Study Report

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Durability evaluation framework for new building materials

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Preface

This study report was prepared during the research into a durability evaluation framework for new materials for New Zealand building and construction.

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Abstract

This study developed a generic framework to help facilitate the durability evaluation of new building materials. It described a structurally phased durability evaluation procedure and a general approach for developing testing schemes using a material-component-environment paradigm. These were supported by a number of core components formulated within this study.

This study designed, built and commissioned a specialised weathering rig with rotating and spraying functionality. It can be used to technically support some of the specific methods designed for material durability evaluation according to the approach and procedure discussed in this report. It may also enhance the capability of investigating material-environment interactions by adjusting exposure details in systematic ways, particularly solar irradiation and dominant air contaminants.

Keywords

Building material, durability, service life, evaluation, methodology.

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Executive summary

This study developed a generic framework to help facilitate the durability evaluation of new building materials, this being a challenging endeavour. This framework included two interconnected parts:

- A structurally phased durability evaluation procedure.
- A general approach for developing testing schemes using both top-down and bottom-up approaches within a material-component-environment paradigm.

These two parts were supported by a number of core components developed within this study:

- Review of durability requirements and pathways for NZBC compliance and durability evaluation activities from both research and testing perspectives.
- Description of a number of examples of new materials developed for building and construction applications:
    - Timber treated with new preservatives
    - Thermally modified timbers
    - Ferritic stainless steels
    - High-performance concretes
    - Zinc-based alloy coatings and paints
    - Thermal spray coatings
    - Thermal diffusion galvanising coatings
    - Self-healing coatings
    - Insulation materials.
- Compilation of accelerated and non-accelerated durability evaluation methods and relevant New Zealand and international standards.
- Compilation of factors and/or parameters critical to the durability evaluation of some building materials:
    - Concrete
    - Insulation materials
    - Metallic building components
    - Polymeric materials and components.
- Compilation of service life prediction methods, models and tools:
    - Deterministic
    - Stochastic
    - Computational
    - Engineering design.
- Compilation of expected service lives of some building materials and components:
    - Timber
    - Zinc-based alloy coatings
    - Organic paints
    - Typical building components.

This study designed, built and commissioned a weathering rig with the capability of rotating from the east to the west by following the sun, spraying specific solutions and controlling sample inclination angle. It can be used to:

- conduct experiments that aim to better understand the degradation behaviours, processes and mechanisms of materials through their interactions with the environment

- evaluate the durability of building materials under more-controlled exposure conditions
- technically support some of the specific methods designed for material durability evaluation according to the approach and procedure discussed in this report.

As technologies evolve, a myriad of new materials are emerging that offer potential cost, performance and environmental benefits. New materials can be distinctly different from conventional materials in terms of composition, microstructure and/or processing. They may also demonstrate a variety of complexities in functional property and in-service condition adaptability. For example, conventional coatings protect metallic substrates with a physical barrier or electrochemical effects. New-generation coatings can even actively release inhibitors to regulate the surrounding micro-environments with appropriate triggers or heal themselves when damaged, offering improved protection and durability.

The building and construction industry is willing to use new materials and the components that are constructed with these new materials. However, one prerequisite for the industry to do this is that reliable information is available to demonstrate that these new materials and components satisfactorily meet the New Zealand Building Code (NZBC) durability requirements.

Overall, this study will contribute to the development of dynamic processes for evaluating the properties, performance and durability of specific new building materials (see Figure 1). These processes may help manufacturers, suppliers or evaluators collect, integrate and interpret data and information for the purpose of achieving NZBC durability compliance effectively and efficiently.

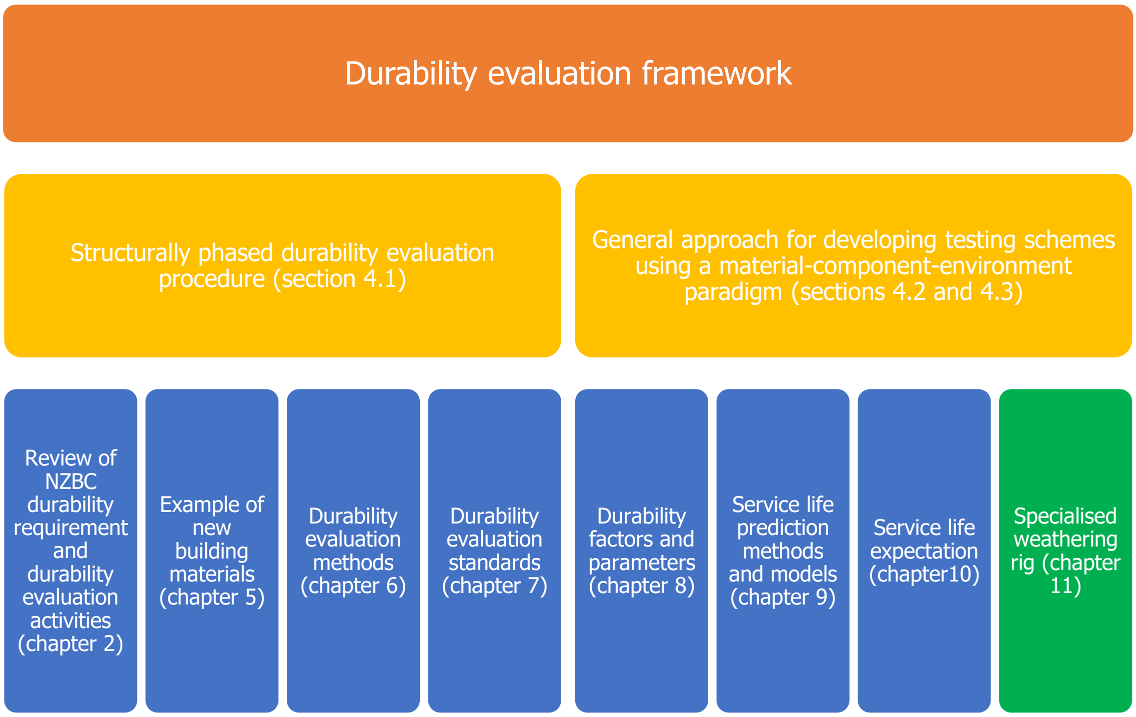


Figure 1. Core components of the durability evaluation framework developed in this study.

1. Introduction

There are a limited number of metallic materials and coatings such as aluminium, copper, stainless steel and galvanised zinc coating with recognised durability that can be chosen as acceptable building solutions. Even then, the sustainability of the production processes of some of these materials such as hot-dip galvanising has recently been questioned. Alternative materials are therefore needed to sustain future building and construction practices.

The evolution of materials for building and construction has a rapid pace. Technological advances have led to the development of new materials comprising of ceramics, composites or those utilising nanotechnologies. For example, innovative coatings have been manufactured with the capability of regulating micro-environments or self-healing, therefore providing better protection than conventional counterparts that rely on barrier or galvanic effects. These new materials have the potential to deliver a solid basis for more-affordable, more-environmentally friendly and more-durable buildings.

The performance-based New Zealand Building Code (NZBC) requires any functional component used on a building to meet the minimum durability requirements. Consequently, the performance and durability of any material or material system for building and construction must be evaluated thoroughly for acceptance. This is critical to encourage the building and construction industry to embrace new materials over the building life cycle – design, construction, maintenance, renovation, alteration and/or retrofitting.

Continuous efforts are devoted to evaluating the performance, durability and properties of building materials in international and national contexts to facilitate their pathways for building code acceptance. Based on publicly available literature, some of these activities have been discussed and summarised in the following chapters. This information was used to develop a durability evaluation framework that has two interconnected parts supported by a number of core components.

2. Review of literature

2.1 NZBC durability requirements

Ensuring that buildings have an appropriate durability has always been an important aspect of building regulations. The NZBC is a performance-based rather than a prescriptive code (Buchanan, Deam, Fragiacomo, Gibson & Morris, 2006; Buckett, 2014). Its durability section (B2) sets minimum durability requirements for functional building elements with normal maintenance, depending on their criticality of function and ease of replacement (Edhouse, 2015).

More specifically, the following durability requirements have been given:

- Building elements have a life not less than 50 years:
    - that provide structural stability to the building
    - that are difficult to access or replace
    - for which failure to comply with the NZBC would go undetected during the building's normal use and maintenance.
- Building elements are to have a life of 15 years:
    - that are moderately difficult to access or replace
    - for which failure to comply with the NZBC would go undetected during the building's normal use but would be easily detected during maintenance.
- Building elements are to have a life of 5 years:
    - that are easy to access and replace
    - for which failure to comply with the NZBC would be easily detected during the building's normal use.

2.2 NZBC compliance

In practice, NZBC durability requirements have the following implications for the building and construction industry:

- Manufacturers or importers must provide evidence to clearly demonstrate that building materials or products will meet or exceed the minimum durability requirements.
- Building practitioners, specifiers and consenting authorities must clearly understand how these descriptions can be manifested as accurate specifications and use of appropriate materials to achieve the required durability.

The NZBC includes Acceptable Solutions (AS) and prescriptive construction methodologies for a small number of building materials and products. If these were strictly followed during design and construction, they would be NZBC compliant. However, these are focusing primarily on building materials and construction methods that have a reasonably long history of use under New Zealand conditions.

The NZBC has an approved Verification Method, B2/VM1, to offer generic guidance that proof of performance should be demonstrated by in-service history, laboratory testing or analogy with similar products or situations. This intends to permit or encourage innovations with building design, construction technique and/or material. However, how to ensure these innovations will comply with the NZBC is a big challenge.

A lack of reliable and relevant information has been widely recognised by the industry as a primary barrier to support innovations. This is perceived as the result of the following (Clark & Bennett, 2011):

- It is difficult to thoroughly investigate the durability of materials and to establish their reference service lives by determining the factors that may affect their durability. This is even more challenging for the manufacturers when considering time, cost and resources required.
- The availability of numerous standards and test methods does not mean the durability of any building material and/or product can be assessed properly. Durability is defined by the complicated interactions between a material and its in-service environment. A number of tests are always necessary to collect information and data that is relevant, reliable and appropriate for durability evaluation. This requires the evaluator to have an in-depth understanding of testing methodologies, material characteristics, in-service environments and degradation mechanisms.
- Lab-based accelerated methods are commonly used to produce data and information for durability evaluation and/or service life prediction. It is challenging to develop and verify the correlations between accelerated testing results and real performance under in-service conditions. This is particularly true for new materials when exposed to new environments.

There is a demand for evidence-collecting methodologies that will help demonstrate NZBC compliance.

2.3 Product assurance framework

Assurance options available to demonstrate how a specific building product will comply with NZBC durability requirements (Building Performance, 2016) include:

- technical information
- independent assessments
- industry-based schemes
- appraisals
- product certification (CodeMark).

2.3.1 Technical information

Technical information is fundamental to all the above options and is commonly required to be presented as a product technical statement that has the following details and/or descriptions (Cunninghame, 2011a, 2011b; Gardiner, 2015, 2016):

- Description of the building product and its intended use.
- Details of the manufacturer.
- Date of issue (or revision) and relevant links.
- Purpose, use and limitation – where and how the building product can be used, particularly the use relevant to New Zealand’s environment and types of buildings.
- NZBC clauses relevant to the building product and evidence to support compliance with the performance requirements of those clauses.
- Design, construction and installation instructions and requirements for designers, builders and tradespeople and maintenance requirements for building owners.
- Organisations that can provide technical support.

2.3.2 Independent assessments

An independent assessment is normally completed by competent organisations and can be used to verify and/or endorse the information from manufacturers' or suppliers' own testing and analysis.

2.3.3 Industry-based schemes

An industry-based scheme is appropriate for ensuring families of products comply with specified and/or audited industry requirements and has the following merits:

- The scheme framework is outlined with publicly available rules.
- Scheme compliance is independently audited regularly with a publicly available programme.
- A breach of the scheme will lead to penalties that have been clearly stated upfront.
- The ongoing integrity of the scheme is maintained by a governance structure consisting of industry, user and independent representatives.

For example, the New Zealand Ready Mixed Concrete Association and Insulated Glass Unit Manufacturers' Association developed schemes for ready-mix concrete and glass products respectively. Members of these organisations are responsible for ensuring their products meet the requirements of the scheme, and products are assessed by recognised organisations.

2.3.4 Appraisals

An appraisal is a technical opinion of a building product or system's fitness for purpose by extensively assessing a range of relevant performance factors with a competent third party. Typical performance factors may include:

- NZBC requirements
- performance under test conditions
- performance under in-service conditions
- accuracy of the product's technical information
- manufacturing procedures and quality control systems
- specific installation systems and/or processes relevant to the building product
- limitations of a product's intended scope of use.

To appraise a building product with few or no innovative features, a standard assessment process might be appropriate. For products that are entirely or partially new or innovative, specific procedures may be designed to undertake tests to derive results essential to performance and durability assessment.

2.3.5 Product certification

Product certification is a voluntary scheme to evaluate and certify building products with accredited product certification organisations, and it provides a robust way to show that a building product meets NZBC requirements. It might be the best option for a manufacturer or supplier that wants to introduce products that are innovative or novel to the market or would have significant consequences if they fail.

2.4 Acceptance criteria

From the 1970s, the International Code Council Evaluation Service started to evaluate the code compliance of new or innovative building products using acceptance criteria.

Most new and/or innovative products require specific acceptance criteria developed for their evaluation. Acceptance criteria are described in a document that provides a comprehensive list of criteria and requirements that must be satisfied to demonstrate building code compliance (Morrison, 2008; Moore, 2011; Nanni, Ekenel & De Caso, 2015).

A typical acceptance criteria document may include:

- purpose – reason for development
- scope – scope or limits of application
- reference – relevant building codes and/or standards
- basic information – product description, packing and identification, testing in the laboratory, test report(s) and product sampling requirements
- testing requirements – material type, basic physical/mechanical properties, fabrication method/process and product limitations
- test methods and performance requirements – tests required to assess performance, test set-ups, test methods, acceptable boundary conditions, permitted test variance, analysis methods and requirements
- initial/ongoing quality control, inspection and/or assurance requirements
- evaluation report recognition – format and minimum content requirements.

An evaluation report is one of the ways to demonstrate a specific building material or product will meet the requirements of a prescriptive building code and offer some benefits:

- Building practitioners may be more confident that a new or innovative building material or product will have building code compliance and therefore are willing to use it.
- Architects and specifiers can perform design more efficiently.
- Building code officials can use evaluation reports to facilitate and expedite their reviewing and approving process.
- Building inspectors will have a clearly defined scope of field inspection.
- Manufacturers may gain higher industry confidence and wider market acceptance of their products.
- Building owners and users may be more confident that the new materials or products used in their buildings are performing as they expected and/or required and sometimes may offer more benefits.

Similar building products by the same or different manufacturers can be evaluated by the same evaluation report provider using the same acceptance criteria, making the practice more consistent. However, acceptance criteria developed by a specific organisation might not be accepted and used by other organisations to issue an evaluation report. This is particularly evident since different countries have different building codes. Some are prescriptive, while others are performance-based (Arnold & Meriwether, 2016).

2.5 Durability indicator/index

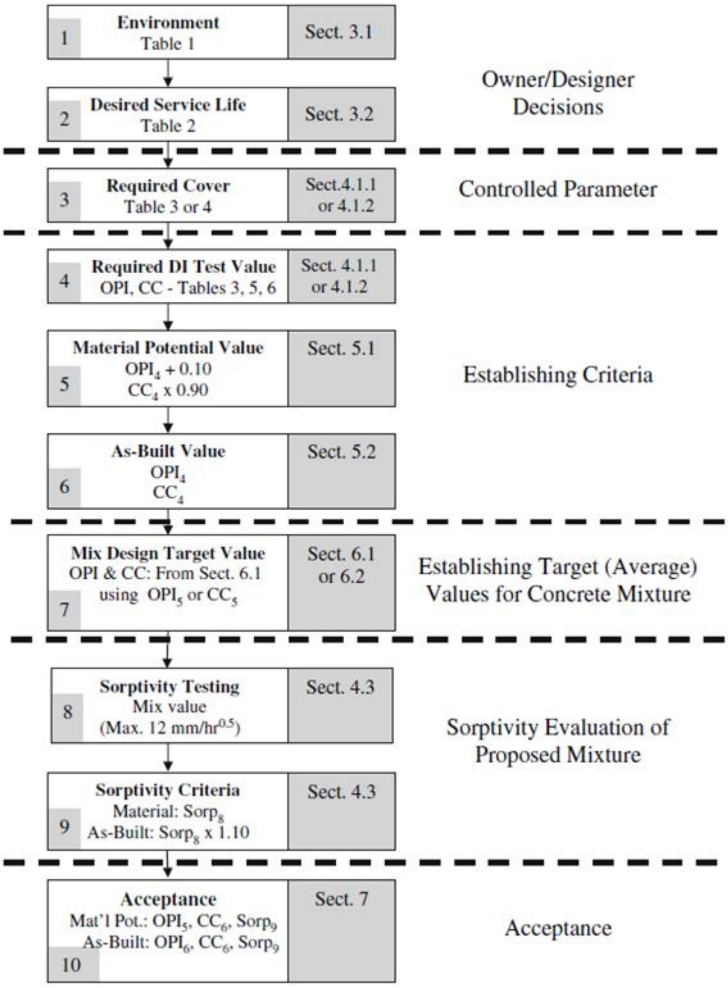
The performance and durability of a building material are based on its chemical, mechanical and physical properties and/or other properties critically relevant to the in-service conditions (Carlsson, 2003; Yang, Wu, Noguchi & Isshiki, 2014). To evaluate durability and to predict service life, it is necessary to develop strategies that can use fundamental material properties and consider interactions between the material and its in-service environment. An example of this is described below.

The concept of a durability indicator or index has been developed to describe, control and evaluate degradation and to predict durability of concrete (Baroghel-Bouny, 2002; Andrade & Izquierdo, 2005; Beushausen, Alexander & Torrent, 2008; Baroghel-Bouny, Kinomura, Thiery & Moscardelli, 2011; Santhanam, 2013; Sengul, 2014; Beushausen & Fernandez Luco, 2015).

A durability indicator or index is a quantifiable physical or engineering parameter that is sensitive to material, processing and/or in-service environment. Typical examples for concrete (Ekolu & Murugan, 2012; Maroliya, 2012; Nganga, Alexander & Beushausen, 2013; Chandra Paul & Van Zijl, 2013; Kubissa, Jaskulski & Brodnan, 2016) include:

- binder type
- chloride conductivity
- cover depth
- oxygen permeability
- ratio of water to binder
- type and degree of curing
- water sorptivity.

Figure 2 shows the steps used to establish durability indicators and corresponding acceptance criteria to control the durability of concrete materials and structures.



Source: Muigai, Alexander & Moyo, 2016

Figure 2. Establishment of durability indicators and acceptance criteria for concrete.

A durability index approach, based on the following principles, has been developed to improve the quality of reinforced concrete construction (Alexander, 2018):

- Reinforced concrete durability depends primarily on the quality of the cover or surface layer, i.e. its ability to protect the reinforcing steel.
- Improved durability can only be assured if a relevant durability parameter(s) can be measured.
- The quality of the cover layer should be characterised using parameters that influence deterioration processes and that are linked with relevant transport mechanisms.
- Index tests are needed to cover the range of durability problems, each index test being linked to a transport mechanism relevant to that process.
- The usefulness of index tests is assessed by reference to actual durability performance of structures built using the indexes for quality control purposes.

Correspondingly, a framework based on this approach for the design of durable concrete materials may consist of the following components:

- Identifying functional design requirements and desired service lives as specified by building codes and relevant standards.
- Characterising in-service conditions that may include:
  - distance from the sea and exposure to airborne sea salt particles
  - exposure to damp
  - exposure to wind-driven rain
  - exposure to other airborne pollutants
  - orientation of structure.
- Specifying parameters, properties and/or variables that should be measured and/or controlled.
- Establishing acceptance criteria.
- Developing test methods that can measure specific properties and/or durability indicators.
- Characterising candidate materials using these test methods.
- Studying in situ performance of candidate material.
- Applying results to practical construction.

If correlations between durability indicator values and field performance can be confirmed, this approach could be accepted and used to assess quality and durability of other building materials (Frenette, Beauregard & Derome, 2007; Alexander & Beushausen 2008; Obla, Lobo & Kim, 2015; ElZomor & Parrish, 2016).

2.6 Summary

NZBC is performance-based and has minimum durability requirements for any functional component to be used on a building – 5, 15 and 50 years. How to assess the durability of new materials for NZBC acceptance and therefore to encourage their development and industrial adoption is a huge challenge to manufacturers, evaluators, researchers and regulators.

A product assurance framework with a number of generic options has been developed to support building materials or products accepted by the NZBC. Within this framework, new materials or products may require extensive assessments that are supported by adequate technical information such as testing reports and assessment opinions.

It is not uncommon to find out that testing methodologies that are capable of producing data and information required for assessing the durability of a material concerned are not always available. Frequently, a group of methods is necessary to develop a procedure to test the material in characterised and controlled environments, to analyse the data produced and to evaluate the durability.

The durability of a material is a reflection of its interactions with its in-service environment. It is then highly necessary to explore how fundamental characteristics of a material such as composition and microstructure can contribute and correlate to its durability. An example of research in this direction is the development of a durability indicator or index for specification and use of durable materials.

3. Objective

This study aimed to develop a generic framework for materials durability evaluation.

This framework includes two interconnected parts:

- A structurally phased durability evaluation procedure.
- A general approach to develop testing processes and/or schemes for specific building materials using both top-down and bottom-up approaches within a material-component-environment paradigm.

These will be supported by a number of core components:

- Materials:
  - A generic database of some examples of new building materials.
- Evaluation tool:
  - A compilation of durability evaluation methods.
  - A compilation of materials specifications and durability evaluation standards.
  - A compilation of factors and/or parameters that are relevant to durability and durability evaluation.
- Interpretation tool:
  - A database of service lives of typical building materials and components.
  - A compilation of service life prediction methods, models and/or tools.

This study also aimed to develop a weathering rig that can combine field exposure with cyclic wet-dry functions and variable solar irradiation. It is expected that this rig can be used to

- technically support some of the specific methods designed for material durability evaluation according to the approach and procedure discussed in this report
- enhance the capability of investigating interactions between the material and its environment by controlling material exposure details in systematic ways
- evaluate the durability of building materials under more-controlled exposure conditions.

4. Durability evaluation framework

The evaluation framework aims to provide technical guidance about the durability evaluation of new building materials. It has two interconnected components:

- A structurally phased durability evaluation procedure.
- A general approach for developing testing schemes using a material-component-environment paradigm.

4.1 Durability evaluation procedure

The structurally phased durability evaluation procedure aims to help answer questions frequently asked by manufacturers, suppliers or evaluators such as:

- what a durability evaluation process should include
- how to interpret results for durability evaluation and service life estimation.

This procedure has a number of components that are technically supported by the corresponding sections of this report. These components will now be discussed in detail below (see Figure 3).

Material: This includes a database of some examples of new building materials (chapter 5) and a compilation of relevant standards that have specifications for materials for building and construction (part of chapter 7). For example, NZBC E2/AS1 has requirements for pressed metal tiles from a material perspective:

- Steel:
    - Base metal thickness of 0.39 mm minimum.
    - Grade G300.
    - Selected for corrosion protection according to the intended exposure zone according to NZBC E2/AS1 Table 20 *Material selection*.
- Aluminium:
    - Base metal thickness of 0.7 mm minimum.
    - Minimum 5000 series.
    - Prepainted aluminium has a surface finish complying with AS/NZS 2728[1].

