An international perspective on performance-based specifications for concrete durability, with a suggested framework for implementation

Prepared by:

Florah Mosoy

Supervised by:

Emeritus Prof Mark G Alexander

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Department of Civil Engineering
University of Cape Town, Private Bag Rondebosch, 7700
South Africa 7700

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Abstract

Reinforced concrete (RC) is one of the world's most durable building materials. However, outdated and insufficient durability specifications often lead to the early deterioration of RC structures, escalating global maintenance costs. Prescriptive durability specifications for reinforced concrete (RC) often include mix design parameters such as minimum cement content and maximum water/binder ratio, which are intended to contribute to durability. However, achieving a specific compressive strength alone does not guarantee durability. These rigid regulations stifle innovation in design and construction and often fail to capture the durability characteristics of modern concrete. Even if a mixed design complies with specifications, it may not achieve its intended service life under varying exposure conditions.

This study establishes an international perspective on using performance-based specifications for concrete durability, contrasting them with the commonly used prescriptive-based specifications. Performance-based approaches allow for customizing concrete mixtures to meet specific performance goals by focusing on measurable properties that ensure performance under particular conditions. These requirements can be applied to various stages, including design, service life modelling, specification, pre-qualification, and conformance evaluation.

The study involved a review of current durability provisions in selected standards from the USA, Canada, Australia, Europe, India and South Africa, followed by an analysis of performance-based specifications implementation in these countries. Key factors influencing the adoption of performance-based specifications, such as regulatory frameworks, industry practices, and environmental exposure classification systems, were examined.

The study proposes a practical framework for adopting performance-based specifications for concrete durability, covering aspects such as verifying environmental exposure conditions, concrete cover requirements, material constituents, alternative cementitious materials, testing methods for performance specification and also regulatory framework. This framework aims to educate professionals on the practical implications of performance-based specifications and promote its adoption for enhancing the durability and sustainability of concrete structures.

By addressing these elements, this study provides a framework to establish a structured, adaptable approach that ensures concrete structures meet desired durability and service life requirements under specific environmental conditions. This framework prioritizes measurable performance criteria over rigid prescriptive measures, enabling tailored concrete mix designs that address exposure conditions, material quality, and maintenance expectations. By doing so, the proposed framework promotes innovation, sustainability, and cost-effectiveness in concrete construction, ultimately enhancing structural resilience and reducing long-term repair and maintenance costs.

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Special thanks to my mother, Esther Msaky, for her unwavering belief in me and for teaching me the values of hard work, unconditional love, support, understanding, perseverance, and faith.

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Glossary

Concrete Cover	The thickness of the reinforcement steel between it and the nearest concrete surface acts as a barrier to harmful substances.
Design Service Life	The intended period when a concrete structure is expected to function at its required performance level without significant repairs or replacements.
Durability	The ability of a material structure to withstand wear, pressure, or damage over time while maintaining its intended function.
Performance Specifications	A set of clear, measurable, and enforceable guidelines that specify the functional requirements for hardened concrete based on its intended application. This category contains both hybrid and performance-based specifications.
Performance-Based Specifications	Specifications that use durability indicators through Performance Test Methods (PTMs) and measurements linked to Service Life Models (SLMs) to estimate the Design Service Life (DSL).
Prescriptive Specifications	A detailed set of instructions defining the materials, methods, and procedures used in a construction project.
Specifications	Detailed documents outlining project requirements, standards, and guidelines. They specify the materials, methods, performance criteria, and quality standards that must be met to ensure that the project or product serves its intended purpose and functions correctly.
Standards	Documents governing and overseeing various aspects of the construction industry. They specify the technical requirements for materials, procedures, equipment, and testing methods to ensure intended performance.

Acronyms and Abbreviations

ACI	American Concrete Institute
AS	Australian Standard
ASTM	American Society for Testing Materials
BIM	Building Information Modelling
BS	British Standards
CCI	Chloride Conductivity Index
CSA	Canadian Standards Association
COTO	Committee of Transport Officials
DI	Durability Index
DSL	Design Service Life
EN	European Standard
IS	Indian Standard
PAPV	Prescriptive Approach with Performance
PBS	Performance-Based Specification
PERFDUB	Approche PERFormantielle de la DUrabilité des ouvrages en Béton
PTMs	Performance Test Methods
RC	Reinforced Concrete
SANS	South African National Standards
SANRAL	South African National Road Agency Limited
SCMs	Supplementary Cementitious Materials
SLMs	Service Life Models
W/B	Water to binder ratio
W/CM	Water to cementitious material ratio
WSI	Water Sorptivity Index

1. Introduction

1.1 Background

Reinforced concrete (RC) is known as one of the most durable construction materials in the world (Mutheiwana, 2013). Still, early deterioration of RC structures can, in some measure, be traced back to inadequate and outdated durability specification requirements. While RC has a high compressive strength (Grantham, Majorana & Salomoni, 2019), maintenance and upkeep costs of concrete structures worldwide are increasing rapidly.

Concrete durability depends on its constituents and their properties, curing period, workmanship, and exposure environment. The production method, compaction, placing and curing of concrete are just as crucial to long-term durability as the materials used for production. There is also a misconception that the concrete strength is directly proportional to its durability. However, research has shown that the permeability of the concrete matrix is just as important (Mehta, 1991). Therefore, the approach for concrete specifications for durability is seen as one of the areas where an improvement can be made, particularly by shifting from traditional prescriptive methods to performance-based specifications that more directly address long-term service life requirements.

Historically, the durability of concrete was based on prescribed limiting values for selected mix design parameters, such as water/binder ratio, cement content, and compressive strength. Prescriptive requirements often fail to resemble the durability characteristics of modern concrete types and hinder innovation and economic and ecological design and construction (Beushausen, Torrent & Alexander, 2019). This is because prescriptive specifications often disregard using various admixtures, aggregate types, and alternative binders and do not consider site construction practices (Beushausen, Torrent & Alexander, 2019). Prescriptive specifications continue to dominate in civil engineering practice despite their conservativeness that leads to fewer chances to optimise concrete production costs and compromising sustainability in the long term. In addition, while prescriptive standards provide simplicity, they often fail to account for the complexity of modern engineering challenges, including the need for extended service life, varying environmental conditions, and the push for more sustainable, high-performance concrete structures. This rigidity may lead to premature deterioration, limited adaptability to local conditions, and inefficiencies in materials usage. It is a fact that even if a mixed design is compliant with specifications, it can fail to meet its allocated service life based on its exposure conditions. Therefore, prescriptive approach does not guarantee stated durability.

Performance-based specifications (PBS), on the other hand, are based on specified performance criteria, i.e., measurable concrete properties that can assist in ensuring the performance of concrete under a particular exposure condition. Performance approaches can be applied at various stages and for multiple purposes, including design, specification, pre-qualification, and as-built structure conformity assessment (Beushausen, 2016). Removing the limit on the types of materials used for concrete mixes and their proportions allows for tailor-

made concrete mixtures that focus on specific performance objectives (Kurtis, Kahn & Nadelman, 2013). PBS also allow for innovation in the mix design for concrete. However, the practical implementation of performance-based concrete specifications is still a challenge to overcome.

Globally, there is a movement to adopt PBS and research is also being conducted to evaluate the viability of PBS in construction projects (Mosier & Yoon, 2023). Efforts such as the French Approche PERFormantielle de la DUrabilité des ouvrages en Béton (PERFDUB) program and the Prescription to Performance specifications (P2P) initiative of the US National Ready-mix Concrete Association (NRMCA, 2024) (Linger & Cussigh, 2018) and also the joint effort between the Georgia Department of Transport in the USA in collaboration with the Georgia Institute of Technology were instrumental in their countries (Kurtis, Kahn & Nadelman, 2013).

Some countries have started to implement performance-based durability design into their standards. For example, in Canada, Switzerland, and South Africa, elements of PBS have already made their way into particular national standards (Beushausen, Torrent & Alexander, 2019). Nevertheless, implementing PBS has yet to be widely adopted (Dlamimi, 2019). There are difficulties in selecting the test parameters used to evaluate performance, an area needing more research. Also, the need for standardisation of tests used to measure the performance of the concrete will have to be addressed.

Since there are minimal adoption strategies or standardisation for adopting performance-based approaches, this dissertation will investigate the strategies for the adoption of PBS.

1.2 Problem statement

Despite the recognized benefits of Performance-Based Specifications (PBS) for enhancing concrete durability, flexibility, and sustainability, their global adoption remains slow and inconsistent, particularly in practical applications and integration into local standards. This disconnect between the theoretical potential of PBS and its widespread implementation constitutes a significant problem, as prescriptive specifications, which provide rigid guidelines for materials and methods, continue to dominate civil engineering practice but often fail to address the complexities of modern engineering challenges, leading to premature deterioration and inefficiencies. The slow transition to PBS is compounded by considerable technical, regulatory, and economic barriers, including the lack of standardized and reliable testing methods, resistance to change within the conservative construction industry, regulatory complexity across different jurisdictions, uncertainty surrounding long-term performance validation, and the initial costs associated with specialized testing and expertise, hindering a unified and effective shift towards more durable and adaptable concrete structures worldwide.

This dissertation aims to address this gap by studying the global adoption of PBS. The study will involve the exploration of existing standards around the world, such as AS 3600 (2009), AS 1379 (2008), ACI 318 (2019), CSA A23.1/23.2 (2019), BS 8500-1: 2015+A2:2019, IS 456 (2000), fib Model Code 2020 and COTO (2020), to grasp the current state of durability specifications and analyse how prescriptive and PBS are being applied in practice. By reviewing

these standards, the project will seek to trace the development of PBS over time and analyse their trends towards more performance-based approaches. Additionally, the study will explore case studies to dissect notable implementation strategies used during the adoption of PBS from regions where PBS has been implemented successfully, such as Europe and South Africa. These case studies will offer valuable insights into the evolution of PBS and the practical strategies that facilitated their adoption.

1.3 Study Objectives

1.3.1 Aim

To perform a review of international practices in performance-based specifications for concrete durability and to propose a practical framework aimed at facilitating wider, effective adoption.

1.3.2 Objectives

i) To review and compare performance-based and prescriptive specifications.

ii) To investigate international trends in PBS.

iii) To analyse the implementation process of PBS in selected countries

iv) To create a practical framework allowing the implementation of PBS for concrete durability.

1.4 Study Questions

i) What justifies the use of PBS for ensuring the durability of concrete?

ii) What are the international trends on PBS?

iii) What methods are used to implement PBS for concrete durability?

iv) What challenges are faced when implementing PBS in practice?

v) How can a practical framework for adopting PBS for concrete durability be developed?

1.5 Study Assumptions

i) It is assumed that key international standards and relevant published case studies regarding PBS are sufficiently accessible for comprehensive review.

ii) It is assumed that the underlying principles of concrete durability and PBS concepts are sufficiently coherent across different regions to allow for meaningful comparison and synthesis, despite variations in specific test methods or regulatory details.

iii) It is assumed that the reviewed standards and literature accurately reflect the documented practices and state of knowledge at the time of their publication.

1.6 Scope and Limitations of the Study

This study focuses on PBS for concrete durability, comprehensively comparing it with traditional prescriptive-based approaches. The research encompasses an extensive review of existing specifications and guidelines related to concrete durability from various countries, including Australia, Europe, the United States, South Africa, India, and Canada. It examines the implementation of PBS in different countries, highlighting successful approaches and challenges encountered. In addition, the fib Model Code 2020 is also reviewed. The study proposes a practical framework for implementing PBS, including strategies for adaptation to specific exposure conditions and environmental classification systems. Furthermore, it explores the factors driving PBS adoption, such as sustainability demands, durability requirements, and economic efficiency. The research analyses performance test methods (PTMs) used to assess concrete durability and considers the roles and responsibilities of concrete producers, engineers and contractors in implementing PBS.

While this study offers valuable insights into PBS for concrete durability, it is essential to acknowledge its limitations. The research primarily focuses on specific countries, with selection based on relevance and the availability of source materials. As such, the findings of this research are by no means exhaustive. The study is based on a literature review and existing specifications, so it may not capture the most recent developments or unpublished industry practices. The availability and accessibility of data on PBS implementation in different countries may have limited the depth of analysis in some areas. The proposed framework may also require further validation through extensive field testing and long-term performance monitoring.

1.7 Layout of the Dissertation

Chapter 1: Introduction

The chapter provides an overview of the emergence of PBS for concrete durability, contrasting it with traditional prescriptive-based approaches. The chapter begins by highlighting the critical importance of concrete durability. It provides background on the historical dominance of prescriptive specifications, which have often been inadequate in meeting the evolving demands of modern construction. The problem statement emphasizes the slow global adoption of PBS despite its demonstrated advantages, particularly in infrastructure projects requiring long-term durability. The research objectives are focused on reviewing and comparing both specification methods, examining international trends, and analysing case studies from regions such as Europe and South Africa where PBS has been successfully implemented.

Chapter 2: Review of Prescriptive and Performance-Based Specifications

This chapter explores performance and prescriptive specifications for concrete durability, beginning with an overview of concrete durability and deterioration mechanisms. Doing so establishes a foundational understanding of RC durability and the corresponding durability specifications. It introduces key concepts such as the durability of concrete, different forms of deterioration mechanisms, and the transport mechanisms that influence the ingress of harmful agents.

The chapter then focuses on concrete specifications, exploring the current state of PBS and the traditional prescriptive-based approach. The section on concrete specifications provides an overview of the evolution from early prescriptive methods, which rely on fixed material compositions and construction practices, to modern PBS that emphasize concrete structures' long-term durability and performance based on measurable outcomes. Reviewing existing durability and concrete specifications, this chapter highlights the limitations and advantages of traditional methods and PBS.

Chapter 3: Review of Current Durability Provisions in Selected Standards

Chapter three presents a literature review on concrete durability standards, examining key specifications from AS 3600 (2009) and AS 1379 (2008) from Australia, ACI 318 (2019) from the United States, CSA A23.1/23.2 (2019) from Canada, BS 8500-1: 2015+A2:2019 from Europe, IS 456 (2000) from India, fib Model Code 2020 and COTO (2020) from South Africa. Examining the durability provisions highlighted critical areas within the specifications relevant to the discussion, and it is evident that while some specifications have integrated aspects of PBS, this integration remains very low. The chapter explored PTMs for assessing durability and details roles, collaborative design practices, compliance through penalty mechanisms, and quality assurance. The review highlights aligning materials and exposure conditions with performance-based approaches to enhance durability.

Chapter 4: Implementation Process of Performance-Based Specification in Chosen Countries

This chapter explores the implementation of PBS for concrete durability worldwide, addressing the growing demand for PBS in modern construction. It begins by detailing drivers for PBS adoption, including the need for sustainable infrastructure, improved durability, environmental responsibility, innovation, and cost-effectiveness. The chapter reviews various countries' strategies for PBS implementation, highlighting successful cases and identifying essential factors for success, such as a well-defined framework, strong stakeholder collaboration, practical performance criteria, and standardized testing methods. Several implementation strategies are discussed, including the durability index approach from South Africa, The equivalent performance method and the prescriptive approach with performance verifications. Challenges in adopting PBS, such as limited stakeholder involvement, lack of expertise, regulatory hurdles, and variability in concrete materials, are also discussed. This chapter serves to identify effective

strategies for PBS implementation and their associated challenges so that this information can be used to create a practical framework for the implementation of PBS.

Chapter 5: Practical Framework to Implement Performance-Based Specification for Concrete Durability

Chapter 5 outlines a practical framework for implementing PBS for concrete durability based on an analysis of current specifications and requirements. This chapter utilises the work done in previous chapters and supplements it with the attempts of past researchers to establish a practical framework for adopting PBS. It examines existing parameters like concrete strength, cement content, water-to-cement ratio, and cement types for various exposure conditions and the impact of concrete cover on durability. The chapter recommends an environmental classification system to tailor PBS to specific situations, ensuring durability aligns with environmental demands. Emphasis is placed on selecting effective PBS strategies and testing methods to assess performance accurately. Additionally, an emphasis is placed on the reliability of performance tests. As a consequence, the framework suggests a comprehensive testing regimen that combines both the on-site tests and laboratory tests.

Chapter 6: Conclusion and Recommendations

The final chapter concludes with a summary of general observations, recommendations, global trends and future directions. Recommendations were made to raise PBS awareness, foster global knowledge-sharing platforms, and standardize performance tests. The chapter then discusses global trends in PBS implementation, including the standardization of testing methods and international standards. It advances materials, testing, and data analytics, which is vital for future PBS adoption.

2. Prescriptive and Performance-Based Specifications for Concrete Durability: A Review and Analysis

2.1 Review of Concrete Durability and Deterioration

2.1.1 Concrete Durability

Concrete is the most common and widely utilised construction material globally due to its low cost, versatility, and adaptability (Sangoju et al., 2021). It offers various choices regarding structural type, shape, and surface aesthetics. It is a cheap construction material. Concrete durability depends on its constituents and their specifications, curing period, construction workmanship, and exposure environment. The production method, compaction, placing and curing of concrete are just as crucial to long-term durability as the materials used for production. Concrete durability depends on achieving several critical material properties, including low permeability, resistance to chloride penetration, carbonation, and freeze-thaw cycles, as well as resistance to alkali-silica reaction (ASR), shrinkage, and creep. Additional important properties include low surface absorption, good abrasion resistance, and proper finishability. If these properties are not adequately met, the concrete may suffer both structural and aesthetic issues. Structurally, this can result in reinforcement corrosion, cracking, strength loss, long-term deformation, and a shortened service life. Aesthetically, deficiencies in durability properties may lead to visible cracking, discoloration, staining, efflorescence, surface roughness, and an overall poor visual finish, all of which can compromise the appearance and perception of quality in a structure.

The durability design of RC structures should ensure that the structure, as built and in its design environment (exposure conditions), can withstand various aggressive influences for the duration of its design life (Alexander & Beushausen, 2019), justifying the economic investment and meeting the serviceability requirements (Jandová & Vít, 2020). To ensure the structure's durability, durability design involves selecting appropriate materials and structural details (Jandová & Vít, 2020). It requires balancing material properties, environmental factors, and maintenance considerations to create resilient structures that resist deterioration without excessive maintenance costs.

2.1.2 Concrete Deterioration

Concrete structures are subjected to a wide range of aggressive environments and harmful substances. Structures in contact with ground waters, soils or waste waters may be subject to sulphate attack; harbours and other coastal facilities are exposed to seawater with a combined action of magnesium, sulphates and chlorides. As a result, dams, water pipelines, and other structures exposed to soft or carbonated water suffer leaching or become carbonated (Alexander,

Bertron & Belie, 2013). Exposure to these conditions may cause the deterioration of concrete. The numerous interconnected factors depend on the environment's aggressiveness, nature, and physical and chemical processes; these processes are never independent. Figure 2-1 illustrates the causes of concrete degradation, including physical, chemical, biological, and corrosion processes. Physical causes include thermal cracking, abrasion, shrinkage and scaling. Chemical causes involve internal alkali-aggregate reactions and external acid or sulphate attacks. Biological growth on concrete surfaces can also contribute to degradation.

