lack of understanding of material deterioration. Hence, it was required to improve the evaluation and design of structures for long-term durability by incorporating building science principles into structural engineering practice resulting in another standard ISO 13823: 2008 - General principles on the design of structures for durability. The other goal of this International Standard ISO 13823: 2008 is to establish a framework for the development of mathematical models that can forecast the service life of structural components. For concrete slabs subjected to chloride diffusion from deicing salts, such models are currently being developed. Other ISO/TCs are working on these models because they are material dependent. In other words, the purpose of this International Standard is to ensure that all analytical models are included in the limit-states approach, which is currently used to verify and design structures for gravity, wind, snow, and seismic activities.

While this International Standard does not address design procedures for durability, it establishes a solid foundation by identifying a process that begins with the structure's environment, then moves through mechanisms that translate the environment into environmental actions on constituents, resulting in action effects like damage. When creating methodologies for predicting service life, this cause-and-effect mechanism must be considered. Moreover, this standard does not directly address structural sustainability, except in passing references in 8.4 and Clause 10. Most sustainability factors, such as material selection and its impact on waste and energy usage, are outside the scope of this International Standard. (ISO 13823 2012)

Alexander & Beushausen (2019a) Stated that the International Organization for Standardization (ISO) has developed a limit-state technique that is linked to several service life design methodologies. Quantitative models for "loading" (i.e., environmental acts) and "resistance" are used in the methodology (i.e., resistance of the concrete against the considered environmental actions). Full probabilistic method; semi-probabilistic approach (partial factor design); deemed-to-satisfy criteria; and avoidance of deterioration are the design alternatives, which are also represented in the fib Model Code for Service Life Design.

Lacasse, Ge & Laouadi (2018) stated in their guideline on design for durability of building envelopes that the suggested foundation for evaluating a structure's durability is the application of the limit-states method throughout design and verification. Understanding the structural environment, transfer mechanisms, environmental actions leading to action consequences, and degradation that may lead to failure or loss in serviceability of the material, component, or assembly is necessary for each building element. See figure 16. Thereafter, depending on the type of envelope assembly for which the design of durability is to be prepared the appropriate set of environmental actions and corresponding action effects are then defined for a particular wall system based on the anticipated modes of failure and where the cladding, connectors, or the structure is vulnerable to degradation arising from internal and external environmental action.

Another Standard to be mentioned here is ISO 16204:2012 Service life design of concrete structures. This International Standard describes general principles and techniques for verifying the durability of buildings subject to known or predicted environmental actions, such as mechanical

actions, that cause material degradation and performance failure. It is required to assure performance reliability over the structure's design service life. Although fatigue failure due to cyclic load is not covered by this International Standard, failure due to fatigue can be found in ISO 2394. In this standard, decisions are made, and design activities are carried out in a rational service life design process with a selected level of reliability. Three levels of sophistication are identified in the first of two methodologies that have been used. There are a total of four choices. See table 7 below. (ISO/TS 80004-2:2015 2015).

Table 7: The flow of decisions for service life design as stated by ISO 16204

Strategy 1:	Design to resist deterioration			
	Level 1	Full probabilistic method (option 1)		
	Level 2	Partial factor method (option 2)		
	Level 3	Deemed-to-satisfy method (option 3)		
Strategy 2:	Preventing degradation techniques (option 4)			

Following that, as addressed in Clause 6 degradation mechanisms are

- corrosion due to carbonation.
- corrosion due to chloride.
- Freeze/thaw attack without the use of salt water or de-icing chemicals.
- Attack from a freeze/thaw cycle using de-icing chemicals or seawater.

There are well-known mathematical models for these mechanisms, however, the additional processes of degradation: chemical assault; and reactions with alkali aggregates, are not discussed in depth primarily due of the lack of current widely recognized mathematical models, therefore, these incomplete models must be created and adhere to the general principles of Clause 5 for this International Standard to be complete.

CHAPTER 5: DURABILITY PROVISIONS IN INTERNATIONAL CODES

5.1 Durability provisions in the ACI 318 code

Chapter 19 of ACI code 318-19 contains four sections that outline the durability requirements for concrete structures. The chapter covers exposure conditions, durability requirements, properties to be employed in concrete design, and grout durability requirements for bonded tendons.

After specifying the scope, the code identifies the concrete design properties for normal-weight and light-weight concrete. The first characteristic is the compressive strength $f_{\acute{e}}$. The code states that this value must be specified according to durability requirements in table 19.3.2.1, structural strength requirement, applies for normal weight and lightweight concrete, and should be with a maximum specified value for some cases mentioned in the code.

The following section: 19.3 addresses the concrete durability requirements. Based on 19.3.1.1, the code states that members of the structure are designated the proper exposure category and class by the certified design professional. The suitable concrete parameters from table 19.3.2.1 to include in the construction documents are determined using the allocated exposure classes, which are dependent on the severity of exposure. There are no provisions in the code for very dangerous exposures, as those to acids or high temperatures.

5.1.1 Exposure conditions

The code classifies exposure conditions to four categories at which each category has classes depending on the severity of each category; these categories are freezing and thawing (F), Sulphate attack (S), in contact with water(W), and corrosion protection of reinforcement (C). Examples of these exposures are given for freezing and thawing and some guidance is given in the commentary to assist with assigning the proper exposure. A combination of exposures might also be adopted depending on the structure, in such cases, the designer should adapt the most restrictive requirement to obtain a conservative durable design.

5.1.1.1 Freezing and thawing exposure conditions (F)

The code defines four main exposure classes based on severity: F0, F1, F2, and F3. F0 refers to no exposure to F&T cycles. The expected saturation status of the concrete and probable de-icing agent exposure distinguishes the exposure classes F1, F2, and F3 from lowest to highest. F1 is assigned to structures exposed to F&T with limited contact to water, this limited exposure might indicate no saturation or saturation in some areas that is closely oriented to exposure class F2. In such cases, the code recommends the adoption of the more conservative class.

F2 and F3 to structures exposed to F&T cycles with frequent contact to water, with F3 attributed to structures exposed to de-icing agents. These agents improve water absorption and retention, resulting in increased saturation and a more severe exposure class.

Besides de-icing agents, the degree of anticipation to water and its frequency impacts saturation, the more contact to water without adequate drainage or drying will rise saturation, in addition to the location and orientation of the members or structure and the climate. For better guidance, the code provided table R19.3.1 that presents examples for each exposure class.

5.1.1.2 Sulphate attack exposure conditions (S)

ACI 318-19 states for concrete in contact with soil or water that contains harmful concentrations of water-soluble sulphate ions falls under exposure category S. This category is further subdivided into four classes, when concrete is in contact with low concentrations of water-soluble sulphate and harmful sulphate attack is not a concern, exposure class S0 is assigned. For structural concrete members directly in contact with soluble sulphates in soil or water, exposure classes S1, S2, and S3 are assigned. Based on the more significant value of the determined water-soluble sulphate concentration in soil or the concentration of dissolved sulphate in water, the severity of exposure increases from Exposure Class S1 to S3. The code also specifies for structures exposed to seawater, S1 class can be considered.

5.1.1.3 Water exposure conditions (W)

In terms of structures with contact to water, the code defined three classes: If a member is dry while in service, exposure class W0 is assigned to them. members are placed in exposure class W1 if they have the potential to come into constant contact with water, encounter occasional sources of water, or can absorb water from the soil around them. Members assigned to W1 are excluded from the need for low permeability concrete. Members are placed in Exposure Class W2 if they have the potential to come into constant contact with water, encounter infrequent sources of water, or can soak up water from the soil around them. They are also placed in this class if water penetration through the concrete could affect its durability or suitability. The W2 members need concrete that has a low level of permeability.

5.1.1.4 Corrosion Protection of reinforcement exposure condition (C)

Corrosion exposure classifications under ACI 318 include C0 (concrete that is dry or shielded from moisture), C1 (concrete that is exposed to moisture but not to an external source of chlorides), and C2 (concrete exposed to moisture and an external source of chlorides). Seawater, brackish water, de-icing salts, or spray from any of these sources are sources of chlorides. Concrete in the tidal or splash zones, where both water and oxygen are prevalent, is far more susceptible to corrosion than concrete that is entirely submerged in seawater because corrosion rates are much higher in the presence of oxygen.

5.1.2 Requirements for concrete mixture for durability

Table 19.3.2.1 in the code serves as a guide for the concrete mixture specifications based on exposure conditions. The most restrictive criteria must be adapted if there are several exposure conditions. The table requires for each exposure class a maximum value of W/C ratio, minimum value of compressive strength, additional different requirement necessary for these exposures such as air entrained, types and limits on cementitious materials.

The philosophy behind establishing this table is that the key component that affects concrete durability is determined by its resistance to fluid penetration, which is mostly based on the water-

to-cement ratio and the components of cementitious materials used in concrete. The use of cementitious elements, such as fly ash, silica fume, slag cement, or a combination of them, will limit fluid penetration and hence

increase concrete durability for a particular amount of w/c ratio. Thereby, the code restricted the maximum allowed W/C value and permitted the use of ASTM C1202 test (Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration) to determine the concrete's fluid resistance. We can see here the code prescriptive provisions for the values required which will limit the employment of new proven technology to achieve concrete durability.

The code suggests strength testing as an alternative because it can be difficult to determine the exact value of the water cement ratio on the job site using traditional test procedures. The values of \mathbf{f}_{ϵ} provided in table 19.3.2.1 shouldn't be taken as absolute; the design engineer may choose a larger \mathbf{f}_{ϵ} value than those listed there for better consistency in terms of strength and water-to-cement ratio. This is a result of the various concrete mixtures and materials utilized, as well as regional variances. According to the code, a licensed design expert may specify a greater compressive strength value if it complies with the maximum w/c ratio. From this point, we can see here once more that strength is not related to durability and that the code allows specifying other values of strength from the given in the table, this means that the code is not being restrictive regarding this, and that specific amount of strength doesn't guarantee to achieve durable concrete mix. This should be amended in the code.

In general, specifications are given in the code for concrete's minimum compressive strength, maximum w/c, and air volume to withstand FT damage.

5.1.2.1 Requirement for the concrete mixture for freezing and thawing exposure condition

For structures susceptible to freezing and thawing, the code requires a maximum value for W/C ratio that shouldn't be exceeded, a minimum value for compressive strength, air entrained amounts must be as per table 19.3.3.1 and 19.3.3.3 and limits on cementitious materials for exposure F3 is given as per 26.4.2.2(b). No values are assigned for F0 class but for F3 attention is required whether

the concrete is plain or reinforced as the minimal reinforcement required for plain concrete will reduce reinforcement corrosion problems, thus less restrictive values will be required.

The code relates to ASTM C172 for sampling and ASTM C231 or ASTM C173 for air content measuring for the verification of achieving the required values of the limited parameters, however, for other sampling locations or air content measurements, the code allows the design professional to mention that in the project documents including methods for testing and acceptance criteria and sampling guidance.

5.1.2.2 Requirement for concrete mixture for Sulphate attack exposure condition

For structures vulnerable to chemical sulphate attack, the code listed in table 19.3.2.1 the maximum allowed w/c ratio based on the cementitious and SCM content, the minimum compressive strength, cement type and cementitious material and the allowed usage of calcium chloride admixtures. The code clarifies that the principal for choosing cement type is the tricalcium aluminate C_3A content. The code specifies the following for sulphate attack requirement for each exposure class, these requirements are fragmented in chapter 19.3.2 and 26.4.2:

For exposure class S1:

Alternative combination of cement Type II Portland cement with maximum amount of 8% of C3A (ASTM C150), Blended cement with MS designation that depicts moderate sulphate resistance (ASTM C595), moderate sulphate resistance cement (ASTM C1157), or alternative cementitious materials combination to comply with ASTM C1012, and expansion <.1 for 6 months. Maximum w/cm of 0.50 and minimum fć 4000psi.

For exposure class S2

Alternative combination of cement Type V Portland cement with maximum amount of 5% of C3A (ASTM C150), Blended binary and ternary cement with HS designation that depicts high sulphate resistance (ASTM C595), severe sulphate resistance cement HS (ASTM C1157), or other alternative cementitious materials combination to comply with ASTM

C1012, and expansion < .05 at 12 months or <.1 for 6 months. Maximum w/cm of 0.45 and minimum fć 4500psi.

Exposure Class S3 (Option 1)

Alternative combination of cement Type V Portland cement in addition to pozzolan or slag cement (ASTM C150), Blended binary and ternary cement with HS designation that depicts high sulphate resistance plus pozzolan or slag cement (ASTM C595), severe sulphate resistance cement HS plus pozzolan or slag cement (ASTM C1157), or other alternative cementitious materials combination to comply with ASTM C1012, and expansion < .1 at 18 months. Maximum w/cm of 0.45 and minimum fć 4500psi. Pozzolan or slag cement's advantages enable for a higher w/cm than is necessary for Option 2. According to 26.4.2.2(c), the quantities of extra cementitious materials are based on records of successful service or testing.

Exposure Class S3 (Option 2)

- Alternative combination of cement Type V Portland cement with maximum amount of .04% of expansion if considered solely (ASTM C150), Blended binary and ternary cement with HS designation that depicts high sulphate resistance (ASTM C595), severe sulphate resistance cement HS (ASTM C1157), or other alternative cementitious materials combination to comply with ASTM C1012, and expansion < .05 at 6 months or <.1 for 12 months. Maximum w/cm of 0.4 and minimum fć 5000psi. This lower w/cm promotes sulfate resistance by decreasing the concrete's permeability. Utilizing this lower w/cm enables a shorter testing duration to qualify a cementitious system's sulfate resistance in line with 26.4.2.2. (c).
- The code proposes that mixtures including SCMs and meet the ASTM C1012 expansion criteria for Exposure Class S2 can be used for exposure class S3 with a w/cm of 0.40.

In addition to the above clauses, the code clarified that cement types resistant to sulphates are not resistant to other chemically hostile solutions. Moreover, along with the water/cement ratio and

cement type, other elements such as compaction, moist curing, homogeneity, and concrete cover must be recognized to yield the potential features of sulphate-resistant concrete.

5.1.2.3 Requirement for Water Exposure (W)

For structures exposed to water, the code stipulate requirements for each class. For structures in dry environment W0, no restriction on the concrete mix other than minimum value of $\mathbf{f}_{\mathbf{c}}$.

For class W1 for structures exposed to water where low permeability is not significant, the code requires a minimum value for fć, and additional requirement that comply with 26.4.2.2d; that is evidence demonstrating that the concrete mixture conforms with clauses (1) and (2) must be provided. (1) Aggregates are not alkali-silica reactive, or proven mitigation techniques have been used. (2) Aggregates do not react with alkali carbonates. Lastly, for exposure class w2, at which low permeability is essential, a maximum W/C ratio of .5 and minimum \mathbf{f}_{ϵ} together with compliance of provision 26.4.2.2d as W1 class and optimization of SCMs.

The code didn't mention any limits for the usage of supplementary cementitious materials, basically it focused on limiting the water cement ration and compressive strength. Repeatedly, the code is relating $\mathbf{f}_{\mathbf{f}}$ to durability while it is not. To control the water permeability of concrete, using low water cement ratio is one good approach as it will reduce the water in the capillary cavities that cause water permeability as it is influenced by the microstructure of the cement paste and size and quantity of pores. Other technique to limit permeability is the employment of SCM, we can consider here that the code has given no prescriptive specification for that, hence the design engineer and construction team can utilize their proven approaches to limit water permeability.

Another factor that affects structures durability when exposed to water is the aggregate, its type, size, source and constitutes. Even though the size of aggregate, its permeability, grading, and its source affects permeability the code focused on the reactive aggregate. The code allowed the usage of alkali silica reactive particles if mitigation approaches are provided and forbid the use of silica carbonate reacting aggregate. This is to the alkali silica reaction that the ACI 318-19 code is still limited about it, as with the presence of moisture and alkali there is a big chance for ASR to take

place, because it is challenging to forbid water or moisture source such as marine structures, the reduction of alkali presence is more feasible.