Definition: This includes two parts – NZBC durability requirements and in-service conditions. Section 2.1 of this report discusses these requirements. The durability of a material is dependent on its in-service condition, which typically includes atmospheric environment, micro-climate and micro-environment and also its interaction with other materials/components on the building.

- **Atmosphere:** The corrosivity of the New Zealand atmospheric environment has been experimentally monitored and a corrosivity map has been developed and included in section 4 *Durability* of NZS 3604[2].
- **Micro-climate:** Geothermal, industrial and volcanic emissions may present unexpected and unusual durability risks to building materials. Some work has been conducted in New Zealand to monitor their presence in air and to investigate their effects on material degradation.

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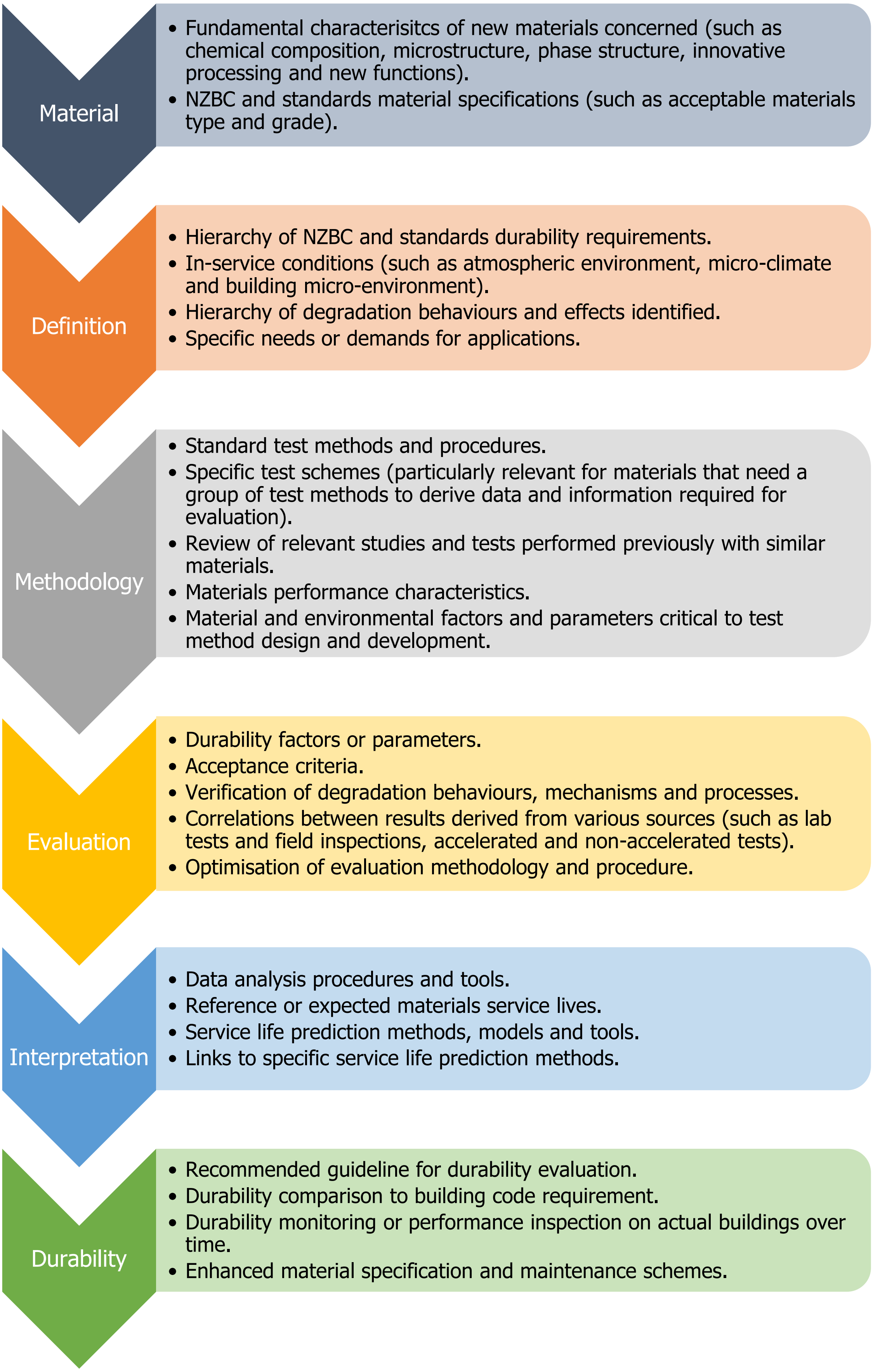
[1] AS/NZS 2728 Prefinished/prepainted sheet metal products for interior/exterior building applications – Performance requirements

[2] NZS 3604 Timber-framed buildings



Material

- Fundamental characterisitcs of new materials concerned (such as chemical composition, microstructure, phase structure, innovative processing and new functions).
- NZBC and standards material specifications (such as acceptable materials type and grade).

Definition

- Hierarchy of NZBC and standards durability requirements.
- In-service conditions (such as atmospheric environment, micro-climate and building micro-environment).
- Hierarchy of degradation behaviours and effects identified.
- Specific needs or demands for applications.

Methodology

- Standard test methods and procedures.
- Specific test schemes (particularly relevant for materials that need a group of test methods to derive data and information required for evaluation).
- Review of relevant studies and tests performed previously with similar materials.
- Materials performance characteristics.
- Material and environmental factors and parameters critical to test method design and development.

Evaluation

- Durability factors or parameters.
- Acceptance criteria.
- Verification of degradation behaviours, mechanisms and processes.
- Correlations between results derived from various sources (such as lab tests and field inspections, accelerated and non-accelerated tests).
- Optimisation of evaluation methodology and procedure.

Interpretation

- Data analysis procedures and tools.
- Reference or expected materials service lives.
- Service life prediction methods, models and tools.
- Links to specific service life prediction methods.

Durability

- Recommended guideline for durability evaluation.
- Durability comparison to building code requirement.
- Durability monitoring or performance inspection on actual buildings over time.
- Enhanced material specification and maintenance schemes.

Figure 3. A structurally phased durability evaluation procedure.

- **Micro-environment:** Material degradation has been found to be position dependent on buildings. NZBC E2/AS1 and NZS 3604 define three typical micro-environments – closed, exposed and sheltered. Note that "hidden" has also been used in E2/AS1. Limited studies have been conducted to understand the formation and characteristics of these micro-environments, in particular, wind-driven rain, salt deposition and local corrosivity. A recent BRANZ study systematically investigated the comparative corrosivity between exposed and sheltered positions on actual buildings in representative New Zealand environments (Li & Marston, 2021). Data, information and knowledge from this study and other publicly available literature can help better understand how micro-environments are formed to affect material durability.
- **Material degradation behaviour/process:** The degradation of a material stems from its interactions with its environment, this being scale dependent, and it has chemical, electrochemical or physical origins. This inevitably leads to changes in its chemical, physical, mechanical and/or functional properties. The degradation mechanisms vary significantly according to the type of materials concerned. For example, most metals and steels will corrode when exposed to the atmosphere. This process is primarily due to an electrochemical reaction between the constituents of the material and oxygen, and this is further catalysed by moisture in the air (Stratmann, 1990). When a dense and compact corrosion product layer is formed on the metal surface, subsequent attacks to the metal substrate will be slowed down or prohibited. In polymeric materials, degradation is mainly resulted from the rupture of a number of specific bonds in the polymer chain under the combined or individual action of light (particularly UV), temperature and oxygen in the air (Vohlídal, 2021). A good understanding of the degradation behaviours, processes and mechanisms of a material when exposed to a specific environment provides a solid basis for making quantitative predictions of its service life. The environmental degradation of some building materials – metals, timbers, concretes and polymers – is briefly discussed in chapter 9 of this report. More information can be found in publicly available literature.

Methodology: The current state-of-the-art methods and standards commonly used for the durability evaluation of building materials are discussed and compiled in chapters 6 and 7. Most standard testing methods can be useful for comparing the relative performance of building materials through accelerated testing in the laboratory under simulated conditions. Some of these can also provide statistical and/or technical guidance for conducting tests in the field. For example, ASTM G198[3] describes a cyclic fog test method that can be used to evaluate the corrosion performance of fasteners driven into timbers treated with preservatives. BRANZ developed a similar lab-based accelerated method that controls the moisture content of the timber by regulating dry/wet periods and the quantity of water sprayed (Li, Marston & Jones, 2011a). The derived corrosion rate results could be analysed together with the determined coating thicknesses and the durability requirements as given by NZS 3604 to estimate the service life of zinc-coated metallic fasteners. Furthermore, it is not uncommon that a number of relevant methods and/or standards are required to characterise the performance and properties of a material from different perspectives. This is critical since a material on a building should not be treated as a component that is isolated from the whole building system.

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[3] ASTM G198 Standard test method for determining the relative corrosion performance of driven fasteners in contact with treated wood

Evaluation: This covers how to produce data and information from tests that are designed to identify durability factors and/or parameters (discussed in chapter 8). Meanwhile, the correlation between accelerated and non-accelerated tests is discussed in chapter 6 to provide guidance on how to optimise methodologies and/or procedures for durability evaluation.

Interpretation: This mainly includes a compilation of service life prediction methods, models or tools (chapter 9) and a database of expected service lives of typical building materials and components (chapter 10). The building material and component examples mainly include timbers, metals, metallic coatings, polymers and organic paints. The service life data was collected from publicly available databases and reports that were supported by field inspections and laboratory and field exposure tests. The data can be used together with the models and methods described in chapter 9 to predict the service life of materials.

Durability: The durability evaluation of building materials is complicated because of the type of materials concerned, the factors and processes involved with degradation and the lack of scientific understanding of these phenomena. Consequently, most evaluation methodologies or procedures are often useful to compare the relative performance of building materials and components. They might be inadequate to produce quantitative data and information, which is essential to predict service life. There is a need to advance the state-of-the-art of performance and durability evaluation methodologies and procedures for service life predictions of building materials. An improved understanding and quantification of the characteristics of a material and its in-service environment and their interactions would be beneficial to manufacturers, suppliers or evaluators.

4.2 Testing scheme development

Materials are the basic components of buildings. Practically, a material will be fabricated into components and installed on the building together with other materials, components and/or structures to deliver its intended function. During its service, it interacts with other materials, components, structures and the surrounding environment – chemically, physically and/or mechanically.

Overall, these actions affect its performance and eventually determine its durability in the building system. This indicates that the fundamental properties of a material can be placed within the building system by linking it upwards through various interactions to contribute to the overall durability of the building.

On the other hand, the NZBC defines the durability requirements for a building component according to its criticality, function and/or in-service environmental conditions on the building, this being 5, 15 or 50 years. When considering the interactions mentioned above, this requirement can be refined downwards to understand durability implications at different levels such as building system, building functional component and building material.

Correspondingly, a material-component-environment paradigm can be proposed to better understand the correlations between the properties of building material, performance of functional component and durability of building system (see Figure 4).

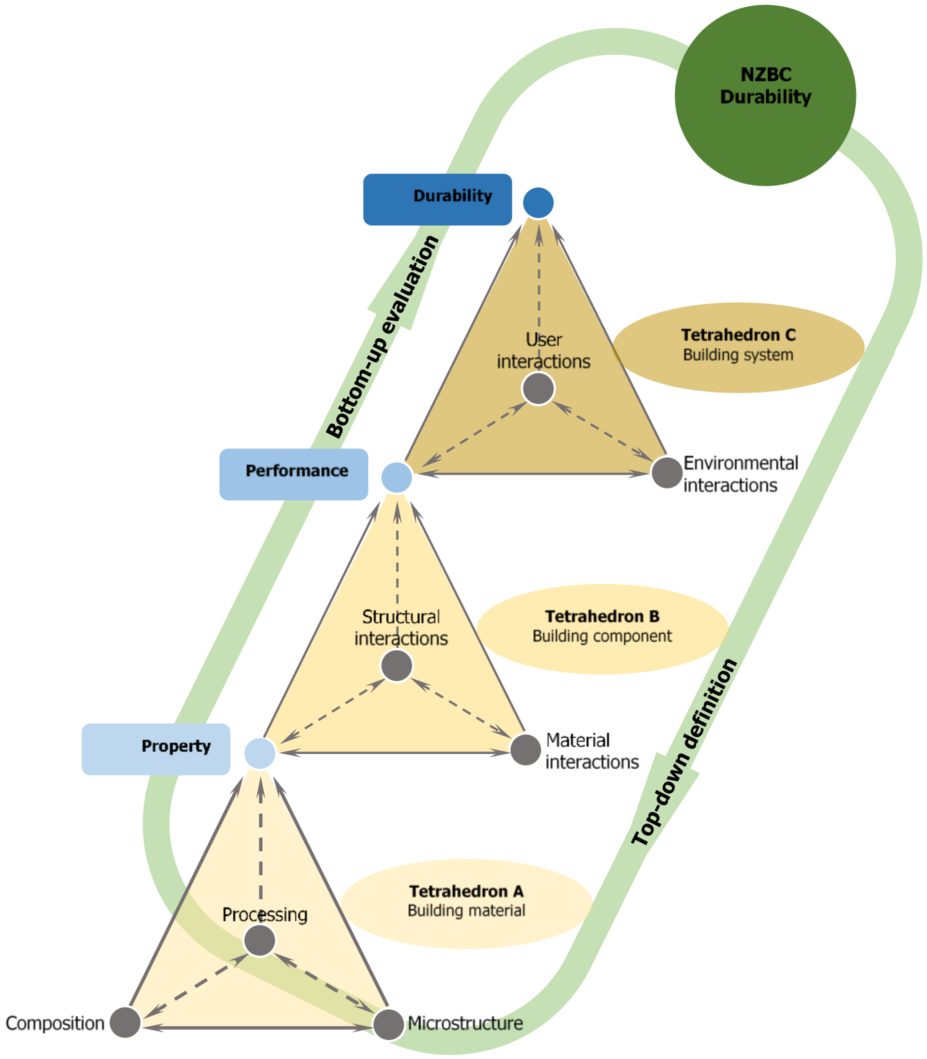

Figure 4. A material-component-environment paradigm for durability evaluation.

This has three tetrahedrons at different levels:

- **Tetrahedron A:** This can be seen at the bottom of the paradigm. The interactions between the composition, microstructure and processing of a specific building material are fundamental to its properties, namely chemical, physical and/or mechanical properties. These considerations are the core of the subject of material science and engineering.
- **Tetrahedron B:** This can be seen at the middle of the paradigm. The interactions between this material and other materials, components or structures on the building play an important role in determining the performance of this material as a functional building component.
- **Tetrahedron C:** This can be seen at the top of the paradigm. The interactions between this material and its surrounding environment result in various chemical, physical and/or mechanical changes. These may negatively affect its capability of performing or maintaining the function(s) for which it is designed and constructed over a specified timeframe within the building system. This is durability. In addition, many other factors may have their influences, individually or collectively.

These three tetrahedrons can be connected tightly together through both top-down and bottom-up analyses to guide the development of testing methodologies/schemes.

4.2.1 Top-down durability refinement

A material delivers its desired function only when it is integrated with other materials and/or components on the building. As such, its durability needs to be investigated in the context of the building system it forms a part of rather than as a single component in isolation. Correspondingly, the overall NZBC durability approach can be interpreted to produce a hierarchy of requirements and/or detailed understanding of degradation at different levels of the whole system.

This is shown as the right-hand side of the paradigm in Figure 4, and it has the following levels:

- **New Zealand Building Code:** Its durability section (B2) sets minimum durability requirements for functional building elements – 5, 15 or 50 years – that are described and applied according to the criticality of function and ease of maintenance and replacement. This durability assignment is not straightforward in practice and needs to be clarified with a good understanding of actual building structure and the in-service environment.
- **Building system:** This ensures a set of essential functions is delivered to meet the overall building performance and durability requirements under in-service conditions. The in-service conditions typically include the atmosphere surrounding the building, micro-climates and/or micro-environments formed on the building due to the interactions between the atmosphere and the building. The usage and maintenance that the system receives during service might also be a part of these conditions. These environmental conditions have various impacts on the building system since they can lead to various consequences such as degradation and even failure. Durability analysis at this level considers the effects of individual environmental conditions/factors and combinations for the identification of degradation behaviour, mechanism and/or process over the specified timeframe.
- **Building functional component:** This aims to better understand the exact function of the component made of the material, i.e. the role of the component within the building system. This helps identify how a functional component interacts with other materials or structures on the building – material interactions and structural interactions – to affect its performance.

  For example, when two dissimilar metals are in contact and exposed to adverse environments, one may suffer accelerated corrosion due to galvanic effects. A typical example is the use of stainless steel fasteners to fix an aluminium roof cladding in marine environments. Galvanic corrosion will preferentially attack the aluminium cladding in the areas around the periphery of the fastener. This deterioration, if not considered and/or regulated properly, will seriously impact the weathertightness performance of the roof cladding, decreasing the durability of the building system.
- **Building material:** This helps identify the fundamental properties of a new material required for fulfilling its function as a component based on the above durability and performance analyses. The refinement of durability delves deeply into understanding and controlling processing conditions, microstructural features and/or chemical compositions of the material.

  For example, to deliver 15-year durability in the sheltered position on a building in zone B, a class 4 screw can be used for fixing if it can demonstrate the following characteristics:
    - Composition: 25–30% tin + zinc.

  - Processing: mechanical plating.
  - Microstructure: porosity rating of 8 according to AS 3566.2[4].
  - Thickness: >45 μm.

This hierarchy indicates that the durability required by the NZBC can be achieved through environmental control, structural design and material tailoring (with a focus on compositional/microstructural modulation and process optimisation).

4.2.2 Bottom-up durability evaluation

As discussed above, the durability required for a functional component within a building system can be refined downwards to identify the desirable properties of the material of which the component is made. On the other hand, this indicates that the properties of a material will be fundamental to the performance and durability of the component to be used as a part of the building system.

The properties of engineered materials depend on their composition, structure, synthesis and processing according to the so-called materials science and engineering tetrahedron – Tetrahedron A of Figure 4 (Askeland & Wright, 2015).

- **Composition:** This is the chemical make-up of a material. Chemical composition is critical to the chemical, mechanical and/or physical properties of a material. For example, zinc-based coatings with magnesium additions normally perform better than conventional zinc coatings under identical conditions (Volovitch, Vu, Allély, Abdel Aal & Ogle, 2011; Shukla, Deepa & Kumar, 2012). It is hypothesised that the addition of magnesium could lead to changes in the composition and structure of the growing corrosion product layer. These changes are beneficial to an improved protection capability.

  The chemical composition of a selected material can be analysed using the following methods (Sibilia, 1988; Saldívar-Guerra & Vivaldo-Lima, 2013):
  - Chromatography: gas chromatography (GC), ion chromatography (IC) and high-performance liquid chromatography (HPLC).
  - Spectroscopy: energy dispersive X-ray analysis (EDS), X-ray fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), Auger electron spectroscopy (AES), inductively coupled plasma atomic emission spectroscopy (ICP-AES), Raman and gas chromatography mass spectroscopy (GC-MS).

  The two most commonly used methods for chemical composition analysis of metals and alloys are XRF and optical emission spectroscopy (OES).
- **Microstructure:** This is the arrangement of atoms as seen at different levels of resolution. The structure of a material at the microscopic scale is called the microstructure. The microstructure of a material is a key determinant of its properties and the performance of engineering structures built with the material. This is commonly seen with many building materials.

  For example, zinc-based coatings produced by mechanical plating or hot-dip galvanising have different responses to the same environmental attack. The hot-dip galvanised coating is dense, uniform and metallurgically bonded to its steel substrate. The mechanically plated coating is porous, non-uniform and weakly bonded since zinc powders are cold-welded onto the steel surface to form it.

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[4] AS 3566.2 Self-drilling screws for the building and construction industries. Part 2: Corrosion resistance requirements.

A variety of techniques can be used to characterise the microstructural features of a material (Krauss, 2015; Krishnan, 2021). These typically include optical microscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic force microscopy (AFM) and electron back-scattered diffraction (EBSD).

- **Processing:** This is how materials are made from naturally occurring or man-made chemicals. As a vital step in manufacturing, it may involve a series of chemical, thermal or physical processes. These are to prepare a starting material, create a shape, retain that shape, refine the shape and structure and alter the mechanical properties as required (Francis, 2016). Structural features developed within a material through desirable processing techniques are essential to deliver the performance required for its intended applications. Common techniques for metallic material processing may include casting, forging, rolling and extruding.

Naturally, the journey to evaluate the durability of a functional component within a building system should start from the analysis of the fundamental characteristics of the material concerned.

The material needs to be characterised thoroughly to establish a baseline for the performance test and durability evaluation, which involves extensive analyses of material-environment interactions. This is actually a bottom-up approach with a sequence of tetrahedrons A → B → C as highlighted as the left-hand side of the material-structure-environment paradigm shown in Figure 4.

By using this approach, the science behind degradation is explored in an integrated whole-systems context. Accordingly, the data and information about the actions, interactions and responses collected from one level could be better interpreted to inform the testing activities of the next level. This helps durability evaluation go beyond the test and see type characterisation.

4.3 Generalised approach

The philosophy for traditional durability evaluations may have the following limitations:

- The interpretation of NZBC durability requirements is focused heavily on the intended function of the component and its ease of replacement. There is a lack of understanding about the fundamental material properties that are affected and controlled by processing conditions, structural features and chemical compositions.
- The designed methodology cannot always properly reflect the intended use and interactions between the material/component concerned and its pairing materials and the surrounding environments. Consequently, it is not always able to induce and/or measure the changes in the properties identified.
- Testing is normally conducted to isolate the effect of one variable at a time although a number of variables are often correlated with each other. The hidden correlations between material parameters, service conditions and environmental variables have not been understood clearly. However, they are essential to the properties, performance and durability of a material in the building system.

Consequently, derived data may not always be adequate to assess the performance of a building functional component and, furthermore, to evaluate durability and estimate service life. Durability evaluation needs to be engineered and tailored to closely match material expectations and demands, this being achieved by facilitating cooperation between theoretical interpretation and experimental characterisation.