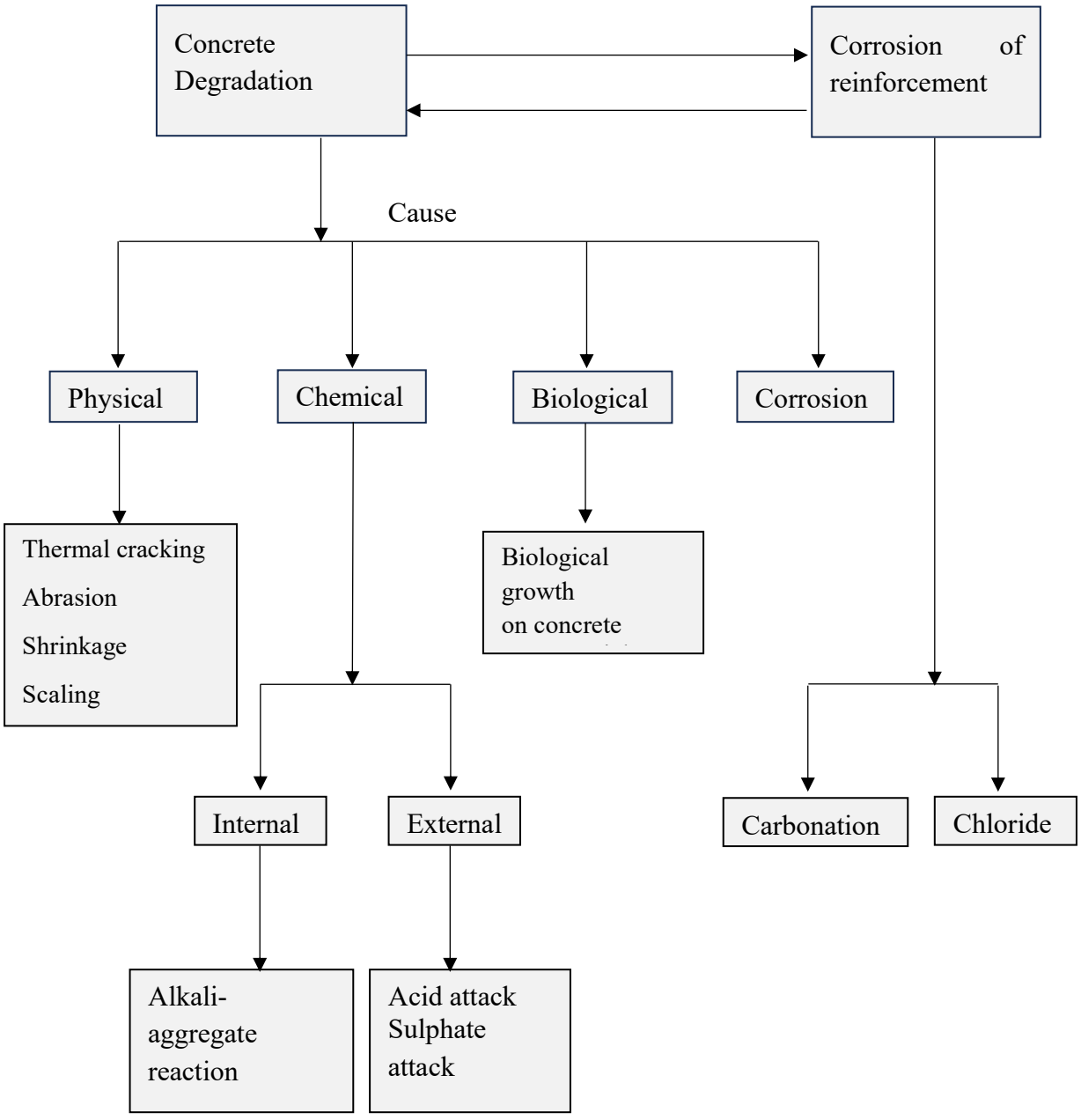

Figure 2:1: Overview of concrete deterioration mechanisms (Boumaaza & Linger, 2020)

Corrosion of the reinforcement embedded within the concrete is a significant cause of concrete degradation. Figure 2-1 provides a more detailed look at the outcomes of the transport processes outlined in Figure 2-2, showing how the movement of substances through concrete leads to various forms of degradation and reinforcement corrosion. These figures provide a comprehensive view of concrete durability issues, from the underlying transport mechanisms to the resulting degradation processes.

The processes that enable the passage of chloride ions, water, sulphate ions, carbon dioxide, oxygen, and electrical current within the concrete determine the phenomena that cause reinforced concrete to deteriorate (Bertolini, 2004). Most types of deterioration in RC structures, except for mechanical damage that influences cracks and easily permits penetrability, are connected to the transport mechanism through the cover concrete (Kropp & Alexander, 2007). In the following section, transport processes that affect the deterioration of RC structures are discussed with the aid of Figure 2-2.

2.1.3 Transport Mechanism

In concrete, four basic mechanisms can be used to explain how fluids and ions move through concrete: capillary action inside cement paste capillaries, permeation caused by a pressure gradient, diffusion caused by a concentration gradient, and migration induced by an electrical potential gradient. The mechanism of transport, the properties of the concrete such as its porosity and the presence of cracks, the binding of the substances being transported by the hydrated cement paste, as well as the environmental conditions present at the concrete's surface (microclimate) and their variations over time, all affect the kinetics of transport (Bertolini, 2004).

The transport mechanisms of water, gases, dissolved ions, and electrical currents significantly influence the durability and performance of concrete. The transportation depends on factors such as the concrete cover, the binding mechanism of the agent being transported, environmental conditions, and transport mechanisms. If the concrete cover structure is more open and connected, there'll be more space for transport and vice versa. Otherwise, the thickness and the integrity of the concrete cover will also decide the extent of transportation.

The binding mechanism in concrete significantly affects transport processes, particularly the movement of ions like chloride (Shazali et al., 2012). The availability of water and aggressive agents, temperature and pressure, pores filled with water, and electrical fields create the microclimate responsible for the variance in transport. Additionally, multiple transport mechanisms exist, including diffusion, capillary absorption, penetration due to hydraulic pressure, and electrical transport. One or a combination of these transport mechanisms will determine the absorption of a particular agent. Hence, the transport rate varies according to the specific transport mechanism involved.

Figure 2-2 provides a comprehensive overview of the factors influencing the transport of various substances, such as gases, water, dissolved ions, and electrical current through concrete. The diagram is structured as a hierarchical flowchart with four primary branches, each addressing critical aspects of the transport process. The first branch, concrete cover, emphasizes the physical

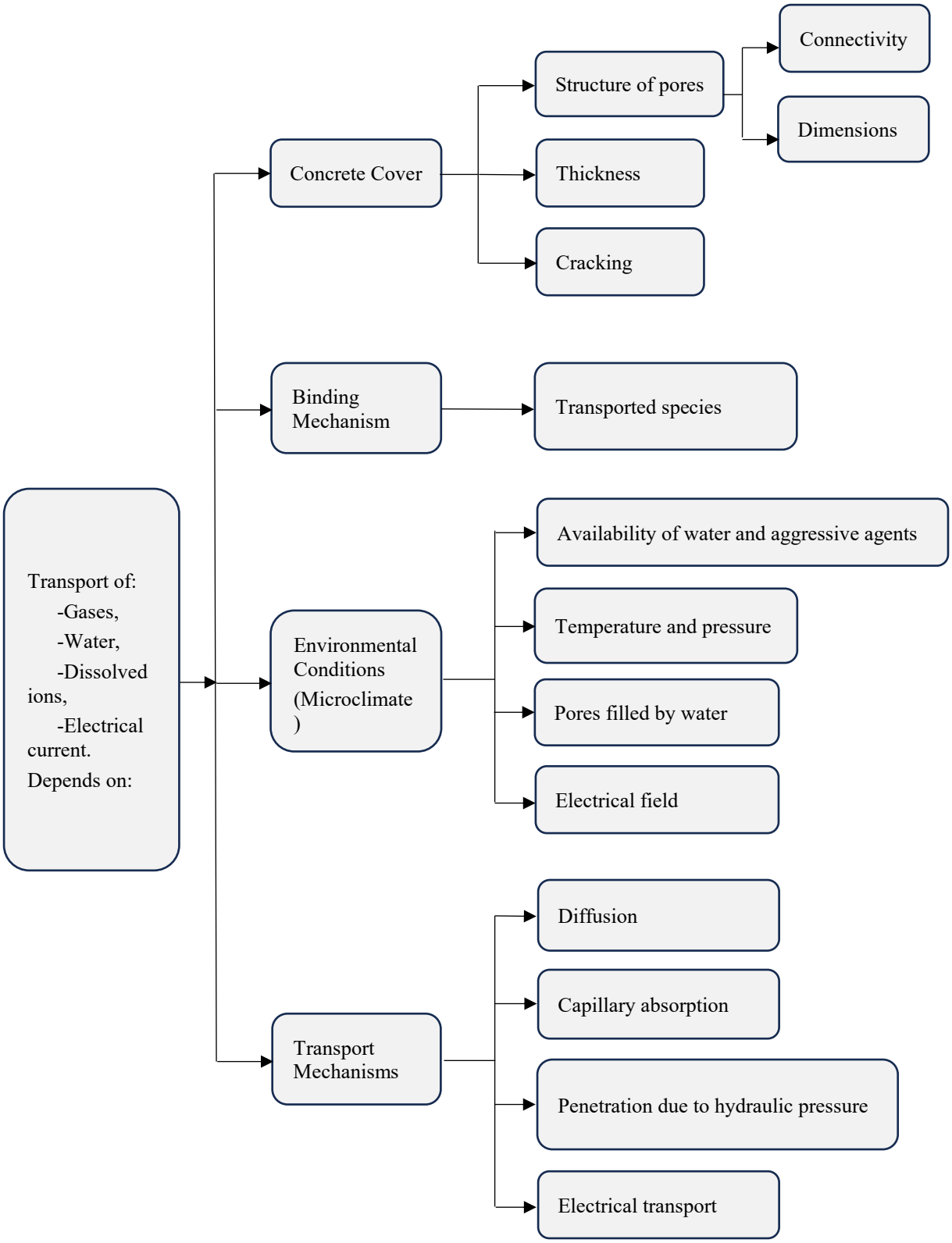

Figure 2:2 : Transport Processes in Concrete (Bertolini, 2004)

properties of the concrete cover, focusing on pore structure (connectivity and dimensions), thickness, and the presence of cracks. The second branch, binding mechanism, highlights the interaction between transported substances and the concrete matrix, suggesting that different species may bind within the concrete differently. The third branch, environmental conditions (microclimate), outlines external factors that affect transport, such as water availability and aggressive agents, as well as variables like temperature, pressure, water-filled pores, and electrical fields. Finally, the fourth branch, transport mechanisms, identifies the various modes through which substances move through concrete, including diffusion, capillary absorption, penetration driven by hydraulic pressure, and electrical transport. Overall, the diagram illustrates the complexity of substance transport through concrete, shaped by the material's physical properties, surrounding environmental conditions, and specific transport mechanisms. This understanding is essential for predicting and enhancing the durability and performance of concrete structures, particularly in aggressive environments (Gjørv, 2014). Understanding these interactions help to design concrete structures that resist degradation and maintain their integrity over time.

2.2 Concrete Specifications

2.2.1 Overview of Concrete Specifications

Concrete specifications play a crucial role in the construction industry, providing the guidelines and criteria to ensure that concrete structures meet the required safety, durability, and performance standards. Specifications are typically categorized into two main types: prescriptive specifications and Performance-based specifications (PBS).

Traditionally, most construction projects have relied on prescriptive specifications defining specific ingredients, proportions, and construction methods for concrete production and placement. This approach focuses on how the concrete is made and used, leaving little room for flexibility or innovation. Prescriptive specifications often dictate specific material requirements such as cement type, aggregate size, water-to-cement ratio, and detailed mixing, curing, and placement procedures.

However, as construction projects have become more complex and the need for sustainable, durable, and cost-effective solutions has grown, a shift towards PBS has emerged. Unlike prescriptive specifications, PBS focuses on the desired outcomes or performance of the concrete once it has been placed and cured. Instead of prescribing how the concrete should be mixed, PBS establishes performance criteria such as compressive strength, durability, permeability, and shrinkage, allowing contractors and engineers to choose materials and mix designs that meet these requirements.

This transition from prescriptive to PBS represents a significant shift in how concrete structures are designed and built. By focusing on the end results, PBS promotes innovation, encourages using alternative materials, and can lead to more efficient and sustainable construction practices. PBS allows for incorporating advanced technologies, such as high-

performance concrete (HPC) and supplementary cementitious materials (SCMs), to meet performance criteria while addressing environmental and cost concerns.

2.2.2 Early Concrete Specifications: Prescriptive Based Specifications

Current specifications are generally prescriptive, laying out methods, materials, processes, and procedures such as limiting values for binder content, w/b ratio, compressive strength, and amount of entrained air (Alexander & Beushausen, 2019) and providing instructions on completing the work. Prescriptive specifications for concrete focus on various construction processes from placement to curing and the properties of raw materials, mix proportions, batching, mixing and transport of fresh concrete (Bickley et al., 2015). Prescriptive-based specifications are based on specified or comprehensive information about the material's qualities and manufacturing processes to guarantee quality and inspection. Prescriptive specifications work on a "deemed-to-satisfy" basis, meaning that if the requirements of the specification are met, the structure is "deemed-to-satisfy" with the specifications for durability (Alexander & Beushausen, 2019).

Prescriptive-based specifications verify conformity with the standard; only compressive strength is assessed. This is carried out on standard samples, which must accurately reflect the circumstances of the actual structure when they are manufactured, cured, and loaded (Prince, Kerala & Kerala, 2022).

2.2.2.1 Advantages of Prescriptive-Based Specifications for Concrete Durability

i) Prescriptive-based approaches can be financially advantageous, as they frequently use standardised materials and construction techniques.

ii) Prescriptive-based design approaches offer a uniform and consistent approach to design; this helps guarantee that structures with comparable functions are constructed similarly.

2.2.2.2 Limitations of Prescriptive-Based Specifications for Concrete Durability

i) The requirements such as maximum water/cement (water/binder) ratio, air entrainment, chloride permeability limits, cover depth requirement, supplementary cementitious materials specification, Alkali-silica reaction mitigation measures are frequently difficult to understand.

ii) Inadequate information regarding exposure conditions

iii) They are often impossible to verify in practice and thus unenforceable.

iv) Only the compressive strength is typically evaluated after the concrete has been mixed and placed to ensure it adheres to the specifications.

v) The approach restricts adopting or developing new strategies and materials, preventing concrete innovation (Alexander & Beushausen, 2019).

2.2.3 Current Concrete Specifications: Performance-Based Specifications

PBS for concrete durability usually concentrates on the anticipated service life of the concrete structure. This service life depends on several variables, including the mix design, the curing process, the environmental exposures, and the intended usage of the structure. PBS for concrete durability includes measuring relevant concrete parameters during the design phase to evaluate the material's resistance to deterioration (Beushausen & Fernández Luco, 2015). Design approaches for performance-based durability are predicated on quantitative durability or service life estimates based on current exposure conditions and measured material properties (Beushausen, Torrent & Alexander, 2019). Proponents of performance specifications say, "Just tell me what you want to be done, do not tell me how to do it" (Hooton, 2006). PBS focuses on the desired outcome rather than describing the methods. This allows contractors flexibility and enables them to find the most efficient ways to achieve the required performance rather than being constrained by rigid instructions.

2.2.3.1 Advantages of Performance-based Specifications for Concrete Durability

i) Enhanced Quality Assurance

By focusing on durability outcomes, PBS allow for a more thorough evaluation of the structure's quality. This means the finished structure can be assessed based on its actual performance over time, and corrective actions can be implemented if the durability requirements are not met. This approach ensures that structures are built to last, with long-term resilience as a primary goal (Beushausen Hans, Torrent Roberto & Alexander Mark G., 2019).

ii) Relevant Testing Parameters

Performance-based approaches identify test parameters that directly relate to durability, such as the quality and thickness of the concrete cover over reinforcement. These parameters are critical for minimizing corrosion risks to embedded steel reinforcement and ensuring the concrete achieves its intended service life, especially in aggressive environments.

iii) Flexibility in Materials and Methods

Unlike prescriptive specifications, PBS impose no restrictions on the choice of materials, mix proportions, or construction methods. This openness encourages using innovative materials, design approaches, and construction techniques as long as they meet the defined performance standards. As a result, contractors and designers have greater freedom to experiment with eco-friendly materials and advanced construction technologies (Cement Association of Canada, 2021).

iv) Alignment with Sustainable Construction Goals

PBS support sustainability initiatives by promoting using materials and practices that reduce environmental impact. This approach aligns well with sustainable construction practices by focusing on the end performance rather than rigid procedures. It encourages using low-carbon materials, recycled content, and practices extending the structure's lifespan.

v) Crucial for Aggressive Environments

These specifications are necessary for structures expected to face severe environmental conditions—such as high salinity, freeze-thaw cycles, or chemical exposure—and for projects with significant social, economic, or environmental stakes. For such high-impact structures, PBS ensure that durability is thoroughly evaluated and optimized for specific conditions.

vi) Reliance on Key Performance Indicators

PBS establish benchmarks for essential performance indicators, including compressive strength, permeability, shrinkage, and resistance to alkali-silica reaction. These indicators are measured using standardized test methods with clearly defined acceptance criteria, providing a measurable and objective basis for assessing whether the structure will meet its intended durability and lifespan requirements.

2.2.3.2 Limitations of PBS for Concrete Durability

i) Test Method Reliability and Standardization

One of the primary challenges with PBS for concrete durability lies in the reliability and standardization of test methods. Many performance tests suffer from insufficient precision and reproducibility, with different laboratories often producing varying results for the same concrete mixture (Alexander & Thomas, 2015).

ii) Correlation with Real-World Performance

The correlation between laboratory test results and actual field performance presents another significant limitation. Laboratory conditions often fail to replicate the complex environmental conditions that concrete structures face accurately. Specifying and testing concrete at the supply stage and after placement and early hardening in the structure ensures a clear distinction of risks and responsibilities between the concrete supplier and the contractor (Alexander & Beushausen, 2019).

iii) Time Constraints

Performance testing of concrete faces significant timing challenges. The extended duration required for tests means results often arrive after concrete placement, making corrective actions impractical. Construction schedules rarely accommodate these lengthy testing periods, creating a fundamental conflict between quality assurance and project timelines.

iv) Economic Considerations

Performance-based concrete testing incurs substantially higher costs than prescriptive specifications due to specialized equipment, trained personnel, additional quality control measures, and potential construction delays.

v) Implementation and Enforcement

Performance-based concrete specifications face implementation challenges due to required technical expertise, unclear responsibility for non-compliance, complex verification testing, and resistance from conservative industry stakeholders.

2.2.4 Comparison Between Prescriptive and Performance-Based Specifications

Specifications play a critical role in ensuring structural integrity, durability, and cost-effectiveness in concrete construction. Traditionally, prescriptive-based specifications have been used, focusing on specific material properties and construction methods, such as mix proportions and curing processes. These specifications follow standardized procedures, emphasizing compliance through fixed criteria for material properties like compressive strength. While these rigid guidelines are straightforward to enforce and minimize risk for stakeholders, they restrict innovation and often result in higher long-term maintenance needs.

Conversely, PBS shift the focus from material properties to the structure's durability and performance over its service life under actual environmental conditions. This approach allows for more flexibility in design and material choices, encouraging innovation and using locally sourced materials, as shown in Table 2-1. PBS rely on durability indicators, like permeability and resistance to chloride ingress, which align closely with the demands of real-world exposure. This flexibility, however, introduces higher responsibility for contractors and designers, as it requires knowledge on deterioration mechanisms, advanced testing methods and careful monitoring to ensure end-performance compliance.

The comparison between prescriptive and PBS highlights a trade-off between immediate cost savings and long-term durability. Although PBS may incur higher initial costs due to comprehensive testing and monitoring requirements, the approach offers superior long-term value through enhanced durability and reduced maintenance needs by designing structures that inherently resist degradation. Conversely, prescriptive-based specifications, while more economical initially and more accessible to enforce due to standardized testing methods, may result in structures requiring more frequent maintenance interventions. This fundamental dichotomy in approach influences all aspects of construction, from risk allocation and innovation potential to ease of enforcement and overall project lifecycle costs.

Understanding the critical differences between these specification types as construction trends evolve is crucial for stakeholders aiming to balance cost, innovation, and structural longevity in concrete design.