Alkali aggregate reaction (AAR) is not defined as a category of exposure, except for the requirement of moisture for it to occur. Alkali-silica reaction (ASR) is the most common kind of AAR; however, a few dolomitic limestones can degrade when used as coarse aggregate due to the alkali-carbonate reaction (ACR). Concrete aggregates with ACR potential must be avoided as stated by the code because standard mitigation strategies like limiting alkali loading or using SCMs are ineffective.

Water exposure can deteriorate concrete structures, it might fill the capillary cavities and expand the concrete, efflorescence, initiate ASR, cause steel corrosion, sulphate attack if they are dissolved in water, freezing, and thawing in cold climate areas and others, thereby when structures are exposed to water, investigations to the dissolved content must be done together with precautions of the effect of water.

5.1.2.4 Requirement for Corrosion Protection of concrete (C)

The code technique to protect the steel from the chloride diffusion that results in corrosion for both non prestressed and prestressed concrete evolves around three main requirements: max allowed w/c ratio, minimum specified compressive strength, and adequate concrete cover according to section 20.5. Moreover, the code specified the maximum allowed chloride limit from internal sources of chloride, the chloride contribution in the concrete material. These chloride limits are based on the mass of total cementitious materials instead of Portland cement alone as SCM proved to be efficient to reduce permeability and limit chloride ingress. Reinforcement coating, corrosion resistance steel reinforcement, adapting concrete cover higher than the stated in 20.4, utilizing SCM such as silica fume are other protection techniques of steel corrosion exposed to chlorides for exposure class C2.

The code restricted the allowable limits of chloride for all exposure classes, this is explained by the tendency of chloride ions presence in the materials used to make concrete regardless of external source. The reason behind giving allowable amount is to have a reasonable chloride content, not

too high to cause early corrosion or too low produced by high-cost processes. For prestressed concrete one value is assigned (.06) whereas for non-prestressed concrete it ranges from (.015 to 1) depending on the exposure class. This is due to the hazardous effect caused by corrosion of prestress reinforcement, the reduction in the cross-sectional area of prestress reinforced steel may cause fracture of the effected steel. Not only that, but also the chloride induced might corrode the aluminum especially if it is in connection with the steel.

Another additional limit for chloride content is mentioned in other section in the same chapter; 19.3.4, the chloride ion content with the usage of stay-in-place galvanized steel for moderate exposure should be treated as exposure class C1 (.3 %) whereas for more sever environment, chloride limit should comply with C2 exposure class that has a more conservative limit (.15 %).

Limiting the chloride concentration in the materials making up the concrete will reduce early steel corrosion, whereas the low water cement ratio and concrete cover will be the barrier for the chloride to reach the steel. A low w/c ratio will reduce the permeability and an adequate high quality concrete cover will tremendously slow down the chloride from reaching the steel and initiate corrosion. The code refers the requirement for the concrete cover into 20.5.

5.1.3 concrete cover requirement

Concrete cover is outlined in the ACI 318 code in chapter 20 that governs the steel material properties, properties to be used for the design, and concrete cover requirements. Section 20.5 deals with the requirement of concrete cover over reinforcement. The values provided by the code from 20.5.1.2 to 20.5.1.5 should be adopted unless the general building code requires higher values for protection of fire. The code divided concrete cover in accordance to casting and reinforcement methods; cast in place for prestresses and non-prestressed concrete, precast for stressed and non-prestressed concrete, and lastly for deep foundations.

Additional requirements for the concrete cover in corrosive environment are also mentioned in the code, according to exposure conditions, concrete cover can be increased as the values stated in the code. Below are further requirements for steel corrosion protection:

- For non-prestressed coated reinforcement: In applications where corrosion resistance of reinforcement is of particular concern, such as in parking structures, bridge structures, and other highly corrosive environments, zinc-coated (hot-dipped galvanized) bars (ASTM A767), epoxy-coated bars (ASTM A775 and A934), and zinc and epoxy dual-coated bars (ASTM A1055) can be used for non-prestressed deformed bars with the compliance of 20.2.1.3 and 20.2.1.7.
- For unbonded steel reinforcement: Sheathing must cover unbonded prestressing reinforcement, and a corrosion-inhibiting substance must entirely occupy the area between the prestressing and the sheeting. Watertight and continuous sheathing must cover the unbonded length.
- 3. For grouted tendons: If exposed to freezing conditions, water in ducts may result in grout bleeding and segregation, corrosion of the prestressing reinforcement, and damage to the nearby concrete. If prestressing reinforcement is exposed in the ducts for a long time before grouting, a corrosion inhibitor should be added to offer temporary corrosion protection.
- 4. For external post tension: the code didn't specify specific requirement, however, it stated that various techniques can be used to prevent corrosion. The corrosion protection offered must be appropriate for the surroundings where the tendons are positioned. Other conditions allow for the protection provided by coatings like paint or protection requirements of the general building code unless the installation of external post-tensioning is only to improve serviceability. Some conditions request for the prestressing reinforcement to be protected by concrete cover or by cement grout in polyethylene or metal tubing.

5.2 Durability Design Provisions in the British Code BS 8500-1

The guidelines in the British Standard for Concrete Durability are presented in a format that has been partially standardized at the European level by EN 206 but has been expanded to cover situations where corrosion of reinforcement is considered. The recommendations were created using a combination of UK expertise and some durability modeling. This first part of BS 8500-1 outlines concrete specification techniques and offers guidelines for the specifier. After specifying its scope, BS 8500-1 lists the normative references followed by definitions and then specifying methods. Based on these specifying methods, the next section of the code identifies the information that should be exchanged between the specifier and concrete producer. Lastly, three annexes are provided in the code.

Annex A that has informative (non-mandatory) nature offers recommendations on the considerations that should be made before choosing the technique of describing and defining requirements. It stated recommendations for the concrete quality that should be specified for a particular exposure classes, desired working life, and minimum cover to normal reinforcement. Stainless steel and non-metallic reinforcing are not addressed. Other sources, such as structural design codes of practice, provide guidance on nominal cover to reinforcement for structural and fire consideration.

Annex B, that has normative nature, identifies tests for air content, density, slump, flow, slumpflow, and additional requirements for compressive strength. Lastly, Annex C that has same nature as annex A and B; informative nature, includes expected cement or combination content with nominal proportions.

It is interesting that the code involves the design engineer (structural, architectural), producer, and user that are referred to as "body" to produce the concrete specification that is defined in the code as "final compilation of documented technical requirements given to the producer in terms of performance or composition". This will enhance the opportunity to provide economical and durable structures by employing UpToDate strategies and methods not stated in the code, this performance approach can be implemented after the approval of the required project parties.

The BS 8500-1 approach for durability design states that design for durability should begin with the concept design stage and progress through the design, detailing, specification, and execution phases, and it can only be realized in practice if maintenance is performed as planned. The BS addresses a portion of this process, namely the determination of exposure conditions, cover to reinforcement and concrete quality for structures to be built in the United Kingdom or similar environments. This approach to providing durability is adequate for most structures as long as the structure has a minimum cover to reinforcement and the concrete is properly specified, supplied, compacted, and cured.

5.2.1 Exposure Conditions

The exposure classes of British standards are divided into six categories and listed in table A.1, which are "No risk of corrosion or attack", "carbonation corrosion", "freeze-thaw", "corrosion caused by chloride in seawater", "corrosion caused by chloride except seawater and chemical erosion".

For each exposure class, the code gives designation for each one with a description and examples for these exposures applied in the United Kingdom. This is very beneficial for the code user as it eases the selection of the environment at which the structure will be erected in and the accompanied allowed limits for other factors. Furthermore, the code accounts for a combined exposure conditions and excludes the combination of corrosion induced by chloride and carbonation. The code justifies this by the adequate concrete cover and quality that can withstand such condition. Overall, the code is comprehensive with these categories as it included most of the environmental circumstances that affect the buildings durability.

5.2.1.1 No risk of corrosion or attack (X0 class)

Applies for all plain concrete except where freeze and thaw, abrasion or chemical attack exist.

5.2.1.2 Corrosion induced by carbonation (XC class)

Applies when concrete exposed to air and moisture and contains reinforcement or other embedded metal non prestressed or prestressed. This Exposure category is subdivided to XC1 for dry or permanently submerged in water exposure, XC2 for wet exposure, XC3and XC3/XC4 combines XC3 moderate humidity and XC4 cyclic wet and dry because it is deemed difficult to differentiate between them for design.

5.2.1.3 Corrosion induced by chlorides other than from sea water (XD classes)

Applies when water containing chlorides, including de-icing salts, from sources other than seawater comes into contact with concrete that contains reinforcement or other embedded metal. This is subdivided into XD1 Moderate humidity, XD2 Wet, rarely dry Reinforced and prestressed concrete surfaces totally immersed in water containing chlorides and XD3 Cyclic wet and dry.

5.2.1.4 Corrosion induced by chlorides from sea water (XS classes)

Applies where sea water or salt from the sea is in touch with concrete that contains reinforcement or other embedded metal. These are subdivided to XS1 for external reinforced concrete and prestressed concrete surfaces in coastal areas exposed to salt airborne but not actual contact with sea water. XS2 for permanently submerged structures, XS3 for tidal, splash and spray zones.

5.2.1.5 Freezing and thawing exposure condition (XF)

Applies where moist concrete is significantly attacked by freeze-thaw cycles, they are subdivided to XF1 for moderate water saturation without de-icing agent, XF2 for moderate water saturation with de-icing agent, XF3 for high water saturation without de-icing agent and XF4 for high water saturation with de-icing agent or seawater.

The standard states that strength is not as important as entrained air for determining the durability against freeze/thaw conditions, while it does diminish 28-day strength by about 5% for every 1% of it. Concrete should have a minimum of 4% entrained air to resist freezing and thawing. Therefore, where the strength class is C28/35 or higher, it is often not possible to use more cement to reduce the w/c ratio to make up for the estimated 20 percent or more strength reduction in air entrained concrete. This is acknowledged in the BS 8500-1 Tables A.4 and A.5, where the maximum strength class may be reduced to C28/35 for air-entrained concrete exposed to freezing and thawing and ingress of chlorides.

5.2.1.6 Concrete exposed to chemical attack (XA)

Applies where concrete is exposed to soil or natural water, for sulphate attack specifically, it includes XA1 for slightly aggressive chemical environment, XA2, XA3 for moderate and highly

aggressive respectively. The code states that these exposure conditions are not used in the UK, however, they shall be used to determine the class for ACEC: Aggressive chemical environment for concrete exposure classes.

5.2.1.7 Concrete exposed to chemical attack from seawater (XAS)

Applies when concrete is exposed to chemical attack, when the concrete surface is in contact with sea water (XAS).

5.2.1.8 Aggressive chemical environment for concrete (ACEC) exposure classes

Concrete deterioration induced by chemical attack can be produced by contact with gases or solutions of many chemicals. However, in the ground, it is usually caused by exposure to acidic solutions or sulphate salt solutions. Based on that, the Building Research Establishment (BRE special digest 1) derived the exposure class for ground chemical attack and the design sulphate class (DS-class). DS class is classified to six site exposures depending on sulphate (SO4) and magnesium (Mg) concentration in ground water and water/soil extract. ACEC exposure classes are grouped based on the acidity of the static and mobile water from natural soil or brownfield. For Static classified water, the suffix s indicates that no additional protective measures are generally required. Concrete in ACEC Classes with the suffix z is designed to withstand acidic conditions and can be made with any of the cements or combinations listed in Table D2 of BRE Special Digest 1.

5.2.2 Combination of environment exposure classes

The code stated some exposure conditions that might exist in specific environments for some structures. This is advantageous and helpful for the specifier to design a durable structure without confusion or missing of any detrimental environment factors, thereby, the designer will choose the proper type and proportion of materials, proper w/c ratio, concrete cover and other design durability measures that will result in high durable design with minimum maintenance cost.

5.2.2.1 Corrosion and freezing and thawing exposure conditions

Any structure that requires the use of reinforcement in a specific environment may be induced to steel corrosion, which will deteriorate R.C concrete and, more critically, prestressed concrete. These environmental conditions may exist solely or in combination. The table below lists these conditions as mentioned in table A1 in BS 8500-1. Whenever embedded steel or reinforcement, one of these four exposure classes should be specified: X0, XC, XD, and XS. (*British Standards Institution 2019*)

Combined Exposure Class	Description			
X0	Reinforced concrete with humidity less than 34%. Very rare situation.			
XC1 and XF3	Mostly exposure class XC1 exists on its own. When the concrete is classified as being exposed to environmental class XC1 due to its permanent wetness, XC1 may be combined with freeze-thaw exposure class XF3.			
XC2 and XF3 and or ACEC exposure	Exposure class XC2 can exist on its own in a buried foundation in soil classified as AC1 or AC 1s where the hydraulic gradient is less than 5 and beyond the zone where freeze thaw attack is a concern. It can also coexist with exposure class XF3 and/or one of the chemically aggressive exposure classes.			
XC3/XC4	Because the recommendations for the concrete specification and cover to reinforcement are the same for XC3 and XC4, exposure class XC3 (moderate humidity) has been combined with XC4 (cyclic wet and dry).			

Table 8. Combined exposure classes in BS 8500-1.

5.2.3 Unreinforced concrete exposure environment conditions

The classification of unreinforced concrete exposure is limited to exposure classes X0, ACEC, XAS, and/or XF. The XC, XD, and XS classes are inapplicable because they specifically address the risk of reinforcement corrosion. Only exposure class X0 can exist by itself. As with XAS exposure, it is not normally necessary to classify in the XF4 exposure class those parts of structures located in the United Kingdom that are in frequent contact with the sea. A concrete aggressive chemical environment (ACEC class) can be used alone or in conjunction with an XF exposure class.

5.2.4 Concrete cover and durability of concrete

The British Standards include criteria for the minimum cover of ordinary carbon steel reinforced concrete and prestressed concrete, but not stainless steel (SS), since SS corrosion resistance varies by type and necessitates specialized advice.

The suggested values for minimum durability cover have been determined to give a low likelihood of the reinforcement becoming excessively corroded and requiring considerable repairs before the end of the intended working life, which is one of the purposes of the concrete cover (design service life). Section A.4.2 of the standard, as well as tables A.3, A.4, and A.5 provide the recommended nominal concrete cover (minimum concrete cover plus or minus variation).

Table A3 presents the nominal value for concrete cover and compressive strength for designated concrete appropriate for regular building and resisting carbon-induced corrosion over a 50-year service life. This table excludes exposure situations XD, XS, and AC-2 or higher since designated concrete is not suited for such exposure.

Tables A.4 and A.5 are intended for use when the specification's designed concrete method is preferred, and they provide normal-weight and lightweight concrete properties and limiting values to resist the XC, XD, and XS exposure classes for intended working lives of at least 50 and 100

years, respectively. These tables only address durability: additional conditions, such as fire and prestressing, may necessitate higher requirements.

The final criterion that the cover must meet is a successful bond transfer. To do this, the code must follow the EC2 code procedure, which is detailed in the Eurocode section.

Due to varying situations, the concrete cover deviation allowance c may be considered to guarantee sufficient concrete cover, as specified in BS 8500-1:

- This practical margin for deviation, c, may be assumed by the designer to be added to the minimum value to ensure acceptable minimum cover due to the level of workmanship on site.
- 2. If the concrete is prestressed, an increase or decrease may be required; the designer must review the applicable design code's national Annex to see if this is required. An increase, for example, may be required for additional safety elements. In the case of stainless steel or additional protection, the national Annex to the design code may also suggest decreasing the minimum cover. A range of (5 15 mm) allowance should be chosen after considering the type of construction and the quality control measures that will be implemented during construction (see BS EN 13670).
- 3. The nominal cover to reinforcement ratio does not need to be increased for exposure situations XC, XD, and XS. However, when the APM (supply sacrificial layer) is designed to resist chemical assault (see A.4.5), the nominal cover to reinforcement must be raised by the thickness of the sacrificial layer.
- 4. While in service, certain types of permanent formwork shield the reinforcement from corrosion, and such formwork may be considered when calculating the cover to reinforcement. Any permanent formwork/waterproofing that is damaged during usage should be assessed, and the implications of such damage should be acceptable. The decision to utilize the "barrier" to reduce concrete quality and/or the minimum cover to
reinforcement is determined by the unique situation and materials proposed. The designer oversees this.