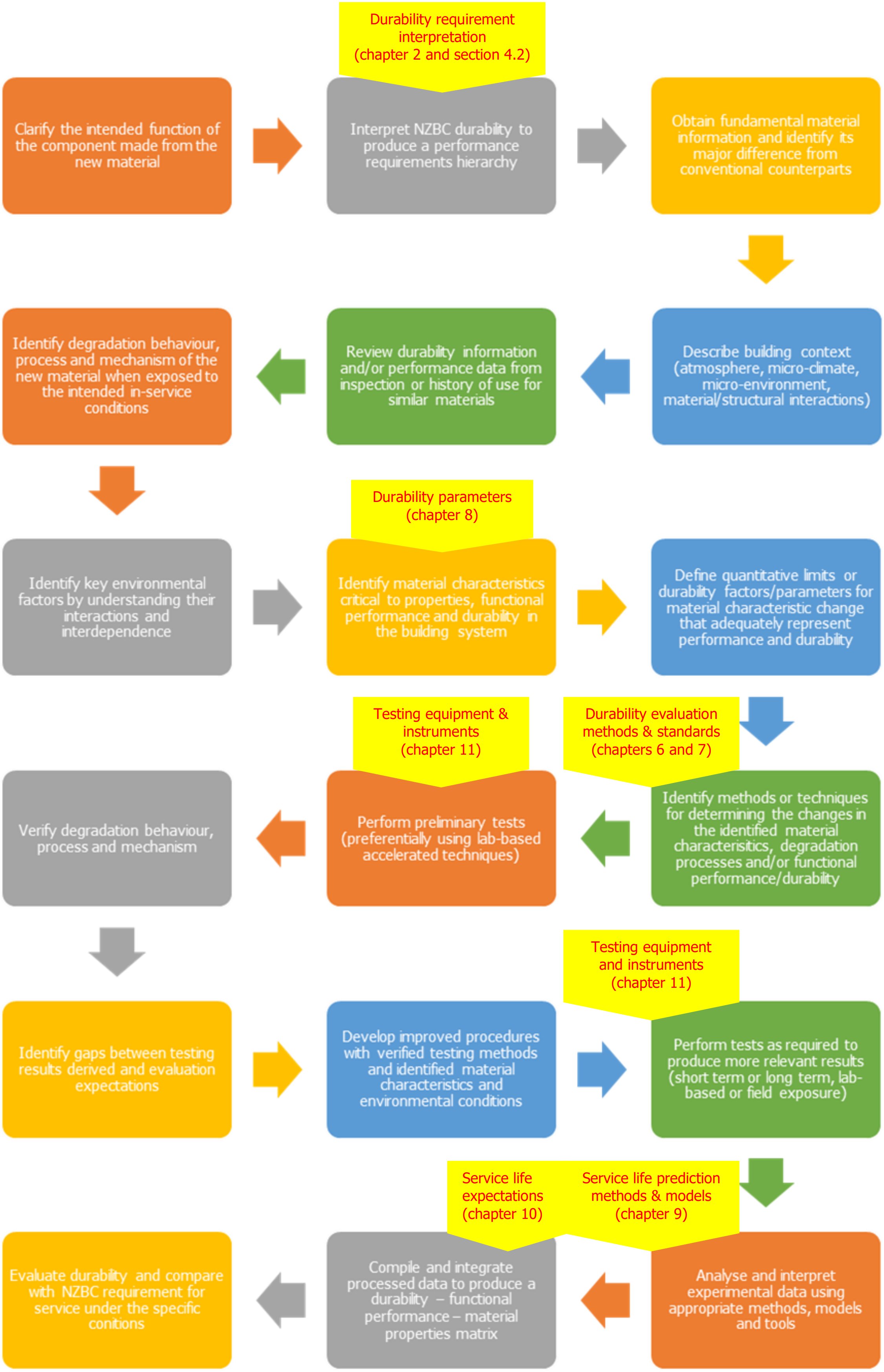


Figure 5. A general approach to develop schemes for durability evaluation of new materials.

The top-down durability refinement and bottom-up durability evaluation approaches discussed in section 4.2 then form a closed loop to support durability evaluation. This helps detail a generalised approach to develop testing schemes (see Figure 5). These schemes may have the potential to provide key information to assess whether a material undergoing degradation can deliver its function within the timeframe required.

5. Some examples of new building materials

The following are examples of some relatively new materials and/or processes that are finding applications in New Zealand building and construction. With respect to durability, they provide challenges when trying to determine their properties, performance and service life for NZBC compliance.

5.1 Preservative-treated timber

Preservatives are widely used to reduce the potential for insect infestation and rotting of timbers to extend service lives in harsh environments. Historically, chromated copper arsenate (CCA) is the most prevalent preservative used since the 1930s (Preston, 2000; Morrell, 2006). However, regulatory standards for use, recycling and disposal of CCA-treated timbers are stringent. From January 2004, the US Environmental Protection Agency banned the use of this preservative for residential use, although its use for certain industrial applications is still allowed. Many European manufacturers voluntarily withdrew this preservative for timber treatment.

Some new preservatives are emerging as substitutes for CCA (Lebow, 2004; Freeman, Nicholas & Schultz, 2006; Morrell, 2019). Two typical examples are alkaline copper quaternary (ACQ) and copper azole (CuAz). Their effectiveness is relying on high levels of dissolved copper, which could significantly promote corrosion of susceptible metals such as steel, zinc and aluminium (Kear, Wu & Jones, 2008, 2009; Li, Marston & Jones, 2011b; Zelinka, 2013). In addition, timbers treated with these chemicals at high retention levels might be susceptible to leaching (Stefanovic & Cooper, 2006; Lin, Chen, Wang & Tsai, 2009).

Recently, finely ground copper-based particles have been dispersed in the carrier suspension together with a co-biocide to provide resistance to insects and fungi (Matsunaga, Kiguchi & Evans, 2009; Lee, Pankras & Cooper, 2014). These new formulations could include micronised copper azole (MCA) and micronised copper quaternary (MCQ) (Freeman & McIntyre, 2008; McIntyre & Freeman, 2009).

The effectiveness of preservatives is related to two factors – distribution in the timber structure and penetration of bioactive components into cell walls and the reaction with cellulose, hemicellulose and lignin. A concern with preservatives containing micronised copper is whether copper penetration into the timber is adequate (Evans, Matsunaga & Kiguchi, 2008; Preston et al., 2008; Xue, 2015; Civardi et al., 2016). Some studies showed that micronised copper particles could release some solubilised copper ions to penetrate the cell wall although mobility was reduced. Consequently, copper has been found in cell walls of timbers treated with MCQ (Stirling, Drummond, Zhang & Ziobro, 2008; Stirling & Drummond, 2009). Specifically, large deposits of particulate copper, 10–700 nm, were detected in lumens and pit chambers by scanning electron microscopy and X-ray microanalysis (Matsunaga, Kiguchi & Evans, 2007).

The corrosivity of micronised copper-treated timbers has been discussed (Freeman & McIntyre, 2008). Data derived from accelerated tests using the AWPA E-12 scheme was inconclusive. In one test, the micronised formulation of copper azole was less corrosive than the standard formulation for galvanised steel but more corrosive for carbon steel. Meanwhile, the micronised formulation was much more corrosive to aluminium. Other tests showed similar trends. In some cases, the micronised formulations were less corrosive, while in other cases, they were more corrosive than traditional formulations under identical exposure conditions (Kofoed & Ruddick, 2010).

5.2 Thermally modified timber

The modification of timber using thermal treatments is not new and has been studied for over 100 years (Stamm & Hansen, 1937). However, it only has recently been renewed due mainly to (Boonstra, 2008):

- declining production of durable timber
- increasing demand for sustainable building materials
- deforestation of especially subtropical forests
- increased introduction of restrictive regulations reducing the use of toxic chemicals.

Thermal modification of timber is normally carried out by exposure to a temperature between 160°C and the char temperature (300°C) and conditions of decreased oxygen availability. There are mainly five commercially available procedures that may differ in terms of process conditions such as the presence of a shielding gas such as nitrogen or steam, humid or dry processes and/or use of oils (Navi & Sandberg, 2012; Sandberg, Kutnar & Mantanis, 2017). These include:

- Thermowood – Finland
- Plato Wood – Holland
- OHT oil heat treatment – Germany
- Bois Perdure – France
- Rectification – France.

New heat treatment processes are also emerging in other countries such as Denmark (WTT) and Austria (Huber Holz).

The thermal treatment at different temperatures may lead to various changes in the chemical composition and anatomical structure of timbers by degrading their cell wall compounds and extractives (Bourgois, Bartholin & Guyonnet, 1989; Esteves & Pereira, 2009). The chemical change is heavily dependent on timber species, duration and temperature, with the treatment temperature being the most important factor:

- **20–150°C:** timber dries, beginning with the loss of free water and finishing with bound water.
- **180–250°C:** timber undergoes important chemical transformations.
- **250°C and above:** carbonisation processes start with the formation of CO_2 and other pyrolysis products.

Thermal modification significantly influences timber properties (Esteves & Pereira, 2009; Dunningham & Sargent, 2015; Sandberg, Kutnar & Mantanis, 2017; Zelinka, Passarini, Matt & Kirker, 2020):

- **Mass:** Loss of mass is a typical effect of the thermal modification process. A decrease in mass up to 20% can occur depending on the type of process.
- **Mechanical property:** Two of the most affected mechanical properties are the resistance to bending in static (MOR) and dynamic tests (impact bending). Timber generally becomes brittle, and its strength is reduced. This normally makes timber unsuitable for structural applications.
- **Hygroscopicity:** As a result of the loss of hygroscopic hemicellulose polymers, thermal modification processes lead to a decrease of hygroscopicity. However, in some cases, the decreased hygroscopicity can be recovered by moistening.
- **Dimension stability:** As the equilibrium moisture of timber is decreased, its dimensional stability is normally improved.

- **Wettability:** This normally decreases between 130°C and 210°C, with a maximum at approximately 190°C.
- **Durability:** Thermal modification normally leads to an improvement in resistance against biodegradation. An increased resistance to rot has been reported when the timber is not in contact with soil. The resistance to termites is variable and depends on the timber species as well as the termite species. Thermally modified radiata pine may not be able to be resistant to Australian termite species.
- **Corrosivity:** Limited research has shown that thermal modification may make certain timber species more acidic and increase their corrosiveness.

5.3 Ferritic stainless steel

Ferritic stainless steels are not generally alloyed with nickel (Ni) but with molybdenum (Mo) and sometimes, aluminium (Al) or titanium (Ti) (ISSF, 2007). Their chromium (Cr) contents usually range from 15–18% but can be as low as 11% or as high as about 30% in exceptional cases (Schweitzer, 2003; Bhadeshia & Honeycombe, 2006).

Some ferritic stainless steels have been developed for architectural applications (see Table 1) (Oka & Kuriyama, 1999; Shiokawa, Yazawa & Okada, 2008).

Table 1. Chemical composition of some ferritic stainless steels (wt.%).

Steel	Alloying element									
	Cr	Ni	Mo	Cu	Ti	Si	Nb	Al	Mn	C
404 GP	21.0	-	-	0.4	0.3	-	-	-	-	-
445 M2	22.1	-	1.20	-	0.19	0.18	0.23	0.09	0.20	0.01
RSX-1	17.8	0.2	1.45	-	-	0.10	-	-	0.15	0.003
R445MT	22.0	0.2	1.50	-	-	0.10	-	-	0.15	0.004
R24-2	24.0	0.2	2.00	-	-	0.29	-	-	0.10	0.004
R30-2	29.6	0.1	2.09			0.13			0.11	0.003

Ferritic stainless steels with a high content of chromium (>24%) and further molybdenum alloying (2%) have been used for roofs or the exteriors of buildings located in coastal or near coastal regions in Japan (Kim & Lee, 2001). Ferritic stainless steels with relatively low contents of chromium (18–22%) and molybdenum (1.5%) have been used in inland areas where salt deposition might be limited.

404 GP and 445 M2 ferritic stainless steels have been introduced into the Australasian region as alternatives to austenitic stainless steels AISI 304 and AISI 316 respectively. They can be used for roofing and facing applications (Austral Wright Metals, 2010).

5.4 High-performance concrete

Concrete is the most widely used material in building and construction around the world. Every year, approximately 3 tonnes are used per person (Gagg, 2014).

5.4.1 High-performance concrete

Typically, high-performance concrete consists of cement, water, fine sand, plasticiser, fly ash and silica fume, and it has a low water-cementing materials ratio of 0.20–0.45

(Zhang & Li, 2013). Some characteristics required for high-performance concrete may include (Kosmatka, Kerkhoff & Panarese, 2003):

- high strength – 70–140 MPa at 28–91 days
- high early strength – 20–28 MPa at 3–12 hrs or 1–3 days
- high modulus of elasticity – >40 GPa
- high abrasion resistance – 0–1 mm depth of wear
- high durability and long life in severe environments
- low permeability and diffusion – 500–2000 coulombs
- resistant to chemical attack
- high resistance to frost and de-icer scaling damage
- toughness and impact resistance
- volume stability
- ease of placement
- compaction without segregation
- inhibition of bacterial and mould growth.

The essential differences between high-performance and normal concretes are related to the differences in composition of hydrated cement paste, pore structure and interfacial transition zone (see Table 2) (Büyüköztürk & Lau, 2007).

Table 2. Differences between normal and high-performance concretes.

Characteristics	Normal concrete	High-performance concrete
Composition of hydrated cement paste	Amorphous and intrinsically porous calcium silicate hydrate (C-S-H) gel.	Hydrated cement paste is strengthened by reducing gel porosity through the enhanced formation of crystalline C-S-H gel.
Pore structure	Only capillary pores are reduced.	Porosity is lowered by adding suitable fine admixture such as silica fume or fly ash to fill up the empty space inside concrete. Pore connectivity is lowered effectively because very fine particles can block capillary network.
Interfacial transition zone	The strength of the interfacial transition zone is low, promoting bond cracking along the boundaries of aggregates under external loading.	Interfacial transition zone is toughened by lowering water-to-cementitious materials ratio (<0.2) and by improving particle packing. These are achieved by adding superplasticisers and fine admixtures.

5.4.2 Ultra-high-performance concrete

Ultra-high-performance concrete (UHPC) has a compressive strength higher than 150 MPa and a self-consolidation property (Zdeb, 2013). It has a very low water-cementitious material ratio, and it contains cementitious component, quartz powder, quartz sand, superplasticiser and high-strength steel or non-metallic fibres. Its design follows four basic principles (Prem, Bharatkumar & Iyer, 2012; Shi et al., 2015):

- The porosity and pore size distribution are effectively reduced and improved by the use of superplasticiser, incorporation of very fine reactive mineral admixtures, close packing of raw materials and decrease of water to cementing materials. The average pore size can be less than 5 nm, meanwhile the fraction of pore volume can be 1–2% (Vernet, 2004).

- A dense and uniform microstructure is developed due to:
  - close packing of solid particles
  - hydration and pozzolanic reactions in cementitious materials
  - improvement of the interfacial transition zone.

  Nano-sized particles can be used to fill the gaps between cementitious materials and aggregates, therefore reducing porosity and increasing particle packing density. They can also accelerate cement hydration via a nucleation and growth mechanism (Abbas, Nehdi & Saleem, 2016). Typical nano-sized particles include silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3), titanium dioxide (TiO_2) and zirconium dioxide (ZrO_2).
- The size of micro-cracks is significantly decreased, and the inhomogeneity of concrete is reduced by using quartz sand with a diameter of 400 μm instead of coarse aggregates.
- The toughness is significantly increased with the use of carbon and steel fibres.

Ultra-high-performance concrete normally exhibits greater durability than normal concrete due mainly to its unique characteristics (Fehling, Schmidt, Walraven, Leutbecher & Fröhlich, 2014; Wang et al., 2015; Spiesz & Hunger, 2017):

- **Low permeability:** Ultra-high-performance concrete has a typical permeability coefficient of ~0.0005 at 98 days, whereas normal concrete has a typical permeability coefficient of 0.0015 at 98 days.
- **High chloride penetration resistance:** Chloride diffusion coefficients for ultra-high-performance concrete, high-performance concrete and normal concrete have been reported as 2×10^{-14} m^2/s, 6×10^{-13} m^2/s and 1×10^{-12} m^2/s respectively (Roux, Andrade & Sanjuan, 1996).
- **High carbonation resistance:** It is very difficult for carbon dioxide (CO_2) to penetrate into ultra-high-performance concrete. The 28-day mean depth of the carbonation was less than 0.30 mm (Liu, Sun, Lin & Lai, 2003).
- **High freezing-thawing resistance:** Ultra-high-performance concrete has a very high resistance for external water penetration, and the presence of steel fibres could inhibit the propagation of cracking. It has been reported that, after 600 freeze-thaw cycles, the durability coefficient of ultra-high-performance concrete was larger than or equal to 100 and its mass loss was almost zero (Liu et al., 2003).

5.5 High-performance insulation material

Insulating materials can reduce unwanted heat losses or gains and hence decrease the energy demands of heating and cooling systems. The global insulation market size is expected to be valued at US$101 billion by 2025 (Grand View Research, 2019). Traditional thermal insulation materials such as glass wool, mineral wool, expanded polystyrene (EPS), extruded polystyrene (XPS) and polyurethane (PUR) foam have challenges to meet energy efficiency and/or safety requirements.

Current high-performance thermal insulation materials may include the following:

- **Vacuum insulation panel (VIP):** An evacuated foil-encapsulated open porous material (Baetens et al., 2010; Conley, Cruickshank & Baldwin, 2018; Chan et al., 2019). Its thermal conductivity typically ranges from 3–4 mW/(m·K) as new to 8 mW/(m·K) after 25 years ageing.

- **Gas-filled panel (GFP):** A gas of lower thermal conductive than air such as argon (Ar), krypton (Kr) and xenon (Xe) instead of vacuum is used (Shrestha, Desjarlais, Chu & Pagan-Vazquez, 2016). Typical thermal conductivities of prototype air-filled and argon-filled GFPs are 46 mW/(m·K) and 40 mW/(m·K), respectively (Baetens, Jelle, Gustavsen & Grynning, 2010).
- **Aerogel:** Silica (SiO_2) aerogel features the presence of cross-linked chains with a large number of air-filled pores (Yu & Liang, 2016). The average pore size is 1–100 nm and can be modulated by controlling reaction conditions. These pores take 80–99.8% of the total aerogel volume. Thermal conductivity as low as 4 mW/(m·K) could be reached. However, commercial products normally have a thermal conductivity of 13–14 mW/(m·K) at ambient pressure. Silica aerogel has been used in a wide variety of insulation applications such as window glazing systems, exterior walls, roofs and building slabs (Berevoescu, Stoian & Dan, 2009; Baetens, Jelle & Gustavsen, 2011; Riffat & Qiu, 2013; Berardi, Zaidi & Kovisto, 2018; Curto & Cinieri, 2020; Lamy-Mendes, Pontinha, Alves, Santos & Durães, 2021).
- **Phase change materials (PCM):** Latent heat is released or absorbed when the material is changing its phase. The integration of PCM into the building envelope has long been recognised a potential solution to enhance energy storage capacity and rationalise energy use (Song, Niu, Mao, Hu & Deng, 2018; Sivanathan et al., 2020). Common PCMs can be categorised into organic (paraffins, fatty acids), inorganic (hydrated salts and metallics) and eutectic (capric acid/myristic acid, lauric acid/stearic acid, myristic acid/palmitic acid and palmitic acid/stearic acid) (Kalnæs & Jelle, 2015).
- **Vacuum insulation material (VIM):** A homogeneous material with a closed small pore structure where a vacuum is maintained (Rashidi, Esfahani & Karimi, 2018; Sova, Stanciu & Georgescu, 2021). Typical thermal conductivity is less than 4 mW/(m·K) in pristine condition.
- **Gas insulation material (GIM):** A homogeneous material with a closed small pore structure filled with air or other gases of low thermal conductivity such as argon (Ar), krypton (Kr) or xenon (Xe) (Jelle, 2016). Typical thermal conductivity is less than 4 mW/(m·K) in pristine condition.
- **Nano insulation material (NIM):** Thermal insulation is mainly achieved due to the open or closed nano-porous (or nanocellular, 0.1–100 nm) structure (Jelle, Gustavsen & Baetens, 2012; Gao, Sandberg & Jelle, 2014; Wicklein et al., 2015; Sova, Stanciu & Georgescu, 2021). An open-porous structure could result in capillary condensation of water after a long exposure to humid environments. NIM with a closed porous structure may have a higher resistance to humidity and thus have a higher potential as a high-performance insulation material.

The service life of thermal insulation products for use in buildings is expected to be 30–80 years, depending on the type of material and the in-service condition. The use of new thermal insulation materials has been rapidly spreading, and they have become attractive alternatives. However, there is a lack of information on their durability.

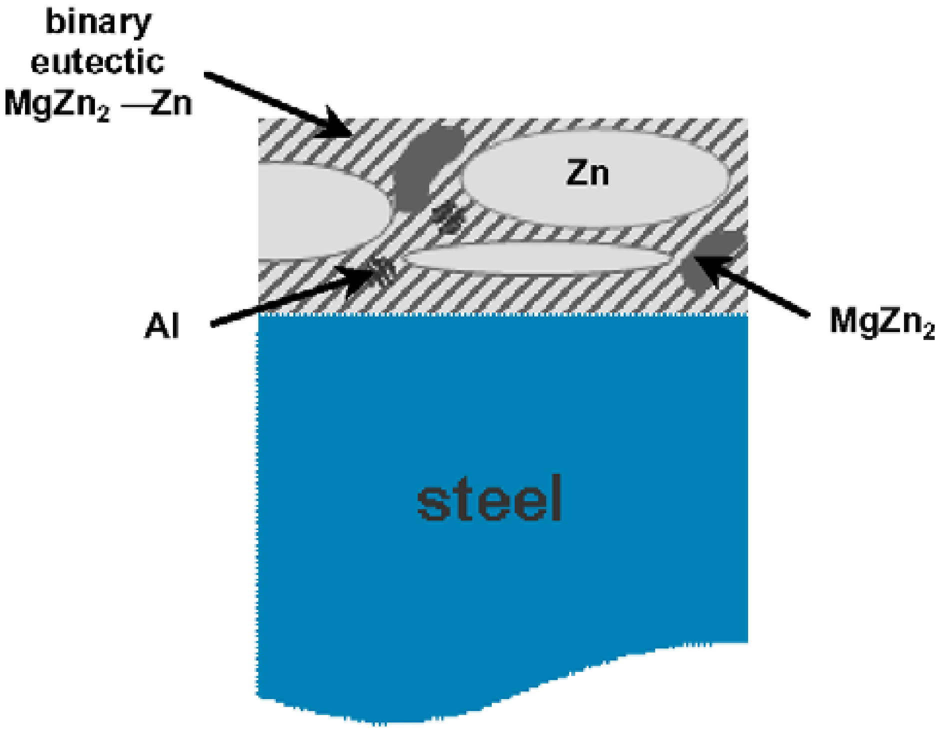
The performance of aerogel-enhanced insulation products, including plasters and blankets, has been studied using accelerated temporal ageing processes including freezing and thawing cycles and exposure to elevated temperature and high humidity (Nosrati & Berardi, 2017). The thermal resistance of aerogel boards and blankets remained almost constant, and only a small increase of thermal conductivity was observed over the accelerated ageing periods. Meanwhile, the thermal resistance reduction in aerogel plasters was obvious and the thermal conductivity increased by approximately 17% over the first 70 cycles. No significant increase of thermal conductivity was observed afterwards.

Moisture transport and absorption in thermal insulation materials is responsible for their structural damage and performance deterioration over time under in-service conditions (Hoseini & Bahrami, 2017).

5.6 Zn-Al-Mg coating

Zn-Al-Mg coatings have typical alloying elements of aluminium and magnesium (Prosek, Larché, Vlot, Goodwin & Thierry, 2010). The aluminium and magnesium contents in the coatings, developed in Japan, varied from 0.2 to 11.0 wt.% and 0.1 to 3.0 wt.%, respectively. The European systems typically have 0.4–2.0 wt.% aluminium and 1.0–2.0 wt.% magnesium. Zn-11Al-3Mg-0.2Si (Super Dyma) and Zn-6Al-3Mg (ZAM) have been commercially available since the late 1990s for building applications.

Zn-Al-Mg alloy coatings consist of a hcp zinc phase, an fcc aluminium phase and a laves phase $MgZn_2$ (Yu, Li, Liu, Li & Xue, 2012). The laves and hcp phases also occur in the form of a binary eutectic. The fcc aluminium, $MgZn_2$ and the hcp zinc can form a ternary eutectic (see Figure 6) (Schuerz et al., 2009).