Table 2-1: Comparison Between Prescriptive-Based Specifications and PBS

Key Features	**Prescriptive-Based Specifications**	**Performance-Based Specification**
Focus	Material properties and construction processes (e.g., mix proportions, curing)	Performance of the structure over its service life, based on in-situ conditions
Design Approach	Follows standardized procedures and predefined material compositions	Allows flexibility in design and material choices based on performance requirements
Key Parameters	Compressive strength; material proportions	Durability indicators (e.g., permeability, resistance to chloride ingress, carbonation)
Flexibility	Limited – materials and methods must meet rigid criteria	High – encourages innovation and use of locally available materials
Testing and Verification	Tests on standard samples, usually focusing on compressive strength only	Tests focus on in-situ performance and durability under actual exposure conditions
Innovation	Restricts the use of new materials or techniques	Promotes innovation in materials and construction techniques
Risk	There is less risk for stakeholders, as adherence to specifications ensures compliance	Shifts more responsibility to designers and contractors for end results
Construction Process	Emphasizes process control (mixing, curing, placement)	Emphasizes end-performance under real-world conditions
Ease of Enforcement	Easy to enforce due to standardized testing methods	More challenging due to the need for reliable performance-based testing
Cost	Often more economical, as it uses standardized methods and materials	Can be more costly due to additional testing and monitoring requirements
Maintenance and Service Life	This may result in structures needing more frequent maintenance or repairs	Structures are designed for durability, minimizing long-term maintenance costs

2.3 Conclusion

Concrete durability specifications ensure that RC structures can withstand aggressive conditions for their intended service life. This includes selecting suitable materials, workmanship, exposure conditions, concrete cover and construction techniques. Durability specification aims to satisfy economic and serviceability requirements, ensuring that the structure continues to function. The specification approaches utilised for concrete durability are frequently prescriptive-based specifications and PBS.

Prescriptive-based specifications focus on the materials, construction methods, and processes used in concrete production. They follow rigid, predefined criteria that ensure compliance through adherence to specific material compositions, curing methods, and other processes. The essential advantage of this approach is its simplicity and the ease with which it can be enforced, as it relies on standardized tests like compressive strength. However, its main drawback is that it offers limited flexibility, stifles innovation, and does not account for real-world exposure conditions or long-term durability. It also restricts innovative materials and methods, often leading to structures that may meet immediate strength criteria but deteriorate prematurely in the field due to unaccounted environmental factors.

On the other hand, PBS shift the focus from materials and processes to the overall performance of the concrete structure throughout its service life. This approach emphasizes durability, resistance to environmental factors, and long-term strength, allowing designers and contractors more flexibility in choosing materials and methods that meet specific performance criteria. While PBS encourage innovation and can lead to more durable structures, they require advanced testing and monitoring, which can increase upfront costs and the complexity of enforcement. Nevertheless, focusing on performance can lead to structures with improved durability, reduced long-term maintenance costs, and greater adaptability to varying environmental conditions.

3. Review of Current Durability Provisions in Selected Specifications

This chapter examines the current state of PBS durability in selected standards. The objective is to show the progress and possibly indicate future developments for performance-based durability specifications. This chapter will cover several important specifications from different standards, such as performance test methods (PTMs), a clear definition of the functional requirements for concrete producers and contractors, encouraging collaborative design of concrete mix design and materials selection between producers and contractors, quality assurance, material constituents and exposure conditions.

With the growing interest in PBS for concrete durability, several countries have adopted these specifications for concrete construction. Notably, the United States, Canada, India, Australia, and South Africa (SANRAL) have developed PBS for concrete structures to ensure enhanced durability. This chapter reviews current concrete durability provisions within standards from selected key countries and regions to provide a broad international perspective on the adoption and nature of Performance-Based Specifications (PBS). The selection of the United States (ACI 318), Canada (CSA A23.1/A23.2), Europe (BS 8500), Australia (AS 3600 & AS 1379), India (IS 456), and South Africa (COTO 2020) was based on several criteria. These include their significant global and / or regional influence on concrete standards and construction practices, the representation of diverse climatic and environmental exposure conditions relevant to durability, the illustration of varying approaches and stages in the adoption of PBS principles (ranging from established prescriptive codes incorporating performance elements to specific performance-based frameworks like the South African Durability Index method), and the relative accessibility of their standards and associated research literature. This selection aims to capture a representative range of current international practices and challenges in specifying concrete for durability. In addition, the fib Model Code 2020 will also be reviewed since it offers a broad perspective that transcends national standards. The following are the international trends in specifications for concrete durability for the selected standards from different countries and their rationale.

3.1 United States

The USA is a frequent model for other countries, often setting the standard for best practices. Its diverse range of climates provides a unique opportunity to examine how these standards effectively respond to the multifaceted challenges of varying environmental conditions.

The Prescriptive-to-Performance (P2P) initiative for concrete durability highlights the shift in the U.S. concrete industry from traditional prescriptive specifications towards performance-based approaches. According to the National Ready Mixed Concrete Association (NRMCA), the P2P initiative promotes PBS that define concrete quality based on measurable outcomes instead of fixed mix proportions or ingredients.

In conventional prescriptive specifications, durability is assumed to result from specific mix requirements like a set water-cement ratio or the inclusion of certain admixtures. However, these ingredients or ratios don't always translate to durable concrete, especially under different environmental conditions. On the other hand, performance specifications specify concrete properties that must be achieved, such as minimum compressive strength or resistance to chloride ion penetration, allowing producers flexibility in material selection and mix design to meet these criteria. This approach encourages innovation, potentially reducing costs and enhancing sustainability by optimizing resources.

The ultimate aim of the P2P initiative is to adapt these performance-based standards widely across the U.S., allowing for customized, durable concrete solutions that respond directly to environmental demands and infrastructure needs (Bickley et al., 2008).

3.1.1 American Concrete Institute (ACI 318:19)

Chapter 19, Table 19.3.1.1 of ACI 318-19, clause 19.3.1 outlines performance criteria related to concrete design and durability requirements. This section incorporates performance requirements focused on concrete durability, encompassing requirements for concrete subjected to sulphate conditions as per AST C1012, "*The Standard Test Method for length change of hydraulic cement mortars exposed to sulphate solution".* The specified sulphate limits and acceptance criteria are presented below.

- Moderate sulphate exposure class (SO) should have a maximum expansion of less than 0.10%
- Severe sulphate exposure class (S1) should have maximum expansion between less or equal to 0.10% to less than 0.20%.
- Very severe exposure class (S2) should have maximum expansion between less or equal to 0.20% to less or equal to 2.0%.
- Extreme exposure class (S3) should have maximum expansion greater than 2.0%

Per ACI 318-19, specifically clause 26.4.1.1.1, the building code requirements for structural concrete advise using hydraulic cement that adheres to AST C1157. This specification encompasses cements designed for both general and specialized applications.

An advance is being made with alternative cement materials to concrete mixtures. However, the proposed concrete mixture, formulated with alternative cement, must undergo rigorous testing to verify its compliance with the structural, fire, and durability performance requirements specific to the application before it can be approved. It is possible that some alternative cement will not work well with the structural concrete. As a result, specifications are provided for assessing the suitability of substitute cement, as explained by the ACI318-19 clause R26.4.1.1.1 (b), which encourages concrete construction licensed design professionals to adopt new technologies reasonably and thoughtfully.

3.2 Canada - Canadian Standards Association (CSA A23.1:19/CSA A23.2:19)

Canada's climate has a wide range of extremes. In the northern regions and areas like the Yukon and Northwest Territories, winter temperatures can drop below -40˚C. In the southern regions, such as southern Ontario and the Prairies, summer temperatures can exceed 35 ˚C. Besides that, Canada also has significant seasonal variability and extremes in precipitation. This variability demonstrates how Canada's climate spans from one extreme to another, making it challenging for RC durability design. Testing concrete performance in various weather scenarios is crucial to creating specifications to ensure that structures can withstand temperature changes and freeze-thaw cycles, among other challenges. It can be argued that adopting PBS to make durability design more efficient and cost-effective would be desirable in a region like this. Nevertheless, the CSA A23.1/A23.2. is still majority prescriptive.

3.2.1 Alternative Methods for Specifying Concrete

The standard provides valuable insight into the concept of performance specifications, highlighting their applicability when the owner requires the concrete supplier to take responsibility for the concrete's performance upon delivery. Conversely, it places the contractor in charge of assuming responsibility for the concrete's performance after it has been placed. This approach offers a balanced division of responsibilities, ensuring that concrete performance is rigorously addressed at every stage of the construction process.

A thorough list of possibilities is provided in Table 3-1, based on CSA A23.1/A23.2. It clearly defines the duties and responsibilities of the parties involved, ensuring that the project will be approached in a well-structured and planned way.

This comprehensive guideline delineates the distinct roles and responsibilities assigned to each participant within the construction industry. It expounds upon the essential coordination among them to guarantee the final product aligns with the established performance criteria and that quality control processes are harmonious and indicative of compliance.

For instance, clause 4.1.2.2 of the standard stipulates that the contractor must thoroughly review project specifications before concrete ordering. Achieving successful specifications and concrete supply necessitates a collaborative effort involving the owner, contractor, and supplier. This collaborative endeavour should encompass a high level of communication, encompassing the provision and assessment of pertinent documents and preconstruction meetings.

3.2.1.1 Owner

The owner oversees crucial aspects of the construction process, including additional performance and certification requirements and structural and durability requirements. Under the owner's supervision, the project's structural integrity is guaranteed to meet all requirements, such as strength at various ages and durability under specific exposures. The owner safeguards the longevity and safety of the structure, both necessary for its intended use, by putting these

standards in place. Additionally, the owner's input goes beyond structural concerns, including general needs, specific performance volume stability, sustainability targets, and architectural specifications.

This all-encompassing strategy promotes unity between the project's goals and the produced results, guaranteeing that the end product satisfies expectations for both functionality and aesthetics. Additionally, the owner's active involvement in construction encourages effective quality control methods. By defining certification requirements and quality assurance protocols, they uphold accountability and conformity to industry standards while lowering the risk of mistakes, hold-ups and costly rework. Ultimately, the owner's active participation ensures the project meets its sustainability, quality, safety, and functionality objectives. Their involvement is essential to the project's success at every level because it promotes accountability, alignment, and, ultimately, the creation of a well-built and long-lasting construction project. This commitment to excellence helps bridge the gap between vision and reality.

Table 3-1: Alternative Methods for Specifying Concrete based on CSA A23.1/A23.2.

Owner	Contractor	Concrete Producer
Required structural criteria include strength at age. Required durability criteria, including the class of exposure. Additional criteria for durability, volume stability, architectural requirements, sustainability and any additional owner performance, pre-qualification, or verification criteria. Quality management requirements. Whether concrete producers shall meet certification requirements of concrete industry certification programs. Any other properties that might be required to meet the owner's performance requirements.	Work with the producer to establish concrete mix properties to meet performance criteria for plastic and hardened concrete, considering the contractor's criteria for construction and placement and the owner's performance criteria. Submitting documentation demonstrating that the owner's pre-qualification performance requirements are met. Prepare and implement a quality control plan to ensure the owner's performance criteria are met, and submit documentation demonstrating the owner's performance requirements.	Certify that the plant, equipment, and all materials used in concrete comply with the requirements of this standard. Certify that the mix design satisfies the requirements of this standard. Certify that the production and delivery of concrete will meet the requirements of this standard. Certify that the concrete complies with the specified performance criteria. Prepare and implement a quality control (QC) plan to sustain performance requirements. Verify that the concrete producer meets industry certification requirements. Submit documentation to the owner's satisfaction demonstrating that the proposed mix design will achieve the required strength, durability, and performance requirements.

3.2.1.2 Contractor

The contractor effectively collaborates with the concrete producer to specify and achieve specific mix characteristics that satisfy the performance requirements for plastic and hardened concrete. In this partnership, the construction and placement requirements of the contractor are considered in addition to the owner's performance standards. The contractor must also present supporting documentation to demonstrate that they have fulfilled the pre-qualification performance standards. They also must design and implement a comprehensive quality control plan that ensures the owner's performance standards are fulfilled, and they must turn in the documentation proving it.

Therefore, the contractor's active participation ensures the project meets its quality, performance, and compliance objectives. Their expertise, collaboration with the concrete producer, and implementation of quality control measures are crucial in mitigating risks and ensuring successful project outcomes. Therefore, their involvement is vital for delivering a high-quality, durable construction project that meets the owner's requirements and expectations.

3.2.1.3 Concrete Producer

The concrete producer assumes several crucial duties throughout the project. These include confirming that the plant, machinery, and materials adhere to the applicable standards, ensuring the mix design satisfies the requirements, and ensuring that the procedures for production and delivery follow the guidelines. They must also provide the required paperwork to confirm compliance with industry certification requirements and implement a strong quality control plan to safeguard the contractor's and owner's performance criteria. Ensuring quality, consistency, and dependability is therefore crucial. For projects to be successful and risks to be minimised, their knowledge, proactive approach to quality control, and adherence to standards are essential. Consequently, their enthusiastic engagement is vital for delivering high-quality, durable concrete that meets the owner's and contractor's performance requirements.

3.2.2 Performance Criteria

Annex J within CSA A23.1/A23.2 outlines concise information and advice for selecting between prescriptive or performance approaches when specifying and ordering concrete based on Table 4.3. This section briefly summarises the performance option detailed in Annex J of CSA A23.1/A23.2 and summarizes its effectiveness in improving overall performance.

The subsequent section delineates the essential components of performance-based specification options highlighted in the Annex.

i) Definitions

The definitions of key concepts essential for precise concrete specification in performance criteria are established in Annex J. It includes several phrases necessary for clear comprehension and expression when describing concrete application performance specifications requirements. The following definitions apply in this Annex;

- Contractor’s quality plan

Coordinate tasks undertaken by the contractor to guarantee alignment with the owner’s specifications and project requirements.

- Owner’s quality plan

The deliberate activities carried out by the owner to assure stakeholders (in a private company) or the public (in a public organization) regarding the supervision of the quality of concrete construction.

- Pre-construction and pre-placement meetings

Meetings among members of the construction team to review significant aspects of concrete construction before commencement (pre-construction) and address specific concerns related to the placement of an individual concrete element or during a designated placement period (pre-placement)

- Qualification testing

Concrete must be assessed to ascertain its ability to fulfil the required performance standards before the initiation of the construction stage.

- Quality control plan

The contractor’s quality control operations are planned by specifying parameters such as testing and sampling frequency and by accepting or rejecting criteria for non-conformance.

ii) Performance specification

- Performance concrete specification

A performance concrete specification defines a construction product with mandatory language for the end result and measures the performance requirements using recognized industry standards and techniques. Then, it is up to the contractors, manufacturers, subcontractors, and materials suppliers to decide what procedures, supplies, or actions they use. This standard or other widely used standards and specifications, such as cementitious materials, admixtures, aggregates, or construction techniques, may be cited in certain situations to meet performance criteria.

- Performance criteria

Annex J outlined specifications for concrete in both its plastic and hardened states. In the plastic state, crucial criteria encompass workability, uniformity, placeability, setting time, and

finishability. These criteria are particularly relevant to the concrete producer and /or contractor. In the hardened state of the concrete, fundamental criteria involve physical properties such as compressive, flexural, or tensile strength and modulus, as applicable. Additionally, considerations extend to the rate of strength development, durability in the expected environment (including resistance to corrosion, abrasion, and other deterioration processes), volume stability (limitations on acceptable volume changes due to shrinkage, creep, and thermal differentials caused by the heat of hydration), and other criteria such as appearance and architectural characteristics (e.g. acceptable levels of shrinkage cracking, surface texture, geometrical requirements such as flatness and levelness, and drainage slope). While most of these criteria concern the specifier and /or owner, concrete producers and contractors may also find interest in some cases. A vital consideration is ensuring that the performance requirements align with acceptable industry standards and other criteria, including appearance and architectural characteristics (i.e., limitations on adequate levels of shrinkage cracking, surface texture (e.g., non-skid finish, steel trowel), and geometrical requirements (e.g., flatness and levelness), slope for drainage). Most of these criteria interest the specifier and /or owner, but in some cases, the concrete producer may also be interested. An essential element is the performance requirements that should be satisfied and measured by acceptable industry standards.

- Specifying performance criteria

Creating a concrete performance specification that outlines achievable and quantifiable objectives using recognized industry standards and techniques is difficult. Owners typically write specifications for themselves, and while they may have long-term interests, this is not always the case. Therefore, it is essential to specify the necessary performance criteria to allow them to be measured early in the concrete's life cycle and utilized to confirm that the long-term performance standards will be met. As a result, the verification procedures become a crucial component of the performance approach's success. The owner's performance requirements cannot be validated at the right time without a thorough and trustworthy verification process, and the procedure is not.

iii) Roles and Responsibilities

Annex J outlines each stakeholder's obligations and functions within the construction industry. It further delineates the collaboration among these entities to guarantee the outcome adheres to performance criteria, ensuring alignment between quality control procedures and a demonstration of compliance.

iv) Selecting an alternative

In a performance-based contract, the producer or contractor for concrete is responsible for providing the necessary materials and techniques to meet the performance standards which the owner sets. Concerns about specifications, the verification process, specifications components, and quality management are crucial when evaluating performance.

3.2.3 Material Constituents and Components

According to CSA A23.1/A23.2 clause 1.5, the owner can include additional supplementary specifications customized to the demands of their particular project. The proprietary materials, construction techniques, or any other topics not covered by this standard may be the subject of these supplementary specifications. Protecting and upholding the required quality standard is the primary goal, ensuring that the project is ideally aligned with the owner's objective and vision.

The owner's satisfaction with the concrete mix is a crucial factor per CSA A23.1/A23.2 clause 4.1.1.1.5. This combination must demonstrate its effectiveness in generating concrete that can survive the prescribed exposure conditions, mainly when using hydraulic cement and supplementary cementitious materials. The main goal is to ensure that the concrete blend meets the expectations and needs of the owner and is not merely compliant but also suitable for the intended use.

The standard's clause 4.2.1 emphasizes recognizing that not all hydraulic cement and supplementary cementitious materials may be easily accessible within a particular region. Designers should take this vital issue into account when planning the project. It ensures that the project's theoretically sound parameters are also practically feasible in light of its geographical setting.

3.2.4 Testing and Evaluation

Table 3-2: Testing and Evaluation.

Test Method	Applicable Classes	Acceptance Criteria
Chloride Ion Penetrability (CSA A23.2 – 23C)	C-XL, A-XL, C-1 and A-1	The owner may specify chloride ion penetrability
Air-Void System (ASTM C457)	F-1, C-XL and C-1	Average spacing factor < 0.23mm, no test > 0.26mm < br > For w/cm ≤ 0.36, Average spacing factor < 0.25mm, no test > 0.30mm.
Sulphate Attack Resistance (ASTM C1012)	S-1 (very severe)	Max expansion ≤ 0.05% at 6 months or ≤ 0.10% at 12 months
	S-2 (severe)	Max expansion ≤ 0.05% at 6 months or ≤ 0.10% at 12 months
	S-3 (moderate)	Max expansion ≤ 0.10% at 6 months

Significantly, CSA A23.1/A23.2 incorporates a range of test methods accompanied by clearly defined acceptance limits to assess the performance of in-situ concrete. The procedures are outlined below.

Table 3-2 shows the test methods of CSA A23.1/A23.2, their classes and the designated acceptance criteria. According to the standard clause 4.1.1.11, The owner may also specify chloride ion penetrability as an acceptance test. Class C-XL, A-XL, C-1 and A-1 will have their chloride ion penetrability assessed as a qualification test in compliance with CSA A23.2 – 23C. The penetrability of chloride ions must meet the standards given in Table 2 of CSA A23.1/A23.2.