5.2.5 Recommendations for the resistance of environment exposure

Mainly, the code approach for resistance of harmful environment is the concrete quality and minimum concrete cover. The concrete quality requirements depend on the desired working life, minimum concrete cover, structural requirements, and any additional protective measures specially for aggressive chemical environment.

To specify concrete for these exposures, the code allowed the usage of durability modeling and parameters in accordance with EN 206:2013+A1:2016 5.3.3 when the requirements are found restrictive.

5.2.5.1 Concrete properties and limiting values for reinforcement corrosion resistance

For reinforced and prestressed concrete, steel should be protected against steel corrosion when exposed to environments that might initiate it, as mentioned in the standard, XC, XD, and XS. The code recommends in table A.3 the adaption of designated concrete and nominal concrete cover for reinforcement for normal building exposed to corrosion induced by carbonation, carbonation and freezing and thawing, and aggressive chemicals.

For exposures XC, XD, and XS, adopting designed concrete method of specification is preferred, and when 50-years or 100-years' service life is desired for normal and light weight concrete, the code provides limits for durability considerations in tables A.4 and A.5. These limits are the nominal concrete cover, maximum water to cement ratio, and cement type or a combination of them, aggregate quality is taken as secondary factor and concrete compressive strength is considered as indirect factor to control these limitations. These tables don't include limiting values for corrosion resistance caused by freezing and thawing and aggressive environment, if such exposure exists, designer should refer to table A.9 and A.12 however these tables are not related to steel corrosion protection.

Additionally, these tables didn't forbid the use of supplementary cementitious materials, such as natural pozzolana, natural calcined pozzolana, high reactivity natural calcined pozzolana, fly ash, GGBS, limestone fines, or silica fume, or combinations of these materials, forming ternary or quaternary cementitious blends, however, they are not considered cement content and do not contribute to the w/c ratio unless they are demonstrated to be demonstrably equivalent using the equivalent concrete performance concept (ECPC) as defined in BS 8500-2:2015+A2:2019.

Even though the British standard allows the use for SCM as recommended in table A.6, it doesn't provide any guidance on their applications, moreover, there are some other materials that have limited use in the UK and not permitted to be used by a producer unless agreed.

Models for predicting concrete requirements for long-life structures in chloride environments do not produce identical results and inferring performance from existing structures has numerous practical issues. As a result, there is some uncertainty in the recommendations for a working life of at least 100 years in chloride (XD) and sea water (XS) environments. Relying solely on cover and concrete quality may not be the most cost-effective solution. Other techniques, such as stainless steel or nonferrous reinforcement, barriers, coatings, and corrosion inhibitors, may be considered in these situations, but these techniques, too, have uncertainties. For more information on these techniques, the code recommends consulting specialized literature, such as Technical Report on the Concrete Society.

For prescribed concrete, as well as designated and designed concrete, the concrete chloride class (the number in the classification representing the maximum chloride ion by mass of cement or combination) must be specified when the default chloride class does not apply. Table A.8 lists the chloride classes that are recommended for specific concrete uses containing reinforcing steel. There is no guidance for galvanized reinforcing steel, epoxy coated reinforcing steel, corrosion resistant reinforcing steel, or any other type of non-steel reinforcement.

5.2.5.2 Concrete properties and limiting values for freezing and thawing resistance

Table A.9 gives concrete properties and limiting values to resist the XF exposure classes. These recommended concrete qualities are suitable for an intended working life of both "at least 50 years" and "at least 100 years". The limiting values for concrete to resist freezing and thawing are the concrete strength, air entrained, cement type or combination, alternative designated cement, and other requirements.

Each 1% of entrained air reduces 28-day strength by about 5%, but strength is not as important as entrained air in determining durability against freeze/thaw conditions. A minimum of 4% entrained air is recommended for concrete to resist freezing and thawing. So, where the strength class is C28/35 or higher, it is not generally practical to compensate for the potential 20% or more strength reduction by using additional cement to reduce the w/c ratio. This is acknowledged in BS 8500-1 Tables A.4 and A.5, where the maximum strength class for air-entrained concrete exposed to freezing and thawing and chloride ingress is reduced to C28/35.

5.2.5.3 Concrete properties and limiting values for chemical attack resistance

To design for durability against aggressive chemicals, the standard provides table A.10, for each aggressive chemical exposure class from table A.2, the code limits the nominal cover as stated in BS EN 1992-1-1, and design chemical class (DC-class), this design chemical class contains the intended working life, hydraulic gradient, and concrete quality. Additional protective methods are also given in combination with DC class in table A.11. When DC and APM are employed together, modifications for DC should be done as required.

After the specifier choose the AC class from table A.10 and designate DC class, he should refer to table A.12 for the concrete quality requirement and concrete composition, the table provides values for maximum W/C ratio, cement or combination of cement type and content.

5.2.5.4 Concrete properties and limiting values for sea water resistance

For sea water exposed concrete structures, particularly for chemical attack, the BS 8500-1 gives guidance for sulphate attack resistance for reinforced concrete in tables A.4 and A.5, whereas for plain concrete, the code provided table A.13 to limit the maximum allowed w/c ratio, minimum

cement, or combination content and an indicative strength. Adding to that, the standard also considered the cause of sulphate attack from the concrete constituent: aggregate. Sulphate in aggregate (A.7.5) and Alkali-aggregate reaction A.8.2.

Even though sulphate concerns caused by natural aggregates are uncommon in the United Kingdom, natural aggregates with sulfate levels high enough to cause concrete disruption exists all over the world. If the aggregate source is new or suspected of containing sulphate, sulphate content tests on the aggregates are recommended prior to acceptance. These extra amounts of mobile sulphates from aggregate or any composition from concrete will result in expansion and damaging of concrete, thereby, the BS 8500-1 refers to BS8500-2:2015+A2:2015 for limitation of sulphate amount in concrete constitutions.

Delayed ettringite formation, one of the products of sulphate attack that has an expanded volume from the concrete is formed when the temperature of concrete reaches above 70° C, either due to heat of hydration or high temperature curing. In such cases, the standard in A.8.2 refers to BRE Information Paper IP 11/01 for mitigation measures.

Another deteriorating agent for concrete exposed to seawater is the alkali-silica reaction that is more common than alkali aggregate reaction in the UK. In section A.8.1 the BS8500-1 discusses the difference in assigning responsibility in BS 8500-2:2015+A2:2019, 5.2 and BS EN 206:2013+A1:2016, Note 1 -6.2.3, nevertheless, the code didn't specify which approach to follow. BS 8500-2 gives this responsibility to the producer as he is more knowledgeable of the materials, which BS 8500-1 supports, on the other hand BS EN 206 gives the responsibility for the specifier which is challenging for them.

5.3 Durability Design Provisions in the European code EN 1992.1.1

The Eurocode EN 1992.1.1 provisions for the design of durability are outlined in section 4. As most of the design codes, the provisions are deemed to satisfy. The section is divided to four main categories: the first one is general from (1-6) provisions that includes definitions and general requirements followed by environmental conditions based on EN206-1, after that, the code gives requirement for durability, and the last section methods for verification.

Furthermore, the Euro Code specifies that the necessary protection of the structure shall be formed by considering its intended use, design working life, maintenance program, and actions, as well as the potential significance of direct and indirect actions, environmental conditions, and consequential effects (e.g., deformations due to creep and shrinkage). Steel reinforcement corrosion protection is assumed to be dependent on the density, quality, and thickness of the concrete cover, as well as cracking. Controlling the maximum w/c ratio and minimum cement content yields the cover density and quality, which may be related to a minimum strength class of concrete.

The code specifies that in some cases, when this document is considered nationally, an open criterion is allowed to be adjusted according to that country circumstances, these provisions are 4.4.1.2 (3), 4.4.1.2 (5), 4.4.1.2 (6), 4.4.1.2 (7), 4.4.1.2 (8), 4.4.1.2 (13), 4.4.1.3 (1)P, 4.4.1.3 (3), 4.4.1.3 (4)

5.3.1 Exposure Conditions

The exposure classes mentioned in the code in table 4.1 are according to EN 206-1, hence they are very similar to the exposure conditions in the BS standards that are also with accordance to the same. However, the code states that in addition to the listed conditions, other aggressive and indirect exposures: chemical, physical, and mechanical must be considered. The chlorides contained in concrete, alkali aggregate reaction, soluble acids or sulphate salts, and the purpose of the structure such are all causes of chemical attack while temperature change, abrasion and water penetration are all causes of physical attack

The exposure conditions from table 4.1 are summarized as below:

5.3.1.1 No risk of corrosion or attack (X0 class)

Applies for all plain concrete except where freeze and thaw, abrasion or chemical attack exist in addition to reinforced structures in very dry areas.

5.3.1.2 Corrosion induced by carbonation (XC class)

Applies when concrete exposed to air and moisture contains reinforcement or other embedded metal non prestressed or prestressed. This Exposure category is subdivided to XC1 for dry or permanently submerged in water exposure, XC2 for wet exposure or rarely dry, XC3 moderate humidity concrete inside buildings with moderate or high air humidity or external concrete protected from the rain, and XC4 cyclic wet and dry Concrete surfaces subject to water contact, not within exposure class XC2.

5.3.1.3 Corrosion induced by chlorides (XD classes)

XD1 moderate humidity Concrete surfaces subjected to chlorides in the air, XD2 Wet, rarely dry Pools for swimming Concrete elements exposed to chloride-containing industrial waters, XD3 Cyclic wet and dry bridge parts exposed to chloride-containing spray, Pavements, and **car park** slabs.

5.3.1.4 Corrosion induced by chlorides from sea water (XS classes)

XS1 Exposed to airborne salt but not in direct contact with sea water Structures near or on the coast, XS2 Parts of marine structures that are permanently submerged, and XS3 Tidal, splash, and spray zone's marine structure components.

5.3.1.5 Freezing and thawing exposure condition (XF)

Applies where moist concrete is significantly attacked by freeze-thaw cycles, they are subdivided to XF1 for moderate water saturation without de-icing agent, XF2 for moderate water saturation with de-icing agent, XF3 for high water saturation without de-icing agent and XF4 for high water saturation with de-icing agent or seawater.

5.3.1.6 Concrete exposed to chemical attack (XA)

For all these classes, the code refers to EN 206-1, table 2. XA1 Slightly aggressive chemical environment XA2 Moderately aggressive chemical environment and XA3 Highly aggressive chemical environment.

Other than exposure classes, the code states that the composition of the concrete influences both the reinforcement's protection and the concrete's resistance to attack. Annex E lists the indicative strength classes for each environmental exposure class. As a result, higher strength classes may be chosen than are required for the structural design. In such cases, in the calculation of minimum

reinforcement and crack width control, the value should be associated with the higher strength (see 7.3.2 -7.3.4).

5.3.2 Durability Requirement

The code states that achieving the desired service life requires adequate measures for the protection of structural elements from the environmental actions, hence, durability requirements must be accounted in the structural design, material selection, construction specific details, implementation, quality assurance, inspection, verifications, special precautions (e.g., use of stainless steel, coatings, cathodic protection).

The Eurocode has also assigned values for maximum water cement ratio, minimum strength of concrete, minimum cement content and concrete grade, and minimum concrete cover. To derive these parameters, the design engineer should follow an integrated procedure introduced by the EC2 code. This procedure starts with specifying the concrete environment interaction categories: bond and durability environment.

The input for the durability environment consists of structure class, exposure class, and strength class. Based on structural class, the other two variables are specified, hence, the code provided two matrices that are the basic nominal cover requirement matrix and the indicative strength requirement matrix. The first matrix connects structural class and exposure class. The first matrix connects the structural class to the exposure class, while the second matrix connects the strength class to the exposure class. Following the selection of these two criteria (applicable basic nominal cover and applicable strength class), further modifications are made to account for different design life, slab geometry, special quality control procedures, and concrete casting conditions. Modifications are also made to account for the use of a higher grade of concrete than specified in the relevant strength class and air entrainment. Following the determination of the adjusted minimum needed cover and employed strength class of concrete, country-specific adjustments are authorized.

5.3.3 Methods for verification - concrete cover

The code defined the concrete nominal cover in equation 4.1 as the minimum cover in addition to

allowable design deviation. Nominal cover is shown in the project drawings.

The minimum concrete cover should be adequate to ensure a secure transfer of bond force, protect the reinforcement from corrosion, and has a sufficient fire resistance. Consequently, the code provided in table 4.2 the minimum cover value to guarantee safe bond force transfer and workability depending on reinforcement arrangement and type.

For durability, the minimum allowable cover is given in tables 4.4N and 4.5N as per the exposure classes and structural classes. Moreover, the code relates for the minimum concrete cover recommended nationally by each country's annex for extra safety requirements.

If stainless steel is used, the code recommends a reduction in the cover as well as employing extra protection such as coating. For the case of freezing and thawing, the given cover value in table 4.4 is sufficient however the code recommends considering special attention for the constitutes of concrete.

For abrasion resistance, the code gives the option for extra concrete cover as a sacrificing layer for exposure conditions (K value), however, special attention for the aggregate must be considered as EN206-1.

The nominal cover is the value of minimum cover required that is adequate for bond force transfer and durability in addition to deviations. A value of 10mm is recommended by the code but a reference for the country's national annex is recommended.

This deviation might be an increase or reduction. The code dictates that reduction can be done when manufacturing is subjected to a quality assurance system that includes measurements of the concrete cover and also where it is possible to ensure that a highly accurate measurement device is used for monitoring and nonconforming members are rejected. On the other hand, the code allows for increase of the cover when casting concrete against uneven surfaces such as ribbed finishes or exposed aggregate, should be increased.

5.4 Durability design provisions in ISO 13823 standard

5.4.1 The standard approach and application for Durability design

The approach of the previous international codes for the durability design focused on exposure conditions for the environment with limited values for durability parameters such as strength, w/c ratio, SCM for each exposure class. However, the ISO 13823 approach addresses the failure of structures related to the materials and provide general guidelines for verifying durability of structures subject to recognized or probable environmental actions, including mechanical actions, that cause material degradation and performance failure which is presented in the limit state method. This code is intended to be used in conjunction with ISO 2394: A structure's resistance to gravity, wind, snow, and earthquakes is tested using general concepts on structural reliability. The standard considers structural engineering approach that incorporates building science concepts to assess and design structures for durability.

This standard can be applied when a minimum service life is desired, for a newly designed structures, for the evaluation of existing structures and for non-structural components that affect concrete durability.

5.4.2 The standard basic concepts for Durability verification

The standard advises the adoption of limit-states method given in figure 1, section 6. For the design and verification of structure durability, to do that, an understanding of the environment influences where the structure will be erected, the transfer mechanism of these influences into the structure, the environmental actions that also includes structure aging and their effect, which result in structure component damage.

The chart below illustrates the factors that requires understanding to design for durability and their provisions in the ISO standard, for their corporation in the limit state, refer to figure 1 in the ISO 13823 standard.



Figure 16. Concept for durability approach based on ISO 13823.

5.4.3 Structure environment and environmental actions

The standard defines the structure environment as external or internal impacts on a structure (e.g., rain, de-icing salts, UV, humidity) that can result in an environmental action (agents) that are also defined as chemical, electrochemical, biological, physical and/or mechanical action causing material degradation of a component. Annex B, particularly table B1 presents the most common influences categorized by their location: outside and inside environment. The outside category is subdivided into atmosphere and water, or ground. These influences might transform into agents (environmental actions) that will result in actions on the concrete component surface or inside. These influences causing agents are provided in table B2, annex B.

The table below summarizes the effect of the existence of influences and agents combined.