Source: Schuerz et al., 2009

Figure 6. A schematic of hot-dip galvanising Zn-Al-Mg alloy coating cross-section.

Mg has also been alloyed into Zn-55%Al-1.6%Si alloy coating (Li, Gao et al., 2014). The aluminium-rich dendrite area does not change much, and it retains its original dendritic structure. The Mg-rich phase sporadically appears in the zinc-rich interdendritic area and increases with Mg content. With a further increase of Mg to 2.5 wt.%, some well-crystallised Mg-containing dendritics (similar to $MgZn_2$) can be found. In general, aluminium is distributed in the aluminium-rich dendrites, while zinc and magnesium are abundant in the zinc-rich interdendritic area.

The corrosion behaviour of hot-dip Zn-6%Al-(0-3)%Mg alloy coatings has been investigated using a cyclic corrosion test and a 5-year exposure to severe marine and rural environments (Komatsu, Izutanit, Tsujimura, Andoh & Kittaka, 2000; Shimizu, Yoshizaki, Miyoshi & Andoh, 2003). Results showed that corrosion resistance was improved with increasing Mg content and Zn-6%Al-3%Mg was performing better than Zn-4.5%Al-0.1%Mg and Zn-0.2%Al.

In general, corrosion performance improvement has been explained as follows:

- The morphology, phase composition and microstructure of the corrosion products could be changed due to Mg addition, and this change was believed to improve corrosion resistance (Chen, Guo, Zhu, Gao & Han, 2017; Dong et al., 2017; Wang, Kong & Che, 2019). Zinc-based corrosion products such as simonkolleite [$Zn_5(OH)_8Cl_2{\cdot}H_2O$] and zinc hydroxysulfate [$Zn_4(OH)_6SO_4{\cdot}xH_2O$] are protective under most exposure conditions. Their protection capability could be improved by the incorporation of Mg^{2+} since their transformation into soluble hydroxide, carbonate or sulphate complexes or less-compact products, could be partially inhibited (Tanaka et al., 2001; Yamamoto, Kumon, Taomoto & Entani, 2007; Prosek, Nazarov, Bexell, Thierry & Serak, 2008; Diler, Rioual, Lescop, Thierry & Rouvellou, 2012; Li et al., 2012; Li, Zhou et al., 2014; Salgueiro Azevedo, Allély, Ogle & Volovitch, 2015). Insoluble zinc-based corrosion products detected on Zn-Al-Mg alloy coatings were identified as: zinc chloride hydroxide [$Zn_5(OH)_8Cl_2{\cdot}H_2O$, simonkolleite], $Zn_6Al_2(CO_3)(OH)_{16}{\cdot}4H_2O$, $ZnCl_2{\cdot}4Zn(OH)_2$, aluminium oxides and layered double zinc–aluminium hydroxides [ZnAl-LDH] with the general formula $Zn_xAl_y(A)_m(OH)_n{\cdot}zH_2O$ (Schürz et al., 2010; Shimoda, Nakazawa, Nomura & Marimoto, 2011; Volovitch, Vu, Allély, Abdel Aal & Ogle, 2011; Persson, Thierry, LeBozec & Prosek, 2013; LeBozec et al., 2013). These layered double hydroxides were considered to possess good barrier properties.
- Stable Zn-Al corrosion products containing Mg were formed, and this could slow down corrosion attack to the residual coating layer and the underlying steel substrate (Tsujimura, Komatsu & Andoh, 2001).
- $MgZn_2$ in the zinc-rich interdendritic area could decrease the electronegativity and corrosion rate of the zinc-rich interdendritic area (Sugimaru et al., 2007).
- A synergistic effect of Al and Mg has been reported (Shih, Hsu, Sun & Chung, 2002; Britto, Radha, Ravishankar & Kamath, 2007). The incorporation of Al or Mg ions can make corrosion products less soluble, more efficient and more stable (de Rincón et al., 2009; Uranaka & Shimizu, 2012).

5.7 Zinc flake coating

Zinc or zinc/aluminium flake coatings have been developed for the surface treatment of steel parts in automotive and construction industries (Ishikawa & Takayama, 2014; Chatterjee, 2016; Oleksiak, Kołtało & Poloczek, 2021). Typical coating thicknesses range between 6–14 µm.

Zinc flakes are traditionally produced by flattening zinc dust, typically in a ball mill. This process is done in dry and wet milling processes and dip-spin process (Scott, 2011). The flakes are capable of overlapping to give a high surface area contact between the zinc and steel substrate. Aluminium flakes can also be added. Chromium oxide is normally used as the binder. A sodium silicate-based sealer is applied over the base coat to provide additional protection and also to control the lubricity of parts.

The corrosion resistance of zinc flake coatings is normally explained by the following:

- **Barrier effect:** The overlapping zinc and aluminium flakes provide a physical barrier between the steel substrate and corrosive environment.
- **Galvanic action:** Zinc corrodes preferentially to protect steel.
- **Passivation:** Corrosion products tend to slow down corrosion of zinc and steel.
- **Self-repairing:** Corrosion products such as oxides and carbonates could migrate to the damaged area to repair the coating and restore barrier protection.

5.8 Zn-Ni alloy coating

Zn-Ni alloy coatings have been developed to protect steels from corrosion in building, mining and automotive sectors (Conde, Arenas & de Damborenea, 2011; Gnanamuthu, Mohan, Saravanan & Lee, 2012; Maniam & Paul, 2021). They are commonly produced using electrodeposition and have three phases (Müller, Sarret & Benballa, 2002):

- **α-phase:** a solid solution of zinc in nickel with an equilibrium solubility of about 30% Zn.
- **γ-phase:** an intermediate phase with a composition of Ni_5Zn_{21}.
- **η-phase:** a solid solution of nickel in zinc with a very low amount of nickel.

Zn-Ni alloy coatings are prone to sacrificial dissolution due to the limited amount of Ni in the deposits (Müller, Sarret & Benballa, 2001; Rahman, Sen, Moniruzzaman & Shorowordi, 2009). To improve their corrosion protection capability, several methods and systems have been developed:

- **Composition modulated multilayer (CMM) coatings:** CMM coatings are composed of various alternating thin metal or alloy layers (Maciej, Nawrat, Simka & Piotrowski, 2012; Rao, Hegde & Bhat, 2013; Rashmi, Elias & Hegde, 2017). They were found to have approximately three times higher corrosion resistance compared to optimal monolithic alloy coatings. The enhanced performance was attributed to the formation of new interfaces, allowing the lateral spreading of corrosive media rather than directly penetrating into the substrate (Rahsepar & Bahrololoom, 2009).
- **Composite electrodeposition:** The incorporation of SiO_2 nanoparticles into Zn-Ni alloy coatings using direct current deposition has been investigated (Hammami, Dhouibi, Bercot, Rezrazi, & Triki, 2012). In comparison with Zn-Ni alloy coatings, composites Zn-Ni-SiO_2 alloy coatings have:
    - a higher percentage of Ni and an incorporation of silica in the deposit
    - a mixture of two phases – zinc and γ-phase with smaller crystallite size
    - a higher microhardness and thermal stability.

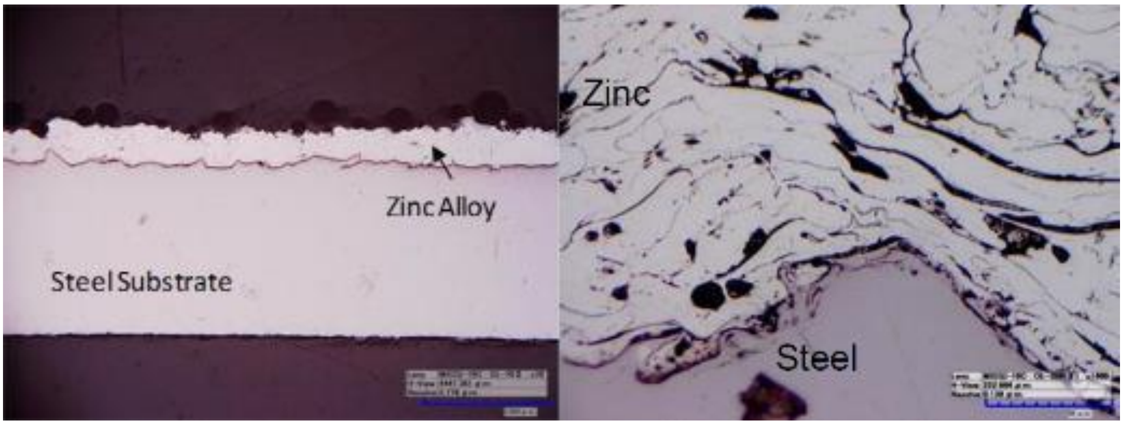
  Other particles such as Al_2O_3, Fe_2O_3, TiO_2, SiC and WC have also been incorporated into Zn-Ni alloy coatings to modify their corrosion resistance (Praveen & Venkatesha, 2011; Sajjadnejad, Mozafari, Omidvar & Javanbakht, 2014; Mahmud et al., 2015; Conrad & Golden, 2018; Kumar, Lakshmikanthan, Chandrashekarappa, Pimenov & Giasin, 2021). Ceramic particles in alloy coatings can act as a barrier to the development of pits induced by chloride. The preferred locations for pitting are shifted from the interface to the areas adjacent to the matrix-nanoparticle interface (Sun, Flis-Kabulska & Flis, 2014). The presence of oxide/carbide particles can also reduce the active surface area for corrosion due to their low electrical conductivity.
- **Composite Zn-Ni coatings with nanoparticles made by the CMM technique:** CMM Zn-Ni alloy coatings with Al_2O_3 and SiO_2 nanoparticles have been reported (Ullal & Hegde, 2013, 2014; Shourgeshty, Aliofkhazraei, Karimzadeh & Poursalehi, 2017). A Zn-Ni-SiO_2 coating with 300 layers was reported to be 107 times more corrosion resistant than a monolayer Zn-Ni-SiO_2 coating.

5.9 Thermal spray coating

Thermal spraying is a process where finely divided metallic or non-metallic materials are deposited in a molten or semi-molten state to form a coating (Hermanek, 2001; Tejero-Martin, Rezvani Rad, McDonald & Hussain, 2019). It typically comprises of:

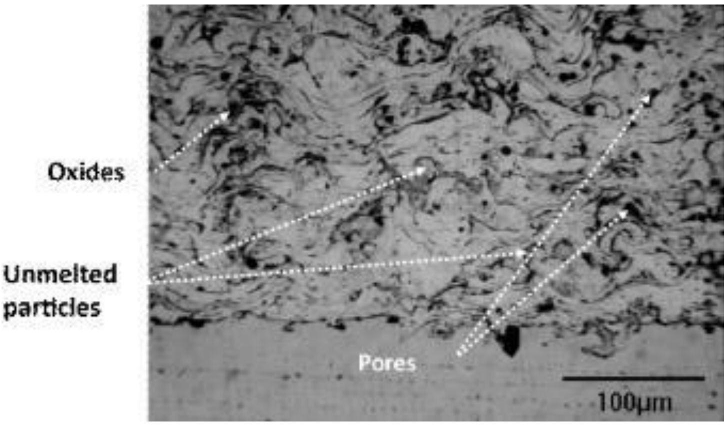
- direct current arcs or radio frequency discharge-generated plasmas
- plasma transferred arcs
- wire arcs
- flames, high velocity oxy-fuel flames (HVOF)
- high velocity air-fuel flames (HVAF)
- detonation guns (D-gun).

Thermally sprayed coatings normally contain pores, unmolten or partially melted particles and cracks (see Figures 7 & 8). Pores, especially when they are connected together, are detrimental to corrosion resistance. These pores should be cured through sealing or by post-thermal treatment.



Source: Lau, Sabbir & Fancy, 2015

Figure 7. Thermally sprayed zinc coating on steel.



Source: Fauchais & Vardelle, 2012

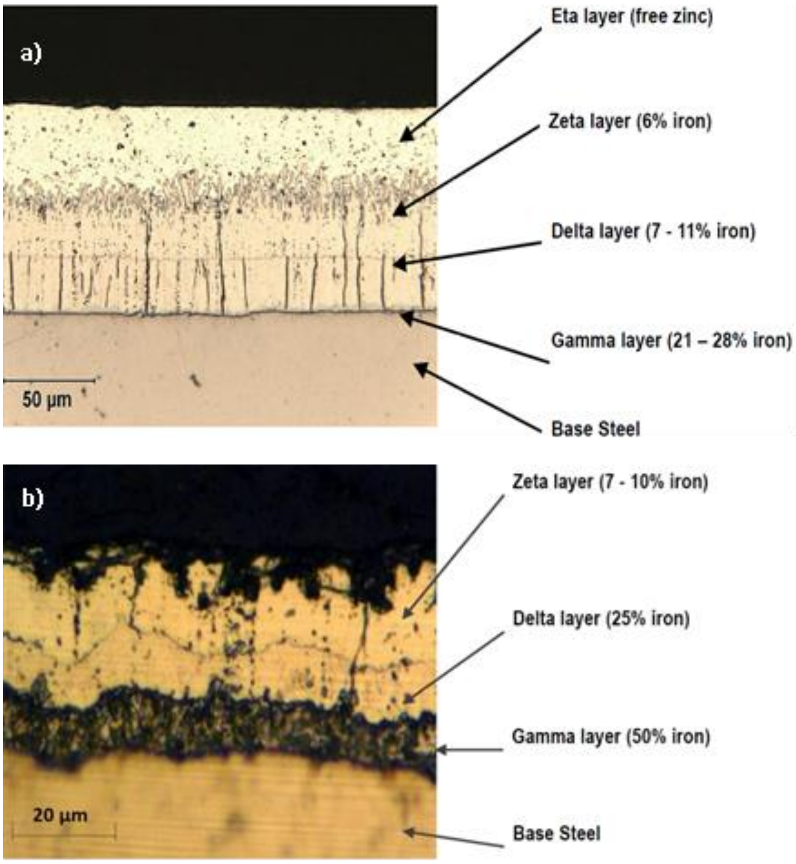
Figure 8. Stainless steel coating (AISI 304L) deposited by air plasma spraying on steel substrate.

Organic sealants such as epoxies, phenolics, furans, polymethacrylates, silicones, polyesters, polyurethanes and polyvinylesters are used for sealing purposes. Inorganic sealants such as aluminium phosphates, sodium and ethyl silicates, sol-gel type solutions and chromic acid are commonly used for high-temperature applications. Molten metals can also be used to seal and strengthen thermally sprayed coatings.

Thermally sprayed zinc, aluminium and zinc-aluminium alloy coatings are widely used to protect steel surfaces in harsh environments (Fauchais & Vardelle, 2012; Fauchais, Heberlein & Boulos, 2014; Sadeghi, Markocsan & Joshi, 2019; Echaniz, Paul & Thornton, 2019; Syrek-Gerstenkorn, Paul & Davenport, 2020).

5.10 Thermal diffusion galvanising coating

The thermal diffusion galvanising (TDG) process involves vapour diffusion of zinc into metal parts such as fasteners to create zinc-iron alloy layers for corrosion protection (Galedari, Mahdavi, Azarmi, Huang & McDonald, 2019; Kania & Sipa, 2019).



Source: Evans, 2014

Figure 9. Coating cross-section microstructure: (a) hot-dip galvanised and (b) thermal diffusion galvanised.

In a typical thermal diffusion galvanising process, steel components and metal powders are rotated in a closed cylinder inside an oven and heated to 320–500°C according to ASTM A1059/A1059M[5]. This leads to the formation of gamma (solid Zn ions in Fe), delta ($Fe_{11}Zn_{40}$) and zeta ($FeZn_7$) layers (see Figure 9) that are similar to those by hot-dip galvanising. Typical coating thickness is 12–150 µm (Agritek Industries, 2009).

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[5] ASTM A1059/A1059M Standard specification for zinc alloy thermo-diffusion coatings (TDC) on steel fasteners, hardware, and other products

5.11 Zinc-rich paint

Zinc-rich paints or primers have a long history of development and application and are one of the most effective coating systems used to protect steel components from corrosion (Shi, Liu & Han, 2011; McMahon et al., 2019; Hussain, Seetharamaiah, Pichumani & Shilpa Chakra, 2021). They normally contain zinc dust or powder (e.g. sphere of 5–10 μm in diameter) mixed with binders (either organic resins such as epoxy, polyurethane, alkyd or inorganic silicates) (Xie, Hu, Tong & Wang, 2004).

These types of zinc-rich paint coatings have been described in SSPC-Paint 20[6]:

- **Type I-A inorganic post-curing vehicles:** They are water soluble, include alkali metal silicates, phosphates and modifications thereof, which must be subsequently cured by application of heat or a solution of a curing compound.
- **Type I-B inorganic self-curing vehicles:** They are water reducible, include water soluble alkali metal silicates, quaternary ammonium silicates, phosphates and modifications thereof. These coatings are cured by crystallisation after evaporation of water from the coating.
- **Type I-C inorganic self-curing vehicles:** They are solvent reducible, include titanates, organic silicates and polymeric modifications of these silicates. They rely on moisture in the atmosphere to complete hydrolysis, forming polysilicates.
- **Type II organic vehicles:** They include phenoxies, catalysed epoxies, urethanes, chlorinated rubbers, styrenes, silicones, vinyls and other suitable resinous binders. The organic vehicles may be chemically cured or may dry by solvent evaporation. Under certain conditions, heat may be used to facilitate or accelerate hardening.

Three dust class levels (the amount of zinc in the dry film) are also listed:

- Level 1: ≥ 85%
- Level 2: 77–85%
- Level 3: 65–77%.

Typically, the deterioration of a zinc-rich paint coating has three stages (Ault, n.d.).

- **Stage 1:** A continuous film is formed to effectively isolate the substrate from the environment after application.
- **Stage 2:** Sacrificial protection is provided when defects are produced in the coating to expose the substrate to the harsh environment. This protection depends on the amount and type of moisture present, the electrical connectivity of the zinc particles to each other and the substrate and the purity of the zinc particles.
- **Stage 3:** Sacrificial protection will cease when the zinc particles are depleted in the coating. However, the steel substrate could still be protected to some extent by the inhibitive effects from zinc-containing corrosion products.

Zinc-rich paints may not perform as well as hot-dip galvanising coatings under similar conditions (Krzywicki, 2006).

Zinc-rich paints vary in zinc content in the dry film, particle size and binder type. Consequently, their performance varies (Feliu, Morcillo & Feliu, 2001; Hammouda, Chadli, Guillemot & Belmokre, 2011; Sofiana & Nodab, 2014; Nagasawa, Okada, Otsuka & Ohtsuka, 2018). In general, zinc-rich paints using inorganic binders perform

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[6] SSPC-Paint 20 Paint Specification No. 20 Zinc-Rich Coating Type I – Inorganic and Type II – Organic

better than those using organic binders. Inorganic zinc-rich paints can be formulated with a higher volume of zinc to provide a longer service life through an enhanced cathodic protection effect.

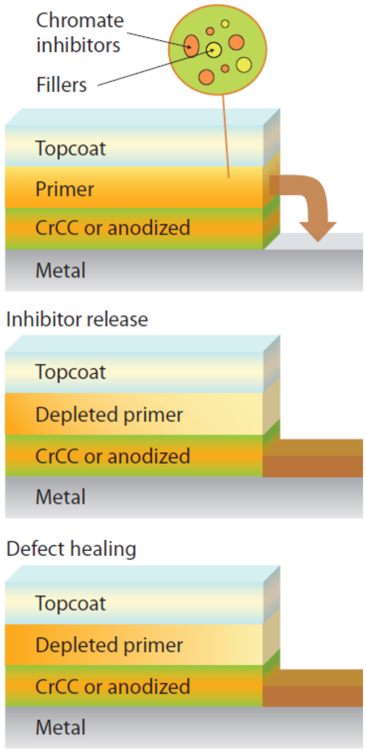
Corrosion performance of zinc-rich paints can be improved by using lamellar zinc powder or adding carbon black, graphene sheets or polymer-clay nanocomposites. These additions can provide superior barrier properties and/or cathodic protection effects (Marchebois, Touzain, Joiret, Bernard & Savall, 2002; Meroufel & Touzain, 2007; Meroufela, Deslouis & Touzain, 2008; Armelin, Martí, Liesa, Iribarren & Alemán, 2010; Akbarinezhad, Ebrahimi, Sharif & Ghanbarzadeh, 2014; Liu, Liu et al., 2018).

5.12 Self-healing coatings

Conventional protective coatings gradually lose their structural integrity and protective properties due to chemical, mechanical or thermal interactions with the environment. It would be desirable if a coating could repair damage so that corrosion could be inhibited or stopped before its durability has been seriously reduced.

5.12.1 Chromium-based self-healing coatings

Self-healing coatings were originally developed with the incorporation of hexavalent chromium (Cr^{6+}) (Kendig & Buchheit, 2003; Pokorny, Tej & Szelag, 2016). The self-healing capability was related to the formation of a protective oxide film in the damaged area where Cr^{6+} was reduced to Cr^{3+} (see Figure 10) (Zhao et al., 2001; Hughes, Cole, Muster & Varley, 2010). During the conversion process, a certain amount of chromate, retained in the form of CrO_4^{2-} or $Cr_2O_7^{2-}$, can be reduced to produce an insoluble and protective layer of Cr_2O_3 or $Cr(OH)_3$.



Source: Hughes et al., 2010

Figure 10. Schematic illustration of post-damage healing in chromate based self-healing coating.

However, Cr^{6+} has known toxic effects. Its use in self-healing coatings has been progressively reduced and completely banned by the EU directive of the Registration, Evaluation, Authorization and restriction of Chemicals (REACH) in 2017.

5.12.2 Active corrosion protection coatings

Coatings that can heal damage or recover functional performance with minimal or no intervention are being actively developed as 'green' Cr^{6+} replacements in the protective coating industry (Lamaka et al., 2007; Toohey, Sottos, Lewis, Moore & White, 2007; Williams, Trask, Knights & Bond, 2008; Li et al., 2009; Park & Braun, 2010; Huang & Yang, 2011; Jadhav, Hundiwale and Mahulikar, 2011; Samadzadeh, Boura, Peikari, Ashrafi & Kasiriha, 2011; Borisova, Mohwald & Shchukin, 2011; Liu, Zhang, Wang, Wang & Wang, 2012; Balaskas, Kartsonakis, Tziveleka & Kordas, 2012; Yi, Yang, Gu, Huang & Wang, 2015; Qiao, Li, Wang, Zhang & Cao, 2015; Poornima Vijayan & Al-Maadeed, 2016; Zhang et al., 2018; Yang, Mo, Li & Gu, 2019; Ye, Bi, Cui, Zhang & Li, 2020; Zhang, Zhang, Yaseen & Huang, 2020; Paolini et al., 2021).

Based on the way that self-healing effect occurs, coatings can be classified as the followings:

- How self-healing is initiated:
    - Activated by an external stimulus such as changes in temperature, pH or pressure, mechanical action and/or externally applied radiation.
    - Activated without external stimuli.
- The type of self-healing:
    - Intrinsic self-healing through self-reactions such as hydrogen bonding, ionomeric coupling and thermal reactions.
    - Extrinsic self-healing by embedding self-healing components into the substrate.

In general, self-healing coatings can be grouped as shown in Table 3.

Table 3. Typical types of self-healing coatings.