Clause 4.3.3.3 in CSA A23.1/A23.2 suggests the utilization of ASTM C457, titled "Standard Test Method for Microscopical Determination of Parameters of the Air-Void system in Hardened Concrete," to assess the air-void system in concrete subjected to freeze/thaw conditions, such as class F-1, C-XL and C-1. The specified requirements are as follows;

i) The average spacing factor should be below 230 μm, and no test should exceed 260 μm.

ii) For concrete with a water-to-cement ratio (w/cm) of 0.36 or less, the average spacing factor should be less than 250 μm, with no test surpassing 300 μm.

iii) Table 3 within CSA A23.1/A23.2 outlines the prescribed limits and acceptance criteria aligned with ASTM C1012 for concrete subjected to sulphate attack. The performance requirements are as follows;

- For sulphate exposure classes S-1 (very severe), the maximum expansion should not exceed 0.05% at 6 months or 0.10% at 12 months.
- For sulphate exposure classes S-2 (severe), the maximum expansion should not exceed 0.05% at 6 months or 0.10% at 12 months.
- For sulphate exposure classes S-3 (moderate), the maximum expansion should not exceed 0.10% at 6 months.

3.3 Europe (BS 8500-1:2015+A2:2019)

European organizations and standard-setting bodies primarily influence international construction specifications. Examining the approach of the European region allows for identifying patterns that have far-reaching impacts on global standards. This review will focus on the prominent BS tied to the EN system, which has a separate specification.

The British standards offer recommendations for the design and construction of concrete structures with an emphasis on performance criteria such as durability, structural safety, and serviceability, as well as the use of innovative materials and construction techniques to improve durability. BS 8500-1:2015+A2:2019, in particular, is a British Standard that complements BS EN 206 and provides guidance on specifying concrete for durability. It was published in 2019 as a second amendment to incorporate further updates and improvements based on industry feedback and technological advancements.

3.3.1 Performance Criteria

Five approaches for concrete specification are provided to the specifier by BS 8500-1:2015+A2:2019. The following is a brief description of these methods:

i) Designated concretes.

Designated concretes were developed to make the specification of designed concretes more straightforward, comprehensive, and dependable. They do not cover all applications or allow the use of any potential concreting material. The requirement that the producer hold current accredited certifications for production control and product conformity is a critical component of the designated concrete concept; as a result, designated concretes are only applicable in situations where third-party certification is selected as the option in specifying concrete.

ii) Designed concretes.

BS 8500-1:2015+A2:2019 guides specifying designed concrete, a type of concrete mix where the proportions of the constituent material are determined by the designer based on specific performance criteria requirements. Concrete designs are suitable for various purposes and are applicable in a wide range of scenarios. For instance, they can substitute for designated concrete, especially when the requirements are outside those covered by designated concrete.

- Where special cement or combinations are required, e.g., low heat of hydration.
- Where the concrete is exposed to one of the chloride or seawater exposure classes.
- Where lightweight or heavyweight concrete is required.
- Where strength class is required other than those covered by designated concrete.
- Where strength is required for the concrete and third-party certification is not required.

iii) Prescribed concretes.

The specifier can prescribe the precise composition and constituents of the concrete using this method. This choice only applies to certain situations because it does not include any performance requirements or requirements for compressive strength. If prescribed concrete is specified, the specifier is responsible for any preliminary testing to confirm that the proportions will achieve the anticipated performance in the fresh and hardened states with an appropriate margin.

iv) Standardized prescribed concretes.

Standardized prescribed concretes are applicable if the concrete is being site-batch produced on a small site or coming from a ready-mixed concrete producer without authorized third-party certification.

v) Proprietary concretes

This strategy is suitable when the concrete must achieve a specific performance utilizing predetermined test procedures. The project specification and concrete producer are consulted while choosing the proprietary concrete.

3.3.2 Exposure Classification

Clause A.2.1 of the BS 8500-1:2015+A2:2019 states that the exposure might not immediately fulfil the descriptions in the exposure classes for some specific elements or structures. In these circumstances, designers should rely on their judgment for that application or seek specialist advice.

3.3.3 Material Constituents and Components

The standard considers supplementary cementing materials such as fly ash and silica fume. The following deterioration processes were investigated: cracking, spalling, corrosion brought on by chloride penetration and carbonation, and freeze-thaw attack. The following criteria were used to evaluate test methods: Carbonation, Natural carbonation, Accelerated carbonation, Cembureau method, Torrent method, Chloride penetration, Rapid chloride migration method, Chloride profiling method, Reinforcement corrosion, Two-electrode method, Freeze-thaw damage, capillary suction of water and Capillary suction of de-icing solutions (Hooton, 2006).

3.3.4 Quality Control and Assurance

BS 8500-1:2015+A2:2019 clause 5.1 outlines the crucial information to be provided by the specifier or user in the specification process to the producer. This essential information includes:

- The designated method for placing and finishing the concrete.
- In cases where identity testing is not confined to instances of doubt or random spot, explicit details regarding the type of test, the concrete volume subject to assessment, and the number of tests to be conducted.
- Specification on whether a non-accredited laboratory will be employed for identity testing.
- As applicable, authorization is required to transport concrete to the delivery point via a non-agitating vehicle.

Furthermore, BS 8500-1:2015+A2:2019 clause 5.2 adds information from the concrete producer to the specifier. This vital information encompasses:

i) The strategy employed to mitigate the harmful alkali-silica reaction and, as applicable, includes:

- Detailed service record
- Confirmation of compliance
- Alkali content of the concrete

ii) The specifications for the aggregate mixture's type, composition, and standard strength class.

iii) In cases where porous flint aggregates are intended for freeze-thaw-resistant aggregate concrete, a proven track record demonstrating successful utilization for a minimum of 10 years under freezing and thawing conditions is required.

iv) The defined approach for ascertaining the water absorption characteristics of fine lightweight aggregates.

In compliance with BS8110-1-1997 clause 2.3, it is recommended that an inspection procedure be established to verify that the construction aligns with the design. This inspection protocol should encompass materials, documentation, workmanship, and construction. Prove that the being delivered satisfies the demands or claims made. Any party interested in the results of the evaluation may conduct a conformity assessment, also known as a third-party conformity assessment, or it may be done independently by a body. Testing, inspection and certification are a few examples of conformity assessment procedures. Product conformance certification is a conformity assessment conducted by an accredited third-party conformity assessment authority.

According to BS 8500-2:2015+A1:2016 clause 12.4, extraordinary inspections are warranted exclusively when the producer has failed to identify non-conformities or to respond adequately.

3.4 Australia (AS 3600:2009 & AS 1379:2008)

In coastal areas, concrete structures are subjected to the corrosive effects of saltwater, which can cause concrete to deteriorate over time. Understanding Australian concrete performance can help create long-lasting concrete mixes for coastal areas. Australia stands out as a leader due to its distinction in PBS. Both owners and producers profit from the remarkable framework the AS 3600 provides for assessing and maintaining product quality. Creating and adopting quality management systems remain a worthwhile goal for the concrete industry, even though North America might take some time to embrace this strategy fully (Hover, Bickley & Hooton, 2008).

3.4.1 Performance Criteria

Standards Association of Australia, Committee BD-002 (2009) provides a comprehensive and innovative approach to constructing plain, reinforced, and prestressed concrete. Established in 2009, these standards are notable for the careful consideration given to design life, which is an impressive 50 ± 10 years. Constructing structures is only one aspect of this all-encompassing strategy, and another is making concrete that stands the test over time.

The standards give priority to the long-term resilience of construction and members in a world where concrete structures are faced with a variety of environmental challenges. The code emphasizes the significance of making concrete not just to last but for a very long time, so durability is essential.

3.4.2 Quality Control and Assurance

The standard AS 1379-08 clause C1.3.15 provides a guideline for evaluating concrete quality that aligns with customer preferences, ultimately assisting in the project's success. The project assessment guideline accepts that the person ordering the concrete is what ultimately determines the concrete's quality.

3.5 India (IS 456: 2000)

India is experiencing rapid infrastructure growth and urbanization. In this situation, there is an exceptionally high need for durable concrete to ensure the longevity of vital infrastructure. Due to its diverse environmental conditions and rapid urbanization, Indian Standard (IS 456: 2000) will be reviewed for its concrete durability specifications.

A considerable step has been taken to increase the durability of concrete with the most recent version of IS 456: 2000. The necessary concrete durability clauses established in the 1978 edition are the foundation for this version, reflecting our understanding of concrete technology's durability. Experts in the field of concrete technology have recently expressed concern over the durability of concrete construction. There is now a global imperative to develop consistent durability standards that can withstand the test of time and shifting environmental conditions.

This updated standard strongly emphasises strengthening the built-in safeguards against potential threats to structural integrity. Construction is essential, but laying a strong foundation for strength, endurance, and resilience is just as important.

3.5.1 Performance Criteria

IS 456:2000 clause 8.1.1 states that it is essential to consider the mix composition, workmanship, design and detailing, and the level of exposure anticipated for the concrete throughout its service life. Consideration should be given to the accuracy of the current testing regimes for control and compliance when selecting the concrete mix to provide adequate durability under these conditions.

3.5.2 Material Constituents and Components

IS 456:2000 clause 5.2 encourages the use of supplementary cementitious materials in concrete, such as pozzolans, fly ash (pulverized fuel ash), silica fume, rice husk ash, metakaolin, and ground granulated blast furnace slag. The standard also allows using any type of cement as long as it suits the project goals.

3.5.3 Quality Control and Assurance

IS 456:2000 from clause 10.1.1 describes effective quality assurance measures that must be implemented to guarantee that the final structure's characteristics match those specified during initial planning and design. The construction process should produce desirable qualities such as strength, functionality, and long-term resilience to reduce life cycle costs. Accurate design, using

suitable materials and components provided by manufacturers, skilful workmanship during construction by the contractor, and responsible upkeep throughout the structure's lifespan, including timely maintenance and repairs by the owner, are just a few of the essential aspects of quality assurance in construction.

3.6 South Africa (COTO: 2020)

Because of its extensive coastline, South Africa is subject to the corrosive effects of saltwater from the Atlantic and Indian Oceans on numerous concrete structures. Research on developing durable concrete mixtures for coastal areas can inform how well concrete performs.

Based on the transport properties of chlorides, water, and oxygen, durability indices have been created to describe cover concrete. To forecast the possible durability of a reinforced concrete structure, one should be familiar with the penetrability of fluids through the porous structure of hardened cement paste (Beushausen & Fernández Luco, 2015). The penetrability of these fluids can be measured using Chloride conductivity, Oxygen permeability and Sorptivity tests.

3.6.1 Performance Criteria

Clause A13.4.7.1 of the COTO 2020 states that the Contractor is responsible for ensuring the performance of all concrete, both in its fresh and hardened states, regardless of any variations in the quality of cement or supplementary cementitious materials between batches. The Engineer must approve the specific concrete mix proportions and any modifications. The Contractor's quality control system and scheduling must account for the concrete's hydration phase. During this phase, appropriate measures must be taken to safeguard the freshly placed concrete from any activities that could disrupt the hydration process.

3.6.2 Material Constituents and Component

According to COTO clause A13.4.4, the Contractor is responsible for designing and ensuring the performance of all concrete mixes used in the structures. The selected mix proportions must provide sufficient workability and finishability for their intended applications while meeting the specified strength, durability, and performance requirements in fresh and hardened states. The mix design must achieve an average compressive strength above the specified characteristic strength, accounting for expected concrete properties and testing methods variability. Durability index and post-concreting cover testing must meet the minimum, maximum, or nominal values, with permissible deviations as outlined. If the Engineer approves the modifications, mix designs may be adjusted during the project to meet strength, durability, and consistency requirements.

Preconstruction laboratory test results and the proposed mix design must be documented and submitted for approval before concreting activities begin. Concrete operations may only proceed after receiving approval for the mix design. The Contractor must account for adequate time in the design and approval process schedule, particularly for durable concrete applications.

3.6.3 Quality Control and Assurance

The COTO clause A1.2.8.1 on process quality control specifies that if there are any PBS, the contractor must implement a quality management system to guarantee and show that the necessary performance standards have been fulfilled and, when appropriate, will be maintained for the duration indicated in the contract documentation. To validate the compliance of the works with all pertinent requirements and specifications, the contractor shall conduct testing and measurement following requirements established in the contractor's quality management system. Before beginning work on the element of the works, the contractor must agree with the Engineer on all process control sampling, testing, measurement, and approval procedures.

As outlined in COTO clause A1.2.8.2, it is within the Engineer's purview to make specific requests for sampling, tests, and measurements of the final product. These requests are made to verify and ensure that the final product aligns with the designated design requirements.

3.6.4 Testing and Evaluation

Concrete durability is a critical factor in ensuring structures' long-term performance and sustainability. The COTO Standard provides comprehensive guidelines for evaluating concrete durability through Clause A20.1.5.1(c), which specifies crucial testing methods, including the

i) The oxygen permeability (OPI) test.

ii) The chloride conductivity (CCI) test.

iii) The water sorptivity (WS) test.

The COTO Standard also includes additional clauses that comprehensively address various aspects of testing related to construction materials and concrete performance. These include:

- Clause A20.1.5.8: Accelerated test method for determining the potential alkali reactivity of aggregates.
- Clause A20.1.4.1: Testing of aggregates.
- Clause A20.1.4.2: Testing of cement, extenders, and admixtures.
- Clause A20.1.4.3: Testing of concrete.
- Clause A20.1.4.9: Testing of surface treatments.
- Clause A13.4.8.4: Tests ordered by the Engineer.

These provisions collectively establish a robust framework for evaluating and ensuring the quality and durability of construction materials.

3.7 *fib* Model Code 2020 (MC2020)

The *fib* Model Code 2020 represents a significant evolution in concrete standards, intended to serve as a basis for future national and international codes while also being a practical document

for design. It explicitly aims to bridge the design of new structures with the life-cycle management of existing ones, covering assessment, intervention, and dismantling. A core philosophy underpinning MC2020 is the integration of sustainability requirements holistically, aligned with performance-based approaches informed by risk and reliability analysis.

3.7.1 Performance Criteria

MC2020 strongly advocates for a Performance-Based Design (PBD) approach to durability. Instead of relying solely on prescriptive limits, it emphasizes defining performance requirements linked to the structure's intended service life, exposure conditions, and target reliability levels. Key aspects include:

- Durability Performance Indicators (DPIs). The code promotes the use of DPIs – measurable material or structural properties directly linked to deterioration mechanisms. A valid DPI should be meaningful regarding the mechanism, measurable via standardized tests, usable for conformity assessment at defined performance points, and preferably integrated into performance prediction models.
- Life-Cycle Perspective. Performance is evaluated over the structure's entire life cycle, considering potential degradation mechanisms such as carbonation, chloride ingress, freeze-thaw attack, chemical attack, ASR, and delayed ettringite formation (DEF).
- Reliability-Based Formats. MC2020 incorporates both semi-probabilistic (using partial safety factors and full probabilistic formats (using statistical distributions for variables) for verifying durability limit states against target reliability levels.
- Sustainability Integration. Performance requirements are tied to broader sustainability goals, considering environmental impact and life-cycle cost/benefit analysis.

3.7.2 Material Constituents and Components

MC2020 moves significantly away from prescriptive requirements for material composition compared to previous codes, fostering innovation:

- Flexibility. The PBD approach allows for flexibility in material selection, including cements, SCMs (Supplementary Cementitious Materials), aggregates, and admixtures, provided the final concrete meets the specified performance criteria.
- Eco-Efficient Concretes. This flexibility is particularly crucial for accommodating eco-efficient concretes (e.g., those with reduced clinker content or novel SCMs), whose durability characteristics may differ significantly from traditional concrete and require performance validation.
- Residual Prescriptive Rules. However, MC2020 acknowledges that for certain complex deterioration mechanisms or where reliable performance tests are still evolving, prescriptive rules remain necessary. This is evident in sections dealing with specific chemical attacks (like sulphate or acid resistance) or mitigation strategies for ASR and DEF, which often rely on limiting certain constituents (e.g., C3A content, alkali content, specific SCM types).

3.7.3 Quality Control and Assurance / Conformity Control

The implementation of PBD necessitates robust conformity control procedures. MC2020 outlines principles that align with established quality management practices. It requires clear identification of the quality characteristics (DPIs) and their threshold values for acceptance. The framework mandates a defined sampling plan and specifies the "Point of Performance" where compliance is assessed (e.g., production plant, delivery, in-situ). Successful PBD implementation depends heavily on clearly defined responsibilities and contractual agreements between all stakeholders (owner, designer, supplier, contractor, laboratory). Additionally, MC2020 requires predefined actions to be taken if test results fail to meet the specified criteria. These comprehensive conformity control mechanisms ensure that performance-based designs maintain their integrity throughout the construction process.

3.7.4 Testing and Evaluation

Testing is fundamental to the PBD approach in MC2020, serving to measure performance indicators and verify compliance. The approach focuses on measurable indicators, where tests are specifically selected to quantify relevant DPIs linked to specific deterioration mechanisms. MC2020 emphasizes the use of well-defined, standardized test methods for measuring these DPIs to ensure reliability and comparability across projects. The complementary guidance details various test methods relevant to MC2020's approach, including several key test types that support the performance-based evaluation framework. This systematic testing methodology allows practitioners to objectively assess concrete performance against established criteria rather than relying solely on prescriptive specifications.

The complementary guidance details various test methods relevant to MC2020's approach, including:

i) Transport Properties: Tests for gas permeability (e.g., cembureau test (kO), air-permeability index (kT), Oxygen permeability index (OPI), liquid permeability, capillary suction (sorptivity), chloride diffusion/migration.

ii) Carbonation: Accelerated and natural carbonation tests.

iii) Freeze-Thaw: Tests measuring scaling or internal damage.

iv) Chemical Resistance: Specific tests related to sulphate resistance.

In summary, the *fib* Model Code 2020 provides a comprehensive, forward-looking framework that strongly promotes performance-based specifications for concrete durability. It emphasizes measurable indicators (DPIs), links performance to reliability and life-cycle considerations, allows material innovation (especially for sustainable concrete), but retains prescriptive rules where necessary, all underpinned by robust conformity control and standardized testing protocols.

3.8 Summary of Main Points from Table 3-3

To summarize Table 3-3, various countries, from the USA and Canada to Europe, Australia, India, South Africa, and now codified in the influential fib Model Code 2020, have recognized the value of moving beyond purely prescriptive methods to predict and ensure the durability of concrete structures. While the specific approaches vary, a clear global trend towards incorporating performance-based principles is evident.

Distinct strategies emerge from the comparison: South Africa stands out with its direct measurement of material performance using specific Durability Indexes (OPI, WS, CCI). The USA (ACI 318) and India (IS 456) primarily rely on prescriptive standards but allow for or are gradually incorporating performance-based elements and alternative materials under specific conditions. Canada (CSA A23.1/A23.2) and Australia (AS 3600) offer more defined pathways for both prescriptive and performance options, notably encouraging collaboration between producers and contractors to meet specified outcomes. Europe (BS 8500/EN 206) utilizes a hybrid approach, combining prescriptive limits with performance requirements, particularly for specific exposure classes.

The fib Model Code 2020 represents perhaps the most comprehensive and forward-looking performance-based framework reviewed. It establishes Performance-Based Design (PBD) as a core principle, integrates durability within a life-cycle management and sustainability context, and formalizes the use of Durability Performance Indicators (DPIs). Its reliance on reliability-based verification (both semi-probabilistic and full probabilistic) and its explicit requirement for defined stakeholder roles and contractual agreements mark a systematic shift towards performance assurance. While MC2020 flexibility in material selection, particularly for eco-efficient concretes, it pragmatically retains prescriptive rules where PBD is complex or underdeveloped (e.g., specific chemical attacks, ASR/DEF).

Common threads across many performance-oriented standards include stringent quality control and assurance procedures, testing methods designed to verify compliance (though methods and standardization vary), and consideration of specific environmental exposures to tailor durability requirements.