Influence	Agent	Effect of the influences and environmental agents			
Moisture and	Water in any of	Water, either as an active agent or as a medium for the			
contaminant	its states	transmission of other agents, is a significant factor in the			
		corrosion of metals, the rotting of wood, and the			
		degradation of other materials.			
		The freezing and thawing of moisture in porous materials			
		leads to loss of performance and damage.			
		Frosting of water in moist and fine grained soil will lead to			
		a serious damage in foundations or retaining walls.			
		Chloride from de-icing salts or industrial sources are a			
		major cause for roadways infrastructures in cold regions.			
		Acid rain/ snow is detrimental for structures.			
Air and	Oxygen, Carbon	Similar to water, it might be an active agent or as a			
contaminant	dioxide, Sea	transfer medium for other harmful agents.			
	Spray, Oxides,	Oxygen with the presence of moisture will cause steel			
	Particulates	corrosion and stone deterioration.			
		Carbon dioxide will reduce concrete alkalinity throughout carbonation process and lead to corrosion. Air can transfer harmful agents such as chlorides (sea spray). Particulate matter in the air deposited on surfaces can			
		contribute to both physical and cosmetic material			
		deterioration such as salts and dust.			
Soils and	Sulphates and	The impact of soil contaminants is determined by their			
ground	other salts,	combination, concentration, and soil type.			
contaminant	acids, chemicals,	Contaminants such as solvents, oxidizing agents, can			

Table 9: Effect of the environment influences and environmental agents

	chlorides,	chemically react with plastics and dissolve or degrade
	electric current	them. Bacterial activity can affect the deterioration of soil
		materials directly or indirectly.
		Salts dissolved in groundwater might cause efflorescence.
		Stray electrical currents in the ground can fasten
		corrosion of a metallic objects.
Biological	Microorganisms,	Direct action of living organisms (e.g., fungi decaying
agent	insects, animals,	wood) or the action of by-products of plant or animal life
	plants	(e.g., sulphate reducing bacteria corroding metals) might
		deteriorate structure components.
		Termite attack on wood and wood-based materials is the
		most common insect problem.
		Rodents such as mice and rats cause significant damage to
		electric cables by gnawing organic materials and PVC
		casings.
		Birds, their nests, and droppings can cause mechanical or
		chemical damage (by pecking at soft materials) (corrosion
		of steel bridges exposed to bird droppings).
		The clogging of drains and gutters by roots and leaves is a
		major cause of plant damage, resulting in water damage
		to building components. Trees absorb water from the soil.
		which can cause differential settlement in some soils.
Temperature	Freezing and	Temperature variation has a significant effect of material
	thawing	deformation.
		Thermal stresses cause buckling bowing loss of
		nerformance for the components
		chemical processes are accelerated by temperature
		increase or decrease. Such as correction

Solar	UV and IR	Solar radiation deteriorates organic materials, if adequate
Radiation	radiation	energy is absorbed chemical reaction might occurs that
		results in a gradual change in the material properties, such
		as embrittlement, yellowing, or fading of the colour.
		UV radiation also interacts with other agents, such as
		temperature and humidity, to significantly accelerate
		deterioration.
		The daily cycle of solar radiation can cause large
		temperature swings on exposed surfaces. This causes
		cyclic dimensional changes as well as an increase in the
		number of freeze-thaw cycles.
Chemical	Two materials in	Galvanic corrosion occurs when dissimilar metals come
incompatibility	contact can	into contact.
	accelerate	Steel and zinc corrosion is accelerated in certain woods
	deterioration	and wood containing certain preservative chemicals.
		In contact with moist concrete or mortar, lead and some
		aluminium alloys corrode.
		Plastic crazing or fracture when in contact with certain
		sealants

5.4.4 Transfer mechanism

The standard states that understanding the transfer mechanism at which the agents cause deterioration for the structure can control their impact in addition to proper modelling for the deterioration process. Transformation processes such as gravity, drainage, condensation may accelerate or inhibit the environmental influences to turn into agents that have an environmental impact on or within the structural system's constituent parts.

Annex C provides three tables that present most common transfer mechanisms with examples.

5.4.5 Environmental Actions and Actions effect

Environmental actions are the results of agents impact the structures and might lead to performance loss. These actions have different forms; chemical, physical, electrochemical, biological, and mechanical that might exist alone or as a combination and damage the structures.

Action effect is the damage occurred in the structure due to environment action, this includes damage, loss of resistance, unacceptable aesthetics.

Annex D, table D.1 shows examples of environmental actions and action effects in structural materials and the agent's description that caused deterioration along with the current employed design options.

5.4.6 Limit States

Not only should the environmental action and action effects be considered, but also the limit states (such as fracture, motions, gaps, appearance, and material weakening) that correlate to the component failing to perform as intended.

The standard gives three limit state cases defined as follows:

- Ultimate limit state: defined when the resistance of the member or structure is less than or equal to the internal mechanical forces.
- Serviceability limit state: defined when local damage or appearance or relative displacement affect the function of the structure.
- **Initiation limit state**: defined by the onset of deterioration of a component preceding the occurrence of the serviceability or ultimate limit states defines this limit state.

Even though it's out of the standard scope, the code mentioned a limit state of mould growth resulting from moisture accumulation as it impacts human health.

5.4.7 Durability basic requirements in the standard

The standard requires that the service life of the structure or its components shall exceed the design

life as given in equation 1 provision 7.1.

For protected components against agents, the service life is given in equation 2, provision 7.1 the service life is the total time of the deterioration initiation and service life after the initiation.

The standard distinguishes between the component and structure service life, and it states that the structure service life depends on its member's service life. If these members predicted service life is less than the structure service life, they must be monitored and replaced. Renovation of structures requires revision of service life.

Moreover, the limit state analysis for durability performed using Equations (1), (2), (5), or (7) applies to structural systems as well as to their individual parts. Systems analysis, such as fault-tree or cause-tree analysis, can be used to assess the durability of a system if it can be conceptualized as a well-defined, logical assemblage of components.

To check for durability basic requirements given in 7.1, the standard states either using service life format in provision 7.2.2 or limit state format 7.2.3.

Provision 7.2.3.1 stated that the basic requirement for durability for ultimate limit state ULS is given in equation 5; at any time (t) throughout the design life of any member td, the resistance capacity R(t) is greater than or equal to the action effect S(t).

Provision 7.2.3.2 stated that the basic requirement for durability for serviceability limit state SLS is given in equation 7; at any time (t) throughout the design life of any member td, the serviceability state Slim > the action S(t).

Provision 7.2.3.3 stated that the basic requirement for durability for initiation limit state can be evaluated according to ULS or SLS by assuming that exposure (y1, t) = 0.

5.4.8 Design life of a structure and its component

The client and the proper authority should decide on the design life of a structure. In ISO 2394:1998, Table 1, typical design life categories for structures are listed.

The design life of an element should be determined based on the following factors: the design life of the structure (8.3), exposure conditions, complexity and cost of maintenance or replacement (8.4), the outcomes of a component failure in terms of the correction expenses, disruption, and operation, and the potential danger to users or other parties (8.5 and table 1), current and future availability of compatible components, and technical or functional obsolescence.

5.4.9 service life prediction of a structure and its component

Provision 9.1.1 states that the predicted service life of a structure or components shall be evaluated based on experience (9.2), modelling (9.3), and testing (9.4). According to Figure 1, all techniques used to calculate anticipated service life should be established on a solid foundation of building science principles.

Prediction based on experience is based on information gathered through examination of existing facilities in accordance with ISO 15686-2, as well as local experience with structures comparable to those in concern and environmental initiatives. Modeling and research in accordance with 9.3 and testing (9.4) are required if adequate experience cannot be obtained.

Prediction by Modeling might be mathematical utilizing material models, conceptual (based on Figure 1), or testing (standard tests based on Figure's 1 concepts).

Prediction by testing is contained in ISO 15686-2 that provides procedures for testing such as accelerated testing.

5.4.10 Durability design strategies

Section10 and annex E explains how to use service life planning, quality construction, detail verification, and a general design strategy to ensure that all materials and elements in an assembly last longer than the desired design life without needing maintenance or replacement. However, a maintenance strategy and presumptions from the design phase should be considered, followed by a determination of when replacement is justified.

Additionally, the standard involves the communication between the owner, contractor, designer, fabricator, supplier, and professions in the design process for the durability for each stage of the

project as listed in annex E. This approach is very beneficial as each party has its own input and experience to identify any deteriorating agent, hence, mitigation for such factors can be adopted.

CHAPTER 6: COMPARISON FOR DURABILITY DESIGN AND PROVISIONS IN INTERNATIONAL CODES AND STANDARDS

6.1 Concept and approach

Generally, the ACI 318-19 code, BS 8500-1, EN 1992.1.1 have similar approach for durability requirements, they provide provisions for the environment effect and recommend limits for critical values that directly impact concrete structure durability and methods for durability verification with variations among them of the details and given values. On the other hand, ISO 13823 has a different approach, it provides the limit state method and a comprehensive guidance of the process of structure deterioration, starting from the environmental influence (exposures) that turns into agents throughout a transfer mechanism that will exert action and result in environmental effect. The understanding of this mechanism - as per the standard - is essential to design against these influences, consequently, the service life of the structure will be longer than the design life. The varying level of complexity of exposure conditions in the studied documents are obvious, Eurocode and British standards are the most detailed whereas the ACI 318 is basic and ISO standard has a different approach with no subdivisions for the environment influences.

6.2 Exposure conditions comparison

The ACI 318-19 code has four categories of exposure classes that are subdivided into further 14 subclasses according to their severity. The British standard BS 8500-1 and Europe code EN 1992.1-1 have the same exposure conditions except for the category of chemical attack due to sea water that is mentioned in the British standard but not in Europe standard. These later two codes based their exposure conditions on EN 206 code, consequently, the British standard has seven exposure categories that are further categorized to 19 subclasses whereas the EN1992.1-1 has six main exposure categories that are subdivided into 18 classes according to their severity.

The American standard exposure classes are provided at a high level and no examples are mentioned for such cases except for F exposure compared to the other studied codes and standards, however a brief guidance is given in the commentary section which has to be revised and extended to assist the code practitioners specify the right class. These exposure categories are limited to freezing and thawing, sulphates, corrosion and contact with water. On the other hand, EC2 and BS exposures are explained clearly with examples. Finally, ISO 13823 listed 11 influences that has same concept of exposure categories, these influences might be outdoor on indoor the structure, no subdivision due to severity is provided, nonetheless, the standard dictates that after assigning the deterioration assessment by experience, modelling and testing, severity of the environment can be decided based on some factors and referred to seven references that a variety of material design standards have produced or are establishing an environmental severity categorization relevant for constituent materials.

Freezing and thawing

For freezing and thawing, in the ACI 318-19, the code considers degree of saturation, water exposure and the employment of de-icing agents, and for the British and Europe standard, they focus for each class on the water saturation concentration and the usage of de-icing agents. Even though it seems that all the three documents considered the same factors, they classified the classes differently, the ACI 318-19 considers two main environmental conditions, the absence for freezing and thawing (F0) and the presence of these cycles (F1, F2, F3), moreover, the degree of saturation of water and the usage of de-icing are allocated for the (F1, F2, F3). In comparison, the British and Europe standard have two main categories, moderate and high-water saturation, each one is subdivided to two classes, with and without usage of de-icing agents. In contrast, the ISO 13823 doesn't categorize the freezing and thawing as the compared codes, it is listed as an agent due to the influence of temperature and it must be considered in the durability design process.

ACI 318-19		BS 8500-1		EN 1992: 1-1	
Class/Design	Description of the environment	Class/Design	Description of the environment	Class/Design	Description of the environment
FO	Concrete not exposed to freezing-and thawing cycles	XF1	Moderate water saturation without de-icing agent	XF1	Moderate water saturation without de-icing agent
F1	Concrete exposed to freezing and thawing cycles with limited exposure to water	XF2	Moderate water saturation with de-icing agent	XF2	Moderate water saturation with de-icing agent
F2	Concrete exposed to freezing-and- thawing cycles with frequent exposure to water	XF3	High water saturation without de-icing agent	XF3	High water saturation without de-icing agent
F3	Concrete exposed to freezing-and- thawing cycles with frequent exposure to water and to de- icing chemicals	XF4	High water saturation with de-icing agent or sea water	XF4	High water saturation with de-icing agent or sea water

Table 10. Freezing and thawing exposure conditions comparison in international codes.

Chemical and sulphate attack

The other environmental exposure in the ACI 318-19 is the sulphate attack, it is sorted into two groups according to its source; soil and water, for each source, classification as per the concentration is adopted, thereby, classes S0, S1, S2, and S3 represent concentrations from lowest to largest. On the other hand, the EN 1992.1-1 included chemical attack from natural soil or ground water, three classes are given with reference to EN 206-1 table 1 that includes their quantities, as per the aggressiveness of the environment, XA1, XA2, XA3.

Although the BS 8500-1 has similarity to the Eurocode, and such exposures doesn't exist in the UK, more comprehensive exposure classes are specified, six site exposure DS (design sulphate attack) classes depending on magnesium and sulphate amounts, and ACEC (aggressive chemical environment for concrete) exposure classes based on acidity and water mobility. Adding to that is the exposure category chemical attack from sea water which is not included in the Eurocode.

From the ISO 13823 aspect, the chemical and sulphate agents act as an influence from the soil and ground containment, it explains that any contaminants might affect materials that are in contact with it. The effect of these agents depends on their amount, combination, and soil type. These contaminants could be solvents, oxidizing agents, salts, sulphates, and sulphate- reducing bacteria. The standard then mentions that special concrete types and mortar mixes can be used to limit their effect. No specific concentrations are given or designated classes.

ACI 318-19		BS 8500-1		EN 1992.1.1	
Exposure Category	Class/Design	Exposure	Class/Design	Exposure	Class/Design
		Category		Category	
Water-soluble	SO, S1, S2,	Chemical	XA1, XA2, XA3	Chemical	XA1, XA2, XA3
sulphate SO4 in soil	S3	attack by		attack by	
% by mass		aggressive		aggressive	
(S classes)		ground (XA		ground (XA	
		classes)		classes)	

Table 11. Sulphate attack exposure conditions comparison in international codes.

Dissolved sulphate	SO, S1, S2,	Chemical	XAS
SO4 dissolved in	S3	attack from	
water ppm (S		seawater (XAS	
classes)		classes)	

In contact with water

Despite of the detrimental effect of water in contact with structures, the British standard and Eurocode didn't provide a direct exposure category for it, whereas the American code provided an exposure category that is subdivided into three classes based on the presence of water contact and the requirement of low permeability (W0, W1, W2). Additionally, the analyzed ISO standard contained water exposure (agent) in all its states (liquid, gas and solid) and with its different mechanism to react with different contaminants and impact the structure durability. The Eurocode mentioned it as part of physical attack arising from water penetration.

Reinforcement corrosion

For this exposure condition that is very damaging for the structures and if not repaired might lead to performance loss, the Eurocode and the British standard are more compendious than the American code and ISO standards are more specified. The Eurocode and British standard grouped corrosion conditions according to the source of agent that is initiating this reaction: carbonation, chlorides induced by sea water, chlorides induced by other than sea water, and no corrosion borne environment which are subdivided into classes according to their frequent and severe exposure.

Moreover, the British standard included combination of exposures, as corrosion might be initiated with freezing and thawing, these exposures might occur simultaneously, these exposures are XC1 and XF3, XC2 and XF3 and or ACEC exposure.

Unlike the American code that limited this category into three classes based on moisture and chloride existence. Corrosion in the ISO 13823 standard is mentioned in different sections and for

different metals, corrosion as per the standard might be initiated by chemical compatibility, electrical current in the ground and presence of moisture and chloride under the effect of multiple environmental action such as the environmental atmosphere, marine structures, type of soil, cracked concrete and masonry.