Corrosion inhibitor-based		
Organic containers carrying corrosion inhibitor	Container: • Chitosan • Polymer electrolytes nanocapsule (layer-by-layer) • SiO_2/polyethyleneimine/ polystyrenesulfonate layer-by-layer • Cellulose nanofibre	Inhibitor: • Ce^{3+} • 2-Mercaptobenzothiazole • Dodecylamine • Calcium nitrite • Isorbide derivative
Inorganic container carrying corrosion inhibitor	Container: • Cerium molybdate • Mesoporous SiO_2, TiO_2 and CeO_2 nanoparticle • Hollow titanium dioxide spheres • Cerium titanium oxide • Hollow cerium molybdate nanoparticle • Halloysite tube • $CaCO_3$ microbead	Inhibitor: • Benzotriazole • 2-Mercaptobenzothiazole • Ce^{3+}

Ion-exchange clay carrying corrosion inhibitor	Clay: • Mont-morillonite (MMT) • Layered double hydroxide (LDH)	Inhibitor: • Indole-3-butyric acid • −Benzoate • −Vanate • −Phosphate • −Nitrate • Ce^{3+}
Healing agent-based		
• Epoxy resin • Dicyclopentadiene (DCPD) • Vegetable oil (linseed oil, soybean oil)	Healing agents are released under external stimulation to initiate polymerisation reactions, forming cross-linked structures to bond cracks.	
Microvascular-based		
Capillary or hollow fibres are interdigitated into the matrix material and extended to various parts of the coating. When subjected to external mechanical shock, the microvascular channel is broken to release a repair agent to the crack that then restrains the corrosion process.		

5.13 Chemically bonded phosphate ceramics

Chemically bonded phosphate ceramics (CBPCs), also known as phosphate cements or phosphate ceramicrete, are normally synthesised through acid-base chemical reactions between phosphoric acid (or acid phosphates) and metal oxides at room temperature (Yang, Zhu, Zhang & Wu, 2000; Wagh, 2013, 2016; Machado, Arcaro, Raupp-Pereira, Bergmann & Montedo, 2021). The microstructure of CBPCs is similar to ceramics, with highly crystalline structures. Metal oxides typically used include ferric oxide (Fe_2O_3), aluminium oxide (Al_2O_3), zinc oxide (ZnO), ferrous oxide (FeO), magnesium oxide (MgO) and calcium oxide (CaO). CBPCs can be grouped according to the type of metal cations such as zinc phosphate ceramics (ZPCs) and magnesium phosphate ceramics (MPCs).

Coatings based on CBPCs normally consist of a two-component acid phosphate and a water-based slurry that contains base minerals and metal oxides. These components are mixed together and sprayed onto the metal surface. The acid phosphate and oxides in the slurry interact with the metal substrate to form an insoluble, stable oxide layer that contains approximately 60% iron with phosphate, potassium, magnesium, silicon, hydrogen and oxygen. A ceramic outer layer forms on the top of this oxide layer. These coatings provide abrasion and corrosion resistance (De Guire, 2011; Sabbir, Fancy, Lau & DeFord, 2017).

The degradation of CBPCs coatings has been investigated and the following mechanism proposed (Sabbir, 2017):

- Degradation is initiated by alternate wet and dry cycles as well as interactions with moisture in the environment.
- Degradation of the barrier ceramic and porosity present in the CBPCs coating facilitate ingress and moisture retention within the coating.
- Coating constituents react with moisture and form magnesium phosphate hydrate as well as other intermediate products.

- Coating constituents such as phosphorus and magnesium may leach out, increasing coating porosity.
- Increased porosity facilitates moisture ingress into the coating substrate and corrosion initiates at the coating–steel substrate interface.
- Iron-rich corrosion products react with phosphate compounds to form iron phosphate hydrate.

CBPC coatings are compatible with aluminium, Portland cement, gypsum and steel and have found applications in the building and construction sectors (Wagh, 2013). CBPCs are also ideal binders for wood and natural fibre composites. These composites have advantages over traditional wood composites including

- better durability
- higher impart toughness in frozen environments
- improved flame-retardant potential
- higher moisture resistance
- lower susceptibility to biodegradation
- improved noise isolation.

The corrosion performance of CBPC coatings can be improved with specific additions such as nano-sized particles, silica sol, carbon nanotubes and glass flake (Liu, Bian, Zhao & Wang, 2018; Xu, Bian, Aradhyula, Chavali & Zhao, 2019; Yan et al., 2019; Zhang, Liu & Ding, 2020; Tang, Liu, Bian, Guo & Zhao, 2020).

6. Durability evaluation methods

6.1 Introduction

Given the complexity of factors involved, the durability evaluation of building materials is not an easy task. Various approaches, methods, procedures and techniques have been developed to evaluate the durability of materials and components according to their material nature, function and in-service condition on buildings.

6.2 Non-accelerated methods

Field exposure tests, where materials are fully exposed to natural atmospheric environments, are able to produce reliable results to determine the degradation behaviours and durability of these materials. Such tests have long been performed with a variety of materials. They offer a good representation of the actual service life and, more importantly, a baseline for durability evaluations with other techniques under simulated conditions.

Atmospheric exposure has generally been used for service life prediction of metal-based materials and/or structures at purposely selected and monitored sites. Morphological characterisation and measurement of the relevant mechanical property and weight loss (corrosion rate) are commonly used to quantify the degradation of a particular material in a specific environment.

An obvious limitation of non-accelerated field exposure testing is that it may require a long time (such as several years) to deliver data and results that are complete, reliable and meaningful for analysis and interpretation (Montgomery, Curran, Calle & Kolody, 2011). During this period, environmental variables that are involved in or contributing to material degradation may change.

Another challenge is the effects of the initial atmospheric exposure conditions on degradation behaviours and kinetics. Some studies indicated that the starting season could affect the initial corrosion product formation and thereby the corrosion rate during the entire testing period (Lloyd & Manning, 1990; Santana Rodriguez, Santana Hernandez & Gonzalez Gonzalez, 2002; Corvo, Minotas, Delagado & Arroyave, 2005). It has also been found that extreme weather events and patterns such as storms could play a dominant role in the atmospheric corrosion of metals.

6.3 Accelerated methods

The development of accelerated evaluation methods that can produce results that have good correlations with those obtained from field exposures would be very valuable.

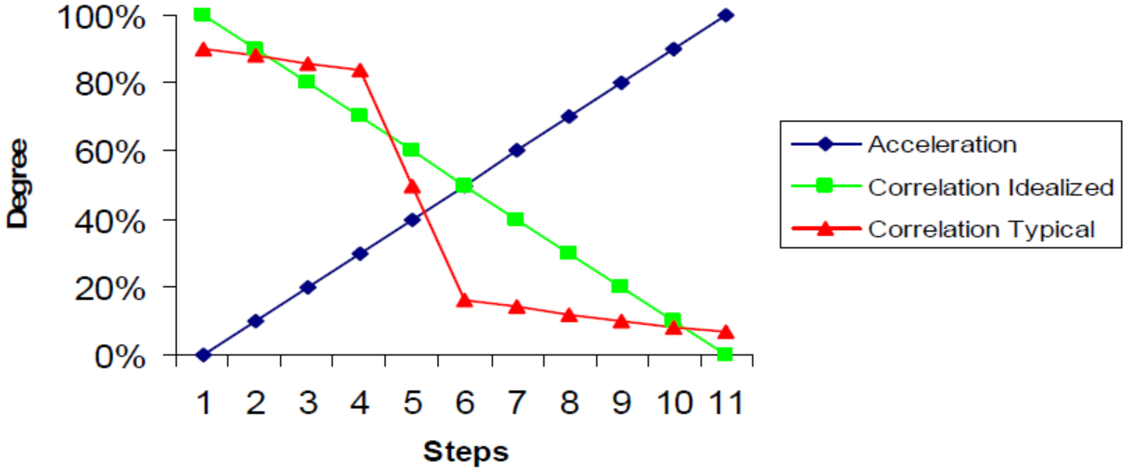
6.3.1 Principle

To design accelerated methods for efficient durability evaluation, the conditions and/or parameters established must reflect and/or simulate the in-service conditions as accurately as possible. Several principles should be implemented (Klyatis, 2012):

- Understanding the mechanisms and science behind the degradation of materials under in-service or field exposure conditions.
- Treating material and its environment as a system.

- Accurately simulating in-service or field-exposure conditions by identifying characteristic factors and revealing their dynamics of change.
- Accurately simulating the influences of individual multi-environmental groups. A multi-environmental group can be a combination of air pollution, solar irradiation and climate.
- Using appropriate approaches or procedures to model individual influences under in-service or field-exposure conditions. For example, air pollution can be a complex combination of gaseous pollutants and particulate matters released from various sources.
- Accurately simulating the variations and characteristics of individual influences. For example, if temperature is an important factor, its maximum and minimum values and variation behaviours must be simulated appropriately.
- Designing special field testing schemes together with laboratory testing procedures for accelerated durability evaluation when necessary.

Ideally, the results derived from accelerated tests should correlate, as highly as possible, with those derived from tests conducted under in-service or field exposure conditions. However, an increase of acceleration will normally lead to a decrease in correlation. Typically, there is a threshold where the correlation remains reasonably good (see Figure 11).



Source: Crewdson, 2008

Figure 11. A schematic showing correlation between simulation and acceleration.

Accelerated methods should also be designed to minimise the amount of extrapolation required. However, it might be difficult on a practical level to verify acceleration relationships over the entire range of interest. Any departures from the assumed acceleration model should be explored based on data derived from accelerated tests. However, the available data may have limited ability to detect model inadequacies.

6.3.2 Method of acceleration

Two approaches are commonly combined and applied to accelerated testing:

- **Time compression:** This is defined as a line-up of stresses observed in a real application, a reproduction of the outdoor environment omitting periods where the climatic stresses are known to be under a critical level such as at night.
- **Acceleration:** This is to increase the magnitude of a climatic stress over the level of a real-time application.

Accordingly, a variety of methods have been developed and used to accelerate material degradation and to evaluate durability in a shorter timescale:

- **Increasing exposure to environmental influences:** Some materials may only be periodically exposed to their in-service conditions. A continuous or increased exposure will reduce the period normally required for degradation if this will not change the degradation mechanism.
- **Increasing the intensity of the environmental influences:** An increase of the intensity of environmental variables can normally accelerate degradation. For example, an increase of temperature can accelerate chemical degradation processes.
- **Increasing the level of stress:** This may include increasing amplitude in temperature cycling and the rate of change of certain environmental influences.

Combinations of these methods are also commonly employed to accelerate material degradation.

6.3.3 Acceleration factor

6.3.3.1 Temperature

Temperature normally has influences on chemical or physical processes such as diffusion and mass transfer directly or indirectly. Therefore, it has been frequently used in the design of accelerated material durability evaluation processes or procedures.

The Arrhenius equation is used to describe the temperature effect on chemical reaction rate (Escobar & Meeker, 2006):

$$R(Temp) = \gamma_0 exp\left(\frac{-E_a}{k_B \times Temp\ K}\right) \qquad \text{Eq-1}$$

where

R – reaction rate
Temp K – thermodynamic temperature in K (Temp °C + 273.15)
k_B – Boltzmann's constant or universal gas constant
E_a – reaction activation energy
γ_0 – constant, characteristics of the material being tested.

For a simple one-step chemical reaction, E_a is the activation energy. However, the chemical process that is responsible for materials degradation may have multiple steps. Each step may have its own rate constant and activation energy. This complicated process can still be approximated by the Arrhenius relationship, particularly if one step in the degradation process is rate-limiting and controls the rate of the entire reaction. However, in most situations, E_a should treated as a quasi-activation energy.

The Arrhenius relationship time-acceleration factor is then described as:

$$AF(Temp, Temp_U, E_a) = \frac{R(Temp)}{R(Temp_U)} = exp\left[E_a\left(\frac{11605}{Temp_U K} - \frac{11605}{TempK}\right)\right] \qquad \text{Eq-2}$$

where

$Temp_U$ – material or product use temperature
E_a – reaction specific quasi-activation energy.

When Temp > $Temp_U$, AF(Temp, $Temp_U$, E_a) > 1.

Based on the physical theory on the effect of temperature on a reaction rate, the Eyring relationship can be described as (Escobar & Meeker, 2006):

$$R(Temp) = \gamma_0 \times A(Temp) \times \exp\left(\frac{-E_a}{k_B \times Temp\ K}\right) \qquad \text{Eq-3}$$

where A(Temp) is a function of temperature depending on the specifics of the reaction dynamics. Practically, the following relationship is used:

$$A(Temp) = (Temp\ K)^m \qquad \text{Eq-4}$$

where m = 0, 0.5 and 1.

The Eyring relationship time-acceleration factor is then given as:

$$AF_{Ey}(Temp, Temp_U, E_a) = \left(\frac{Temp\ K}{Temp_U\ K}\right)^m \times AF_{Ar}(Temp, Temp_U, E_a) \qquad \text{Eq-5}$$

where $AF_{Ar}(temp, temp_U, E_a)$ is the Arrhenius acceleration factor as described in Eq-2.

When limited data is available, the estimation of E_a depends strongly on the value of m. It has been shown that the acceleration factor obtained from the Eyring relationship that assumes m is known and estimates E_a from the data is monotone decreasing with m. Consequently, the Eyring relationship tends to give smaller acceleration factors and a smaller extrapolation range when m >0. When m <0, the Arrhenius relationship gives a smaller acceleration factor and a conservative extrapolation to actual temperatures.

6.3.3.2 Temperature cycle

Temperature cycling could impact material degradation (Escobar & Meeker, 2006). The Coffin-Manson relationship is commonly used to define the number of cycles to failure:

$$N = \frac{\delta}{(\Delta Temp)^{\beta_1}} \qquad \text{Eq-6}$$

where

ΔTemp – temperature range
δ and β_1 – properties of material and test set-up

and the acceleration factor is described as:

$$AF(\Delta Temp) = \frac{T(\Delta Temp_U)}{T(\Delta Temp)} = \left(\frac{\Delta Temp}{\Delta Temp_U}\right)^{\beta_1} \qquad \text{Eq-7}$$

6.3.3.3 Humidity

Humidity can be used to accelerate material degradation, particularly if the degradation process involves chemical or electrochemical reactions. It is commonly observed that an increase of environmental humidity will lead to faster failure of paint coatings.

Humidity is commonly used in conjunction with temperature for accelerated testing. For example, AWPA E12[7] creates an environment of 50°C and 90% RH to accelerate metal corrosion in treated timber.

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[7] AWPA E12 Standard method for determining corrosion of metal in contact with treated wood

Acceleration with a combination of temperature and humidity can be described by the following two relationships (Meeker & Escobar, 1998):

Peck's relationship

$$AF(Temp, RH) = \frac{R(Temp, RH)}{R(Temp_U, RH_U)} = \left(\frac{RH_U}{RH}\right)^{\beta_1} exp\left[E_a\left(\frac{11605}{Temp_U K} - \frac{11605}{TempK}\right)\right] \quad \text{Eq-8}$$

Klinger's relationship

$$AF(Temp, RH) = \frac{R(Temp, RH)}{R(Temp_U, RH_U)} \quad \text{Eq-9}$$
$$= \left[\left(\frac{RH_U}{1 - RH_U}\right)\left(\frac{1 - RH}{RH}\right)\right]^{\beta_1} \times exp\left[E_a\left(\frac{11605}{Temp_U K} - \frac{11605}{TempK}\right)\right]$$

6.3.4 Correlation

The acceleration provided by an accelerated test can be determined by relating its results to those derived from a non-accelerated test and defined as (Bauer, 2000):

$$A = \frac{x_{test}}{x_{field}} \times \frac{t_{field}}{t_{test}} \quad \text{Eq-10}$$

where:

A – acceleration factor
x_{test} – response from accelerated test
x_{field} – response from field exposure
t_{field} – duration of field exposure
t_{test} – duration of accelerated test.

The acceleration factor has been found to be related to the type of materials tested and accelerated tests used (Chong, 1997; Knudsen, Steinsmo, Bjordal & Nijjer, 2001). In addition, it may vary over time if the non-accelerated field exposure test was performed in natural environments with highly variable conditions. The acceleration factors can be increased by intensifying the accelerated testing conditions, therefore decreasing the time periods required for the occurrence of degradation and the collection of data for durability evaluation. However, this intensification may change degradation mechanisms or processes, leading to unreliable or less-realistic evaluation (Jacques, 2000; Mallon et al., 2002; Pospíšil et al., 2006).

The correlation coefficient can be used to define how well an accelerated test correlates with the non-accelerated test, and this is normally calculated by (Andrews et al., 1994; Carlozzo et al., 1996; Hoeflaak, de Ruiter & Maas, 2006):

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad \text{Eq-11}$$

where:

r – correlation coefficient
x_i – single response value from test A
$\bar{x}$ – average response value from test A
y_i – single response value from test B
$\bar{y}$ – average response value from test B.

6.4 Accelerated testing schemes

6.4.1 Concept of accelerated testing

Accelerated testing schemes are required to establish relevant environmental conditions and testing procedures for a specific material. This should include three steps (Yang, Wu, Noguchi & Isshiki, 2014):

- **Step 1:** Understanding the scientific mechanisms behind the degradation of a specific material when exposed to its in-service environment. This typically includes identifying the cause of degradation, the microstructural changes in the material, as well as the type and characteristics of the environment.
- **Step 2:** Determining the most appropriate equipment and procedure for accelerated testing and the optimal degradation factors and conditions.
- **Step 3:** Setting the reproduceable degradation factors of the accelerated testing. This is delivered by extensively analysing a material that has been exposed to the accelerated testing under controlled conditions, local environmental conditions, degradation behaviours and effects of the degradation factors identified.

6.4.2 Continuous salt spray

This method has been standardised under the designation ASTM B117[8] or ISO 9227[9]. It typically creates a fog using 5 wt.% sodium chloride (NaCl) solution with a neutral pH at 35°C. It has been proven to have a poor correlation with the test conducted under actual in-service conditions. The following might contribute:

- Continuous exposure at a high temperature does not allow any stress relaxation.
- Use of 5 wt.% NaCl solution produces unrealistic environmental conditions. Airborne contaminants produced from the sea have other chemicals such as magnesium chloride and sulphates. In other environments, airborne contaminants will be dominated by ammonia, fertiliser chemicals and oxides of nitrogen or sulphur, leading to different degradation behaviours, processes and mechanisms.

6.4.3 Cyclic salt spray

Cycling steps have been incorporated into the salt spray testing procedure to better simulate in-service environments (Bos, 2008) with the following benefits:

- Regular temperature variations can allow for thermally induced expansion and contraction of the materials (Whitehouse et al., 2000; Miszczyk & Darowicki, 2001).
- Absorption of water from humid air or surface deposition during a wet period can lead to volume expansion and then stress generation. A dry period can lead to volume contraction, producing different stresses. The cycling of such stresses can induce defects for further changes or degradation (Jacques, 2000).
- Wet and dry cycles can contribute to the successive formation and drying of corrosion products. This is particularly evident for polymeric coatings. The mechanical stresses produced at the coating-substrate interface can significantly affect the (wet) coating adhesion (de Wit, van Westing & van der Weijde, 1997).
- Corrosion on coated steel is faster during wet-dry transitions. During the initial wetting period, corrosion increases rapidly as corrosive deposits accumulated on the surface dissolve. Corrosion then decreases with continuous wetting. Corrosion

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[8] ASTM B117 Standard practice for operating salt spray (fog) apparatus

[9] ISO 9227 Corrosion tests in artificial atmospheres – Salt spray tests

will increase during the drying period due to the increased ionic activity when the surface electrolyte concentrates and the increased supply of oxygen.

6.4.3.1 Modified salt spray

ASTM G85[10], as a modified version of ASTM B117, introduces five simulated environmental conditions.

- **Continuous acetic acid salt spray:** Also referred to as ASS, specimens are exposed to a continuous indirect spray of acidified (pH 3.1–3.3) salt solution at a rate of 1.0–2.0 mL/80cm^2/hr at 35°C. It is useful in performance assessment of decorative chromium electroplating. The test typically runs for 144–240 hrs.
- **Cyclic acidified salt spray:** Also referred to as MASTMAASIS, it can be used to test exfoliation of certain aluminium alloys.
  - Cycle 1 – 0.75 hrs exposure to a continuous indirect spray of acidified (pH 2.8–3.0) salt solution at a rate of 1.0–2.0 mL/80cm^2/hr at 49°C.
  - Cycle 2 – 2 hrs air drying at 49°C.
  - Cycle 3 – 3.25 hrs exposure to 95% RH at 49°C.
- **Cyclic acidified seawater spray:** Also referred to as SWAAT, it can be used to determine the relative corrosion resistance of coated or uncoated aluminium alloys and other metals in severe marine environments.
  - Cycle 1 – 0.5 hrs exposure to a continuous indirect spray of acidified (pH 2.8–3.0) synthetic seawater solution at a rate of 1.0–2.0 mL/80cm^2/hr at 49°C.
  - Cycle 2 – 1.5 hrs exposure to >98% RH at 49°C.

  The temperature can be reduced to 24–35°C for organic coatings.
- **Cyclic sulphur dioxide (SO_2) salt spray:** It can be used to evaluate the relative corrosion performance of materials that are likely to be used in environments that have the presence of SO_2, salt spray and acid rain.
  - Cycle 1 – continuous indirect spray of neutral (pH 6.5–7.2) salt water or synthetic seawater at 1.0–2.0 mL/80cm^2/hr at 35°C. The chamber is dosed with SO_2 gas at a rate of 35 cm^3/min/m^3 for 1 hr in every 6 hrs of spraying.
  - Cycle 2 – 0.5 hrs continuous indirect spray of neutral (pH 6.5–7.2) salt water or synthetic seawater solution at a rate of 1.0–2.0 mL/80cm^2/hr at 35°C, 0.5 hrs of SO_2 gas dosing at a rate of 35 cm^3/min/m^3 at 35°C and 2.0 hrs of high humidity soak at 35°C.
- **Cyclic dilute electrolyte salt fog/dry test:** Also referred to as Prohesion, it can be used to evaluate the relative performance of paint coatings on steel and prefinished steel building products.
  - Cycle 1 – 1.0 hr exposure to a continuous indirect spray of dilute acidified (pH 5.0–5.4) salt solution at a rate of 1.0–2.0 mL/80cm^2/hr at 21–27°C.
  - Cycle 2 – 1.0 hr exposure to air drying at a temperature of 35°C.

6.4.3.2 ISO 14993

The standard, ISO 14993[11] can reproduce corrosion in outdoor salt-contaminated environments by using the conditions given in Table 4 with:

- metals and their alloys
- metallic coatings (anodic and cathodic)
- conversion coatings

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[10] ASTM G85 Standard practice for modified salt spray (fog) testing

[11] ISO 14993 Corrosion of metals and alloys – Accelerated testing involving cyclic exposure to salt mist, dry and wet conditions

- anodic oxide coatings
- organic coatings on metallic materials.

Table 4. Cyclic testing conditions according to ISO 14993.

Cycle	Condition
Salt fog	Temperature: 35°C
	Salt solution: 5 wt.%
	Duration: 2 hrs
Heating	Temperature: 60°C
	RH: <30%
	Duration: 4 hrs
Moisture	Temperature: 50°C
	RH: >95%

6.4.3.3 ISO 11997-1

The standard, ISO 11997-1[12] is designed to determine the resistance of coatings to one of four representative cycles (A, B, C and D).