In conclusion, the evolution reflected in Table 3-3, culminating in the comprehensive approach of MC2020, shows a growing global commitment to improving concrete durability and sustainability. While the approaches differ – from durability indexes testing (South Africa) to hybrid systems (Europe, Australia) and the fundamental PBD framework (MC2020) – the underlying goal is ensuring concrete performs reliably under specified conditions throughout its intended service life. Collaboration, clear performance metrics (like DPIs), robust conformity control, and targeted testing are central to this shift. As environmental challenges intensify, integrating performance-based criteria, potentially guided by frameworks like MC2020, offers a pathway to balance innovation, reliability, and enforceability in concrete specifications worldwide.

Table 3-3: Summary of Performance-Based Specification Criteria.

Performance-based Specification Criteria	**Fib Model Code 2020**	**USA ACI 1318: 2019**	**Canada CSA A23.1/A23.2**	**Europe BS8500-1:2015+A2:2019**	**Australia AS 1379 AS 3600**	**India IS 456:2000**	**South Africa COTO 2020**
Performance Test Methods (PTMs).	Emphasizes Durability Performance Indicators (DPIs) linked to deterioration mechanisms. Requires standardized, measurable tests for conformity assessment (e.g., transport properties, carbonation, F-T resistance, chemical resistance). Basis for semi-probabilistic and full probabilistic verification formats.						Clause A20.1.5.1 (c) provides Testing for the concrete durability Index, including the following The oxygen permeability (OPI) test. The chloride conductivity (CC) test. The water sorptivity (WS) test.
Clear definition of functional requirements, such as concrete producers and contractors	Requires clear definition of performance targets (linked to service life, exposure, target reliability levels). Stresses the need for clearly defined responsibilities and contractual agreements among all stakeholders (owner, designer, supplier, contractor)		The standard explains performance specifications, emphasizing their relevance when owners expect concrete suppliers to guarantee performance upon delivery while contractors are responsible for performance after placement.	BS 8500-1:2015+A2:2019 clause 5.1 outlines the crucial information to be provided by the specifier or user in the specification process to the producer. BS 8500-1:2015+A2:2019 clause 5.2 adds information from the concrete producer to the specifier.			Clause A1.2.8.2, it is within the Engineer's purview to make specific requests for sampling, tests, and measurements of the final product.

Collaborative design of concrete mix design and materials selection between producers and contractors.	Facilitates collaboration by setting performance goals, allowing producer/contractor flexibility in mix design optimization. Requires defined contractual framework and mutual agreement on the adopted performance-based process.		Annex J within CSA A23.1/A23.2 outlines concise information and advice for work with the producer to establish concrete mix properties to meet performance criteria for plastic and hardened concrete, considering the contractor's criteria for construction and placement and owner's performance criteria.		The standard AS 1379-08 clause C1.3.15 provides a guideline for evaluating concrete quality that aligns with customer preferences, ultimately assisting in the project's success. The project assessment guideline accepts that the person ordering the concrete is what ultimately determines the concrete's quality.		The COTO clause A1.2.8.1 states that, Before beginning work on the element of the works, the contractor must agree with the Engineer on all process control sampling, testing, measurement, and approval procedures.
Quality assurance	Central focus on QA through Conformity Control based on measured DPIs. Requires defined sampling plans, performance points (production, delivery, in-situ), standardized testing protocols, and compliance criteria linked to reliability.	Advance on alternative cement materials for concrete mixture, but proposed mixtures must undergo testing to ensure they meet performance requirements before approval.	Prepare and implement a quality control plan to ensure the owner's performance criteria are met, and submit documentation demonstrating the owner's performance requirements.	BS 8500-1:2015+A2:2019 clause 4.3.3 (a) proves that the being delivered satisfies the demands or claims made.		The Indian Standards IS 456:2000, n.d.) from clause 10.1.1 describes effective quality assurance measures that must be put into place to guarantee that the final structure's characteristics match those specified during initial planning and design.	Clause A1.2.8.1 addresses process quality control, requiring contractors to set up and keep up a quality management system to guarantee that PBS are fulfilled for the duration of the contract as specified in the documentation.

Material constituents	Primarily performance-based, offering flexibility for innovative materials and SCMs (incl. eco-efficient concrete) if performance is met. Retains some prescriptive guidance/rules for specific complex issues (e.g., ASR/DEF mitigation, severe chemical attack) where PBD alone is insufficient or complex.	Clause 26.4.1.1.1 advises hydraulic cement to conform to AST C1157, which covers cement for both general and particular applications.	The producer or contractor for concrete is responsible for providing the necessary materials and techniques to meet the performance standards which the owner sets.			The Indian Standards IS 456:2000, n.d.) clause 5.2 encourages the use of supplementary cementitious materials in concrete, such as Pozzolans, Fly ash (pulverized fuel ash), Silica fume, Rice husk ash, Metakaolin, and Ground Granulated Blast Furnace Slag. The standard also allows using any type of cement as long as it suits the project goals.	Clause A13.4.7.1 of the COTO 2020 states that the Contractor is responsible for ensuring the performance of all concrete, both in its fresh and hardened states, regardless of any variations in the quality of cement or supplementary cementitious materials between batches. The Contractor is responsible for designing and ensuring the performance of all concrete mixes used in the structures., according to COTO clause A13.4.4.
Exposure conditions	Detailed classification of exposure conditions linked to specific deterioration mechanisms. Performance requirements (DPIs, target reliability) are explicitly tied to the specified exposure conditions and severity.	Chapter 19, Table 19.3.1.1 of ACI 318-19, Clause 19.3.1, in compliance with ASTM C1012, includes performance standards for concrete exposed to sulphate conditions.		Clause A.2.1 of the BS 8500-1:2015+A2:2019 states that the exposure might not immediately fulfil the descriptions in the exposure classes for some specific elements or structures. In these circumstances, designers should rely on their judgment for that application or seek specialist advice.			

4. Implementation Process of Performance-Based Specification in Chosen Countries

4.1 Introduction

PBS make building more robust, safer, and more efficient structures easier. Shifting the focus from prescriptive codes to achieving desired durability performance outcomes, offers greater flexibility and innovation in the building industry. This shift aims to enhance durability, sustainability, and overall performance of concrete structures by optimizing mix designs, encouraging innovation, and focusing on actual performance outcomes rather than prescriptive ratios.

This chapter delves into the implementation process of PBS in various countries, exploring the key themes that emerge from these applications. The primary objective is to examine how different countries translate PBS's core principles into practical realities. The discussion is not just an exploration of the technical and procedural aspects but also an examination of the broader contextual factors, such as regulatory environments, stakeholder engagement, and the integration of local materials and practices. By investigating these implementations, we aim to:

i) Understand Diverse Implementation Approaches:

Various countries bring unique perspectives and regulations to the discussion. Analysing these varying approaches can provide valuable insights for the broader application of PBS.

- Explore how different countries have approached the transition from prescriptive to PBS.
- Highlight the steps and stages involved in the implementation process in each country.

ii) Compare and Contrast Different Frameworks:

Compare the PBS frameworks adopted by various countries to understand the similarities and differences in their approaches.

iii) Identify Key Success Factors and Challenges:

Understanding the hurdles and successes other countries face can inform the development and refinement of PBS implementation strategies.

- Analyse the factors that have contributed to successful implementation,
- Identify common challenges faced during the implementation process.

The chapter is structured to first provide an overview of the global context and the need for PBS in concrete durability, followed by a detailed examination of the implementation process in selected countries, highlighting their unique approaches. A comparative analysis will then draw out common themes and divergent strategies.

4.2 Global Context and Need for PBS

Modern concrete structures are expected to perform well beyond simply withstanding designed loads. Sustainability, occupant comfort, fire safety, and resilience against natural hazards are all crucial considerations. PBS allows for a holistic approach to design, ensuring structures meet these diverse performance objectives without affecting the longevity of the concrete structure. Several key drivers propel the global shift towards PBS for concrete durability, and the following sections discuss them.

4.2.1 Environmental Sustainability

Concrete production and usage significantly contribute to greenhouse gas emissions. PBS encourages using alternative materials and innovative construction methods that reduce the carbon footprint of concrete structures. The NRMCA of the USA has outlined recommendations for how designers, contractors, producers, and government agencies can work together to create new specifications to lower concrete's carbon footprint. These guidelines emphasize maintaining the cost-effectiveness, strength, and durability that make concrete a preferred construction material compared to alternatives (NRMCA, 2022). PBS also promotes optimising material usage, leading to more sustainable construction practices. This includes the potential for recycling and using locally sourced materials, thereby minimizing environmental impact. It is essential to recognize that cement is responsible for about 35 ± 10% of the global emissions from the construction sector (Habert, 2020). Shifting standards from prescriptive specifications to PBS could encourage reducing cement usage and incorporating new supplementary cementitious materials in concrete mixes, helping to lower greenhouse gas (GHG) emissions across the industry (Lolli et al., 2023).

4.2.2 Enhanced Durability and Longevity

By focusing on the actual performance of concrete in real-world conditions, PBS ensures that structures are more durable and require less maintenance over their lifespan. This leads to a reduction in lifecycle costs and enhances the longevity of infrastructure (Lolli et al., 2023). Additionally, PBS allows for customising concrete mixes and construction techniques to adapt better to specific environmental conditions, such as extreme temperatures, humidity, or exposure to aggressive chemicals (Bickley et al, 2006).

4.2.3 Innovation and Technological Advancements

Fosters innovation in the construction industry by not being tied to specific materials or methods. It encourages developing and adopting new technologies, materials, and construction practices to lead to more efficient and cost-effective solutions while achieving the desired performance outcomes (Lolli et al., 2023). Moreover, advanced testing methods and predictive modelling techniques are integral to PBS. These technologies enable more accurate predictions of concrete performance and facilitate continuous improvement in construction practices (Muigai, 2009).

4.2.4 Economic Efficiency

PBS provides flexibility in material selection and construction methods (Lobo et al, 2006), allowing for optimization based on cost, availability, and performance requirements. This flexibility can lead to more economically efficient project delivery. Although the initial implementation of PBS may require higher investment in testing and validation, the overall cost savings over the structure's lifespan can be significant. This includes reduced maintenance costs and longer service life.

4.2.5 Regulatory and Market Pressures

Regulatory bodies worldwide increasingly recognise the benefits of PBS and incorporate performance requirements into building codes and standards. This regulatory shift significantly drives the adoption of PBS (Barbhuiya & Das, 2023). There is a growing demand from clients and stakeholders for more durable, sustainable, and cost-effective construction solutions. PBS meets this demand by providing performance assurance through measurable outcomes.

4.2.6 Accountability and Transparency

PBS shifts the focus from following rigid rules to demonstrably achieving performance goals. This fosters a more collaborative and transparent design process, where all stakeholders' designers, contractors, and building owners share a clear understanding of the desired outcomes (Taylor, 2004).

4.3 Conditions for Performance-based Specifications

For effective PBS, the following are the conditions to be satisfied;

4.3.1 Clear Performance Objectives Requirements

Identifying clear and measurable performance goals for the concrete structure's durability is essential. These may involve requirements for long-term durability, crack resistance, protection against environmental factors such as freeze-thaw cycles and chemical exposure, and service life predictions. Relevant codes, standards, and project-specific guidelines should be consulted to determine appropriate performance criteria (H. Beushausen et al., 2015).

4.3.2 Understanding of Exposure Conditions

The determination of the proper durability criteria for the concrete mix requires an understanding of the exposure conditions. Examine the particular environmental factors that the concrete will be subjected to, such as changes in moisture, temperature, and chemical exposure, as well as any possible mechanical loads. Based on the severity, classification of exposure conditions can be done. Durability tests should be conducted on trial concrete mixes under simulated exposure conditions. These tests help fine-tune the mix design for performance.

4.3.3 Material Selection and Mix Design

To ensure the concrete mix meets the necessary performance criteria, carefully choose materials and develop a mix design that aligns with these standards. Consider elements such as the quality of aggregates, cementitious materials (including supplementary materials such as fly ash or slag), chemical admixtures, and the water-to-cement ratio to enhance durability. Perform laboratory tests and use modelling techniques to assess how different mix designs perform under anticipated exposure conditions. It is essential to consider the materials used in concrete production and how they are proportioned and shaped within the formwork when developing fluid flow test criteria, as these factors are key indicators of the concrete's future durability (Sugandhini et al., 2022).

4.3.4 Quality Control and Testing

Implement comprehensive quality control measures throughout construction to ensure the concrete mix meets the required performance specifications (Kurtis, Kahn & Nadelman, 2013). This may include testing raw materials, concrete batches, and evaluating the properties of hardened concrete on-site. Develop quality control plans and procedures to ensure compliance with PBS. Clear acceptance criteria and testing methods must be outlined to verify and enforce these requirements. Testing may be needed for pre-qualification and job site approval (Lobo, Lemay & Obla, 2006). The standards should allow the contractor and producer flexibility in designing a mix that meets performance criteria (Bickley et al., 2015).

4.3.5 Performance Testing and Evaluation

To assess concrete durability, employ a balanced approach combining targeted field and laboratory tests. Focus on critical indicators such as chloride ion penetration resistance and permeability in the lab, supplemented by selective non-destructive field testing. For critical structures or harsh environments, consider more extensive testing. Clearly define test procedures and acceptance criteria in performance specifications, ensuring they are achievable and relevant to the project's needs. Implement a risk-based testing regime, with more rigorous pre-qualification for critical applications and streamlined worksite approval processes to maintain construction efficiency. While testing provides valuable data, it should be interpreted within the context of local conditions and historical performance.

4.3.6 Documentation and Compliance

Maintain detailed records of the construction processes, test results, performance evaluations, and concrete mix designs. This documentation provides essential information for quality control, project management, and future maintenance while also serving as evidence of compliance with PBS. Prepare comprehensive reports summarizing the findings from evaluations and performance testing (Hooton et al., 2015).

4.3.7 Collaboration and Communication

Foster collaboration and communication among owners, testing laboratories, designers, contractors, and material suppliers throughout the project. Ensure that all parties understand

the expectations, specifications, and performance objectives related to the concrete's durability. Keep everyone updated on progress during the construction phase and promptly address any issues or concerns. The producer and contractor will work together to determine the mix proportions that meet placement and finishing needs, such as flow and setting time, while maintaining the performance requirements of the hardened concrete (Lobo, Lemay & Obla, 2006). Flexibility in the mix design is also necessary to account for seasonal environmental changes and variability in material sources during construction (Lobo, Lemay & Obla, 2006).

4.3.8 Continuous Improvement

It is essential to regularly review and improve PBS by considering feedback from past projects, advancements in technology, and changes in industry standards or regulatory requirements. Identify areas for improvement and lessons learned to enhance the effectiveness and efficiency of future projects. The specifications should be updated to integrate best practices and innovations in concrete durability (Lobo, Lemay & Obla, 2006).

The conditions above for PBS present a marked contrast to traditional prescriptive approaches in concrete construction. Where PBS require clear and measurable performance goals, prescriptive specifications operate on predetermined requirements based on historical data and established industry practices. This fundamental difference eliminates the need for extensive performance testing but may not optimize for specific project conditions.

Regarding exposure conditions, prescriptive specifications utilize standardized exposure classifications with predetermined mix requirements, contrasting with the detailed environmental analysis required in PBS. While this standardization simplifies the design process, it may not adequately address unique or complex exposure scenarios, potentially leading to overdesign in some situations while underperforming in others.

In material selection and mix design, prescriptive specifications mandate specific material types and proportions, diverging from the flexibility offered by performance-based approaches. These requirements typically include minimum cement content, maximum water-cement ratio, and strict aggregate gradation requirements. While ensuring consistency, this approach restricts innovation and may not capitalize on locally available resources or emerging technologies.

The prescriptive specifications' quality control and testing regime focuses primarily on verifying compliance with specified mix proportions and basic fresh concrete properties. This simplified testing protocol reduces complexity but may not provide comprehensive insight into durability performance. Similarly, performance evaluation in prescriptive specifications relies on standard test methods focused on material properties and essential mechanical characteristics, assuming that meeting specified material properties will result in adequate durability performance.

Documentation requirements under prescriptive specifications are more streamlined, typically requiring only essential batch records, material certificates, and standard test results. While this reduces administrative burden, it limits the availability of detailed performance data

for future reference. The traditional approach also delineates project participants' responsibilities more precisely, potentially limiting innovation opportunities through collaborative problem-solving.

Finally, where PBS emphasize continuous improvement through project-specific learning, prescriptive specifications evolve primarily through formal industry standard updates and code revisions. This structured approach ensures stability but may slow the adoption of new technologies and innovative solutions in concrete construction practices. The prescriptive methodology relies on proven methods and materials, with changes implemented only after extensive industry-wide validation and consensus.

These contrasts highlight the trade-off between the simplicity and established reliability of prescriptive specifications versus the potential for innovation and optimization offered by performance-based approaches.

4.4 Performance-Based Specification Implementation Strategies

PBS implementation strategies for concrete durability depend on the countries, available resources, and specific environmental conditions. Here are some key strategies and approaches:

4.4.1 Durability Indexes Approach

The durability index approach to performance-based durability specifications for concrete structures involves a systematic methodology (Ballim & Alexander, 2018) that emphasizes using durability indexes to quantify the potential durability of concrete based on its resistance to the ingress of aggressive agents, along with service life prediction models.

The durability index approach emphasizes measurable, concrete properties over prescriptive mix designs while utilizing standardized tests to assess key durability indicators, such as sorptivity, oxygen permeability and chloride conductivity. This method is material-agnostic, accommodating various binder combinations and innovative materials. Additionally, it provides a foundation for site quality control and compliance testing.

A suite of durability index tests has been developed in South Africa to evaluate the in-situ properties of concrete that influence its durability (Alexander, Santhanam & Ballim, 2011). These tests yield parameters related to deterioration mechanisms, including the Sorptivity Index, Oxygen Permeability Index and Chloride Conductivity Index. The tests can be applied to laboratory and field concrete samples (Nganga, Alexander & Beushausen, 2013).

The durability indexes have been empirically related to service life prediction models (M. G. Alexander et al., 2017). Index values and variables such as reinforcement cover and environmental exposure class can be input parameters for service life models (M. G. Alexander et al., 2017). This allows for rational determination of the design life based on the concrete's performance (Beushausen & Alexander, 2008).

Limiting values of durability indexes are used in construction specifications to ensure the necessary concrete quality for the required service life and exposure environment (Govender & Mark, 2019). Close collaboration between constructors and specifying authorities is required

to agree on appropriate index limits based on the aggressiveness of the exposure conditions (Ballim & Alexander, 2018).

PBS using the durability index approach are now regularly used in the South African construction industry (Ballim & Alexander, 2018). Extensive testing programs were conducted to assess the repeatability and reproducibility of the index tests across different laboratories. Initiatives such as better operator training and test equipment refinement have improved this approach's acceptance and implementation (Ballim & Alexander, 2018).

4.4.1.1 Durability Index Approach Case Study - South Africa

South Africa has been at the forefront of developing and implementing the DI approach. The durability index method has been incorporated into national standards (SANS 3001-CO3-1,2,3). Its application extends to significant infrastructure projects, including bridges and marine structures (Nganga, Alexander & Beushausen, 2013).

The method employs three primary indexes: the Water Sorptivity Index, Oxygen Permeability Index and Chloride Conductivity Index. Limits for these indexes are established based on exposure classes and design life and used in conjunction with cover depth specifications. These tests predict the service life of concrete structures and ensure compliance with performance specifications (Nganga, Alexander & Beushausen, 2013). Two of these tests (oxygen permeability and chloride conductivity) have been adopted as national standards (SANS-3001-CO3-1, 2, 3, 2015), and the water sorptivity test is being prepared as a national standard (Ballim & Alexander, 2018). These tests enable the development of semi-empirical service life prediction models, which are crucial for durability design and ensuring the long-term performance of concrete structures.

The durability index method has demonstrated several benefits, including improved durability of structures in aggressive environments (Beushausen & Alexander, 2008), facilitated the use of blended cement and supplementary cementitious materials, and enhanced quality control on construction sites.