ACI 318-19		BS 8500-1		EN 1992.1.1	
Exposure	Class/Design	Exposure	Class/Design	Exposure	Class/Design
Category		Category		Category	
Corrosion	C0, C1, C2	No risk of	X0	No risk of	X0
(C classes)		corrosion or attack		corrosion or	
				attack	
		Corrosion induced	XC1, XC2,	Corrosion	XC1, XC2,
		by carbonation	XC3 and	induced by	XC3
		(XC classes)	XC4 (XC3/4	carbonation	XC4
				(XC	
				classes)	
		Corrosion induced	XD1, XD2,	Corrosion	XD1, XD2,
		by chlorides other	XD	induced by	XD
		than from sea		chlorides	
		water (XD		other than	
		classes)		from sea	
				water (XD	
				classes)	
		Corrosion induced	XS1, XS2,	Corrosion	XS1, XS2,
		by chlorides from	XS3	induced by	XS3
		sea water (XS		chlorides	
		classes)		from sea	

Table 12. Reinforcement corrosion exposure conditions comparison in international codes.

water (XS classes)

Other exposure conditions

The researched Eurocode and ISO standard mentioned other exposure conditions that the British standard and American code didn't include, the Eurocode includes them as indirect aggressive actions that might have a form of chemical attack, that arises from: the function of the structure such as liquid storage, or solutions of acids or sulphate salts (EN 206-1, ISO 9690), chlorides contained in the concrete (EN 206-1), or alkali-aggregate reactions (EN 206-1, National Standards). Or the form of physical attack, arising from: temperature change, abrasion, and water penetration (EN 206-1).

For the ISO, inclusion of solar radiation such as UV and IR radiation, chemical incompatibility and biological agents are adapted as deteriorating agents for concrete structures.

6.3 Comparison for durability requirement and critical limit parameters

The ACI 318-19 approach for durability design considers limiting values for parameters related to the mix design that impact durability by restricting the penetration of harmful materials into concrete, for each exposure condition, the code specifies minimum values for compressive strength, max w/c, and additional requirements related to the resistance of exposure conditions.

Even though the British standard BS8500-1 provides limits for the values related to durability, it is more comprehensive than the ACI 318 code, and it explains that durability design should be included in each phase of the project, from initiation (concept), into design and detailing, material specification, execution, and this design can be achieved if the maintenance plan is implemented. Concrete cover and concrete quality are the focus of the standard, concrete quality depends on the

desired service life, exposure conditions, minimum cover to reinforcement, and additional protective measures for aggressive exposure.

The EC2 and ISO standard didn't provide limited values for durability design parameters such as the British and standard code, however, the EC2 code states that – as also mentioned in the BS8500-1- requirements of concrete durability should be considered in all project phases and provides in annex E values for strength of concrete assigned to each exposure class, additionally, the code gives thorough explanation for the designation of concrete cover and values for the concrete cover for exposure conditions, as the code indicates that the constitutes of the concrete directly impact corrosion protection and resistance to attack.

The ISO 13823 does not identify design procedures for durability, it establishes a sturdy framework by defining a process that begins with the structure's environment and progresses through mechanisms that convert this environment into environmental actions on component materials that result in action effects such as damage. This cause-and-effect mechanism must be considered while designing methodologies for predicting service life.

For freezing and thawing exposure, the American and British documents have common parameters with different values, however, the British code has more details and specified for service lifetime of at least 50 years and 100 years. Water cement ratios in the British standard are in the range of (.45-.6) which are higher than the ACI 318-19 that are designated between (.4-.55), more details about entrained air and aggregate size and type are found in the British standard, no specific type of cement given in the American code while in the British standard types and alternatives of cement are listed. Other details given in the BS 8500-1 and not seen in the American code is for pavements and hardstandings.

For the sulphate attack, the American code and British standard share the same basic requirements for design: w/c ratio, cement type, employment of SCM, however, the British standard is more detailed and well defined than the American code which provides basic exposure classes and design criteria. No service life specification or minimum concrete cover criteria is provided in the ACI 318, even though the code allowed for performance specification of the type and quantity of SCM,

the requirements are not comprehensive to include different critical situations as discussed in the exposure classes' part, thus, requirements are not available for such situations in the code.

On the other hand, the British standard facilitate the process for the designation of design parameters, beginning with identifying the design sulphate class DS and ACEC class from table A.2, after that, the DS class will be adjusted and as per the desired service life, the design practitioner will access table A.10, A.11, A.12 for the required minimum concrete cover, design class and additional protection, w/c ratio and cement type and SCM.

Comparing the maximum allowed W/C ratio, the British standard has a wider range (.35 to .5) due to the wider criteria of classes, whereas the American standard allows the range (.4 - .5). As discussed earlier, the lower water cement ratio the less permeable the concrete cover. The water cement ratio and other durability design values might differ between multiple codes even though they share same exposures, this is because the availability of raw materials and geographical conditions. For example, China and the UK have a similar exposure to the environment, however, exposure conditions and detail levels might vary due to these factors, thus, these differences are acceptable and an understanding of the available materials and technologies' role in this deviation is necessary.

Combined exposure conditions are also accounted and stated clearly, the BS 8500-1 explains such situations, for example, freezing and thawing or chloride with sulphate, in these cases, the guidelines in Table A.12 must be compared to the recommendations in Tables A.4 or A.5 for chloride induced corrosion resistance and/or Table A.9 for freeze thaw resistance, and the most restrictive values, e.g. highest nominal cover, lowest maximum w/c ratio, must be chosen and specified.

For water exposed to water, both the American and British standard stated limited values for w/c ratio and allows the usage of SCM. Not only that, but they also mentioned provisions about reactive aggregate restriction. BS standard points again to sulphate attack from sea water.

For steel corrosion, the ACI 318-19 code, BS8500-1 both stated maximum value for W/C ratio and minimum concrete cover. Both codes specified minimum compressive strength, however the British standard relate to it indirectly.

Although the ACI-318 code didn't consider all the sources of steel corrosion and didn't provide a detailed thorough exposure class, such as corrosion induced by carbonation, it considers a critical source for the chloride which is from the materials making up the concrete. The code limits the contribution of chloride in the concrete matrix to avoid early corrosion initiation. Whereas the British standard recommended cement types and the max. aggregate size.

Another important factor that limits the chloride ingress to the concrete is the employment for SCM that will reduce the water cement ratio and remain the workability of concrete in acceptable state. Both the American and British documents reflect their understanding of that; however, they didn't provide any guidance or details. The American standard limits their use into 50% of mass of cementitious materials for the calculation of allowable chloride limit. Cement types are also given together with aggregate quality.

Repeatedly, the British standard include the requirements and their limitations for a specified service life of 50 and 100 years, this service life concept is totally absent in the American standard.

Concrete cover in EC2 is related to bond transfer (reinforcement) and environment conditions (exposure conditions), same as BS that related its value to EC2. The ACI 318-19 specifies that concrete cover value depends on exposure to environment (moisture and temperature) and concrete casting method. When concrete is pre-casted, better-quality control can be achieved and hence reduction for concrete cover value can be considered.

CHAPTER 7: CRITIQUE REVIEW FOR DURABILITY DESIGN AND PROVISIONS IN INTERNATIONAL CODES

7.1 Exposure Classes

The specification of exposure classes for structures is the first step in durability design and service life modeling; thus, design codes and standards provide designers with these exposure conditions that adhere to a general common framework of assigning different levels of severity based on the considered damaging mechanism.

Exposure classes should be comprehensive to include all possible environmental conditions that threats buildings durability, they must have a wide range of options and must be clear otherwise they will result in unconservative design structures or overlay conservative design structures. Nevertheless, a very detailed or subdivided exposures might lead to complicated unnecessary design. Hence, they must be simple and used as an engineering tool for the purpose of durable and economic design of structures.

The studied existing exposure conditions are established to develop a prescriptive durability design approach rather than performance-based methods, they are related to prescriptive parameters (strength, w/c ratio and so forth) that has specific limited values. some of these exposures like the Eurocode and British standard might be indirectly applicable to performance-based methods, however these approaches need more detailed input particularly for modern structures, such as relative humidity, temperature, concentrations of surface chloride and carbon. As the world is moving toward performance-based approaches, these exposures need to be improved and combined with supplementary guidelines for a detailed and accurate assigning of exposure conditions.

ACI 318-19 code exposure conditions are limited compared to the other studied documents, they cover four main exposures that are subdivided to 13 classes, these exposures are very simple and doesn't include all the possible environmental actions. This shortcoming might lead to non-durable designs or costly ones as the design practitioner will provide a worst-case scenario design. Moreover, the code gave examples for exposure conditions only for freezing and thawing category

unlike the other studied documents, however a brief explanation is given in the commentary section that needs to be expanded and associated with examples, this will limit the challenge in interpretation exposure classes that is currently inconvenient and might lead to incorrect designation.

The first exposure category in the ACI 318-19 code is freezing and thawing, the philosophy of subdividing it into groups is the amount of saturation of water in the members and the time of freezing, if there is sufficient water inside the pores and freezing and thawing took place, the frozen water will exert internal tensile stresses on the concrete and cause cracks. The amount of saturation is not necessarily to be for the entire member, any portion of saturation that is vulnerable to cause tensile stress on the concrete after freezing must be considered, regardless of the dryness of the inner part. When deciding which exposure classes to assign, records of similar members' performance in similar existing structures in the same broad area might also be helpful.

For the same exposure category, the Eurocode and British standard covered the probable cases, there is a small variation between them and the ACI code that assigned a category for no exposure and didn't include the de-icing for limited water exposure. Even though some structures are exposed to limited water, deicing agents might be employed, and this will increase water saturation.

Another point to mention is that the ACI code states that for exposure with limited contact with water, F1 category is accounted, however, it is challenging to decide if this limited exposure result in saturation of water or no, consequently, for a safe choice, designers designate F2 exposure. This should be a concern to be investigated and a method of testing or modelling to be proposed to avoid extra unnecessary cost in the design. The code should consider all possible cases for a proper durability design.

For the EC2 and BSI, classes are similar, they cover situations of moisture levels with and without de-icing agents, nonetheless, they need to clarify the definition of "moderate" as some countries considered it as lower than the critical degree of saturation and adopted XD3 exposure class, therefore, the structures were designed for a different exposure. A clear criterion should be provided to avoid such confusion.

Despite the fact that in the United Kingdom structures with frequent exposure to the sea, XF4 can be neglected, the code didn't omit it as it might be applied to other locations or nations that adapt this standard.

The second exposure category in the American code is sulphate attack, in the ACI 318-19 code and Eurocode, multiple factors need to be considered for the exposure condition to sulphates and the exposure conditions need to be extended. Firstly, is the source of sulphates due to industrial and/or agriculture effect as the code is silent about this source, even though it is not a standard case it should be included to guid the design engineer for such cases.

Secondly is the frequency of water exposure; whether it is static (continuous contact) or dynamic (fluctuating contact to water or humidity) as this affects the chemical reaction and ion diffusion; continuous immersion in water will limit the mechanism of chemical reaction. Adding to that dynamic water exposure will result in physical attack, due to salt crystallization, which is also not outlined in the code and must be stated separately as this form has a different mechanism, causes and mitigation approaches.

Thirdly, type of cation associated with the sulphates has different rate, mechanism and effect on the concrete deterioration, many scholars studied this concept and found that, in ascending order, the deteriorating effect of the cations are calcium, sodium/potassium, and magnesium. Hence, type of sulphates must be included in the exposure conditions as each of them attack concrete differently.

Another important factor that affects sulphate attack is the chloride, studies showed that chloride will limit Sulphate ingress and other factors must be considered to design for economical and durable concrete. The British standard is comprehensive for this exposure.

The third exposure category that is mentioned in the American code and ISO standard and not in EC2 and British standard is water exposure. Water might act as an agent itself or as a carrier for other agents that could damage the structure such as chlorides and sulphates, therefore, the code assigned exposure class for structures in dry environment and in contact with water where low permeability is/isn't required. The ISO standard is more coherent in explaining such exposure and

pointed at very important effect that is acidic rain which the American standard needs to include.

The other critical impact of water is alkali silica reaction; obviously, the studied codes didn't mention exposure category for this environmental condition apart from the requirement of moisture, this could be explained by the factors that need to combine to begin the reaction, alkali are mostly from the materials making up the concrete whereas moisture is from the environment. Thereby, the Eurocode related it as a cause of chemical attack, whereas the British standard assigned the responsibility of avoiding it to the supplier, ISO standards mentioned it as a deteriorating agent and ACI mentioned it's mitigation within durability design requirement.

The fourth and last exposure category mentioned in the ACI 318-19 code is reinforcement corrosion, in contrast with the EC2 and BS that are well defined, the American standard is very simple and does not do justice to informed durability design as it doesn't cover all the possible factors that induce corrosion, it considered the effect of moisture with and without chloride sources. This approach doesn't cover the steel corrosion due to carbonation or chloride from different sources, or as stated in the BS 8500-1 the combined effect of freezing and thawing and corrosion. Additionally, steel corrosion might be as a secondary deterioration after cracks or spalling resulting from other durability limiting factors such as sulphate attack, F&T, ASR and so forth which the EC2 code indicated in X0 exposure class. Moreover, chloride sources might come from the concrete constitutes that has to be controlled. All these mentioned factors must be accounted to avoid steel corrosion and provide durable design.

The Eurocode and British standard categorized corrosion of steel reinforcement into no corrosion category, X0, the British code is detailed about that whereas EC2 can expand its application on reinforced structures not only indoor but also outdoor structures in arid dry areas.

Exposure class XC1 includes two scenarios which relates to carbonation mechanism and corrosion induced by carbonation. XC1(wet) exposures can be neglected and XC1 (dry) is same as X0 conditions, thereby, this category needs to be revised as it has no relevant function to be applied.

In spite of the adequate details for XC classes in the EC2 and BS, another exposure class should be added to include areas with high CO2 concentrations such as tunnels, car parking, industrial areas. This will assist designers to include the CO2 levels with the relative humidity amounts in their design for durability.

Another exposure category related to corrosion is the case at which it is induced by chlorides from sources other than sea water, this includes de-icing water, chloride in swimming pools and industrial water, and for cyclic wet and dry. The latter case designated by XD3 needs to be handled carefully by the design practitioner as it is hard to be quantified, particularly for nonstandard situations. Another thing to consider for XD3 class is the note given from the revision of the Norwegian Annex to EN206-1 that EC2 and BS are based on. This modification includes a warning that exposure to XD3 in interior parking garages may be more severe than exposure to XD3 on a highway structure. This is because of the action of salt slurry precipitation accompanied by wetting/drying on the slab surfaces of indoor parking garages, as well as the resulting increase in surface salt concentrations over time. This effect requires further analysis and quantification before it can be considered in the establishment of revised de-icing salt exposure classifications.

For structures exposed to marine environment, steel corrosion might be initiated from the presence of chlorides either dissolved in water or airborne, to better understand the mechanism of chloride transport, the exposed areas from the structure can be divided into fully submerged with water, tidal, splash and spray zone and zones that are not in direct contact but exposed to salts. See figure 17. The severity of chloride ingress differs for each zone.



Figure 17. Marine exposure classes and mechanism of chloride transfer based on EC2 and BS

Despite of the high concentration of chloride in the sea water, for saturated concrete, the lack of oxygen reduces the cathodic reaction and hence the reinforcement corrosion rate and, in any case, the critical chloride threshold is substantially greater than in air zones. As a result, a lower exposure class is regarded appropriate when compared to splash/tidal zones.

The higher exposure is given for the tidal, splash and spray situation. During wetting, soluble chloride ions are delivered to the concrete surface, throughout drying, evaporation of surface water causes crystallization of chloride salts near-surface zone. Chloride ion movement occurs as a combination of absorption, diffusion, and convection during wetting and drying cycles, leaving a much larger concentration of chloride ions in the concrete element's convection zone. Because chloride transport occurs exclusively via diffusion under permanently submerged settings, the concentration gradient controls the rate of chloride ion transfer. Adding to that, concrete structures partially immersed may develop wick action, which happens when sea water containing dissolved chloride ions is transferred from the submerged zone to dry concrete surfaces, where evaporation increases the concentration of surface chloride ions. When not permanently immersed, these effects, together with macro-cell corrosion, justify a more severe exposure class. As a result, it is proposed that no changes be made to this class.