Cycle A: This is specified in Japanese Automobile Standards JASO M 609-91[13] and JASO M610-92[14]. The number of cycle repeats is to be sufficient for 1000 hours total test time, unless otherwise agreed (see Table 5). It has good correlation with natural exposure for thermosetting paints.

Table 5. Cyclic testing conditions according to ISO 11997-1 Cycle A.

Step	Condition	Temperature (°C)	Duration (min)
1	Salt fog: (50 ± 10) g/L NaCl, pH: 5–8	35 ± 2	10
2	Dry	60 ± 2	130
3	Dry	50 ± 2	15
4	Wet: 95–100% RH	60 ± 2	75
5	Dry	60 ± 2	145
6	Dry	50 ± 2	15
7	Wet: 95–100% RH	60 ± 2	10
8	Steps 5-7 repeated 4 times		
9	Dry	35 ± 2	

Source: Daniotti & Re Cecconi, 2006

Cycle B: This is based on the VDA 621-415[15]. The number of cycle repeats is to be sufficient for 840 hours total test time, unless otherwise agreed (see Table 6). It has

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[12] ISO 11997-1 Paints and varnishes – Determination of resistance to cyclic corrosion conditions – Part 1: Wet (salt fog)/dry/humid

[13] JASO M 609-91 Corrosion test method for automotive materials

[14] JASO M610-92 Cosmetic corrosion test method for automotive parts

[15] VDA 621-415 Testing of corrosion properties of vehicle paint by alternating cycles tests

reasonably good correlation with natural weathering for thermosetting paints in vehicle corrosion.

Table 6. Cyclic testing conditions according to ISO 11997-1 Cycle B.

Step	Condition	Temperature (°C)	Duration (hrs)
1	Salt fog: (50 ± 10) g/L NaCl, pH: 5–8	35 ± 2	24
2	100% RH	40 ± 2	8
3	(50 ± 20)% RH	23 ± 2	16
4	100% RH	40 ± 2	8
5	(50 ± 20)% RH	23 ± 2	16
6	100% RH	40 ± 2	8
7	(50 ± 20)% RH	23 ± 2	16
8	100% RH	40 ± 2	8
9	(50 ± 20)% RH	23 ± 2	16
10	(50 ± 20)% RH	23 ± 2	48
11	Return to Step 1		

Source: Daniotti & Re Cecconi, 2006

Cycle C: This cycle was developed for use with water-soluble and latex paint systems and has a good correlation with natural weathering. The number of cycle repeats is to be sufficient for 1000 hours total test time, unless otherwise agreed (see Table 7).

Table 7. Cyclic testing conditions according to ISO 11997-1 Cycle C.

Step	Condition	Temperature (°C)	Duration (min)
1	Salt fog: 0.31 g/L NaCl + 4.1 g/L $(NH_4)_2SO_4$, pH: 5–8	30 ± 2	210
2	Dry	40 ± 2	210
3	(75 ± 15)% RH	40 ± 2	1470
4	Dry	30 ± 2	102
5	Salt fog: 0.31 g/L NaCl + 4.1 g/L $(NH_4)_2SO_4$, pH: 5–8	30 ± 2	210
6	95–100% RH	30 ± 2	378
7	Dry	35 ± 2	180
8	Dry	25 ± 2	120
9	Return to Step 1		

Source: Daniotti & Re Cecconi, 2006

Cycle D: This is specified in Japanese Standard JIS K 5621-2003[16] for comparing the relative corrosion resistance of paints, varnishes and similar materials. It comprises of the repeating cycles in Table 8 and normally repeats for 28 cycles (168 hrs).

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[16] JIS K 5621-2003 Anticorrosive paint for general use

Table 8. Cyclic testing conditions according to ISO 11997-1 Cycle D.

Step	Condition	Temperature (°C)	Duration (min)
1	Salt fog: 0.31 g/L NaCl + 4.1 g/L $(NH_4)_2SO_4$, pH: 5–8	30 ± 2	30
2	Wetting at (95 ± 3)% RH	30 ± 2	90
3	Drying	50 ± 2	120
4	Drying	30 ± 2	120

The following transition times apply:

- 10 minutes from salt spray to wetting
- 15 minutes from wetting to drying at 50°C
- 30 minutes from hot drying to drying at 30°C

6.4.3.4 GM 9540P

GM 9540P *Accelerated corrosion test* was developed by General Motors to evaluate the corrosion performance and mechanisms of automotive assemblies and components using an accelerated laboratory procedure.

Table 9. GM 9540P cyclic corrosion test.

Interval	Description	Time (minutes)	Temperature (±3°C)
1	Ramp to salt mist	15	25
2	Salt mist cycle	1	25
3	Dry cycle	15	30
4	Ramp to salt mist	70	25
5	Salt mist cycle	1	25
6	Dry cycle	15	30
7	Ramp to salt mist	70	25
8	Salt mist cycle	1	25
9	Dry cycle	15	30
10	Ramp to salt mist	70	25
11	Salt mist cycle	1	25
12	Dry cycle	15	30
13	Ramp to humidity	15	49
14	Humidity cycle	480	49
15	Ramp to dry	15	60
16	Dry cycle	480	60
17	Ramp to ambient	15	25
18	Ambient cycle	480	25

Source: Placzankis, Miller & Matzdorf, 2003

It consists of 18 separate stages, including saltwater spray, humidity, drying, ambient and heated drying (see Table 10). The test solution is composed of 0.9 wt% NaCl, 0.1 wt% $CaCl_2$ and 0.25 wt% $NaHCO_3$ (pH: 6–9). The typical test duration is 80 cycles.

6.4.3.5 Volvo cycle

The Volvo cycle or Volvo indoor corrosion test (VICT) was developed to simulate the outdoor corrosion environment of a typical automobile through a statistical factorial design (Forsgren, 2006). There are four variants of the Volvo cycle.

The VICT-2 variant, which uses constant temperature and discrete humidity transitions between two humidity levels, is described below:

- Step 1 – 7 hrs exposure at 90% RH and 35°C.
- Step 2 – continuous and linear change of RH from 90% to 45% at 35°C in 1.5 hrs.
- Step 3 – 2 hrs exposure at 45% RH and 35°C.
- Step 4 – continuous and linear change of RH from 45% to 90% at 35°C in 1.5 hrs.

Twice a week, on Monday and Friday, Step 1 is replaced by the following:

- Step 5 – samples are taken out of the test chamber and submerged in or sprayed with 1 wt.% NaCl solution for 1 hr.
- Step 6 – samples are removed from the salt bath and excess liquid is drained off for 5 min. The samples are put back into the test chamber at 90% RH for at least 7 hrs before the drying phase.

Typically, the test is running for 12 weeks.

6.4.3.6 SAE J2334

The standard, SAE J2334[17], is a statistically designed, field-correlated testing procedure for automotive substrates and coatings. It is based on a 24-hr cycle and each cycle consists of:

- 6 hrs exposure at 50°C and 100% RH
- 15 min salt application (0.5 wt.% NaCl + 0.1 wt% $CaCl_2$ + 0.075 wt.% $NaHCO_3$)
- 17 hrs and 45 min drying at 60°C and 50% RH.

The typical duration test is 60 cycles.

6.4.3.7 Kesternich testing

Kesternich testing is a common name for sulphur dioxide testing. It was originally designed by Wilhelm Kesternich in 1951 to simulate the damaging effects and the corrosive influence of acid rain on coated or uncoated metals when exposed to polluted industrial environments (Kesternich, 1965). It is a condensation cycle test in an acidic environment.

The sample is exposed for 8 hrs to an atmosphere of 100% RH and 40°C. At the start of these 8 hrs, sulphur dioxide (SO_2) is added to a certain volumetric concentration. After this, the sample is conditioned for the next 16 hrs at room temperature (18–28°C) and ambient relative humidity (max. 75%). The test cycle can be repeated for 2–50 cycles or more.

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[17] SAE J2334 Laboratory cyclic corrosion test

The standards, ASTM G87[18], DIN 50018[19], ISO 3231[20] and ISO 22479[21] are typical for Kesternich exposure.

6.4.4 Advanced cyclic testing

Accelerated testing schemes with advanced cycles have been developed to evaluate the degradation of metallic materials exposed to a variety of natural environments (Lin & Wang, 2005; Antunes, Ichikawa, Martinez & Costa, 2014). They highlight:

- incorporation of wet-dry cycles
- incorporation of UV irradiation cycle
- combination of fog/dry cycles with UV irradiation and condensation cycles.

6.4.4.1 ASTM D5894

The standard, ASTM D5894[22] describes how to compare the performance of paints on metals. It uses alternating periods of exposure in two different cabinets:

- **UV/condensation:** This includes 4 hrs UV at 0.89 W/(m^2·nm) at 340 nm at 60°C and 4 hrs condensation at 50°C using UVA-340 lamps. Total duration for one complete cycle in this cabinet is 168 hrs.
- **Salt fog/dry:** This includes 1 hr salt spray at ambient temperature and 1 hr dry-off at 35°C. The solution is 0.05 wt.% sodium chloride and 0.35 wt.% ammonium sulphate. Total duration for one complete cycle in this cabinet is 168 hrs.

6.4.4.2 ISO 20340

The standard, ISO 20340[23] includes:

- methods that determine the composition of the separate components of the protective paint system
- methods for durability evaluation of the protective paint system
- criteria to be used to evaluate testing results.

Table 10. ISO 20340 cyclic testing options.

Option 1	Option 2
72 hrs salt spray 5 wt.% NaCl at 35°C	72 hrs salt spray 5 wt.% NaCl at 35°C
24 hrs drying at -20°C	24 hrs drying at 23°C
72 hrs condensation/UV • 4 hrs UV at 60°C • 4 hrs condensation at 50°C	72 hrs condensation/UV • 4 hrs UV at 60°C • 4 hrs condensation at 50°C

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[18] ASTM G87 Standard practice for conducting moist SO_2 tests

[19] DIN 50018 Testing in a saturated atmosphere in the presence of sulfur dioxide

[20] ISO 3231 Paints and varnishes – Determination of resistance to humid atmospheres containing sulfur dioxide

[21] ISO 22479 Corrosion of metals and alloys – Sulfur dioxide test in a humid atmosphere (fixed gas method)

[22] ASTM D5894 Standard practice for cyclic salt fog/UV exposure of painted metal, (alternating exposures in a fog/dry cabinet and a UV/condensation cabinet)

[23] ISO 20340 Paints and varnishes – Performance requirements for protective paint systems for offshore and related structures

It typically has two procedures as shown in Table 10. The duration for one complete cycle is 7 days (168 hrs), while the total testing duration is 25 cycles (4,200 hrs).

6.4.4.3 ISO 11474

The standard, ISO 11474[24], is to accelerate outdoor corrosion exposure by intermittently spraying. The solution of sodium chloride (3 wt.%) is sprayed twice a week, 3–4 days apart, onto the test surface, simulating and enhancing the environmental stress prevailing at marine environments. The duration of this test is normally 6 months.

This accelerated test is especially useful for comparative performance assessment of:

- metals and their alloys
- metallic coatings (anodic and cathodic)
- organic coatings on metals
- chemical conversion coatings.

6.4.5 Others

6.4.5.1 Steady-state moisture test for metal corrosion in timber

Two standard test methods have been developed to determine the corrosion rate of metal in contact with timber using high steady-state moisture exposure:

- AWPA E-17 *Standard method for determining corrosion rates of metals in contact with treated wood* – A metal coupon is sandwiched between two pieces of preservative-treated timber. The timber-metal assembly is then placed in a conditioning chamber at 49±1°C and 90±1% RH for an exposure of >240 hrs.
- ASTM G198 *Standard test method for determining the relative corrosion performance of driven fasteners in contact with treated wood* – Fasteners are driven into treated timber specimens of appropriate sizes. The fastener-timber assembly is then placed in an environmental chamber maintained at 32±2°C and 95±3% RH for an exposure of >120 days (2,880 hrs).

6.4.5.2 Cyclic fog test for metal corrosion in timber

A cyclic moisture test has been described in ASTM G198 to determine the corrosion resistance of fasteners (metal, metal-coated and non-metallic-coated) in contact with timber treated with preservatives. The exposure includes 48 hrs of fog (1.0–2.0 mL/hr, 24±3°C) followed by a minimum of 72 hrs and a maximum of 120 hrs of drying (35±2°C). The total duration is 120 days (2,880 hrs).

6.5 Case study

6.5.1 Case A

Two accelerated methods have been designed to evaluate the atmospheric corrosion performance of a steel against natural exposure to urban or industrial atmospheres (Antunes, Ichikawa, Martinez & Costa, 2014).

- **Test method A:** This was based on ASTM D5894 and included alternating periods of exposure between a fog/dry cabinet using the Prohesion cycle and a UV

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[24] ISO 11474 Corrosion of metals and alloys – Corrosion tests in artificial atmosphere – Accelerated outdoor test by intermittent spraying of a salt solution (Scab test)

irradiation and condensation cabinet. The Prohesion cycle was composed of a 1 hr fog cycle using a solution of 0.35 wt.% $(NH_4)_2PO_4$ and 0.05 wt.% NaCl, alternated with 1 hr air drying period at 35°C. In the UV irradiation and condensation cabinet, the samples were exposed to UVA irradiation for 4 hrs followed by 4 hrs of condensation, according to ASTM G53[25]. A full cycle was comprised of 7 days exposure in each cabinet. The total test duration had 4 cycles.

- **Test method B:** This consisted of 7 days of continuous salt spray according to ASTM B117 and 7 days of exposure to UVA irradiation and condensation according to ASTM G53. A full cycle was comprised of 7 days exposure in each cabinet. The total test duration consisted of 4 cycles.

The composition of the corrosion products formed on the steel samples after these accelerated and natural exposures was analysed with Raman spectroscopy, Mossbauer and XRD. Iron oxide-hydroxides including lepidocrocite (γ-FeO(OH)), goethite (α-FeO(OH)) and magnetite (Fe_3O_4) were detected. It was found that the corrosion products formed on the steel samples exposed to test method A were similar to those on the samples exposed naturally. A poor correlation was found between test method B and natural exposure. Akaganeite (β-FeO(OH)) was identified as the major corrosion product formed on the steel samples exposed to test method B conditions.

6.5.2 Case B

A two-phase investigation has been developed to identify test methods that can be used to assess the corrosion protection performance of coatings in marine atmospheres (see Table 11) (Knudsen, Steinsmo, Bjordal & Nijjer, 2001).

Table 11. Accelerated test methods.

Test	Standard
NORSOK test	NORSOK M501 *Surface preparation and protective coating*
Salt spray test	ISO 7253 *Paints and varnishes – Determination of resistance to neutral salt spray (fog)*
Mebon Prohesion test	NORDTEST NT BUILD 228 (cyclic salt spray, ASTM G85)
Volvo test	Volvo Corporate Standard 1027, 1375 procedure 2A

Correlation coefficients for maximum and average scribe creep have been calculated to measure the relationship between the accelerated and field tests.

The NORSOK test was able to differentiate the good and the inferior coatings. The correlation coefficients between the NORSOK test and the field test were 0.62 and 0.76 for Phase 1 and Phase 2 respectively, calculated from average scribe creep results.

The overall correlation coefficients for average scribe creep between the field test and salt spray test and the Mebon Prohesion test was 0.34 and 0.34 respectively.

The correlation coefficient for average scribe creep between the Volvo test and the field test was 0.77. Meanwhile, the correlation for maximum scribe creep was 0.54.

Both the NORSOK test and the Volvo test are cyclic tests that include drying of the coatings. In the salt spray test according to ISO 7253, the coatings were wet during

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[25] ASTM G53 Practice for operating light- and water-exposure apparatus (fluorescent UV-condensation type) for exposure of nonmetallic materials

the whole testing period. The cycles in the Mebon Prohesion test were not long enough for the coating to dry between the spraying intervals. It seemed that cyclic wetting and drying was important in achieving high correlations.

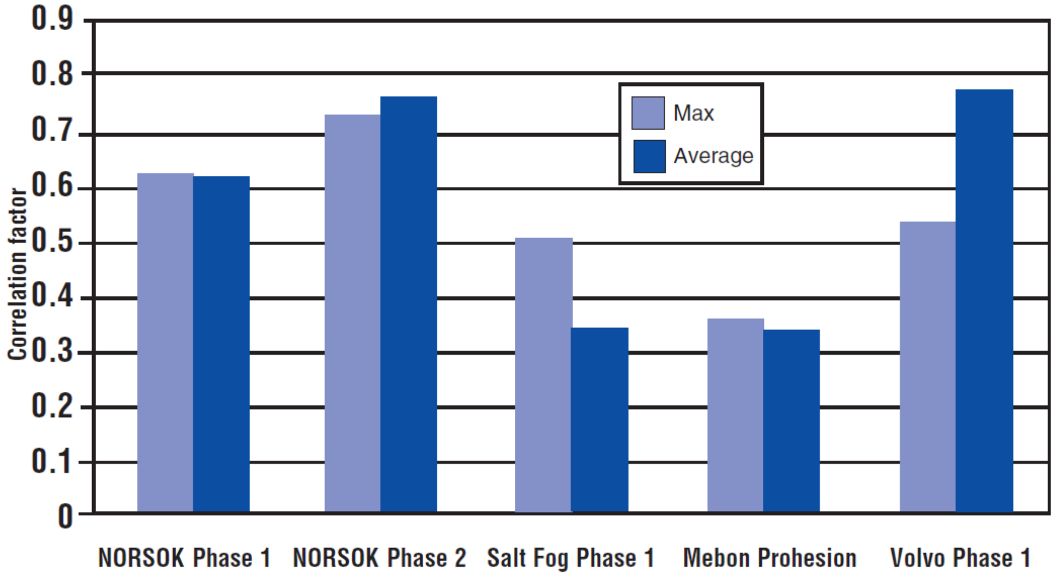


Figure 12. Correlation factors between accelerated and field tests.

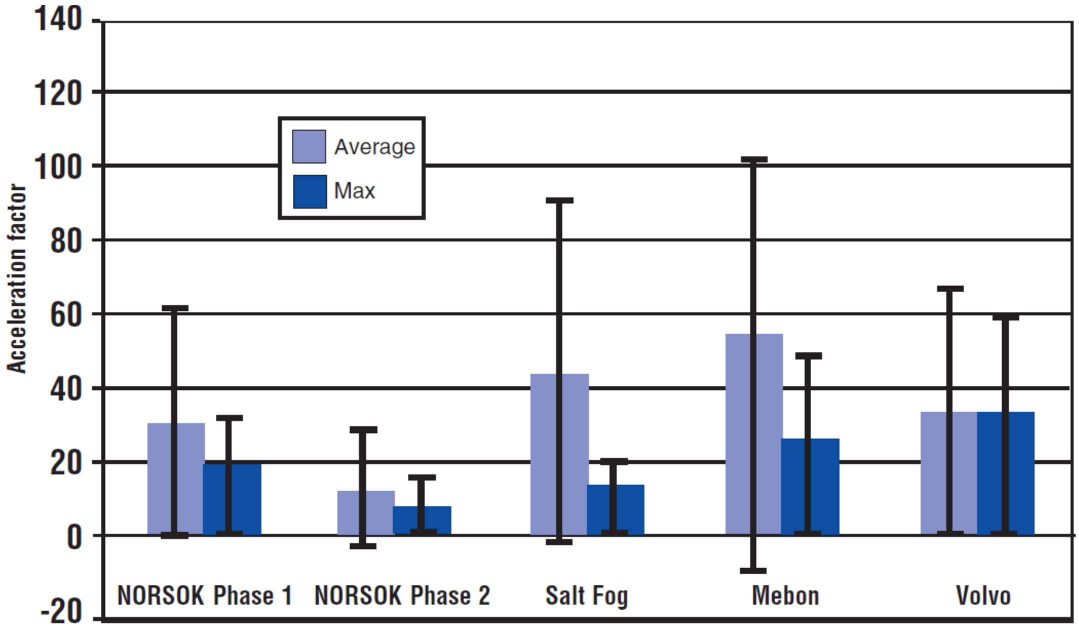


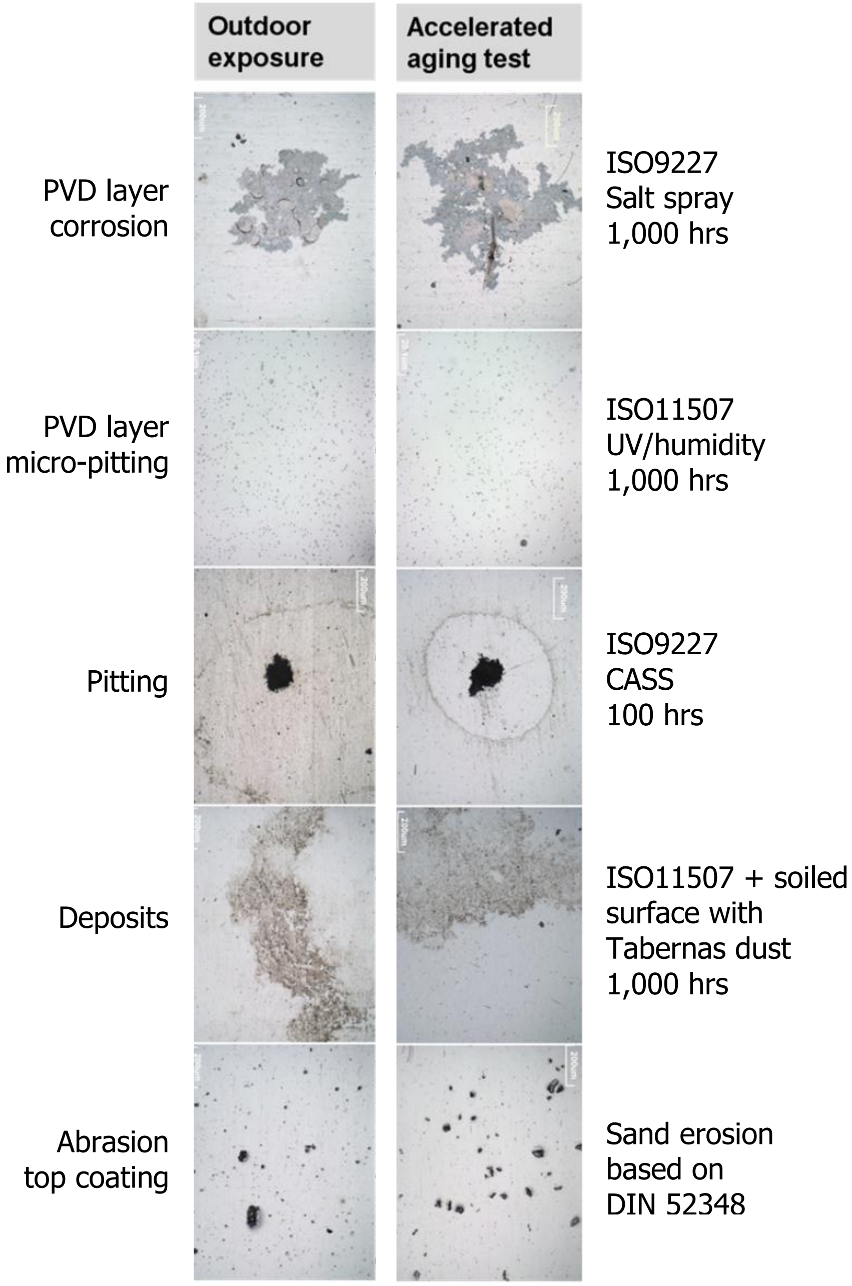
Figure 13. Acceleration factors between scribe creep in accelerated and field tests.