The durability index method offers several advantages, including promoting innovation in concrete mix design, providing quantifiable measures of potential durability (Alexander, Ballim & Stanish, 2008), and potentially being more cost-effective than prescriptive approaches in the long term. However, it also faces challenges, requiring specialized testing equipment and trained personnel (Nganga, Alexander & Beushausen, 2013), higher initial costs due to additional testing requirements, and potential resistance in regions with prescriptive solid traditions.

To further enhance the effectiveness of the durability index method, future research and development should focus on integrating it with service life prediction models, developing rapid, on-site test methods, and expanding its coverage to encompass a broader range of degradation mechanisms.

The durability index approach provides a framework for performance-based durability design that links concrete properties to service life prediction and allows for rational

specification of concrete quality. Its practical implementation has yielded valuable lessons for other countries seeking to adopt similar performance-based methodologies.

4.4.2 Prescriptive Approach with Performance Verification

The prescriptive approach with performance verification (PAPV) combines traditional prescriptive specifications with performance-based testing and verification. It aims to leverage the simplicity and familiarity of prescriptive methods while incorporating the benefits of performance-based approaches to ensure durability. It's regularly used as a transitional strategy in countries moving towards full PBS.

The Prescriptive base provides precise, specific requirements for materials and methods, while the performance verification step supplements prescriptive requirements with performance testing. This creates flexibility that allows for innovation within a familiar framework and mitigating risk, combining the safety of prescribed methods with the assurance of performance testing.

Prescriptive elements typically include concrete mix design specifications (minimum cement content, maximum water-to-cement ratio, aggregate grading), cover-to-reinforcement requirements based on exposure conditions, material selection (cement type, aggregate quality, admixture limitations), and construction practices (curing requirements, placement methods, compaction standards).

The hybrid approach provides a familiar framework for practitioners while offering the confidence of performance-based design. It allows innovation within a proven baseline, fostering dynamic and adaptable specifications. Additionally, the hybrid approach provides a precise quality control structure, ensuring that prescriptive requirements and performance targets are met. This makes it more easily adopted in regions transitioning from purely prescriptive approaches.

Conversely, the hybrid approach may face challenges. Discrepancies between prescriptive requirements and performance results can lead to conflicts or uncertainties. Careful selection of performance criteria and test methods is essential to ensure the effectiveness and reliability of the approach. Furthermore, due to the additional testing and analysis, the hybrid approach may require more time and resources than purely prescriptive methods. While it allows for some innovation, it may still be more restrictive than a fully performance-based system. This approach can be integrated with other approaches, such as service life modelling to set performance targets and reliability concepts to define acceptance criteria for performance tests.

4.4.2.1 Prescriptive Approach with Performance Verification Case Study - France

FD P18-480 technical specifications, an output of the PERFDUB project, exemplify a sophisticated implementation of the Prescriptive Approach with Performance Verification. This hybrid strategy is a transitional framework, bridging the gap between traditional prescriptive specifications and fully performance-based approaches (Mai-Nhu et al., 2022).

The PERFDUB approach is designed to work harmoniously with the established EN 206 standard, forming the basis for European concrete specification. This integration is achieved through several mechanisms:

Concretes specified using the performance method are still required to comply with EN 206/CN. This ensures that the fundamental requirements of the standard are met, maintaining consistency with existing practices.

The introduction of specific designations - BPPS (Béton Performantiel à Propriétés Spécifiées) and BPCP (Béton Performantiel à Composition Prescrite) - allows for precise identification of concretes that have been specified using performance-based methods. This designation system facilitates the coexistence of prescriptive and performance-based approaches within the same regulatory framework.

Table 4-1: Performance Thresholds Based on Accelerated Carbonation Tests.

Exposure Classes	**Modulation according to resistivity class at 90 d, XP P18-481 (Ω.m)**	**Accelerated carbonation rate according to XP P 18-458 $V_{acc,k,90d}$ (mm/(day)$_{0,5}$)**	
		DSL 50 years	**DSL 100 years**
XC1	< 100	4	4
	100 to 175		
	>175		
XC2	<100	3	2.6
	100 to 175	3.5	3
	>175		
XC3	<100	1.8	1.8
	100 to 175	2.2	
	>175		
XC4	<100	1.8	1.8
	100 to 175	2.2	
	>175	3*	2.2*
*Corresponds to the cover value greater than XC3 and high resistivity, slows corrosion propagation.			

The PERFDUB approach maintains compatibility with the exposure classes defined in EN 206 while introducing refinements for more precise specifications. For example:

- XC1 is concretely located in a permanently dry environment.
- XS3 is subdivided into XS3m (tidal or splash zone) and XS3e (area exposed to sea spray)
- XD3 is differentiated into XD3f (frequent salting) and XD3tf (very frequent salting)

This refinement allows for more targeted durability specifications while maintaining alignment with the familiar EN 206 framework and establishes the foundation for setting performance thresholds according to exposure classes.

Either the Accelerated Carbonation Test according to XP P 18-458 or the porosity accessible to water according to NF P18-459 can be used to justify compliance. Table 4-1 and Table 4-2 give the thresholds for compliance. Modulation is introduced to each exposure class based on resistivity, as the resistivity of the concrete affects' corrosion propagation time. During formulation validation tests, accelerated carbonation and water porosity tests for the exposure classes XC3 and XC4 are mandatory.

Table 4-2: Performance Thresholds for Water Porosity Divided by Paste Volume Fraction.

Exposure Classes	**Modulation according to resistivity class at 90 d, XP P18-481 (Ω.m)**	**Water-accessible characteristic porosity (according to NF P 18-459) / Paste volume fraction $P_{water,k,90d}/fV$ (%)**	
		DSL 50 years	**DSL 100 years**
XC1	< 100	65%	65%
	100 to 175		
	>175		
XC2	<100	65%	60%
	100 to 175	65%	65%
	>175		
XC3	<100	50%	50%
	100 to 175	55%	
	>175		
XC4	<100	50%	50%
	100 to 175	55%	50%
	>175	65%*	55%*
*Corresponds to the cover value greater than XC3 and high resistivity, slows corrosion propagation.			

The performance-based method can be justified according to the results of chloride ion migration tests for exposure classes XS and XD as defined by XP P18-162. Table 4-3 and Table 4-4 present the thresholds for compliance for design service life of 50 and 100 years.

Table 4-3: Performance Thresholds Based on a Chloride Migration Test.

Exposure Classes	**Modulation according to ageing factor class.**	**Chloride ion migration coefficient according to XP P18-462 $D_{rcm,k,90d}$ (x 10^{-12} m^2/s)**	
		DSL 50 years	**DSL 100 years**
XS1	0.30 to 0.39	16(38*)	9(16*)
	0.40 to 0.49	28	22
	0.50 to 0.59		
	0.60 and above		
XS2	0.30 to 0.39	5(9*)	3(5*)
	0.40 to 0.49	9	5
	0.50 to 0.59	16	9
	0.60 and above		
XS3e	0.30 to 0.39	5	5
	0.40 to 0.49	9	9
	0.50 to 0.59	16	16
	0.60 and above	22	22
XS3m	0.30 to 0.39	2	2
	0.40 to 0.49	3	3
	0.50 to 0.59	5	5
	0.60 and above	9	9
*Applicable for concrete with water porosity measured at 90% less or equal to 13.5%			

Modulation for different exposure classes is done based on the ageing factor.

Table 4-4: Performance Thresholds for Class XD Based on a Chloride Migration Test.

Exposure Classes	**Modulation according to ageing factor class.**	**Chloride ion migration coefficient according to XP P18-462 $D_{rcm,k,90d}$ (x 10^{-12} m^2/s)**	
		DSL 50 years	**DSL 100 years**
XD1	0.30 to 0.39	16(28*)	16(22*)
	0.40 to 0.49	28	28
	0.50 to 0.59		
	0.60 and above		
XD2	0.30 to 0.39	9	9
	0.40 to 0.49	16	16
	0.50 to 0.59	22	22
	0.60 and above		
XD3f	0.30 to 0.39	9	9
	0.40 to 0.49	16	16
	0.50 to 0.59	22	22
	0.60 and above		
XD3tf	0.30 to 0.39	5	5
	0.40 to 0.49	9	9
	0.50 to 0.59	16	16
	0.60 and above		
*Applicable for concrete with water porosity measured at 90% less or equal to 13.5%			

The specifications provide flexibility in combining prescriptive and PBS within a single concrete designation. For instance, concrete might be specified as “BPPS C25/30 XF1/XS2p,” where XF1 is justified using traditional prescriptive requirements, while XS2p is justified using performance-based methods. This hybrid approach enables tailored specifications that leverage the strengths of both techniques, depending on the specific exposure conditions and performance requirements.

Additionally, there’s an allowance for selective performance verification, focusing on specific durability aspects while retaining prescriptive specifications for others. This flexibility facilitates a gradual transition towards PBS, prioritizing an application's most critical durability parameters.

While the approach primarily relies on PBS, it incorporates specific minimum prescriptive requirements to safeguard against inadequate durability. A minimum total binder content is stipulated, varying from 260 kg/m³ for exposure classes XC and XF1 to 300 kg/m³ for other classes.

This ensures the concrete mix is not under-designed even when performance criteria are met. A minimum clinker content of 15% of the total binder is also mandated to guarantee sufficient reactive cement for maintaining basic concrete properties and durability. To maintain a link to established material quality standards, all concrete components must meet general suitability requirements, except those with European technical assessment, according to NF EN 206/CN.

There is also an introduction to a tiered system for implementing performance verification based on the importance of the structure or element as categorised from one to three in Table 4-5. Three application levels are defined: N1 for non-structural or easily replaceable elements, N2 for buildings and routine civil engineering works, and N3 for structures with exceptional importance or long design lives.

Table 4-5: Recommended Levels of Application of the Performance-Based Approach.

Exposure class of the part of the structure **Part of the structure or the element considered**	**XC1**	**XA**	**Other classes**
1	N1	N2	N1
2	N1	N2	N2
3	N2	N3	N3

Category 1, Elements in buildings that don't contribute to the structural stability or non-structural buildings, temporary or easily replaceable elements and works.

Category 2, Buildings and certain routine civil engineering works designed for a 50-year lifespan.

Category 3, Structures designed for a life span of 100 years and exceptional structures (nuclear power plants, dams, tunnels, prestigious buildings, etc.).

The requirements for performance verification increase in stringency with higher application levels. N1 requires basic indicators at 28 days and properties associated with durability at 90 days for the nominal mix only. N2 adds testing requirements for derivative batches and more frequent control testing. N3 includes the most comprehensive testing regime, with quarterly durability property testing for XC, XF, XS, and XD classes. This tiered approach ensures that performance verification is applied proportionately to the criticality of the structure.

This approach integrates performance verification with enhanced quality control measures. Concrete producers must adhere to stricter tolerances on constituent dosages, frequently monitor aggregate and sand moisture content, and regularly check concrete consistency and air content. A suitability testing phase is mandated to verify that the concrete produced under actual conditions meets the performance requirements established in laboratory studies. For higher application levels, ongoing control testing is required to ensure continued compliance with performance requirements, with the frequency of these tests determined by the application level and exposure class.

The strategy implemented in FD P18-480 represents a sophisticated and nuanced implementation of the Prescriptive Approach with a Performance Verification strategy. Carefully integrating performance-based elements into the existing prescriptive framework provides a practical pathway for the construction industry to transition towards more performance-oriented specifications.

The hybrid approach offered by PERFDUB provides several advantages. It maintains continuity with established practices, facilitates industry adoption, allows for targeted application of performance-based methods, and provides a flexible framework for varying levels of performance verification. Additionally, it retains certain prescriptive safeguards to ensure a baseline level of durability. However, this hybrid system's complexity may present implementation challenges, particularly regarding testing requirements and interpretation of results. Future refinements should focus on simplifying the verification process and developing clear guidelines to assist stakeholders in navigating the transition from prescriptive to PBS.

4.4.3 Equivalent Performance Concept

This approach involves defining equivalent performance criteria that allow different materials and construction methods to be used as long as they meet the specified performance requirements. This method is flexible and can accommodate innovative solutions. This concept often includes methodologies for estimating the design working life of concrete structures based on the performance criteria, ensuring that the structures meet the required durability standards.

It is exemplified by the EPMA (Equivalent Performance of Multiple Additions) system, which allows for the use of various supplementary cementitious materials and admixtures by demonstrating that they provide equivalent or superior performance to a reference concrete mix, typically made with Ordinary Portland Cement (OPC).

Key principles of equivalent performance methods include performance equivalence (focusing on achieving equivalent or better performance rather than prescribing specific mix designs), using a standard OPC concrete mix or a reference standard as a benchmark and additionally, focusing on achieving specific performance outcomes rather than prescribing exact materials or methods, requiring proof that alternative approaches meet or exceed the reference standard (equivalence demonstration), considering various performance aspects (multiple criteria), and allowing for innovation and optimization while maintaining quality standards (e.g., innovative use of materials).

The equivalent performance methods can improve durability and reduce environmental impact by focusing on achieving desired performance outcomes, such as strength, durability, and sustainability. Moreover, the equivalent performance method provides a structured approach to evaluating new materials and technologies. This can accelerate the adoption of innovative solutions and drive advancements in the field. Focusing on performance outcomes can also lead to improved durability and sustainability.

4.4.3.1 Equivalent Performance Concept Case Study - EPMA System

The Equivalent Performance of Multiple Additions (EPMA) system was developed to facilitate the use of SCMs and other alternative materials in concrete while ensuring equivalent performance in terms of durability. The system provides a framework for evaluating the performance of concrete mixtures with different combinations of materials, allowing for their use in specific applications if they meet the required performance criteria.

Several international standards and specifications have incorporated the concept of Equivalent Performance of Multiple Additions (EPMA). The American Concrete Institute's ACI 318 is among the most widely referenced concrete codes globally. While traditionally prescriptive, it has integrated performance-based approaches that accommodate multiple SCMs. ACI 318 allows using multiple SCMs, including fly ash, slag, silica fume, and natural pozzolans, as long as the concrete achieves the specified performance targets such as compressive strength, durability under environmental conditions, and permeability resistance. This provides flexibility in mix design, allowing EPMA when specific performance outcomes are met. Other standards with the same concept are the AS 3600 and CSA A23.1.

The EPMA system is based on the principle that different combinations of SCMs and chemical admixtures can achieve equivalent performance to traditional concrete mixtures in terms of durability.

The EPMA system begins by identifying specific performance criteria for the concrete, such as chloride ion penetration resistance, freeze-thaw durability, or sulphate resistance. These criteria are determined based on the anticipated environmental conditions. A reference concrete mix, typically composed of ordinary Portland cement and traditional aggregates, is then selected as the benchmark for comparison. Test mixes incorporating various SCMs and chemical admixtures are designed to match the water-to-cement ratio and workability of the reference mix. These test mixes undergo standardized durability tests to assess their performance relative to the reference mix. The test results are analysed to determine whether the mixes meet or exceed the established performance criteria. If a test mix qualifies, it is approved for use in applications requiring equivalent durability performance. The results of the performance evaluation are subsequently documented.

One of the primary applications of the EPMA system is in marine environments, where concrete structures are exposed to aggressive chloride ions that can lead to corrosion of reinforcing steel. The system has been used to evaluate the performance of concrete mixes incorporating slag and fly ash in achieving equivalent or superior resistance to chloride ion penetration compared to traditional OPC mixes.

The EPMA system has also been applied to develop high-performance concrete for infrastructure projects requiring enhanced durability, such as bridges and tunnels. The system has facilitated high-performance SCMs and advanced chemical admixtures in these applications to achieve superior durability while reducing overall material costs.

The EPMA system promotes innovation, sustainability, and performance assurance in concrete production by focusing on performance rather than prescriptive requirements. However, challenges remain in balancing multiple SCMs and admixtures, which requires a detailed understanding of how each material interacts and affects the overall performance of concrete. In addition, the quality and properties of SCMs, such as fly ash or slag, can vary depending on their source, which requires additional quality control measures to ensure consistent performance.

4.4.4 Durability Specification Methodologies Supplemented with PBS

The above strategies are not exhaustive and may be integrated with one or more methods for added effectiveness. The actual implementation may combine more than one strategy.

i) Multi-prediction Models

Some countries use multi-level prediction models that integrate various factors such as environmental exposure, material properties, and structural design to predict the durability of concrete structures and estimate the service life. The models incorporate chloride diffusion, carbonation, and corrosion initiation (Biondini & Frangopol, 2008). Models can be more accurate, but extensive data and computational resources are required. These models often involve a procedure for verifying durability, which includes statistical evaluation and inspection methods to ensure conformity with the specified requirements (Beushausen, 2015). Examples include Life-365, DuraCrete and STADIUM®, LCPC Empirical models from France, DuraCrete Probability-based durability design from the Netherlands, and DuraCon probability-based durability design from Norway. Prediction approaches can be combined with Reliability-Based Design for probabilistic service life prediction. They are frequently used in conjunction with PBS to set quantitative targets.

ii) Reliability-Based Durability Design

Reliability-based durability design uses probabilistic methods to account for uncertainties in material properties and environmental conditions. Aims to achieve a target reliability level over the design service life.

It is used to model chloride ingress and carbonation, predict time to corrosion initiation, consider variability in freeze-thaw cycles and concrete properties, account for uncertainties in aggregate reactivity and moisture availability, and model variability in load cycles and material fatigue resistance.

It can be combined with durability index approaches (e.g., South African DI) to set performance targets and is often used with service life prediction models.

iii) Statistical Evaluation and Inspection

Statistical methods are employed to evaluate the cover depth of reinforcing steel, ensuring compliance with specified requirements. Inspection by variables or attributes is used to verify conformity. Clear actions are defined in case of non-conformity, including qualitative and quantitative procedures to address deviations from standards. The choice of approach depends on local regulations, available technology, and the specific durability challenges in the region.

4.4.5 Comparative Analysis of Performance-Based Strategies

This section compares and contrasts the PBS implementation of several countries, highlighting key similarities and differences.

South Africa prioritizes the establishment of specific durability indexes as the core of their PBS. These indexes provide quantitative measures of concrete performance over time. The European Union (EU) and the United States (US) systems offer a more flexible approach, allowing for both prescriptive and performance-based methods. This flexibility enables engineers to choose the most suitable approach based on project requirements and available resources.

The EU has established a framework that facilitates a gradual transition from traditional prescriptive methods to PBS. In the US, performance-based elements have been incorporated into existing structural design codes, offering a more flexible approach to concrete design. The Equivalent Performance (EPA) system stands out for its exceptional flexibility, encouraging material innovation and the development of new concrete technologies.

While maintaining a more structured approach, South Africa provides clear and quantifiable performance targets that promote innovation and quality. Although still primarily prescriptive, the EU and US systems balance prescriptive requirements and performance options, fostering a dynamic and innovative environment for concrete design.

South Africa's durability index approach links durability indexes to service life models, directly connecting concrete performance and its expected lifespan. The US also encourages using service life prediction tools, offering a more flexible approach to assessing long-term performance. While other systems may not explicitly address service life modelling, they implicitly consider it through their performance criteria and testing requirements.

In conclusion, while all these approaches aim to enhance concrete durability through PBS, they differ in their specific methodologies, degree of prescriptiveness, and integration with existing standards. The choice of approach often reflects local construction practices, available materials, and regulatory environments. The global trend appears to be moving towards more flexible, performance-oriented systems that can accommodate innovation while ensuring durability and performance.