In this case, the exposure class that needs to be revised is XS1, particularly more details should be given to the term "airborne" as there are multiple factors that affects such chloride ingress, this includes the distance of the structure from the sea, ambient relative humidity, topographical situations, wind features such as its speed, direction, frequency and the formation of salt-laden fog and mist. In light of the South African's experience, they recognized that within a distance of 30km from the sea and a combination of sufficient relative humidity and onshore wind, chloride ingress was initiated contrasting other countries that have less chloride ingress due to low humidity.

Other investigation carried out by Meira et al. (2007) showed that chloride airborne exposure are of higher levels in fog and mist when the relative humidity is low, nonetheless, other researches such as (Sandberg 1995) investigated along ago and showed that at low humidity, chloride induced corrosion is almost negligible. As a result, this exposure should allow national or local environment and topography to assign the severity of the exposure to avoid unconservative design provisions. Thereby, this exposure class can be improved in light of the New Zealand 3101 standard that adapted two exposure conditions with varying distances from ocean based on local topography.

Although corrosion induced by carbonation is widely variable, the American standard didn't include it as exposure condition, this limited concern might be related to the higher cover depth assigned by the ACI-318 than the other studies ones, or due to the usage of SCM or limestone additions to cement. This justification can be reasonable if the code is locally used, however, the ACI 318 code is widely used around the world and should include such exposures that are critical to the service life of structures, in addition to more detailed exposures for chloride induced corrosion. The same applies for the ISO standards that mentioned carbonation induced corrosion and de-icing chloride corrosion. In contrast, despite the limited application of XF4 exposure in the British standard and chemical attack exposures, they kept it as a standard class as it might be applied on other nations or locations.

Another critical factors that are not mentioned in the American, British and Eurocode but considered in the ISO standard are the effect of strong and dangerous chemicals, temperature, solar radiation, and biological agents. Other exposures that can be considered nonstandard such as global warming, running water exposure, and seasonal changes in humidity. The studied codes and

standards are globally used, therefore, a comprehensive, clear, reasonably detailed exposure categories should be provided based on the experiences, studies, and approaches for each one so that the code practitioners can choose the proper first input to the durability design; exposure class and provide safe and economic structural design.

7.2 Requirements for concrete durability in international codes and standards

Durability requirements in the studied American code are based on the concept that durability of concrete structures directly impacted by fluid penetrations, to control this penetration, a limited value of maximum w/c ratio should not be exceeded together with the employment of SCM will restrict the detrimental agents from entering the concrete structure. This approach is also followed by the British standard with more details than the other codes. Verifying w/c value on site using test methods is challenging and can't be accurate, therefore, the ACI 318-19 code relates this value to the strength of concrete as it is easy to test, however, the code allows using higher strength values that are consistent with the max allowed w/c. The ACI 318 code also relates the minimum amount of compressive strength with durability as one of the factors to consider, and states that structures might require higher strength than required for structural purposes to achieve durability.

Strength of concrete is its ability to withstand the applied loads without damage and to remain its stability and integrity. This property is outlined in concrete design and quality control. On the other hand, durability is the ability of concrete to last for a desired lifespan within exposure conditions. These two terms are different and not related, however, they might share some principles such as the usage of low W/C ratio or some additives such as silica fume, at which, when utilized, they produce higher strength and more durable concrete.

Relating durability to the strength of concrete condition needs to be revised as durability of concrete does not depend on strength, a concrete mix with 50 MPA strength doesn't necessarily indicate more durability of 35MPA strength, if 35Mpa is the strength needed for a specific structure. It is better to spend the extra expense of this 15Mpa to enhance the durability by for example using SCM or fly ash rather than extra non required strength and additional cost for durability failure repair.

It is not a correct approach to base the durability of concrete on strength and vice versa, these are two different and not related terms, each of which must be dealt with and achieved separately, thus this condition in provision 19.2.1.1 should be revised.

To resist the effect of freezing and thawing, the code recommends adapting sufficient entrained air to restrict water saturation and provide a room for the expanded frozen water in addition to considering adequate strength. This adequate strength is obtained by using low water cement ratio that will limit water porosity.

As we see here, the code relates the freezing and thawing resistance to strength, this should not be the case and must be adjusted as the higher strength is a result for the usage of lower W/C ratio and the goal is to achieve denser and less permeable concrete regardless of increasing unrequired strength. The structure needs to develop adequate strength to withstand the tensile forces brought on by the freezing of the water flowing through the capillary pores.

Another important factor that must be more focused on is the proper drainage system as such systems will limit the structural member's exposure to water and de-icing agents. Moreover, the code should also recommend the usage of frost-resistant coarse aggregates in the concrete mix when possible.

Other point to highlight here is that the code states if the member is not critically saturated, proper spacing of entrained air bubbles is not necessary, nevertheless, it is not always easy to guarantee that all concrete constructions won't at some point become critically saturated; thereby, air entrainment should always be applied as it is inexpensive insurance.

The Freezing and thawing provisions are fragmented within the chapter, additional requirements for F-T are dictated in 19.3.3 for the total air content percentage required for concrete and shotcrete. For concrete, testing as delivered, table 19.3.3.1 lists percentage of target air content in accordance with the nominal maximum aggregate size and exposure category. Table 19.3.3.3 depicts the target air content regarding mixture type and sampling location for shotcrete. These are followed by details about sampling and air entrained measuring techniques from the ASTM standards. Lastly, the code specifies the maximum amount of pozzolans used for F3 exposure conditions to be in
accordance with 26.4.2.2.

The code specifies the maximum air content, or as called targeted air content, and explained that the increase in this value for the concrete will no further improve the F&T resistance, in fact it will reduce the concrete strength. An adequate amount of air entrained shall be implied and it will perform satisfactorily. On the other hand, for shotcrete, the greater air content of the wet-mix shotcrete tested at the site of delivery is related to the expected air losses during shooting.

Moreover, the code points that the employment of air content will not forbid concrete damage if aggregate types that undergo massive volume expansion are used, however, the code didn't restrict its use or provided a clear provision for the type of used aggregate, in contrast to the BS 8500-1 that specified the usage of F&T resisting aggregate for XF3 and XF4 while air entrained in required.

As the preceding clauses demonstrate, the ACI 318-19 code are prescriptive with regard to freezing and thawing. Since there are many technologies and materials that have been proved to satisfy the necessary durability criteria but cannot be used because the code doesn't expressly permit them, an alternative performance specification must be included. For instance, the maximum w/cm restriction is used as a prescriptive requirement to lessen water penetration and the potential for a section of the member to become sufficiently saturated to cause F-T damage. The single w/cm requirement in the specification, however, does not consider how the composition of the limiting values of strength, air entrained and pozzolans, this will restrict enhancing the state-of-the-art approaches to produce durable concrete.

The British standard has detailed clear limits for durability requirement for exposure conditions, however, for water cement ratio values assigned for F&T exposure, despite of the usage of SCM that can provide low ratio as .35, the w/c ratio values in BS8500-1 are higher compared to ACI 318-19, the standard states that it will not always be achievable throughout the UK. Precast pretensioned concrete units with a strength class of C40/50 or higher and cements having less than 25% fly ash or 46% GGBS have proven to be durable. Upon that, a minimum cover of 35mm for XS1 exposure and 60mm for XS3 exposure is recommended for precast pretensioned concrete with a planned operating life of at least 100 years.

The same discussed point about the minimum strength is adopted in the British code, this concept has to be amended as the strength and durability are independent.

Looking now at sulphate attack requirements in the ACI 318-19 code, according to the information presented in the code requirement, the code offers performance options for the type and quantity of cementitious materials that should be used in conjunction with the appropriate type of cement, depending on the findings of studies on how well those materials defend concrete against sulphate attack. This is very advantageous because it gives the project design and construction team the chance to use high-end proven methods to produce durable concrete, though the code only allows values up to .5, depending on this value as the primary provision of concrete mix doesn't analyse the advantages gained from using SCMs, so it would be better if the code permitted higher w/c ratio values for S1 and S2 which will result in more economical and better workable concrete.

Comparing the requirements in the American code given for exposure class S2 and S3 option1, for the later class, the code permits the use of SCM, nonetheless, the effect of these materials is not reflected on w/c ratio and compressive strength. The expected outcomes from adding SCM is to achieve lower w/c which is not the case here. Revision or at least explanation should be provided to clarify this concern as the extra cost of using SCM is not justified.

In order to make the ACI 318-19 code more comprehensible, it should also include provisions for hazardous chemical exposure and physical sulphate attack, modification in exposure conditions will lead to more requirements such as the sulphate type and chloride presence. Additionally, it is simpler for the design engineer to identify all the sulphate attack-related provisions in one area as opposed to searching through other chapters for other specifications. The code should ideally be coherent with regard to each exposure condition. Compressive strength is not mainly related to durability; thus, these requirements have to be justified, water cement ratio values listed in the table doesn't include light weight concrete.

Despite the fact that mix design parameters are specified in both the American and British documents, the British standard is more detailed and covers most of the situations that impact sulphate attack, it also correlates the amount of minimum concrete cover and the desired service life. for a longer desired service life, additional protection measures are required. Moreover, for

situations of combined exposures, such as chloride and F&T, the standard provides guidance for the limited values selections as per the dominant environment factor which will assist the design to be safe, durable, and economic.

All these mentioned factors must be utilized as a framework to improve the sulphate attack requirement in the American code as it is used globally and should cover the most probable conditions. Thereby, because of the potential for various mechanisms that can contribute to the damage of sulphate-exposed concrete, the exposure conditions, including boundary conditions, must be well defined for different parts of the structure before sulphate-resistant design options such as selecting the required level of concrete quality, using appropriate materials, and curing sufficiently can be considered.

For structures exposed to water, ACI-code requirement for low permeability class is a maximum w/c ratio of .5 and SCM usage. Moreover, the code states that aggregate must not be alkalicarbonate reactive. Alkali silica reactive aggregate should not be used, and if used mitigation measures must be proposed. The code didn't specify the exact elements that may attack the concrete from water, such as chloride that will cause reinforcement corrosion. Unlike the British standard that again included sulphate attack from concrete constitutions and corrosion induced by chloride from sea water.

The ACI 318 code related the concrete cover requirements to the type of reinforcement and casting, for each method, exposure condition, member type and reinforcement size specifies the concrete cover. However, there are other factors that the code should consider providing quality and economical concrete cover. For a particular concrete cover, the reinforcement's corrosion resistance does not meet the ACI 318 durability standards. Exposure conditions must be unified and clearer for the certified engineer between chapter 19 and 20. The use of cementitious materials, low w/c ratio, high quality curing will provide an excellent concrete cover, and these are not mentioned as primary factors for concrete cover specification. The code didn't relate reinforcement details also with the concrete cover, there are multiple chapters in the code that detail the requirements for different types of materials, but there are no cross-references that a credentialed design professional

might utilize to see them as a system. Concrete cover is the most important and first defence line for steel corrosion protection.

For sever exposure conditions or fire, the code recommends higher values for the cover. Yet a higher concrete cover will increase the distance for the hazardous materials to reach the steel, reinforcement will be less effective and cracking risk due to tensile stresses, temperature and shrinkage will increase.

There are more factors that affect concrete permeability which the ACI 318-19 code and BS 8500-1 didn't mention and must be included, such as cement properties, for the same w/c ratio, coarse cement particles will produce more porosity in the cement paste. Curing of concrete also has a vital role in the total porosity, a proper curing, preferably wet curing rather than steam curing will contribute to reduce the pores.

ACI code should consider all these elements that directly affect the cover of concrete and produce a unified, comprehensive, and economic conditions for the concrete cover specifications.

7.3 Durability exposure conditions and requirements among ACI documents

Another topic to cover in this chapter is the discrepancies discovered among ACI documents ACI 201.2R-16, ACI 350 and ACI 318, in terms of providing consistent durability guidelines for chloride-induced corrosion, freezing and thawing resistance, and chemical sulfate assault.

Variations in exposure classes and the durability criteria for these classes were addressed for freezing and thawing. As previously discussed, ACI 318-19 splits this exposure into four classes, which ACI 350 also follows, however, ACI 201.2R-16 separates the F3 exposure condition into two additional categories based on surface finish method: F3a for manual method finish and F3b for machine completed.

ACI 350-06 provides a single recommendation for FT durability, whereas ACI 201.2R-16 and ACI 318-19 make multiple recommendations based on the exposure type. Because of the differences in strength requirement definitions, it is not viable to compare required strength values between ACI 201.2R-16 and ACI 318-19. ACI 201.2R requires a minimum in-place strength before initial

freezing exposure, whereas ACI 318 requires a minimum defined 28-day compressive strength. SCM materials exhibit consistency and relatively similar w/c values are used for exposures F2 and F3. The average air content values for concrete exposed to FT that are advised by ACI 201 and ACI 318 also differ between 201 and 318. The severe and moderate exposure recommendations in ACI 350 match the F3 and F1 categories in ACI 318 perfectly. In comparison to ACI 318 specifications, ACI 201 advises using values that are equal to or greater.

For sulphate attack, it is interesting to find consistency across all of the ACI documents (ACI 318-19, ACI 201.2R-16, and ACI 350-20), all exposure conditions are established based on the sulphates source, and none of them has been considered physical (salt) sulphate attack, which must be adjusted.

For same exposure category, in terms of uniformity of concrete mix standards, ACI 201.2R-16 does not include any strength requirements; it just specifies the maximum w/cm. ACI 318-19 and ACI 350-20 both specify the strength and w/cm specifications. Except for S3, the w/cm limitations in ACI 201 and 318 are the same for all exposure classes. When using a pozzolan or slag cement with Type V cement (Option 1), ACI 318-19 allows for up to 0.45 w/cm, but ACI 201.2R-16 allows for up to 0.40 w/cm. ACI 350-20 contains the most stringent w/cm restrictions of the three documents. The prescriptive cementitious material requirements for ACI 201.2R-16 and ACI 318-19 are the same. Although Type HS designated cement cannot be utilized in S3 exposure with Type V cement, the prescriptive cementitious material standards in ACI 350-06 are comparable to those in the other two documents. The ASTM C1012 test results are used to develop the performance-based cementitious materials standards in all three documents—ACI 201.2R-16, ACI 318-19, and ACI 350-20.

For corrosion, the number of exposure classifications and their descriptions varies amongst ACI documents. ACI 201.2R-16 and 222R-19 have two exposure classes: wet and dry (or protected) circumstances. ACI 318-19 defines three exposure classes: dry or shielded from moisture conditions (C0), wet concrete (C1), and wet concrete with an external source of chlorides from deicing chemicals, salt, brackish water, ocean, or spray from these sources (C2). ACI 350.5-12 specifies a single allowable chloride limit (CA limit) that applies to all exposure circumstances. Furthermore, there is no consistency in CA limits between documents, ACI 201.2R-16 relates to ACI 222R-01. However, ACI 222R changed the CA limitations in 2019, while ACI 201.2R has not been revised since 2016. CA limitations in ACI 201.2R-16 and 222R-19 are based on both acid-soluble chloride (ASC) and water-soluble chloride (WSC) testing, but CA limits in ACI 318-19 and ACI 350.5-12 are based only on WSC testing. Furthermore, ACI 222R-19 and ACI 318-19 specify CA limitations in relation to the mass of cementitious materials, whereas ACI 350.5-12 specifies CA limits in relation to the mass of cement. These discrepancies are very confusing for the design practitioners. Therefore, it is essential to provide a consistent chloride limit among ACI documents.

CHAPTER 8: GENERAL DISCUSSION AND CONCLUSIONS

8.1 Factors affecting durability

Concrete is the most used construction material; it provides safe and cost-effective structures; however, for a variety of reasons, the durability of reinforced concrete is a concern for engineers and countries because restoring and repairing damaged structures is relatively expensive, negatively impacting the national budget, natural resources, environment, and human safety.