Comparing Figure 12 and Figure 13 (Knudsen, Steinsmo, Bjordal & Nijjer, 2001), an inverse relation between acceleration and correlation can be found.

6.5.3 Case C

An accelerated method has been developed to estimate the lifetime of aluminium reflectors (Wette, Sutter & Fernández-García, 2016). It included outdoor and indoor accelerated testing in a laboratory. The accelerated testing programme included:

- copper accelerated acetic acid salt spray – ISO 9227
- UV/humidity – ISO 11507 *Paints and varnishes – Exposure of coatings to artificial weathering – Exposure to fluorescent UV lamps and water*
- damp heat – IEC 62108 *Concentrator photovoltaic (CPV) modules and assemblies – Design qualification and type approval*, Test 10.7b
- humidity freeze – IEC 62108, Test 10.8
- condensation – ISO 6270-2 *Paints and varnishes – Determination of resistance to humidity – Part 2: Condensation (in-cabinet exposure with heated water reservoir)*
- thermal cycling with condensation.



Source: Wette, Sutter & Fernández-García, 2016

Figure 14. Five degradation mechanisms observed on samples exposed to outdoor and accelerating testing conditions.

Five degradation mechanisms identified with the samples exposed to outdoor environments (see Figure 14) were:

- corrosion of aluminium reflection layer
- micro-pitting of the aluminium reflection layer
- pitting corrosion reaching the substrate
- non-removable deposits on the surface
- defects on the protective top coating caused by abrasion through airborne particles.

No single accelerated test was able to reproduce all of these five degradation mechanisms. However, all these mechanisms could be observed with the samples exposed to the accelerated testing conditions.

For example, micro-pitting of the aluminium reflection layer during outdoor exposure was reproduced after 480 hrs of UV/humidity test. Pitting corrosion reaching the substrate was reproduced with the CASS test. This indicated that 164 hrs of exposure in the test chamber was equivalent to 5 years of outdoor exposure.

7. Test standards

7.1 Introduction

The durability evaluation of building materials relies on the development and use of appropriate methods. These methods are expected to provide reliable guidance and/or procedures to characterise the fundamental properties and functional performance of materials or the material systems concerned. The qualitative and quantitative data and information derived are expected to support the predictive analysis for determining the durability and service life when subjected to in-service environments.

Numerous test methods are available from national and international standards. When chosen and used appropriately, they can be useful for performing qualitative and/or quantitative tests for durability evaluation and/or service life prediction.

7.2 Summary of relevant standards

Relevant standards that describe or specify methods or procedures for durability evaluation of building materials are collected and listed in Tables 32–35 in Appendix A. These mainly include AS (Australian Standard), ASTM (ASTM International), ISO (International Organization for Standardization) and NZS (New Zealand Standard).

- Table 32 – Material characterisation
- Table 33 – Environmental characterisation
- Table 34 – Durability evaluation
- Table 35 – Service life planning

8. Durability parameters

8.1 Definition

Material durability is an integral part of the performance of buildings. A good understanding of durability is also critical to the formulation, development and innovation of materials as well as the design, construction and maintenance of buildings.

There are some fundamental material characteristics or factors that are closely linked with material durability. A typical example is the composition and thickness of zinc-based coatings. Meanwhile, in relation to their in-service environmental conditions, there are some parameters that can be used to assess the properties, performance and durability of materials concerned.

An example of where this is used frequently is concrete. Durability indicators or indexes have been identified for the performance-based approach necessary for the development of concrete with improved durability (Alexander, Ballim & Stanish, 2008; Lafhaj & Dakhli, 2019). Typical examples may include chloride conductivity, water porosity/sorptivity and gas/oxygen permeability for concrete durability.

The concept of durability indicator or index can also be developed and used to assess and predict the performance of other materials with respect to their degradation in a given environment.

8.2 Some examples of durability parameters

Some examples of material-related factors and functional parameters that could be used to investigate material performance and evaluate durability have been collected from publicly available literature. They are reviewed and presented in Table 12. Although they are mainly collected from traditional building materials, they could still be useful when identifying the critical characteristics for properties, performance and durability evaluation of new materials.

Table 12. Some examples of parameters relevant to material durability.

Parameter	Method	Criteria	Reference	Remark
Concrete				
Air/oxygen permeability			Salvoldi, Beushausen & Alexander, 2015 Katpady, Hazehara, Soeda, Kubota & Murakami, 2018	Oxygen permeability testing was more sensitive than strength in predicting carbonation resistance of concrete.
Chloride conductivity			Otieno & Alexander, 2015	
Water sorptivity			Lee, 2002 Maroliya, 2012	
Electrical resistivity	ASTM C1760 *Standard test method for bulk electrical conductivity of hardened concrete*		Sengul, 2014	Chloride diffusivity is used as a performance-based specification of durability for the production of new concrete structures in severe environments. A strong relationship between chloride diffusivity and electrical resistivity was obtained although different concrete mixtures and various testing ages were used.
Paint coatings				
Adhesion	ISO 4624 *Paints and varnishes – Pull-off test for adhesion* ASTM D4541 *Standard test method for pull-off strength of coatings using portable adhesion testers*	Standard protective coating: 7 MPa Heavy duty coating: 18 MPa Resistant coating: 18 MPa	Sonke & Bos, 2008	
Tensile strength	ASTM D2370 *Standard test method for tensile properties of organic coatings*	Standard protective coating: 15 MPa Heavy duty coating: 30 MPa Resistant coating: 50 MPa		

Parameter	**Method**	**Criteria**	**Reference**	**Remark**
Elongation		Standard protective coating: 2.5% Heavy duty coating: 5% Resistant coating: 7%		
Impact resistance	ASTM D2794 *Standard test method for resistance of organic coatings to the effects of rapid deformation (Impact)*	Standard protective coating: 2.5 J Heavy duty coating: 5 J Resistant coating: 10 J		
Abrasion	ASTM D4060-01 *Standard test method for abrasion resistance of organic coatings by the taber abraser*	Standard protective coating: 150 mg Heavy duty coating: 80 mg Resistant coating: 10 mg		
Temperature	Differential scanning calometry (DSC), T_g	Standard protective coating: 80°C Heavy duty coating: 120°C Resistant coating: 200°C		
Hardness	ASTM D2583 *Standard test method for indentation hardness of rigid plastics by means of a barcol impressor* ASTM D2240 *Standard test method for rubber property – durometer hardness*			
Chemical resistance	ASTM C868 *Standard test method for chemical resistance of protective linings (withdrawn 2015)* ASTM G20 *Standard test method for chemical resistance of pipeline coatings*			
Maximum and average scribe creep	NORSOK M501 *Surface preparation and protective coating* ISO 7253 *Paints and varnishes – Determination of resistance to neutral salt spray (fog)* ASTM G85 *Standard practice for modified salt spray (fog) testing* Volvo Corporate Standard 1027, 1375 *Accelerated atmospheric corrosion testing – Indoor corrosion test (Procedure 2A)*		Knudsen, Steinsmo, Bjordal & Nijjer, 2001	

Parameter	Method	Criteria	Reference	Remark
Pre-painted sheet metal building products				
Blistering	AS/NZS 1580.481.1.9 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Degree of blistering*	Product Type 3: D2-S4 (Category 4) D3-S4 (Category 5)	AS/NZS 2728 *Prefinished/prepainted sheet metal products for interior/exterior building applications – Performance requirements*	4-year field exposure at sites where panels are rain washed.
		Product Type 4: D2-S2 (Category 4) D3-S2 (Category 5)		
		Product Type 5: D2-S2 (Category 4) D3-S2 (Category 5)		
		Product Type 6: D2-S2 (Category 4) D3-S2 (Category 5)		
Gloss	AS/NZS 1580.481.1.5 *Methods of test for paints and related materials – Exposed to weathering –Change in gloss*	Light: 4 Pastel: 4 Dark: 5		4-year field exposure at sunshine test sites.
Checking	AS/NZS 1580.481.1.7 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Degree of checking*	Light: 0 Pastel: 0 Dark: 5		Sunshine daily average > 8 hrs, solar irradiation >19.8 MJ/m^2.
Chalking	AS/NZS 1580.481.1.11 *Methods of test for paints and related materials – Exposed to weathering –Degree of chalking*	Light: 2 Pastel: 1 Dark: 0		
Colour change	AS/NZS 1580.601.4 *Methods of test for paints and related materials – Colour – Calculation of colour differences*	Light: 2 Pastel: 4 Dark: 5		
Cracking	AS/NZS 1580.481.1.8 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Degree of cracking*	Light: 0 Pastel: 0 Dark: 0		

Parameter	**Method**	**Criteria**	**Reference**	**Remark**
Flaking and peeling	AS/NZS 1580.481.1.10 *Methods of test for paints and related materials – Exposed to weathering – Degree of flaking and peeling*	Light: 0-0 Pastel: 0-0 Dark: 0-0		
Humidity resistance	AS/NZS 1580.481.3 *Paints and related materials – Methods of test – Coatings – Exposed to weathering – Degree of corrosion of coated metal substrates*	Undercut at scribed lines: 2 mm max. with no corrosion of base metal		ASTM D4585 *Standard practice for testing water resistance of coatings using controlled condensation* 500 hrs
	AS/NZS 1580.408.4 *Paints and related materials – Methods of test for paints and related materials – Adhesion (crosscut)*	Loss of adhesion: Rating 0		
	AS/NZS 1580.481.1.9	Blistering: Not worse than rating 3-S2		
	AS/NZS 1580.481.3	Corrosion of base metal: Rating 0		
Corrosion	AS/NZS 1580.481.3	Undercut at scribed lines: 2 mm max. with no corrosion of base metal When base metal is steel, no red rust formation		Salt spray according to AS 2331.3
	AS/NZS 1580.408.4	Loss of adhesion: Rating 0		
	AS/NZS 1580.481.1.9	Blistering: Not worse than rating 2-S3		
	AS/NZS 1580.481.3	Corrosion of base metal: Rating 0		
	AS/NZS 1580.481.3	Undercut at scribed lines: 1 mm max. with no corrosion of base metal		Cyclic corrosion
	AS/NZS 1580.408.4	Loss of adhesion: Rating 0		
	AS/NZS 1580.481.1.9	Blistering: Not worse than rating 2-S2		
	AS/NZS 1580.481.3	Corrosion of base metal: Rating 0		

Parameter	**Method**	**Criteria**	**Reference**	**Remark**
Mechanically plated screws				
Coating composition	AS 3566.2 *Self-drilling screws for the building and construction industries –Corrosion resistance requirements*	Class 3: 98% Zn Class 3: 20–30%Sn + Zn Class 4: 25–30%Sn + Zn		
Coating thickness		Class 3: >40 µm (Zn) Class 3: >25 µm (Zn-Sn) Class 4: >45 µm		
Coating porosity		>Rating 8		
Hot-dip galvanised nails				
Zinc coating mass	ASTM A90/A90M *Standard test method for weight [mass] of coating on iron and steel articles with zinc or zinc-alloy coatings* AS 2331.2.1 *Methods of test for metallic and related coatings – Tests for average coating mass per unit area or for thickness – Dissolution methods – Strip and weigh and analytical*	>320 g/m^2	NZS 3604 *Timber-framed buildings*	Hot-dip galvanising
		320 (≤1.5 mm)	AS/NZS 4680 *Hot-dip galvanized (zinc) coatings on fabricated ferrous articles*	Not centrifuged
		390 (>1.5≤3 mm)		Not centrifuged
		500 (>3≤6 mm)		Not centrifuged
		600 (>6 mm)		Not centrifuged
		250 (<8 mm)		Centrifuged
		390 (≥8 mm)		Centrifuged
Wall ties				
Material type Coating mass	AS 1397 *Continuous hot-dip metallic coated steel sheet and strip – Coatings of zinc and zinc alloyed with aluminium and magnesium* AS/NZS 4680 *Hot-dip galvanized (zinc) coatings on fabricated ferrous articles* AS 1449 *Wrought alloy steels – Stainless and heat-resisting steel plate, sheet and strip*	R0, R1, R2: Z600	AS/NZS 2699.1 *Built-in components for masonry construction – Wall ties*	
		R0, R1, R2: 300 g/m^2		
		R3:		
		R4: AISI 316/316L		
Rubber				
Tear strength		50% of the initial value (25°C in air)	Zhu & Song, 2017	$S = 49.5\exp(-2.86\times10^{-3}t^{0.58})$

Parameter	**Method**	**Criteria**	**Reference**	**Remark**
Polymeric materials				
Creep (linear and non-linear) Time-dependent plasticity Fatigue			Maxwell, Broughton, Dean & Sims, 2005	
Poly(ethylene-terephthalate) (PET)				
Yellowness index (YI) Haze (%)	Damp heat: Constant exposure at 85°C and 85% RH Freeze-thaw: Cyclic exposure of 20 hrs at 70°C and 85% RH and 30 minutes at -40°C Hot QUV: Constant exposure of UVA light at 1.55 W/m^2 at 340 nm at 70°C Cyclic QUV (ASTM G154 Cycle 4): Cyclic exposure of 8 hrs of UVA light at 1.55 W/m^2 at 340 nm at 70°c and 4 hrs of condensing humidity at 50°C in dark		Gok et al., 2017	PET degradation under cyclic exposures combining UV light and condensing humidity is caused by photolytic and hydrolytic mechanisms causing yellowing and haze formation.
Curtain wall joint sealant				
Loss of adhesion during fatigue cycling	ISO 9047 *Building construction – Jointing products – Determination of adhesion/cohesion properties of sealants at variable temperatures* Movement cycle (2 weeks) Weathering cycle (4 weeks): 4 hrs fluorescent lamp UV-A exposure at 62°C followed by 4 hrs moisture condensation at 42°C	Pass/Fail	Wolf, 2004	
Adhesive tapes				
Peel resistance: T-peel for tapes applied to flexible substrate	NS-EN 1296 *Flexible sheets for waterproofing – Bitumen, plastic and rubber sheets for roofing – Method of artificial ageing by long term exposure to elevated temperature*		Fufa, Labonnote, Frank, Rüther & Jelle, 2018	Qualitative correlation between lab and natural ageing tests

Parameter	**Method**	**Criteria**	**Reference**	**Remark**
180 degree for tapes applied to rigid substrates) NS-EN 12316-2 *Flexible sheets for waterproofing – Determination of peel resistance of joints – Part 2: Plastic and rubber sheets for roof waterproofing* Shear resistance: NS-EN 12317-2 *Flexible sheets for waterproofing – Determination of shear resistance of joints – Part 2: Plastic and rubber sheets for roof waterproofing*				
Epoxy adhesives				
Glass transition temperature (T_g) Tensile: ISO 527-2 *Plastics – Determination of tensile properties – Part 2: Test conditions for moulding and extrusion plastics* Flexure: ISO 178 *Plastics – Determination of flexural properties* In-plane shear: ASTM D5379/D5379M *Standard test method for shear properties of composite materials by*	Immersion ageing: ISO 175 *Plastics – Methods of test for the determination of the effects of immersion in liquid chemicals* Continuous condensation: ISO 6270-1 *Paints and varnishes – Determination of resistance to humidity – Part 1: Condensation (single-sided exposure)*		Sousa, Correia & Cabral-Fonseca, 2018	

Parameter	Method	Criteria	Reference	Remark
the v-notched beam method				
Wood preservative semi-transparent coatings				
Colour change Water repellency	JIS K5600-4-6 *Testing methods for paints – Part 4: Visual characteristics of film – Section 6: Colorimetry (Calculation of colour differences)* JISK5600-7 *Testing methods for paints – Part 7: Long-period performance of film*	2-year natural weathering corresponds to: (1) 2,500 hrs xenon lamp test (acceleration factor 7.0) (2) 12-week fluorescent UV lamp test (acceleration factor 8.7)	Ishikawa et al., 2014	Xenon lamp: JIS K5600-7-7 *Testing methods for paints – Part 7: Long-period performance of film – Section 7: Accelerated weathering and exposure to artificial radiation (Exposure to filtered xenon-arc radiation)* Fluorescent UV lamp: EN 927-6 *Paints and varnishes – Coating materials and coating systems for exterior wood – Part 6: Exposure of wood coatings to artificial weathering using fluorescent UV lamps and water*
Glass fibre reinforced polymer (GFRP)				
Glass transition temperature (T_g) Tensile strength Inter-laminar shear strength Flexural strength Modulus of elasticity	ASTM D4475 *Standard test method for apparent horizontal shear strength of pultruded reinforced plastic rods by the short-beam method* ASTM D4476/D4476M *Standard test method for flexural properties of fiber reinforced pultruded plastic rods* ASTM D7028 *Standard test method for glass transition temperature (DMA T_g) of polymer matrix composites by dynamic mechanical analysis (DMA)* ASTM D570 *Standard test method for water absorption of plastics*		Fergani, Benedetti, Oller, Lynsdale & Guadagnini, 2018	SEM/EDX: Fibre deterioration or damage FTIR: Absorption bands: 3400, 3026, 2960, 2928, 2871, 1722, 1608, 1510, 1295, 1160, 920 cm^{-1}

Parameter	Method	Criteria	Reference	Remark
Painted façade rendering				
2 hrs surface water absorption rate	Fog and dew: 48 hrs at 9°C UV: 456 hrs, 290–400 nm, 35–40 W/m^2 Freezing: 10 times for 5 hrs at -10.5°C Rain: 10 times for 7 hrs with acidic water (pH = 2.5) High temperature: 31°C for 180 hrs, 39°C for 100 hrs, 49°C for 75 hrs		Norvaišienė, Burlingis & Stankevičius, 2010	Natural weathering and accelerated cycling tests show similarities in ageing and evolution of moisture characteristic changes.
Hydraulic binder based on fluidised bed combustion ash (FBC ash)				
Compressive strength		$ln0.5 = -A'_0 e^{-\alpha \cdot w} e^{\frac{\beta_0(1-\sigma w)}{T}} \tau$ A'_0 – frequency factor of the system in a dried state α – humidity coefficient of the frequency factor w – humidity of the system β_0 – E_0/R E_0 – molar activation energy of the system in a dried state R – molar gas constant T – Temperature τ – Durability	Fridrichová, Dvořák & Gazdič, 2016	Strength of the cured binder drops to its so-called utility value, which is understood here as being 50% of the initial strength (i.e. its strength after 28 days of hydration under laboratory conditions).
Thermoplastic polyolefin (TPO) roofing membranes				
Microcracking	Accelerated weathering: ASTM D6878 *Standard specification for thermoplastic polyolefin based sheet roofing* and ASTM G155 *Standard practice for operating xenon arc light apparatus for exposure of non-metallic materials* Accelerated weathering: ASTM G154 *Standard practice for operating fluorescent ultraviolet (UV) lamp apparatus for exposure of nonmetallic materials* Heat ageing: ASTM D6878	Onset of microcracking	Xing & Taylor, 2011	Accelerated heat ageing at temperatures up to 138°C are showing very good correlations to other ageing tests.

Parameter	**Method**	**Criteria**	**Reference**	**Remark**
Poly(vinyl chloride) – PVC roofing membranes				
Tensile strength Elongation Low-temperature flexibility	ASTM D4434/D4434M *Standard specification for poly(vinyl chloride) sheet roofing* SIA 280 *Polymer membranes: materials testing and requirements (roofing, waterproofing, water vapour and capillary water barrier)*	35 kN/m 15% -20°C	Beer, Delgado, Paroli & Graveline, 2005	Reinforced PVC roof membrane system could perform in excess of 20–30 years in various climates throughout Europe and North America.
Single-ply roofing membranes				
Tensile strength Elongation at break Elastic limit Low-temperature flexibility Crack bridging Cone penetration resistance Static and dynamic impact tests at different temperatures			Laaly & Sereda, 1980 Rossiter & Mathey, 1983	
BUR				
Tensile strength Thermal expansion and contraction coefficient Thermal shock resistance factor Flexural strength Tensile fatigue strength Flexural fatigue strength Punching shear strength Impact resistance Wind resistance Fire resistance			Cash & Bailey, 1993	Criteria are too stringent.

Parameter	**Method**	**Criteria**	**Reference**	**Remark**
Modified bitumen membranes				
Tear strength Moisture content Water absorption Dimensional stability Low-temperature flexibility	ASTM D5147/D5147M *Standard test methods for sampling and testing modified bituminous sheet material*	Max 0.5% dry mass Max 100 g/m^2 100 hrs at 50°C water soak Max ±1%	Cash & Bailey, 1993	Specific to modified bitumen membranes and not validated by outdoor weathering study.
EPDM				
Tensile strength Ultimate elongation Low-temperature flexibility Dimensional stability Ozone resistance Tear resistance Water resistance			Cash & Bailey, 1993	
Structural sandwich panels				
Shear and compressive strength	Wrinkling test		Hassinen & Pfeiffer, 2010	
Insulation materials – polyurethane				
Thermal conductivity Compressive strength Thickness	DIN EN 12667 *Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance* DIN EN 826 *Thermal insulating products for building applications – Determination of compression behaviour*		PU Europe, n.d.	

Parameter	Method	Criteria	Reference	Remark
	DIN EN 823 *Thermal insulating products for building applications – Determination of thickness*			
Insulation materials – glass wool				
Thermal conductivity	UNI EN 12664 *Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Dry and moist products of medium and low thermal resistance*		Tittarelli, Stazi, Politi, di Perna & Munafò, 2013	
Insulation materials – aerogel-enhanced plasters and blankets				
Thermal conductivity	ASTM C518 *Standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus* EN 12664 EN 12667 ISO22007-2 *Plastics – Determination of thermal conductivity and thermal diffusivity – Part 2: Transient plane heat source (hot disc) method*		Nosrati & Berardi, 2017 Hoseini & Bahrami, 2017 Miros, Psiuk & Szpikowska-Sroka, 2017 Lakatos, 2019	

9. Service life prediction

The evaluation, prediction and verification of the durability, performance and service life of construction materials and building components is a very important part of building design, construction and maintenance. This ensures that buildings will meet NZBC requirements and also the demands of occupiers and owners.

Service life prediction is complex since there are a large number of factors involved. Some methodologies have been developed to produce data through accelerated or non-accelerated tests in laboratory or field assessments or through the inspection of existing buildings for durability evaluation and service life estimation.

In this section, methods, tools and models commonly used for the service life prediction of construction materials are summarised from publicly available literature.

9.1 Service life definition

There are several definitions for service life:

- **ISO 15686 *Buildings and constructed assets – Service life planning*:** This standard defines service life as the period of time after installation in which the buildings or their parts meet or exceed the minimum performance requirements.
- **ASTM:** Its definition is similar to that of ISO 15686. However, it emphasises that, during this period of time, the building and its elements must be subjected to periodic maintenance.
- **CSA S478 *Guideline on durability in buildings*:** It describes service life as the period of time during which buildings or components fulfil the requirements for which they were designed without unexpected costs or maintenance and repair actions.
- **European Organisation for Technical Approvals:** It defines service life as the period of time during which the performance of the product is maintained at a level compatible with the fulfilment of the essential requirements.

In general, the service life of construction materials can be classified into three categories (American Concrete Institute, 2000):

- **Physical or technical service life:** This focuses on the deterioration of construction materials mainly due to the action of the degradation agents and the natural ageing process.
- **Functional service life:** This is directly related to the service level expectations and demands of the users.
- **Economic service life:** This is normally defined as the time elapsing from when the component is used in construction until the instant that it is replaced by a more profitable solution.