Table 4-6: Comparative Analysis of Performance-Based Strategies

Comparative Analysis of Performance-Based Strategies			
	Key Features	**Implementation Process**	**Distinctive Aspects**
South Africa	Employs durability index tests (Oxygen Permeability, Water Sorptivity, Chloride Conductivity) to assess concrete performance. Lab or site	Establishes durability index limits based on exposure conditions and design life. Conducts index tests on trial mixes and during construction. Uses index values for quality control and acceptance criteria.	Empirically links durability indexes to service life prediction models. Chloride and Carbonation-induced corrosion initiation models.
Canada	Rapid chloride ion permeability test (RCPT), Sorptivity, Bulk diffusion, and RCMT	Specifies durability requirements based on exposure classification.	ASTM C 1202 Chloride penetration test
USA	Incorporates performance-based durability design alongside traditional prescriptive requirements.	Defines exposure categories and classes. Specifies performance requirements (e.g., maximum w/cm ratio, minimum f'c). Allows for alternative performance measures with approval.	Emphasizes the use of service life prediction models (e.g., Life-365). Integrates performance requirements with structural design considerations. The use of result specifications (ERS
EU	Combines prescriptive limiting values with an option for performance-based approaches.	Defines exposure classes. Specifies minimum concrete requirements (e.g., w/c ratio, cement content). Allows for performance-based alternatives if equivalent performance is demonstrated.	Provides a framework for transitioning from prescriptive to PBS. Allows for national adaptations within the broader European framework.
France	Chloride diffusion coefficient – effective and apparent Apparent gas permeability Liquid water permeability Initial Ca $(OH)_2$ content Water accessible porosity	Durability Index Test. Classifies concrete based on test results. Specifies durability requirements based on exposure classification.	Emphasizes the use of LCPC Empirical models

4.5 Factors Contributing to Successful Implementation

4.5.1 Collaborative Approach to Specifications Implementation

The successful implementation of PBS for concrete durability has relied heavily on collaboration among various stakeholders. In the US, organizations such as the Federal Highway Administration (FHWA), the NRMCA, and the ACI have worked with government

agencies, industry associations, and academia to promote PBS (Kurtis, Kahn & Nadelman, 2013). At the federal level, the FHWA and Federal Aviation Administration (FAA) have adopted performance-based approaches for crucial infrastructure projects, such as bridges and airport pavements (FAA, 2014).

4.5.2 Establishment of Practical Performance Criteria and Testing

Implementation of PBS for concrete durability has been supported by establishing clear performance criteria and testing methods across various countries. In the USA, PBS includes criteria such as chloride ingress resistance, carbonation resistance, freeze-thaw resistance, sulphate resistance, alkali-silica reaction (ASR) resistance, and permeability. Testing methods, such as the Chloride Permeability Test (ASTM C1202), carbonation tests (ASTM C1876), freeze-thaw cycling tests (ASTM C666), and sulphate resistance tests (ASTM C1012), ensure concrete meets durability requirements. These tests provide measurable outcomes to assess the long-term performance of concrete structures, allowing for verification that performance goals are achieved.

In South Africa, testing methods adopted for PBS include the Chloride Permeability Test to assess resistance to chloride ion penetration, water permeability tests to evaluate moisture resistance, and carbonation depth measurements using phenolphthalein indicators to ensure adequate concrete cover protection. Freeze-thaw testing (ASTM C666) is conducted for structures exposed to freezing conditions, and non-destructive testing (NDT) techniques, such as ultrasonic pulse velocity and rebound hammer tests, are used to evaluate the durability of existing structures without causing damage. These testing methods help ensure that concrete used in various environments meets the necessary performance criteria for long-term durability.

4.5.3 Comprehensive Framework/ Development of Guidelines

Implementing PBS for concrete durability has been primarily supported by developing comprehensive frameworks focused on measurable performance criteria and standardized testing methods. In the USA, organizations such as the ACI and ASTM International have been key players in establishing performance-based standards and providing clear, concrete performance requirements in various environmental conditions. These standards have provided a solid foundation for incorporating durability concerns into concrete design and construction practices.

4.5.4 Training and Education

Training and education have been essential for implementing PBS for concrete durability. Workshops and training programs for engineers, contractors, and inspectors have focused on PBS principles, performance criteria, and testing methods, helping shift from prescriptive to performance-based approaches. Hands-on training and case studies have equipped stakeholders with the skills needed for practical PBS application, supporting widespread adoption.

4.5.5 Incorporation of Pilot Projects/ Case Studies

Pilot projects have been crucial in successfully implementing PBS for concrete durability. These projects were designed to test and validate the PBS approach in real-world conditions, involving key stakeholders such as state Departments of Transportation (DOTs), contractors, and material suppliers.

In South Africa, pilot projects also served as a testing ground for implementing PBS, offering practical feedback to adjust specifications for local conditions. The data and insights gained from these projects have been instrumental in building confidence among stakeholders and demonstrating the real-world advantages of adopting PBS for concrete durability.

4.5.6 Assessment of Existing Standards and Development of Standards

Assessing existing standards has been critical in successfully implementing PBS for concrete durability.

4.5.7 Initiation and Research

Extensive research and initiation efforts have significantly driven the successful implementation of PBS or, at the very least, targets it. For instance, the PERFDUB project in France was a significant step forward in establishing a performance-based framework for assessing concrete durability. By focusing on collaboration, integration of research findings, and practical applications, the project aims to enhance the longevity and reliability of concrete structures.

4.6 Challenges Faced in the Implementation of PBS

Implementation of PBS presents several difficulties, including:

4.6.1 Defining Clear Performance Criteria

Establishing measurable and achievable performance criteria can be difficult. Factors such as exposure conditions, desired service life, and minimum strength requirements must be clearly defined. Apart from that, establishing clear and measurable performance criteria that accurately predict long-term durability is complex. Criteria include chloride penetration resistance, freeze-thaw durability, and carbonation depth must well-defined and tested (Alexander & Thomas, 2015).

4.6.2 The Demand for Special Testing Equipment

The primary obstacles to implementing the new approach are the inadequacy of tests that can be utilised on-site or in the laboratory, a lack of data on acceptable performance levels, and reluctance from various stakeholders to adopt the method. It has been noted that raising awareness among all parties involved is essential to demonstrate the approach's relevance and advantages (Sangoju et al., 2021).

4.6.3 Variability in Testing Methods

Different testing methods and conditions can yield varying results, making standardising performance criteria across various regions and projects difficult. Testing must be repeated to accommodate variations in materials and the introduction of new materials (Beushausen, 2016). A common obstacle to adopting performance specifications is the absence of dependable, consistent, standardized testing methods for assessing concrete performance (Sangoju et al., 2021).

4.6.4 Selection of Appropriate Test Methods

Choosing the correct test methods to assess the desired performance criteria is crucial. Existing test methods might not always accurately predict long-term durability behaviour. There is also an absence of dependable and quick testing methods to assess durability (Lobo et al., 2006) accurately. For example, EN 206-1 (2013), which deals with specification, performance, production and conformity for concrete construction, “avoids” a performance-based approach because of a lack of agreement on test methods (Revista, 2018), a lack of experience in establishing adequate performance requirements accompanied by suitable acceptance criteria (Kessy, 2013).

4.6.5 Requisites for Testing and Validation

Some available tests can be costly, time-consuming, and less accurate than expected. On the other hand, testing technology is still lagging behind performance philosophy (Sangoju et al., 2021); Lolli et al., 2023).

4.6.6 The Shortage of Data Related to an Acceptable Level of Performance

Verifying the long-term performance of concrete structures built with PBS can be difficult due to the relatively new adoption of this approach. Limited historical data might make it challenging to validate performance predictions (Sangoju et al., 2021).

4.6.7 Variability of Concrete Materials

The natural variability in raw materials used for concrete production can affect performance outcomes, complicating the establishment of standardized specifications.

4.6.8 Establishing Quality Control and Assurance Procedures

Ensuring consistent quality throughout construction is vital for achieving the desired performance. Effective quality control plans and robust quality assurance procedures must be established (ACI 318, 2019).

4.6.9 Regulatory and Compliance Issues

PBS for concrete durability face several regulatory and compliance challenges. These include the lack of clear standards, difficulty in verification, conflicts with existing building codes, risk management concerns, and the need for effective quality control measures. Addressing these

issues requires collaboration between industry experts, regulatory bodies, and stakeholders to develop standardized PBS, establish reliable testing protocols, obtain necessary approvals, manage risks effectively, and implement robust quality control measures.

4.6.10 Stakeholder Engagement

They are overcoming resistance, ensuring all parties' buy-in to address stakeholder concerns and gaining acceptance. Collaboration between engineers, contractors, material suppliers, and owners is crucial for successful PBS implementation—the unwillingness of various stakeholders to adopt the approach (Sangoju et al., 2021).

4.6.11 Lack of Technical Expertise

The surveyed agencies identified several barriers to implementation. The most frequent response (32%) indicated that enforcement was the primary challenge to adopting PBS widely. The "Other" category included additional respondent-identified obstacles, which also related to enforcement challenges, such as "contractor resistance," "lack of confidence," "insufficient specification development," and "slow research progress" (Lolli et al., 2023).

4.6.12 The Necessity of Uniform Performance Standards

No widely recognized model performance specifications are guidelines for creating performance-based project specifications (Lobo et al., 2006).

4.7 Conclusion

This review examined the strategies of various countries for implementing PBS, highlighting key themes and considerations critical to their success. The strategies observed, such as South Africa's durability index method, the Equivalent Performance of Multiple Additions (EPMA) system, the European Union's hybrid framework under EN 206, and the United States' integration of PBS in ACI 318, demonstrate the adaptability of PBS concepts to local conditions. These frameworks share common goals despite their differences: increasing concrete durability, encouraging material and design innovation, and ensuring long-term structural integrity. Overall, the results have been positive, with improved durability, increased use of sustainable materials, and more adaptable project-specific solutions reported across regions.

These countries' experiences offer valuable lessons for the construction industry. Key takeaways include defining clear, measurable performance criteria relevant to local environments, establishing reliable testing and quality control measures, and gradually transitioning from prescriptive to performance-driven systems. Furthermore, as seen in the above implementations, PBS has demonstrated the ability to drive innovation and emphasises the importance of solid stakeholder engagement and industry education. These findings underscore the importance of a collaborative, adaptive approach to PBS that considers local contexts while leveraging global best practices.

5. Practical Framework to Implement Performance-Based Specification for Concrete Durability

5.1 Introduction

After exploring multiple strategies used for implementing PBS for concrete durability, this chapter will propose a practical framework for implementing PBS. A framework was proposed for developing PBS in India by (Alexander, Santhanam & Ballim, 2011). The framework outlined a four-stage approach to developing durability specifications for concrete in India. The first stage involved critically evaluating existing durability provisions in Indian standards, including requirements for concrete strength, cement content, water-cement ratio, and environmental classifications. The second stage focused on creating a distress map for different geographic locations across India by collecting information on observed concrete distress, obtaining and analysing core samples, and redefining exposure conditions. The third stage was selecting and evaluating appropriate laboratory and field-based performance indicators, conducting round-robin tests at different laboratories, and finalizing test procedures. The final stage involved preparing a white paper on durability specifications, setting implementation guidelines, and beginning field implementation. This includes identifying suitable sites for field trials and using the new durability specifications in concrete contracts with selected participating producers. The document emphasizes the importance of leveraging existing research and guidelines from international sources such as RILEM technical committees and recent experiences in South Africa. The development process, particularly after the initial implementation, is expected to continue long into the future, with guidelines being revised based on inputs from field implementation. Building upon this, the framework introduced in this chapter will propose a modified approach that prioritizes flexibility to enable broader applications. Building upon this foundational work, this chapter proposes an enhanced and globally adaptable practical framework for implementing Performance-Based Specifications (PBS) for concrete durability. The key contributions presented here involve adapting the original structure for broader international application, expanding on the original stages with greater detail, and introducing critical new components. Notably, a specific Environmental Classification System tailored for PBS is developed, incorporating geographical analysis of degradation and outlining clear implementation procedures. Furthermore, the proposed framework integrates considerations for regulatory provisions, practical implementation strategies, and essential long-term monitoring protocols. The complete enhanced framework, synthesizing these components, is presented on Figure 5-1 to offer a clear, comprehensive, and actionable methodology for facilitating the wider adoption of PBS in the concrete industry.

Figure 5-1 introduces the proposed framework. The framework outlines a systematic methodology for defining performance criteria, selecting appropriate test methods, and establishing acceptance criteria that align with project-specific durability requirements. This framework aims to facilitate the widespread adoption of PBS in the concrete industry.

PROPOSED FRAMEWORK FOR THE IMPLEMENTATION OF PERFORMANCE BASED SPECIFICATIONS

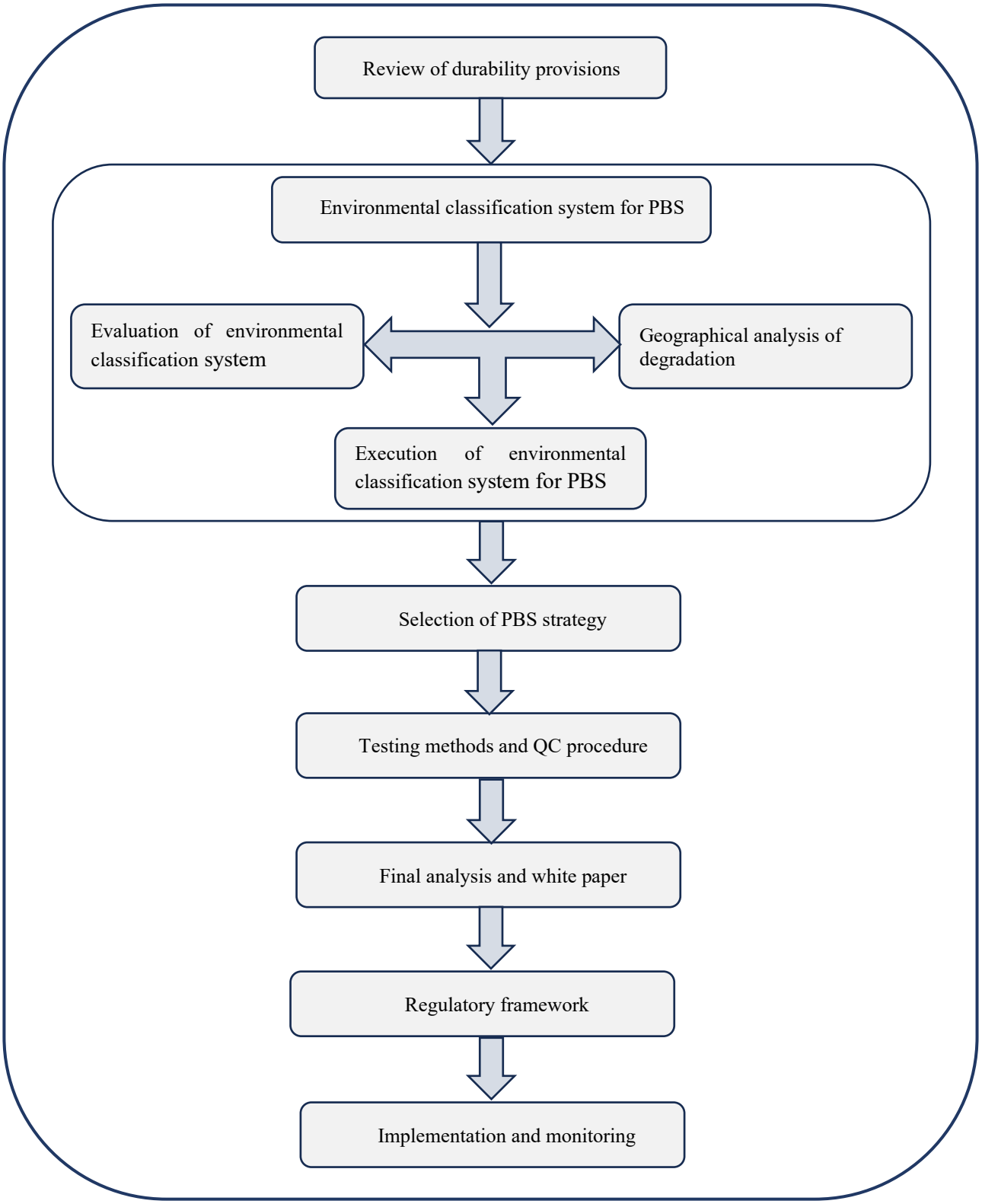

Figure 5:1: Framework for Implementation of Performance-Based Specifications.

5.2 Review of Current Durability Provisions

Most concrete specifications have durability requirements that prescribe a minimum grade of concrete, maximum w/c ratio and minimum cement content for given types of exposure. The following should be evaluated:

5.2.1 Requirements of Concrete Strength, Cement Content and W/C

The concrete strength, cement content, and w/c ratio requirements in traditional prescriptive specifications provide a baseline for concrete quality. These parameters are indirectly considered part of the overall performance goals in PBS.

Instead of specifying a minimum compressive strength, the focus has to be on how the concrete performs in relation to durability over its expected service life. In addition, instead of specifying the amount of cement used, the emphasis should be on the concrete achieving the necessary predefined performance metrics, such as resistance to chloride penetration or carbonation (Roberts et al., 2024). Finally, the w/c ratio is not explicitly mandated. Instead, the concrete must demonstrate sufficient durability characteristics, such as low permeability and high resistance to environmental attacks, which could be achieved through various mix designs optimized for performance.

The concrete strength requirements, cement content, and w/c are still important considerations, but they have become part of a more comprehensive approach to PBS according to the PBS strategy.

5.2.2 Requirements of Special Cement for Different Types of Exposure

The choice of cement should be left to the concrete manufacturer as this aligns with PBS by focusing on the desired end results rather than dictating the specific inputs. This allows for an emphasis on the required performance of the final concrete, such as sulphate resistance or mitigation of alkali-silica reactions, rather than the cement type itself (Thomas, 2020). Concrete manufacturers possess specialized knowledge of local materials and their interactions, enabling them to develop optimal mix designs tailored to specific environmental conditions. Moreover, not prescribing cement types encourages innovation by allowing manufacturers the flexibility to incorporate alternative cementitious materials or innovative cement blends that may offer superior durability.

5.2.3 Specifications for Different Types of Cement with Respect to Impact on Durability

Allowing the concrete producer to select the cement type while focusing on the end result, the durability of the concrete provides several benefits. It allows for a comprehensive mix design approach in which cement type is considered alongside other key factors, such as supplementary cementitious materials, admixtures, and the water-to-cement ratio, resulting in optimal performance (Obla, 2013). This flexibility also enables producers to use locally available materials best suited to specific project conditions, potentially lowering costs and mitigating environmental impact. Furthermore, it promotes innovation by allowing newer or

improved cement types that may provide more excellent durability but are not covered by traditional specifications. Finally, the emphasis shifts from assuming that a specific cement type will ensure durability to verifying the actual durability performance using appropriate testing methods.

5.2.4 Specifications for Concrete Cover

The specification of concrete cover in PBS should similarly be left to the engineer's discretion, focusing on achieving the desired durability outcomes rather than prescribing exact cover thicknesses. Additionally, a provision could be made to ensure a prescribed cover is achieved on-site. In cases where concrete cover is prescribed, the provision above will verify the actual cover after construction and, ultimately, the durability of the concrete. This approach emphasizes the required performance of the structure, such as protection against corrosion, freeze-thaw damage, or chloride ingress, allowing engineers to select the cover based on the specific environmental exposure and durability requirements (Beushausen and Luco, 2015). With their understanding of the local conditions and material behaviours, engineers can optimize the cover design using advanced durability modelling and performance testing to ensure that the concrete meets its service life objectives. By not rigidly defining minimum cover, this approach encourages innovation, enabling engineers to consider alternative protective measures, such as enhanced concrete mixtures or surface treatments, fostering more sustainable and efficient designs while maintaining the long-term performance of the structure.

5.3 Environmental Classification System for PBS

5.3.1 Evaluation of the Environmental Classification System

Exposure classes categorize concrete based on its environmental suitability. Exposure classes are ideally defined based on several environmental factors. These factors include atmospheric conditions, such as the levels of airborne chlorides, sulphates, and carbon dioxide. The type of water exposure, whether freshwater, seawater, or groundwater, and its potential aggressiveness are also crucial considerations. Aggressive chemicals or sulphates in the soil or groundwater should be assessed. Additionally, the frequency and severity of freeze-thaw and wetting and drying cycles the concrete will experience must be considered when determining exposure classes (ACI 318, 2019).