Structure durability is not a new phenomenon anymore; it has been addressed in the last decade, and several studies and research have been completed to further our understanding of this issue, its causes, mechanisms, and mitigation measures. As a result, it must be considered during all phases of the project to ensure that its impact on the structures is minimal.

To construct a durable design, elements influencing the structure's durability must be identified, and an understanding of these factors' effects, transfer mechanisms, and harmful effects are critical in developing a preventive framework to ensure the structure's targeted service life. This is precisely what ISO 13823 highlights, and it can serve as a model for a complete understanding of degradation mechanisms that the ACI 318-19 can incorporate for the next code generation.

Factors influencing durability could be from the concrete system itself or from the environment, as reflected in the studied design codes as exposure conditions and allocated values or design parameters that should not be exceeded or allowed levels of some elements such as chloride in the material constituents of concrete.

As the literature review demonstrates, several studies have been conducted on the materials that comprise the concrete matrix, their behavior under various detrimental conditions or in conjunction with other materials, and their reaction to durability tests. The findings of these experiments show that some materials are effective in repelling harmful influences and that certain combinations can optimize concrete performance. Furthermore, other materials have proven to be detrimental and

hasten concrete deterioration; hence, we can observe in the examined documents that some materials, such as active aggregate, are not permitted to be deployed. Besides that, assigning the right aggressive environmental agents such as sulphates, chlorides, is a critical input for the proper material selection and further mitigation approaches to be included in the durability design plan.

From the above discussion we can conclude that durability design necessitates various inputs and hierarchical phases, which is not an easy task. The structural members, the overall structure, and the structural materials must all be designed by the design engineer. All to meet desired service life within financial constraints. To achieve a uniform good concrete, durability together with strength end economy are required factors to be designed properly.

Durability design is not solely the responsibility of the design engineer, nor is it confined to a single stage of the project; design experts, contractors, and owners all include durability in the design, construction, and maintenance processes. As a result, durability planning is a work that should be considered at every step of a structure's life as follows:

- Owners and design professionals collaborate on durability design prior to construction. Decisions are made about the plan for durability and design service life, as well as the effects of design considerations on durability such as resisting environmental pressures and limiting cracking. Less protection may be provided for components and assemblies that are easy to maintain and repair, whereas more protection may be considered for inaccessible or difficult-to-repair places. Additionally, enclosed (protected) concrete structure may require few to no considerations to persist for decades or centuries, but uncovered monumental concrete structures require care and competence to last.
- Owners, design professionals, and contractors cooperate during construction to ensure that the designed durability is met through proper construction, curing, and quality control. Furthermore, these parties team up to correct any deviations from the original durability plan that may occur during the construction process.
- Finally, once the building is completed, owners and, in some cases, builders are in charge of monitoring and maintenance planning and execution. For builders, this accountability would be for a defined period before passing responsibility to owners. Design professionals

(not necessarily the original design professional) may also be involved to advise Owners and undertake evaluations and repairs.

Thereby, durability objectives should be incorporated at all stages of project design, beginning with the overall framework. The design expert must guarantee that the targeted performance levels for the global structure are met for a particular design service life, environment, and budget. Once the overall structure criteria are established, structural members must also meet design service life goals for individual members, as well as specific capacity and durability requirements. Following the identification of overall project durability goals, the majority of the durability design effort is devoted to translating these objectives into material needs, building specifications with acceptance criteria, and quality assurance/control requirements. A concrete structure will never reach the desired service life goals if durable concrete materials and sound construction procedures are not used.

8.2 prescriptive vs performance specifications

Similar to other design perspectives, design professionals need consensus guidelines to follow. There are two distinct approaches to design methodologies and specifications: 1) prescriptive design, and 2) performance-based design. Historically, the construction industry depended on prescriptive (deemed-to-satisfy) design and specifications to provide concrete structures that met or exceeded project strength and durability criteria. Prescriptive Codes such as the American, British and European define environmental conditions that affect durability, such as chloride exposure, sulphate exposure, freezing and thawing conditions, and so on, and indicate corresponding requirements for water/cementitious materials ratios, air-entrainment, cement replacement with supplementary cementitious materials, and chloride limits, and a design professional or Owner selects the environmental conditions that align with their project, and requirements are set.

Even though design professionals prefer prescriptive codes for their ease of learning and simpler interpretation in addition to be simply translated into prescriptive concrete mixture design specifications that a contractor working with a concrete producer can implement, the resulting

concrete mixture designs are rarely directly measured and verified during the construction process or during operations: compliance with specified water/cementitious materials ratios, compressive strength, and occasionally minimum cement contents serve as indirect evaluations of durability, despite the fact that none of these mixture design characteristics have a direct or linear relationship.

To address this limitation, performance-based design directly addresses these criteria, with the concept that a project team would build a structure with the ultimate goal in mind, considering the Owner's preferred design service life, maintenance plan, and cost.

In practice, performance-based design may imply that a structure can be constructed with greater innovation and creativity, without the use of predetermined materials and systems for a certain structural, durability, or sustainability issue. The performance of a performance-designed structure is then explicitly analyzed to anticipate its performance, specifically the risk of failing to reach its performance objectives, and uncertainty is estimated. If the performance goals are not met, the design or performance goals are altered.

It is vital to highlight that a design professional can use a hybrid design process in which one part of durability is prescriptive and another aspect of durability is performance-based. In this manner, the design expert can maximize the durability design by defining performance requirements where they are required and relying on prescriptive design where more detailed performance needs are not required. Hence, this hybrid design is recommended as it optimize the durability design process at which the advantages of each approach are combined and utilized.

Prescriptive, performance-based, and hybrid requirements each have their own set of benefits and drawbacks. Prescriptive standards such as w/cm, crack management, air entrainment, and cement type and content have traditionally been used by design codes to address durability. Indeed, most of these Codes reviewed offered prescriptive requirements, however to various degrees. In the absence of prescriptive requirements, optional prescriptive means to achieve performance standards were provided. Additionally, these requirements are convenient since they often have a proven track record and are widely applicable to diverse construction types and exposure situations, and a concrete producer has likely manufactured and carefully tested mixtures acceptable for a specific standard. Prescriptive standards are often more than sufficient to assure longevity for

simple constructions with typical exposures. However, in more complicated design scenarios, certain types of structures, long service lives and maintenance/repair/rehabilitation planning, prescriptive requirements may be insufficient. Lastly, Prescriptive criteria allow the design expert to use project resources in areas other than durability design.

On the other hand, performance standards approach concrete durability directly. Design Codes provide the finest chance for concrete mixture optimization by allowing durability performance requirements. This is particularly true considering recent developments in concrete mixture design and the widespread use of extra cementitious materials and admixtures. Performance requirements are the ideal option for constructions subjected to unique exposure conditions or with ambitious project objectives. Hybrid standards were prevalent in the ACI 318 exposure class S3 requires Type V cement but permits alternative cement that meets ASTM C1012 sulfate expansion standards, resulting in hybrid requirements that are alternative.

From the above discussion, we can conclude that alternative hybrid requirements enable the design expert to choose the best durability design approach and specification format for the overall project goals. Prescriptive requirements are also beneficial in that they provide a minimum expected durability performance without the need for extensive concrete mixture design development. Performance requirements are undoubtedly the most effective means of optimizing concrete mixtures for durability, especially as concrete technology evolves; however, performance requirements are the most effective means of optimizing concrete mixtures for durability. Acceptance of alternative hybrid performance requirements in Codes and Standards promotes adoption in project specifications. As a result, the advantages of having alternatives during durability design are realized throughout building. Contractors and suppliers can choose their preferred means of showing durability, but designers are guaranteed a minimum level of durability.

8.3 Durability in the Arab Gulf

The Arab gulf environmental conditions are very harsh, the high ambient temperature, high relative humidity, dust, and seawater are all influences for concrete deterioration. This will cause durability issues during concreting and along the service life of the structure.

As illustrated in the literature review, a wide range of studies investigated measures to minimize the effect of the hot arid or hot dry environment. Scholars tested various materials capable of resisting such exposures and limiting the transfer of harmful agents to the concrete body, such as advanced concrete materials and supplementary cementitious materials.

Another challenge that affects structural durability in these regions is hot weather concreting. Hot weather conditions degrade concrete quality by hastening the rate of moisture loss and cement hydration that happens at higher temperatures. High ambient temperature, high concrete temperature, low relative humidity, high wind speed, and solar radiation are all detrimental hot weather conditions.

Hot weather can cause problems with fresh concrete, such as additional water supply, increased slump loss, elevated rate of setting resulting in placing and finishing difficulties, elevated tendency for plastic cracking, a critical need for prompt early curing, difficulties controlling entrained air, increased concrete temperature resulting in long-term strength loss, and the potential for thermal cracking.

The type of structure, the properties of the materials used, and the experience of the casting and finishing team in dealing with the atmospheric conditions on the site will all influence which precautions to take and when to take them. The following precautions will decrease or eliminate the possible difficulties associated with hot-weather concreting: Cool the concrete or one or more of its ingredients, use a concrete consistency that allows rapid placement and consolidation, reduce the time of transport, placing, and finishing as much as possible, schedule concrete placements to limit exposure to atmospheric conditions, such as at night or during favorable weather conditions, Consider using sunshades, windscreens, fogging, or spraying to reduce moisture loss during installation and finishing. After screeding, add temporary moisture-retaining films. hold a preconstruction meeting to examine the project's safety concerns.

The harsh environment negatively impacts concrete, whether fresh or hardened, and thus precautions must be considered from the design stage to resist harmful environmental effects during the service life of structures and during transportation, casting, and curing to minimize durability initiation and premature degradation.

8.4 Durability design in the international design codes and standards

Building codes evolve with time and technological advancements; various committees are formed to review and study technological advancements and the findings of scholars' research to incorporate the proven beneficial studies into the codes, as well as the demands of the environment, sources, climate, and so on.

The durability of structures has become particularly important to consider in the design process, as early deterioration of structures and unplanned maintenance places financial pressure on governments, affects human safety, and has a negative influence on sustainability. As a result, design codes addressed this issue and provided provisions to guide the design professional.

In this study, four international codes and standards were reviewed, the American code ACI 318-19, the British standard BS 8500-1, the European code EN 1992:1.1 and lastly the ISO 13823. Further comparison for the ACI codes is done for specific criteria to examine the uniformity of the durability exposure conditions and requirements. See table below that concludes the reviewed documents type and focus areas.

Table 13.	Application an	d focus area o	of the reviev	ved interna	tional design	code and standards
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Document	Year	Document tile	Application	Focus Area	Document
			Areas		Туре
ACI 318	2019	Building Code	International	Design for	Code
		Requirements for		new structures	
		Structural Concrete.			
EN	2004	Eurocode 2: Design of	Europe	Design for	Code
1992:1-1		concrete structures - part		new and	
		1-1: General rules and		existing	
		rules for buildings.		structure	

BS 8500-1	2019	Part 1: Method of	United	Design for	Standard
		specifying and guidance	Kingdom	new and	
		for the specifier.		existing	
				structure	
ISO 13823	2008	General Principles on the	International	Design for	Standard
		design of structures for		new and	
		durability		existing	
				structure	
ACI	2016	Guide to durable concrete.	International	General	Guideline
201.2R				Durability	
	2006	Code requirement for	United States	Design for	Code
ACI 330	2000	Code requirement for	United States	Design 101	Code
		environmental engineering		new structures	
		concrete structure.			

Despite the fact that each of the assessed codes has its unique approach to durability, they share some similarities and variations; this is acceptable and permissible considering the differences in their emphasis areas, application areas, and the type of document itself as shown in table 13. However, there are some common requirements and factors for building durability that should be considered. The British standard BS 8500-1 is the most detailed and comprehensive of these codes and standards, followed by the European code EC2 and, finally, the ACI 318-19. The ISO standard is oriented toward durability planning rather than a specific exposure class's restricted value. Specifications are prescriptive dominantly, with a mix of other performance specifications.

For exposure conditions, the ACI 318-19 code must be amended as the specified exposures are very basic and not comprehensive, they do not contain all elements that induce sulphate attack and steel corrosion, leaving the design practitioner with the struggle to decide which requirements to assign for exposures that are not listed in the code. Same for the British and Eurocode, yet they

provide detailed exposure conditions, some exposure classes need to be more precise, such as XC1, XD3 and XS1 as shown in previous critique discussion.

The three codes (ACI, BS, EC2) establish a minimum value for concrete strength for the durability requirements; nevertheless, strength and durability are unrelated, so this requirement must be modified. The other requirements for w/c ratio, air entrained and minimum cement content, and SCM are acceptable; nevertheless, due to the variety of available materials, geographical restrictions, available resources, and technology, no unified values can be assigned for all codes. These codes, however, may allow for further performance standards in addition to prescriptive specifications (hybrid approach). As previously discussed, this approach will optimize the best approaches to achieving durable concrete.

8.5 Investigation findings for ACI 318 code deficiencies and proposed improvement

When comparing the ACI 318-19 code to the other codes, multiple issues in the code were discovered; these shortcomings in the code must be amended, any missing critical provisions must be included, and some areas must be expanded to be more comprehensive; these updates are required for the ACI 318 code to remain the pioneering code used globally. All the development areas that must be accounted for and adjusted in the next version of ACI-318 code are discussed below.

1. Terminology and definitions associated with durability design are relatively limited; many crucial terms are not included in the code; also, these terminologies vary widely across ACI publications; terms are defined in accordance with the document's focus area. This will lead to code practitioner confusion and code interpretation issues. For example, in ACI 318-19, ACI 350, and ACI201.2R, the term "service life" is not defined yet referenced in the comments. In contrast, ACI365.1R and ACI 562 define service life as "the period after installation (or in the case of concrete placement) during which all properties surpass the minimum acceptable values when consistently maintained." Such key terms must be specified in a consistent manner throughout all codes; if a change is required, a different term must be used, either via a new term or the addition of words to include that

modification. Table 14 lists durability related terms and definitions in the studied code which can be considered by ACI committee to update next published codes.

Table 14. Summary	of relevant	durability (design and	service life terms.
Tuble 141 Summary	orrectant	aarasiiity	acoigii ana	Service me terms.

Term	Definition	Reference document
alkali content of concrete	value calculated from the mix proportions and the determined alkali contents of each of the constituents and used for verifying that the alkali content of concrete does not exceed the specified limit.	BS 8500-1
assessment	set of activities performed to verify the reliability of an existing structure for future use.	ISO 13822
cement or combination content	mass of cement or combination contained in a cubic metre of fresh, fully compacted concrete, expressed in kilograms per cubic metre (kg/m3).	BS 8500-1
characteristic service life	value of a predicted service life chosen either on a statistical basis, so that it has a specified probability of being more unfavorable (i.e., lower), or on a non-statistical basis, for instance, based on acquired experience.	ISO 13822
combination	restricted range of Portland cement and additions which, having been combined in the concrete mixer, count fully towards the cement content and water/cement ratio in concrete.	BS 8500-1

design service (or working) life	(Design working life) - assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair necessary. (Design life) Specified period for which a structure or a component is to be used for its intended purpose without major repair necessary.	EC2 and ISO 13822
deterioration	process that adversely affects the structural performance, including reliability over time due to naturally occurring chemical, physical or biological actions, repeated actions such as those causing fatigue, normal or severe environmental influences, wear due to use, or improper operation and maintenance of the structure	ISO 13823
durability	capability of a structure or any of its members to satisfy, with planned maintenance, the required performance over a specified period under the influence of environmental action	ISO 13823
environmental action	chemical, electrochemical, biological, physical and/or mechanical action causing material degradation of a component	ISO 13823
hydraulic gradient	difference in the hydrostatic head of water on opposite sides of a concrete element, in meters, divided by the section thickness, in meters	BS8500-1
initiation limit	• Refer to "durability limit state" and "limit state" state that corresponds to the initiation of significant deterioration of a	ISO 13823

state (ILS)	component of the structure	
licensed design professional	by the statutory requirements of professional licensing laws of the state or jurisdiction in which the project is to be constructed, and who is in responsible charge of the structural design	ACI 318
limit state	state beyond which a structure or component no longer satisfies the design performance requirements states beyond which the structure no longer fulfils the relevant design criteria	ISO 13823 EC2
maintenance	set of activities performed during the working life of the structure to enable it to fulfil the requirements for reliability combination of all technical and associated administrative actions during a component's service life (with the aim of retaining it in a state in which it can perform its required functions	EC2 Iso 13823
minimum cover	depth of cover to reinforcement assumed for the purposes of durability design	BS8500-1
reliability	the ability of a structure or a structural member to fulfill the specified requirements, including the design working life, for which it has been designed. Reliability is usually expressed in probabilistic terms. ability of a structure or component to satisfy the specified design performance requirements within the design service life	EC2 ISO 13823

repair	activities performed to preserve or to restore the function of a structure that fall outside the definition of maintenance	EC2
resistance	capacity of a member or component, or a cross-section of a member or component of a structure, to withstand actions without mechanical failure e.g., bending resistance, buckling resistance, tension resistance	EC2
serviceability	serviceability refers to the ability of the structural system or structural member to provide appropriate behavior and functionality under the actions affecting the system. Serviceability requirements address issues such as deflections and cracking, among others	ACI 318 commentary
serviceability limit states	states that correspond to conditions beyond which specified service requirements for a structure or structural member are no longer met	EC2
structure environment	external or internal influences (e.g., rain, de-icing salts, UV, humidity) on a structure that can lead to an environmental action	ISO 13823
transfer mechanism	mechanism by which influences in the structure environment are, over time, transferred into agents on and within components or prevent such transfer.	ISO 13823
Ultimate	state associated with collapse, or with other similar forms of	ISO 13823

2. Exposure conditions should be extended to incorporate more categories and classes. An integrated environmental exposure classification can be built based on the exposure conditions in the examined code and the recommendations to alter some classes stated in the critical review. The following exposure categories are indicated as a starting point for this area's development. (See tables 15 to 18)

Table 15. Proposed exposure classes for freezing and thawing

Exposure class	Severity	Condition	Example
F1	Low	Concrete exposed to freezing and thawing conditions, but very low probability of concrete being near saturation at time of exposure	vertical surfaces above the level of snow accumulation or horizontal elevated floors in areas protected from direct exposure to moisture.
F2	Moderate	Concrete exposed to freezing and thawing conditions, with a high probability of concrete being near saturation at time of exposure, but no de-icing chemical exposure	vertical surfaces above the level of snow accumulation or horizontal elevated floors in areas protected from direct exposure to moisture.

- vertical surfaces below the level of snow **F3** Severe Concrete exposed to freezing and thawing accumulation; vertical surfaces with conditions, with a high sufficient moisture exposure to allow the probability of concrete to be near saturation prior to concrete being freezing; retaining walls or other vertical near saturation elements with one side exposed to at time of exposure, with de-icing moisture; and slab-on-ground that is not chemical exposure protected from freezing.
- F4a Very Concrete exposed vertical surfaces that may have de-icingto Severe freezing and thawing chemical-contaminated snow piled conditions as well as deagainst them; sidewalks or pavements that icing chemicals - hand receive de-icing chemicals; and concrete finished surfaces that received frequent exposure to seawater as well as freezing-and-thawing conditions.

F4b Very Concrete exposed vertical surfaces that may have de-icingto Severe freezing and thawing chemical-contaminated snow piled conditions as well as deagainst them; sidewalks or pavements that icing chemicals - machine receive de-icing chemicals; and concrete finished surfaces that received frequent exposure to seawater as well as F&T conditions.

Exposure class	Severity	Condition	Example
C-C1	Low	Wet, rarely dry	Reinforced and prestressed concrete
			surfaces permanently submerged in
			non-aggressive water/ permanently in
			contact with soil not containing chloride.
C-C2	Moderate	Moderate	
		humidity	External reinforced and prestressed
			concrete surfaces sheltered from, or
			exposed to, direct rain.
C-C3	Severe	Cyclic wet and	Reinforced and prestressed concrete
		dry	surfaces subject to high humidity, repeated
			wet and drying,
C-C4	Very	High	Reinforced and prestressed concrete
	Severe	concentration	surfaces inside tunnels, car parking,
			industrial areas

Table 16. Proposed exposure classes for carbonation induced corrosion

Table 17. Proposed exposure classes for chloride induced corrosion apart from sea water

Exposure class	Severity	Condition	Example
C-D1	Low	Moderate	Concrete surfaces are exposed to airborne
		humidity	chlorides. Reinforced and prestressed concrete
			wall and structure supports more than 10 m
			horizontally from a carriageway. Bridge deck
			soffits more than 5 m vertically above the
			carriageway.

C-D2	Moderate	Wet, rarely dry	Parts of structures exposed to occasional or
			slight chloride conditions. Reinforced and
			prestressed concrete surfaces totally immersed
			in water containing chlorides. Buried highway
			structures more than 1 m below
			adjacent carriageway.
C-D3	Severe	Cyclic wet and	Reinforced and prestressed concrete walls and
		dry	structure supports within 10 m of a
			carriageway. Bridge parapet edge beams.
			Buried highway structures less than 1 m below
			carriageway level. Reinforced pavements and
			car park slabs.
C-D4	Very	Cyclic wet and	Reinforced and prestressed concrete slabs
	Severe	dry	inside parking garage.

Table 18. Proposed exposure classes for chloride induced corrosion from sea water

Exposure	Severity	Condition	Example
class			
C-S1a*	To be	Exposed to airborne salt but	External reinforced and
	Locally	not in direct contact with sea	prestressed concrete surfaces in
	specified	water	coastal areas.
C-S1b*	To be	Exposed to airborne salt but	External reinforced and
	Locally	not in direct contact with sea	prestressed concrete surfaces in
	specified	water	coastal areas.
C-S2	Moderate	Permanently submerged	Reinforced and prestressed
			concrete surfaces
			completely submerged or
			remaining saturated, e.g.,
			concrete below mid-tide level

C-S3 Severe Tidal, splash and spray zones Reinforced and prestressed concrete surfaces in the upper tidal zones and the splash and spray zone, including exposed soffits above sea water

CS1a*, CS1b* assigned upon distance of the structure from the sea, ambient relative humidity, topographical situations, wind features such as its speed, direction, frequency, and the formation of salt-laden fog and mist

- 3. In contrast to the examined documents, the ACI 318 code does not specify any service life classifications. British and Eurocode durability criteria are subdivided into 50 and 100 years of service life. Other codes, such as the Canadian CSA A478, classified building service life into four categories: temporary (up to ten years), medium life (25-49 years), long life (50 to 99 years), and permeant (minimum 100 years).
- 4. The ACI 318-19 code makes no reference of durability planning, yet ISO 13823 provides a full evaluation of durability planning in relation to service life. This is similarly covered in the Australian CIA Z7/01 and Japan's codes 15 and 16. The British and Eurocode standards state that durability must be addressed at all stages of the project.
- The ACI 318-19 code doesn't address any requirement for future maintenance or repair for structures. Even though ACI 562 covers this material, ACI 318 does not include this Code document as a member of its technical family.
- 6. The code did not include the permission of the project's key stakeholders' contribution for the durability design, unlike British and Eurocode, which allow them to apply their knowledge and experience following approval from the relevant authority.
- In general, the ACI 318 approach to durability is limited to prescriptive criteria for concrete materials and concrete cover based on environmental exposure conditions. Minimal provisions allowed for performance approach.
- 8. The ACI 318-19 code allows for use of stainless steel and other corrosive resistance reinforcement, however, no guidance for the cases where they should be employed.

- Akali Silica reaction and carbonation are very detrimental factors for concrete structures; however, Alkali Silica reaction is mentioned minimally, and carbonation is not considered in the ACI 318 code.
- 10. The code relates the amount of minimum compressive strength with the requirements for durability. These are unrelated elements, and concrete durability is independent of concrete strength.
- 11. Freezing and thawing provisions are fragmented. Provisions include exposure categories that are subdivided into classes. Mainly, usage of air entrained, higher strength and SCM in a prescriptive approach.
- 12. Sulphate attack provisions are dispersed throughout the code; they are prescriptive according to the water cement ratio and the maximum permitted value of compressive strength, whereas the types and quantities of cementitious materials are performance oriented.
- 13. The corrosion resistance of the reinforcement does not align with the ACI 318 durability standards for a specific concrete cover. The document's requirements for various materials are covered in several chapters, without any cross-references that a licensed design professional might use to view them as a system.
- 14. Considerations for crack control and design detailing are not included in ACI 318's provisions of durability.
- 15. The properties of the reinforcement are discussed independently rather than in conjunction with the concrete cover.
- 16. There are no explicit specifications to directly assess or estimate a system's resistance to chloride exposure and/or sulfate resistance over time.
- 17. There is no guidance for complex, specialized structures, or service environments with a mix of chemical and mechanical demands.
- 18. There are no provisions in the Code for particularly severe exposures, such as chemical contact, high temperatures, temporary freezing and thawing during construction, abrasive conditions, or any unique durability issues relevant to the structure.
- The code does not address aesthetics such as final surface finish, this should be specified in the project documents.

20. No examples given for exposure conditions apart from F&T.

Overall, we can conclude that the durability design requirements and recommendations are not comprehensive, not direct, do not encompass extended situations, fragmented, and are not unified or integrated, durability provisions are too simple and insufficient to provide a new structure design that can withstand the aggressive environment for the desired long lifespan .This is a major concern for code practitioners, when compared to other international codes, the code does not provide appropriate direction for durable structural design.

8.6 Challenges for the improvement of next ACI code generation

In addition to the results stated above, one can draw the following conclusions concerning the challenges that might arise when processing new code publications:

- 1. How to improve durability design without compromising the simplicity of interpretation or construction costs.
- 2. Which method shall be adopted to improve the overall durability of concrete and steel components.
- 3. The code has a prescriptive and safety orientation, performance specifications need to be included as well, shall the code include it with the prescriptive specifications or to issue a complimentary performance code document?
- 4. Identifying a reasonable line across structures that require "ordinary" levels of durability and those that demand higher design and construction effort to attain durability in a given environment for a specific amount of time.
- 5. Numerous international codes and standards acknowledge that maintenance and future repairs will be required over a structure's operational life. How can ACI improve the integration of documents created for new designs and existing structures?

CHAPTER 9. RECOMMENDATIONS

This study investigated the durability approach in the ACI 318-19 code and the code provisions addressing it in comparison with other international codes and standards. Many gaps were discovered, and since the development of the new generation of ACI codes is underway, this comparative assessment can be used as a starting point for amendment, and it provides a comprehensive, beneficial review of the situation on durability design in international codes and standards.

Based on the investigation findings, new provisions and criteria should be added to the ACI 318-19 code to make it a more comprehensive and integrated international document, and other complementary documents can be created, but it is preferable to integrate all durability requirements in one document, unless it affects ease of use and interpretation confusion.

The followings are recommended to be included in the next ACI 318 code:

- 1. Terminology related to durability and service life should be standardized. This simple improvement can be done using the suggested table 14 as a starting point.
- 2. Exposure conditions to be extended for a more comprehensive environmental condition. Tables 15 to 18 provides beneficial guidance to begin this improvement.
- 3. Performance-based specifications should be included, either as a complementary document to the code or by expanding chapter 19, or by introducing a new chapter. This document enhancement should assist the design practitioner and construction team on performance metrics to improve durability, as well as direct the construction team on how to safely exceed the prescriptive limits if necessary. If a supplementary performance document is considered, it should be cross-referenced within ACI 318 code.
- 4. The code should enable a hybrid design approach (performance and prescriptive) to benefit from the advantages of durability design, as previously discussed.
- 5. A survey can be created and disseminated to key project stakeholders to assess their degree of understanding of durability design and to analyze their feedback and input

for the guidelines required to achieve durability and intended service life.

- 6. Strength requirements should be revised because this value is unrelated to durability and is independent of it.
- 7. Further research into a method of testing or modeling for saturation to assign appropriate exposure classes F1 and F2.
- 8. Harmonized values for durability standards in ACI standards; w/c ratio, strength, chloride restrictions, and so forth should be developed.
- 9. Clarify the definition of "moderate" in the EC2 code in the freezing and thawing exposure classes, as some countries regarded it as less than the critical degree of saturation and classified it as XD3, resulting in structures constructed for a different exposure. There should be a precise criterion.
- 10. The ACI 318 code should combine concrete cover with reinforcement details and place them in the durability design section.
- 11. Further research should be conducted to develop criteria for directly assessing or estimating a system's resistance to chloride exposure and/or sulfate resistance over time.
- 12. Extend the ACI code to include complicated, specialized constructions or service environments that require a combination of chemical and mechanical demands, extreme exposures, and aesthetics.
- Comparison and Critique review of Durability Provisions and Design Requirement of Various International Design Codes and Standards.
- 14. ASR and carbonation are to be addressed in the studied codes.
- 15. The addition of the new exposure classes as discussed in the British and Eurocode.

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APPENDIX A. KEY DURABILITY PROVISIONS FOR OTHER NATIONAL CODES

A1. Australian CIA 27/01. Durability Planning - 2014

PROVISION DESCRIPTION

REFERENCE

1.4	Durability knowledge is widely documented and constantly updated to reflect new advances around the world. However, no level of durability planning has been used in the design, construction, and maintenance stages to reduce the danger of early deterioration.
2.1	Throughout the project delivery, a durability philosophy will enable capital investment optimization, safety from unforeseen damage, and sustainability through suitable design, construction, and maintenance methods to achieve the asset owner's planned service life and quality of service.
2.3	In extreme exposure conditions, design, and construction to National or International Standards may not accomplish the asset owner's specified design life. Codes do not cover all environmental exposure situations, and unique site micro exposure conditions can be more severe than general exposure conditions, necessitating a durability study.
2.6	Summarize listings of critical tasks linked to durability best practices at various stages of project development and implementation.

3	The purpose and benefits of durability planning are presented for
	stakeholders (Asset Owner, Designer, Contractor, Operator/Maintainer of
	Asset).
4	Table 4.1 summarizes the difference between design life and service life
	using Australian standards, while Table 4.2 provides suggestions on how
	to rationalize which structures merit longer service lives and more
	extensive planning.
5-8	Section 3 includes a detailed discussion of the goals, potential hazards, and
	possibilities for each stage of design and construction.
APP. A	Key durability deliverables and processes are illustrated.
APP. B	An example of a durability checklist is depicted.
APP. C	The inclusion of reliability into durability design is demonstrated.

A.2 Canada Standard. Concrete materials and methods of concrete construction/Test methods and standard practices for concrete A23.1/23.2

Core Feature 1: The owner may use exclusive materials or methods of construction as long as the quality meets the minimum standards of this Standard.

Core Feature 2: A23.1 is a framework document for the A23.2 document and its 45 related test procedures and methodologies. A23.1 only applies to cast-in-place and field precast concrete. Plant made precast concrete is governed by A23.4. Additional CSA S413 standards apply to parking garages. CSA 448.1 governs the repair of concrete structures.

Core feature 3: Subclause 4.1.1 sets prescriptive durability standards, but encourages the use of high-quality materials, rigorous quality control, and good concrete execution. Historical data can be used to qualify materials and concrete mixes.

REFERENCE DESCRIPTION

4.1.1.1	Concrete that will be exposed to weathering, sulphate attack, a corrosive
	environment, or any other degradation process described by this Standard
	in service must meet the requirements of Clauses 4.1.1.1 to 4.1.1.10 and
	7.4 and Tables 1 to 4 and 19, as applicable.
8.1.3	Special performance or material requirements, when mentioned, take
	precedence over other applicable sections of this Standard. Each relevant
	phrase, where applicable, shall cover the selection of mix components,
	quantities, concrete quality, concrete production, putting, and/or curing.
SEVERAL	Tables 1–4 and 17 define various classes of concretes and requirements
CLAUSES	that are generally prescriptive. Table 5 shows alternative specification
	alternatives, including owner-directed options that eliminate the engineer.