Most exposure classes in current specifications primarily rely on qualitative descriptions of the environmental conditions. While they provide a general guideline, some ambiguity can exist.

Conversely, some research proposes quantitative exposure class classifications based on parameters such as chloride content or sulphate concentration. These proposals can offer more precise design considerations but might not be universally adopted in practice.

i) Review of the Current Implementation of Exposure Classes in Selected Standards.

EN 206 (BS 8500)

EN 206 provides detailed exposure classes for various environmental conditions, including chemical attacks, freeze-thaw cycles, and chloride exposure from seawater and de-icing salts. BS 8500 complements EN 206 by providing specific performance criteria and guidance on concrete composition to meet the requirements of each exposure class. These standards are widely recognized and adopted in Europe, ensuring consistency in concrete specifications and performance.

ACI 318

ACI 318 categorizes environmental exposures, addressing various durability challenges such as sulphate attack, freeze-thaw, and chloride ingress. Specifies performance requirements for concrete based on exposure categories, including minimum compressive strength, maximum water-cement ratio, and air-entrainment for freeze-thaw resistance, are given; hence, the specification is prescriptive primarily. Nevertheless, it encourages PBS and allows for innovative materials and methods as long as they meet specified performance criteria.

AS 3600

AS 3600 includes definitions for various exposure environments, such as coastal, industrial, and marine. This standard emphasizes durability by linking exposure classifications to specific performance requirements and material selection guidelines. It tailors these requirements to comply with Australia's unique environmental conditions and construction practices, ensuring its relevance and effectiveness. While not exclusively focused on performance-based classification, these standards provide a solid foundation by incorporating key elements such as defining exposure classes based on environmental factors, linking exposure classes to minimum material properties and protection measures, and encouraging the establishment of performance objectives for structures, aligning with the overall philosophy of PBS.

ii) Effective Exposure Classes System for the Performance-Based Specification.

The effectiveness of an environmental classification system in serving PBS lies in its ability to clearly define exposure conditions and link these conditions to specific performance criteria.

An environmental classification system that effectively serves PBS should have the following requirements:

- Comprehensive Coverage of Environmental Conditions

The system should cover various environmental exposures, including chloride attack, sulphate attack, carbonation, freeze-thaw cycles, and other aggressive conditions. Differentiate between multiple levels of severity for each exposure condition.

- Clear and Specific Classifications

Provide clear and detailed categories for each environmental condition to ensure precise classification of exposure environments. Each classification should be well-defined, with specific criteria and examples.

- Quantifiable Parameters

Use quantifiable parameters (e.g., chloride concentration, sulphate levels, relative humidity to define exposure classes. These parameters should be measurable using standard test methods.

A robust environmental classification system offers several benefits. Engineers can select durable and cost-effective materials by understanding the expected environment and optimizing material selection. Structures designed with proper materials and detailing based on environmental classification often require less maintenance over their lifespan, reducing maintenance costs. PBS allows for exploring innovative materials and construction techniques as long as they meet the defined performance objectives and support innovation. Additionally, choosing durable materials and minimizing maintenance needs can contribute to a more sustainable construction process, enhancing sustainability.

5.3.2 Geographical Analysis of Concrete Degradation

Different geographical regions require tailored PBS due to the varying environmental and geological conditions:

- Coastal Areas: Emphasis on chloride resistance, low permeability, and corrosion inhibitors.
- Cold Climates: High resistance to freeze-thaw cycles, use of air-entraining agents to enhance durability.
- Urban Areas: Consideration of air pollution effects, use of high-performance concrete to resist carbonation and acid rain.
- Arid Regions: Focus on resistance to drying shrinkage, cracking and use of water-retaining admixtures.

Existing concrete degradation can help trace the underlying durability issue prevalent in the area and the recalibration of the exposure conditions. Below is the summary of the steps to be taken,

- Data on the types of concrete distress observed will be gathered from various geographical areas.
- Concrete cores from these locations are extracted, and laboratory evaluations are conducted to determine the mix design (if unattainable), the depth of carbonation, and the chloride profile.
- Reassessing exposure conditions. The environmental classification system should accommodate findings made in this stage.

5.3.3 Execution of Environmental Classification System for PBS

i) Define Exposure Levels

The system should categorize environments based on various factors. Climate, including temperature range, humidity, and precipitation levels, is crucial. Aggressive substances such

as chlorides, sulphates, or other chemicals that can deteriorate materials should also be assessed. The distinction between indoor and outdoor environments is essential due to varying exposure risks. Additionally, atmospheric pollution levels, such as SO_2 or CO_2, can impact material durability and should be considered.

ii) Consider Material Degradation

The system should link exposure levels to potential degradation mechanisms for different construction materials, e.g., concrete corrosion in chloride-rich environments.

iii) Quantitative Data

Provide measurable parameters for each exposure level to facilitate objective classification and decision-making.

iv) Durability Requirements

The system should recommend minimum durability requirements for materials and components based on the classified environment. This could involve:

- Strength and serviceability targets
- Material properties, e.g., minimum compressive strength for concrete.
- Protection measures include coatings and special concrete types.

In conclusion, in this stage, a comprehensive analysis is to be made of existing exposure class systems available worldwide and the existing systems in specific countries where PBS are considered. Current standards, while offering valuable guidance, often rely on qualitative descriptions, which can introduce ambiguity. Integrating quantitative parameters into exposure classifications can enhance precision and facilitate more informed design decisions. Finally, to ensure the effectiveness of an environmental classification system, it should cover a comprehensive range of environmental conditions based on available environmental degradation. Differentiate between varying levels of severity within each exposure category. Provide clear and specific classifications with quantifiable parameters. By adhering to these principles, PBS can be developed that promote the design and construction of durable and sustainable concrete structures under their environment.

5.4 Selection of PBS Strategy

Chapter 4 introduced and analysed various performance-based strategies. Among the options presented, the PAPV strategy is the most conservative. PAPV allows for a gradual transition to PBS while retaining certain aspects of prescriptive-based approaches. This strategy can mitigate resistance from stakeholders and facilitate a smoother implementation of PBS. Other approaches may be considered case-by-case, depending on specific project requirements and circumstances.

5.5 Selection of Testing Methods for Performance Specifications

i) Selection of Appropriate Laboratory-Based Performance Indicators.

When evaluating durability test methods, several factors need to be considered:

The test method must accurately simulate the fundamental degradation mechanisms the concrete will experience throughout its service life.

The tests should be repeatable and reproducible. The test must be consistently conducted in different laboratories, yielding good agreement results.

The test method should be cost-effective and time-efficient to perform.

The test method should be based on a recognized national or international standard to ensure consistency and reliability.

The ideal approach to durability testing often involves a combination of methods. Accelerated testing can provide initial insights, while natural exposure testing can validate these findings realistically.

- A clear definition of mechanisms driving the distress observed in 5.3.2,
- Classify testing methods according to the mechanisms.

ii) Selection of Appropriate Field-Based Performance Indicators.

- Classify testing methods according to the mechanisms identified earlier.
- Study interrelationships between laboratory and field-based methods through measurements of different types of concrete.

iii) Conduct Round-Robin Tests at Different Laboratories.

- Replicate equipment for measurements in the lab and on the field at all participating laboratories.
- Ensure uniformity of equipment when doing round-robin tests at all locations.
- Analyse the effect of the atmospheric/laboratory conditions prevalent at a particular location on the results obtained from the tests.

iv) Analyse test data from different labs and evaluate critical factors affecting results.

Finalization of tests and test procedures.

5.6 Final Analysis and White Paper on Durability Specifications and Beginning of Field Implementation

i) Prepare a white paper on durability specifications.

ii) Identify suitable sites for carrying out field trials.

5.7 Regulatory Framework

i) Develop Comprehensive PBS Guidelines

Formulate a national guideline document that thoroughly articulates the principles of PBS. This document should delineate the benefits and potential limitations of adopting PBS in concrete construction. The guideline should provide a standardized reference for industry professionals and stakeholders, ensuring a consistent understanding and application of PBS practices across various projects and countries.

ii) Identify Suitable Structures for PBS Implementation

Establish criteria to determine the types of structures where PBS can be most effectively applied. This should include identifying specific categories such as buildings, bridges, tunnels, and other infrastructure elements that would benefit from a performance-based approach. By categorizing structures, it will be easier to tailor PBS strategies that address each type's unique durability requirements and performance objectives.

iii) Align with Existing Prescriptive Codes and Standards

Develop a strategy to harmonize PBS with existing prescriptive codes to prevent conflicts and ensure coherence between regulatory frameworks. This step involves reviewing current standards and identifying areas where PBS can complement traditional prescriptive methods, thus facilitating a smooth integration that enhances overall structural durability without creating confusion or contradictions within the industry.

5.8 Implementation and Monitoring

5.8.1 Pilot Projects

Pilot projects are crucial in implementing and monitoring PBS for concrete durability. These projects allow for testing PBS's effectiveness in real-world scenarios, offering insights into practical challenges and areas for improvement. Selected concrete producers participate, adhering to PBS criteria to evaluate their processes, materials, and testing methods against targeted durability goals. Monitoring these pilot projects involves tracking performance metrics, gathering participant feedback, and analysing data to refine the PBS system. These pilots' findings help adjust performance criteria, optimise testing procedures, and establish best practices for broader PBS adoption.

5.8.2 Incentives and Support

To encourage early adoption of PBS, pioneering companies should be incentivised, and additional support should be provided for smaller firms to ease their transition. This may include financial subsidies, technical assistance, or streamlined approval processes, helping smaller companies access necessary resources and training.

5.8.3 Data Collection and Feedback

Gather data from pilot projects and ongoing PBS applications, covering performance metrics, testing results, and field observations. This data informs system improvements, identifying strengths and weaknesses of PBS in varied conditions.

5.8.4 Continuous Improvement

Establish a feedback mechanism that incorporates performance data, user feedback, and advancements in testing or materials. This iterative approach allows for gradually enhancing PBS criteria and practices, fostering alignment with evolving industry needs and technologies.

5.8.5 Periodic Review

Schedule regular reviews and updates of PBS specifications to incorporate the latest research, technological developments, field experience, and adaptations to changing environmental conditions. This ensures the specifications remain relevant and practical.

5.8.6 Life-Cycle Cost Analysis

Evaluate the life-cycle costs for different PBS options, including initial construction, long-term maintenance, and potential repair costs. This analysis helps select PBS approaches that best balance durability and cost-effectiveness over a structure's lifespan.

5.9 Conclusion

When adapted to specific project needs, implementing PBS for concrete durability offers a structured approach to developing robust durability criteria. This framework enhances the durability and longevity of concrete structures, reducing lifecycle costs and minimising environmental impact. It encourages innovation in materials and construction techniques, leading to more sustainable and high-performance concretes. Additionally, it improves quality control and assurance, resulting in more reliable concrete performance, and provides more outstanding design and construction flexibility to meet specific project requirements.

The proposed framework for PBS development includes several key stages: reviewing current durability provisions, adopting an environmental classification system, selecting the appropriate PBS strategy, choosing suitable testing methods, and conducting final analyses before field implementation. Establishing a regulatory framework and ensuring ongoing monitoring are also crucial. Following this comprehensive framework, you can achieve optimized, high-performance concrete solutions tailored to project requirements and performance goals.

6. Conclusion and Recommendations

6.1 Summary of General Observations

Concrete is renowned for its versatility, strength, and durability. Its ability to be moulded into various shapes and its high compressive strength make it ideal for applications ranging from buildings and bridges to roads and dams. Concrete is used in structural and non-structural components, offering durability and resistance to many environmental factors. However, despite its advantages, many RC structures experience early degradation, often within a few years of service. This premature deterioration is commonly caused by environmental exposure and inadequate construction practices.

Premature deterioration occurs when concrete structures degrade faster than expected, significantly affecting safety, functionality, and economic viability. The prevalence of premature deterioration varies widely depending on factors such as climate, exposure conditions, and the quality of construction materials and practices. Deterioration can lead to cracks, spalling, and loss of structural integrity, posing a safety risk. In addition, it can necessitate costly repairs or even replacement of entire structures. This can have significant economic and sustainability consequences.

A comprehensive review of durability provisions for RC structures across various specifications was conducted for this dissertation. The specifications reviewed included AS 3600 (2009), AS 1379 (2008), ACI 318 (2019), CSA A23.1/23.2 (2019), BS 8500-1: 2015+A2:2019, IS 456 (2000), COTO (2020), and importantly, the fib Model Code 2020 (MC2020). It was concluded that while many current national design specifications still rely significantly on prescriptive parameters for concrete durability (such as limits on water-to-cementitious material ratio (w/cm), minimum compressive strength, and cover depth based on exposure conditions), there is a clear international trend towards performance-based thinking, crystallized most comprehensively in the recent MC2020.

While prescriptive specifications provide valuable guidelines for ensuring consistency in material use and construction, their inherent inability to fully address site-specific factors, complex environmental exposures, and long-term performance requirements leaves structures vulnerable to premature durability issues. Even when a mixed design complies with the prescribed specifications, it may not achieve the intended service life. In contrast, performance-based approaches, exemplified by MC2020, Performance-Based Design (PBD), explicitly incorporating concepts like Durability Performance Indicators (DPIs), life-cycle assessment, reliability-based verification, and sustainability as core tenets.

For concrete durability, compared to prescriptive specifications, performance-based approaches are often seen as a more effective solution for enhancing concrete durability and reducing the risk of premature deterioration. These specifications should help RC structures achieve their intended service life and performance by focusing on performance metrics rather than prescriptive measures. Performance-based approaches offer a more holistic, flexible, and tailored solution to concrete durability issues. By focusing on the specific environmental exposures, functional requirements, and long-term performance of the structure, these

approaches can reduce the risk of premature deterioration and increase the longevity and resilience of concrete structures.

Various countries have developed distinct strategies to implement PBS in response to the global demand for PBS and the growing recognition of its importance (Chapter 4). One notable approach is the South African Durability Index Approach, which focuses on quantifying the potential durability of concrete by assessing its resistance to the ingress of aggressive agents and using service life prediction models. This method has been adopted in South Africa, where durability indexes are critical indicators in evaluating concrete performance. Additionally, the Prescriptive Approach with Performance Verification (PAPV) combines traditional prescriptive specifications with performance-based testing to ensure durability. This hybrid strategy is employed in countries transitioning to PBS adoption, as seen in the case of France following the PERFDUB research project. Finally, the equivalent performance concept allows alternative materials and methods to be used in concrete mix design as long as they guarantee equivalent performance. The EPM system exemplifies this approach, enabling the use of SCMs and admixtures by demonstrating performance equivalence to traditional concrete mixes made with Plain Portland Cement. Frameworks like the fib Model Code 2020 aim to provide a unifying structure that can accommodate and guide these various performance-based strategies.

This study revealed a diverse range of strategies for implementing PBS. While this range offers beneficial options, it can also challenge countries transitioning from traditional approaches. A key obstacle lies in determining the objectively superior strategy. To address this, this dissertation proposes a practical framework for PBS adoption (Chapter 5). The framework presents a structured approach for defining performance criteria, selecting appropriate testing methods, and establishing project-specific acceptance benchmarks. Unlike many location-specific frameworks found in other studies, the proposed framework is universally applicable and includes a step for choosing the most suitable PBS implementation strategy.

The framework also recommends adopting an Environmental Classification System tailored to the project's specific geographic and environmental conditions. By classifying exposure levels and linking them to potential degradation mechanisms, such as chloride-induced corrosion in coastal environments, this system would provide clear, measurable parameters for setting durability requirements. The classification should account for climate factors, including temperature, humidity, and precipitation, to ensure appropriate environmental durability standards.

Additionally, selecting appropriate test methods is critical. The framework suggests a comprehensive evaluation of both laboratory-based and field-based performance tests, ensuring the tests simulate the degradation mechanisms the concrete is likely to face. It emphasizes the need for collaboration between laboratories to standardize testing methods through round-robin tests, ensuring consistency and reliability of results.

Finally, the framework outlines the need to develop a regulatory framework, including national guidelines that detail the principles, benefits, and limitations of PBS. A focus on long-term monitoring and evaluation during field implementation is essential to assess the performance of concrete structures over time. Following this comprehensive approach, the

industry can successfully transition to PBS, leading to more durable, sustainable, and cost-effective concrete solutions.

6.2 Recommendations

The future of concrete construction lies, at least partly, in adopting performance-based approaches that can deliver more durable and sustainable structures. To achieve this future, several key actions are necessary:

i) Continued research into advanced materials, testing methodologies, and service life prediction models to support PBS implementation.

Ongoing research is crucial to refine and improve the tools and techniques needed for adequate PBS, ensuring they remain at the forefront of technological advancements.

ii) Enhanced collaboration between researchers, industry practitioners, and regulatory bodies to develop and refine PBS frameworks.

Cross-sector collaboration ensures that PBS frameworks are practical, scientifically sound, and aligned with regulatory requirements, fostering widespread acceptance and implementation.

iii) Investment in education and training programs to build the necessary expertise for widespread PBS adoption.

Developing a skilled workforce through targeted education and training is essential for successfully implementing and managing PBS approaches across the construction industry.

iv) Developing international platforms for knowledge sharing and best practice exchange in PBS implementation.

Global knowledge-sharing platforms facilitate the exchange of ideas, experiences, and best practices, accelerating the adoption and refinement of PBS methods worldwide.

v) Continued integration of PBS principles into building codes and standards to drive industry-wide adoption.

Incorporating PBS principles into formal codes and standards provides a regulatory framework that encourages and eventually mandates performance-based approaches in concrete construction.

6.3 Global Trends and Future Directions

The landscape of PBS for concrete durability is evolving, driven by advancements in materials science, testing technologies, and data analytics. As the construction industry increasingly recognizes the value of PBS in enhancing the longevity and sustainability of concrete structures, several key trends are emerging that will shape the future of this field.

i) Standardization of Test Methods and Acceptance Criteria

One of the most significant trends in PBS is the push towards standardization of test methods and acceptance criteria. As highlighted in the South African approach, the development of standardized durability index tests has been crucial in implementing PBS effectively. The global concrete community is continuing to work on establishing universally accepted test

methods to predict long-term durability performance accurately. This standardization effort aims to address the challenges of variability in testing methods and inconsistency in results.

ii) Potential for Global Standards

The increasing globalization of the construction industry is driving discussions on the feasibility and benefits of integration of PBS globally. While regional differences in environmental conditions, available materials, and construction practices present challenges to a one-size-fits-all approach, there is growing recognition of the value of establishing a common framework for PBS implementation.

The European Standard EN 206 standard provides a model for how regional standards can incorporate prescriptive and performance-based approaches while allowing for national adaptations. This flexible framework could serve as a template for developing global standards tailored to local conditions while maintaining core performance principles.

The benefits of such harmonization would be significant. It would facilitate international collaboration, enable more efficient knowledge sharing, and create a larger market for innovative durability solutions. However, achieving this will require extensive cooperation between national regulatory bodies, international standards organizations, and the global research community.

iii) Advances in Materials Science, Testing Technologies, and Data Analytics. Integration with New Technologies (e.g., Digital Tools for Monitoring)

Advancements in materials science are opening new possibilities for enhancing concrete durability. Developing novel supplementary cementitious materials, high-performance admixtures, and alternative binders expands the toolkit available to concrete producers to meet performance specifications. These innovations are significant in sustainability, as they often allow for reduced cement content and increased use of recycled materials.

Concurrently, integrating new technologies is revolutionizing how concrete performance is monitored and verified. Embedded sensors, Internet of Things (IoT) devices, and artificial intelligence for data analysis enable real-time monitoring of concrete structures. These technologies provide continuous data on factors such as moisture content, chloride penetration, and corrosion initiation, allowing for a more accurate assessment of durability performance over time.

Digital tools are also transforming the design and specification process. Building Information Modelling (BIM) systems increasingly incorporate durability parameters, allowing for more holistic design approaches that consider performance criteria from the earliest stages of a project.

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