A series of criteria developed to evaluate the adequacy of any proposed service life prediction methodologies (Martin, Saunders, Floyd & Wineburg, 1994) are:

- handling large variability in the times to failure for nominally identical specimens
- analysing multivariate data
- separating significant variables from insignificant variables
- fitting both empirical and mechanistic failure models to short-term laboratory-based exposure results

- establishing a connection between short-term laboratory-based and long-term in-service results
- providing mathematical techniques to predict the service life of a system exposed to its intended in-service environment.

Prediction methodologies should also (Bourke & Davies, 1997):

- be easy to learn
- be easy to use
- be quick to use
- be accurate
- be easy to update
- be easy to communicate
- be adaptable
- be supported by data
- link with existing design methods and tools
- be free of excessive bureaucracy
- recognise the importance of innovation
- be relevant to diverse environments
- be acceptable to practitioners and clients alike
- reflect current knowledge
- have a flexible level of sophistication for either outline or detailed planning.

In general, there are two essential parts for the development of service life prediction methodology (Vaz Paulo, Branco & de Brito, 2011):

- **Data collection:** This is to gather information about materials or components and their degradation mechanisms over time. This is achieved mainly through inspection and testing. These usually include either short-term or long-term exposure of building materials or components to degradation agents and then evaluation of the degradation caused by those agents.
- **Data analysis:** This is to process the information collected and to unveil the degradation mechanisms and phenomena. Using this approach, service life can be predicted by using degradation models developed.

9.2 Prediction based on accelerated or short testing

9.2.1 Metal atmospheric corrosion

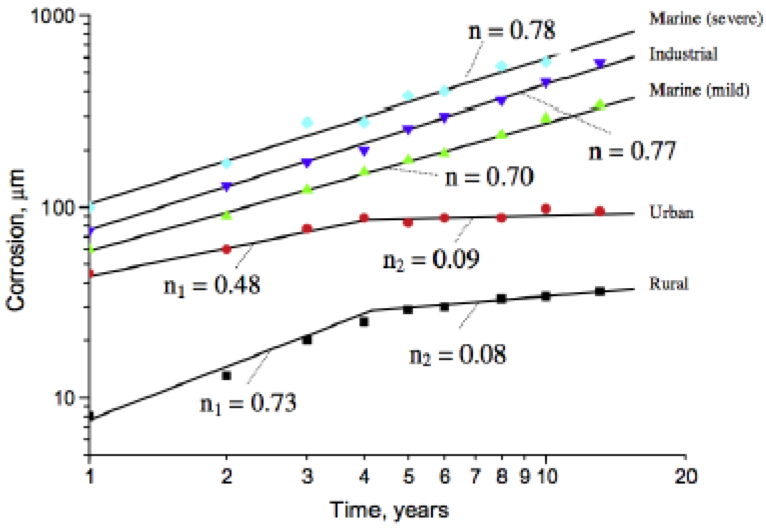
Many research activities have been conducted worldwide to model atmospheric corrosion and establish relationships between metal corrosion rate and environmental parameters (Adikari, Munasinghe & Jayatileke, 2014). One of the most commonly developed is the linear bilogarithmic law (Eq-12).

$$C = kt^n \tag{Eq-12}$$

where

C – corrosion loss
t – exposure time
k – initial corrosion rate, observed during the first year of exposure
n – a measure of the long-term decrease in corrosion rate. It is dependent on the metal, the physical-chemical atmospheric conditions and the exposure conditions.

It has been shown to be applicable for a variety of metals (such as carbon steels, weathering steels and galvanised steels) when exposed to different types of atmospheres (such as rural, marine, industrial and etc) (see Figure 15).



Source: de la Fuente, Diaz, Simancas, Chico & Morcillo, 2011

Figure 15. Corrosion of mild steel versus exposure time for different atmospheric environments.

In Eq-12, *k* is related to meteorological and environmental factors and can be obtained by statistical processing (Mendoza & Corvo, 1999). These factors may include relative humidity (RH), time-of-wetness (ToW), temperature (T) and/or chloride deposition (Cl). A typical description of *k* is as (Simillion, Dolgikh, Terryn & Deconinck, 2014):

$$k = A1 + A2 \times ToW + A3 \times RH + A4 \times Cl + A5 \times T \qquad \text{Eq-13}$$

where the coefficients Ai are fitted constants.

Several dose-response functions have been established to predict the atmospheric corrosion of standard metals such as aluminium, carbon steel, copper and zinc. These functions are based on monitoring results derived from the ISO CORRAG International Atmospheric Exposure Program. They were describing the first-year corrosion rates as a function of the dry deposition of SO_2 and chloride in open air, ambient temperature and relative humidity (Knotkova, Kreislova & Dean, 2010).

Carbon steel

$$r_{corr} = 1.77 \times P_d^{0.52} \times exp(0.020 \times RH + f_{St}) + 0.102 \times S_d^{0.62} \times exp(0.033 \times RH + 0.040 \times T) \qquad \text{Eq-14}$$

$f_{St} = 0.150 \times (T - 10)$ when $T \leq$ 10°C; Otherwise $-0.054 \times (T - 10)$ Eq-15

Zinc

$$r_{corr} = 0.0129 \times P_d^{0.44} \times exp(0.046 \times RH + f_{Zn}) + 0.0175 \times S_d^{0.57} \times exp(0.008 \times RH + 0.085 \times T) \qquad \text{Eq-16}$$

$f_{Zn} = 0.038 \times (T - 10)$ when $T \leq$ 10°C; Otherwise $-0.071 \times (T - 10)$ Eq-17

Copper

$$r_{corr} = 0.0053 \times P_d^{0.26} \times exp(0.059 \times RH + f_{Cu}) + 0.01025 \times S_d^{0.27} \times exp(0.036 \times RH + 0.049 \times T) \quad \text{Eq-18}$$

$f_{Cu} = 0.126 \times (T - 10)$ when $T \leq 10$°C; Otherwise $-0.080 \times (T - 10)$ Eq-19

Aluminium

$$r_{corr} = 0.0042 \times P_d^{0.73} \times exp(0.025 \times RH + f_{Al}) + 0.0018 \times S_d^{0.60} \times exp(0.020 \times RH + 0.094 \times T) \quad \text{Eq-20}$$

$f_{Al} = 0.009 \times (T - 10)$ when $T \leq 10$°C; Otherwise $-0.043 \times (T - 10)$ Eq-21

where

r_{corr} – first-year corrosion rate of metal (μm/a)
T – annual average temperature (°C)
RH – annual average relative humidity (%)
P_d – annual average SO_2 deposition (mg/m^2/d)
S_d – annual average Cl^- deposition (mg/m^2/d).

9.2.2 Polymeric coatings on steel

Wet adhesion is the key factor controlling the lifetime of polymeric coatings under marine hydrostatic pressure. The grey system theory (GST) has been used to study wet adhesion. Grey models (GM) have been established for lifetime predictions of epoxy varnish and epoxy glass flake coatings (Meng, Liu, Liu, Li & Wang, 2017).

$$t = \frac{N}{a} ln \frac{\left[X_{(1)}^{(0)} - \frac{u}{a}\right](1 - e^{a})}{W} + t_1 \quad \text{Eq-22}$$

where

t – theoretical coating service life
W – critical value of wet adhesion
$X^{(0)}{}_{(1)}$ – wet adhesion of a coating/steel system at immersion time 1
a and u – 0.0804 and 7.5778 respectively for epoxy varnish coating/steel system under 0.1 MPa
N – interval of the arithmetic series
t_1 – initial time of the time sequence t.

9.3 Deterministic methods

Service life prediction using deterministic methods normally involves material degradation factors. Based on a good understanding of degradation mechanisms and processes, the material degradation factors can be quantified empirically from ageing tests, real-life assessments or lab tests and then translated into degradation functions. Meanwhile, the degradation condition of a building is characterised at different stages of its service life using a specific classification system for defects and degradation ratings, which are converted into quantitative information. The evolution of degradation is represented graphically by degradation curves that are associated with specific degradation mechanisms (Silva, Gaspar & de Brito, 2014; Silva, de Brito & Gaspar, 2016).

9.3.1 Factor method

Under specific conditions, the factor method allows an estimation of the service life of a particular building component by using a reference service life and a series of modifying factors. The reference service life is, in essence, the expected service life of that type of building components under normal conditions. This method can be demonstrated with the following equation:

$$PSL = RSL \times f_A \times f_B \times f_C \times f_D \times f_E \times f_F \times f_G \qquad \text{Eq-23}$$

where

PSL – the predicted service life
RSL – the reference service life
$f_{A\text{-}G}$ – factors as described in Table 13.

Each factor has a value, whereas the mean is 1.0. ISO 15686-1 assigns values of 0.8, 1 and 1.2 to each factor. Factor values less than 0.8 or greater than 1.2 imply that the chosen reference service life is not suitable and should not be used.

Table 13. ISO 15686 factors.

Agents and factors		**Relevant conditions (Examples)**	
Agent related to inherent quality characteristics	A	Quality of components	Manufacture, storage, transport, materials, protective coatings
	B	Design level	Incorporation, sheltering by rest of structure
	C	Work execution level	Site management, level of workmanship, climatic conditions during execution work
Environment	D	Indoor environment	Aggressiveness of environment, ventilation, condensation
	E	Outdoor environment	Elevation of building, micro-environmental conditions, traffic emissions, weathering factors
Operation conditions	F	In-use conditions	Mechanical impact, category of users, wear and tear
	G	Maintenance level	Quality and frequency of maintenance, accessibility for maintenance

Source: Marteinsson, 2003

To use the factor method, major factors must be determined and assigned with appropriate values. This requires extensive knowledge about the materials concerned and their degradation behaviour and mechanisms. Therefore, it is not easy to be used by people without the right skills and knowledge. It also has other limitations:

- The number and type of factors are not clearly specified and quantified.
- This method does not rank the factors, and all factors have the same weight with respect to degradation and service life estimation.
- The definition of factors is based on the behaviour of the element subjected to a set of conditions, instead of on the influence of individual parameters such as temperature, rainfall and type of use.
- The predicted service life is an absolute value that represents the expectable service life limit and does not provide a reasonable range to guide maintenance or renovation.

The use of default factor values such as 0.8, 1 and 1.2 should not be treated as a standard approach. The actual range of these modifying factors is believed to be dependent on reference service life (Gaspar & de Brito, 2008a; Marteinsson, 2003). Information including the main factors and their normal range, uncertainty and relative importance is needed (Hovde, 2002; Davies & Wyatt, 2004).

A stochastic method has then been used to determine factors through a step-by-step process (Aarseth & Hovde, 1999). This method divides elements into sub-elements, and in this manner, more information is gathered to reduce uncertainty. An example is to divide the environment into indoor and outdoor environments, and the outdoor environment can be further divided into wind-driven rain, ToW, pollutant, air temperature and UV radiation.

Another improvement is treating the factors as probabilistic distributions, and their values are set to the average (50%), the minimum (5%) and the maximum (95%) (Moser, 1999). These probabilistic distributions are combined with the reference service life to calculate the estimated service life of a building material or functional component.

9.3.2 Regression analysis

Regression analysis is widely used in material weathering studies, particularly to establish the correlation between artificial and natural testing results.

Linear regression analysis is commonly used to predict an outcome variable from one or multiple independent variables by a straight line based on the least squares, R^2 (Field, 2009). Multiple linear regression analysis is another regression technique that is capable of modelling a variety of correlations between independent variables and dependent (response) variables (Mata, 2011; Chou & Tsai, 2012). Regression analysis has been applied to predict the service life of building materials (Chai, de Brito, Gaspar & Silva, 2015).

9.4 Stochastic (probabilistic) methods

When considering the uncertainties associated with building material degradation, the degradation process is stochastic in nature and can be described by a series of variables. The most popular stochastic methods are the Markov chain model and logistic regression (Cecconi, 2002; Silva, de Brito & Gaspar, 2016).

9.4.1 Markov chain model

Markov chains can be treated as a series of transitions between given states and have two common types (Morcous & Lounis, 2005):

- **Discrete chains:** This is dealing with those transitions that only occur at specific instants.
- **Continuous chains:** This is dealing with those transitions that occur at any time.

Correspondingly, the uncertainty in the rate of transitions between the states is defined by a probability matrix for discrete-time processes and by an intensity matrix for continuous-time processes.

Markov chain models can be used to predict the future state of stochastic processes based on the present condition (Neves, Frangopol & Cruz, 2006; Cruz, 2013).

When developing a discrete Markov chain model, the performance of a building material or component is represented by a number of discrete condition/state ratings based on its current condition. Its degradation is then defined as a transition process through different conditions. The number of discrete conditions can be varied. However, the total number should be large enough to accommodate representative conditions and small enough to make the method easy to use and odd.

Practically, the model has two key components – initial state probabilities and transition probabilities. These are usually expressed in matrix form. The initial state probability matrix (denoted P) is a matrix that has one row and m number of columns, where m represents the different potential states of a particular process. The transition probability matrix is an $m \times m$ matrix where each column contains the probabilities of staying in a particular state if currently in the m^{th} row state. A transition probability matrix with no recurrent states has every probability left of the diagonal to be zero. This is because once the random variable has reached the next state, it cannot go back to the previous one. Once the initial conditions and transitional probabilities are defined, the future state of a particular random variable can be predicted.

When developing a continuous Markov chain model, an intensity matrix (denoted Q) is established. Based on the transition rates, the probability of transition between states of condition and the mean probability of permanence in these states can be calculated using a Chapman-Kolmogorov differential equation.

The estimation of the intensity matrix can be achieved by various methods. Optimisation procedures are generally believed to be consistent and accurate, ensuring the efficiency of the degradation model. The optimisation is based on the concept of maximum likelihood, which is defined as the predicted probability of occurrence of the observed transitions.

The advantages of Markov chain model are summarised as (Uchwat & MacLeod, 2012):

- capability of developing a prediction model with a limited amount of data
- capability of predicting performance even if data is not complete
- capability of assessing data with stochastic tools including Bayesian processes
- avoiding tedious regression techniques in the presence of a multitude of tributary factors
- avoiding the "survival of the fittest phenomenon".

9.4.2 Logistic regression

Logistic regression can be used to describe the relationship between one or more independent variables and a dependent variable where the outcome is discrete in nature. The dichotomous probability of outcomes is measured by 0 or 1, representing failure and success respectively. A logistic regression model estimates the odds of an occurrence for an event, which is the ratio of the probability of occurrence to the probability of non-occurrence. The natural logarithm of the odds follows a linear model constructed from the independent variables.

$$Ln\left(\frac{p}{1-p}\right) = C_0 + C_1X_1 \qquad \text{Eq-24}$$

or

$$P = \frac{1}{1 + e^{-(C_0 + C_1 X_1)}} \qquad \text{Eq-25}$$

where

p – probability of occurrence
C_0 – a constant
C_1 – a coefficient estimated from the data
X_1 – independent variable.

In this form, the probability of occurrence ranges from 0 to 1 as the natural logarithm of the odds ranges from -∞ to +∞.

Logistic regression has been applied in construction research such as for predicting the economic failure of equipment (Lowe & Parvar, 2004; Hildreth & Dewitt, 2016).

9.5 Computational methods

9.5.1 Artificial neural networks

The fundamental processing elements within the artificial neural networks (ANNs) are neurons (Grossi & Buscema, 2007). Meanwhile, networks, a parallel distributed information processing technique, are arranged in layers. The first layer takes inputs and the last layer produces outputs. The middle layers are hidden layers.

In a typical process, a neuron receives inputs through its synapses, combines them, executes an operation and provides outputs. Typically, the output of a neuron feeds into several synapses, each of which establishes a connection with another neuron within the network.

A typical ANN operation starts with training that modifies the connection weights using a suitable learning method. When single or multiple inputs are imported into the input layer, they are multiplied by weighting factors and then the product is summed. The summation is passed through an activation sigmoid function. The algorithm updates the network weights in such a way that the sum squared error in the network's result is minimised.

Multilayer perceptron (MLP) is the most common type of ANN. It is a fully connected feed-forward network with three or more neuron layers. Each neuron in each layer is linked to all neurons in the next layer and to no others within the network.

MLP learns through patterns of behaviour. Its training is an iterative process. The errors associated with the differences between the actual outputs and the target values are determined and used to improve the network's performance by adjusting its weighting values. Once training is completed, the network is tested using a new set of patterns to evaluate its performance.

ANN models are capable of learning and adapting to new situations. They do not require a knowledge of the processes involved. They are being applied to the analysis of the service life of building components and materials (Freitag, Beer, Graf & Kaliske, 2009; Song & Kwon, 2009; Huang, 2010).

9.5.2 Fuzzy logic

Fuzzy logic encodes and applies human knowledge in a form that reflects an expert's understanding of difficult and complex problems (Negnevitsky, 2002). Fuzzy logic modelling follows three steps: structure identification, parameter estimation and model validation. The fuzzy logic system accepts and passes inputs into a process called fuzzification. In this process, input quantities are translated into linguistic quantities such as low, medium and high. The translated data is then sent to an interference mechanism that applies the predefined rules to generate outputs in linguistic form. The linguistic outputs will go through a defuzzification process to be in numerical form (Gokulachandran & Mohandas, 2012).

Fuzzy logic models can be placed intermediately between numerical and symbolic models. They can be treated as grey boxes and transparent models. Fuzzy logic models usually have better performance and accuracy than classical linear models. The most important advantages of fuzzy logic modelling for service life prediction in building and construction are summarised as (Silva, Vieira, de Brito & Gaspar, 2016):

- high flexibility
- good tolerance to inaccurate data
- capable of modelling systems that are naturally vague and difficult to describe by other models
- can be developed based on the experience of experts
- information based on human observation can be used
- capable of modelling complex non-linear functions
- capable of simplifying and expanding the scope and capability of conventional monitoring methods.

9.6 Engineering design methods

Engineering design methods are a symbiosis between the deterministic and stochastic methods and allow the description of degradation process in a stochastic way. Usually, they are implemented using probabilistic data, leading to deterministic equations.

9.6.1 Failure modes and effects analysis method

Failure modes and effects analysis (FMEA), a risk analysis method, was initially developed to ensure adequate levels of systems reliability and maintainability during the production phase of the aerospace industry. It has been finding applications in the construction sector, particularly for the certification of construction products (Lacasse & Sjostrom, 2004). It typically consists of definition of potential degradation modes, the causes and the consequences for each function/component pair.

The multi-model FMEA approach for the durability evaluation of building materials includes three basic items (Lair, Le Teno & Boissier, 1999):

- FMEA that produces a comprehensive list of degradations, degradation chainings and failure modes (Talon, Boissier, Chevalier & Hans, 2005)
- data compilation
- service life and belief degree assessment using evidence theory.

9.6.2 Performance limits method

The performance limits method evaluates the durability and service life of building materials and components by simulating their performance over time. This is carried out until their physical or performance limit has been reached. The degradation process is evaluated by a chain of events: agents, actions, effects and deterioration. The method typically consists of four components (Daniotti & Lupica Spagnolo, 2007):

- Definition of performance targets.
- Individuation of requirements and specification of performances that the component must supply.
- Translation of performance specifications into technical specifications of functional characteristics and individuation of performance thresholds for service life.
- Evaluation of service life.

The input data for modelling is based on the decay of functional characteristics measured through ageing tests. The component behaviour over time is measured with respect to the decay of their functional characteristics and degradation phenomena.

9.7 Case study

In this section, the application of a number of methods for the service life prediction of building claddings and façades is given and discussed.

9.7.1 Factor method

The service life of ceramic external claddings has been evaluated using the factor method (Galbusera, de Brito & Silva, 2014). This evaluation used the data from a field survey of 195 façades. The reference service life, 51 years, was deduced from statistical data associated with degradation curve and service life distribution over time. The factors affecting façade durability were identified and quantified to optimise the weighting coefficients in different scenarios (see Table 14).

Table 14. Quantification of factors in different scenarios.

Factor	Sub-factor	Scenario					
		1	2	3	4	5	6
A1: Surface	Glazed	1.00	0.95	1.00	1.00	1.00	1.05
	Unglazed	0.85	1.00	1.00	0.80	0.90	0.85
A2: Colour	Light	0.95	0.90	1.00	1.00	1.00	1.00
	Dark	0.95	1.15	1.00	1.00	1.00	1.00
	White	1.00	1.00	1.00	1.00	1.00	1.025
A3: Tile dimension	L<20	1.00	1.00	1.00	1.00	1.00	1.00
	L≥20	0.90	0.75	1.00	0.80	0.90	0.80
B1: Substrate	Masonry	0.85	0.90	1.00	1.00	1.00	1.00
	Concrete	1.20	1.05	1.00	1.00	1.00	1.00
B2: Peripheral joints	Yes	0.75	1.10	1.00	1.00	1.00	1.025
	No	1.05	0.90	1.00	1.00	1.00	1.00
B3: Peripheral protection	Yes	0.95	1.00	1.00	1.00	1.00	1.00
	No	1.05	0.95	1.00	1.00	1.00	1.00
C1: Level of execution	Adequate	1.00	1.00	1.00	1.00	1.00	1.00
	Inadequate	0.50	-0.35	1.00	0.80	0.90	0.50
E1: Façade orientation	North	0.90	0.95	1.00	1.00	0.90	0.95
	East	1.00	1.15	1.00	1.00	1.00	1.00

Factor	Sub-factor	Scenario					
		1	2	3	4	5	6
	South	1.00	0.80	1.00	1.00	1.00	1.05
	West	1.15	1.05	1.00	1.00	1.00	1.05
E2: Wind/rain	Mild	1.20	1.10	1.00	1.20	1.10	1.125
	Average	0.95	1.00	1.00	1.00	1.00	1.00
	Severe	0.90	0.90	1.00	1.00	1.00	0.975
E3: Distance from the sea	<1 km	0.75	0.85	1.00	1.00	1.00	0.925
	>1 km and <5 km	0.95	1.05	1.00	1.00	1.00	0.95
	>5 km	1.20	1.10	1.00	1.20	1.10	1.05
E4: Humidity	High	0.75	0.85	1.00	0.80	0.90	0.90
	Low	1.15	1.10	1.00	1.00	1.10	1.05
G1: Regular maintenance	Yes	1.60	1.15	1.00	1.20	1.10	1.35
	No	0.85	0.95	1.00	1.00	1.00	1.00
G2: Ease of inspection	Current	0.95	0.95	1.00	1.00	1.00	1.00
	Unfavourable	0.90	1.00	1.00	1.00	1.00	0.95

Source: Galbusera, de Brito & Silva, 2014

The service life of ceramic external wall claddings was predicted using Eq-26:

$$PSL = RSL \times A_1 \times A_2 \times A_3 \times B_1 \times B_2 \times B_3 \times C_1 \times E_1 \times E_2 \times E_3 \times E_4 \times G_1 \times G_2 \qquad \text{Eq-26}$$

An improved factor method (where factors are treated as probabilistic distributions) was used to estimate the service life of buildings located in harsh atmospheric environments (El-Dash, 2011).

Table 15. Quantitative classification of modification factors.

Factor	Coastal region			Near coast region		
	Low (5%)	Most likely (50%)	High (95%)	Low (5%)	Most likely (50%)	High (95%)
A	0.40	0.70	0.90	0.70	0.85	1.00
B	1.00	1.00	1.00	1.00	1.00	1.00
C	0.90	1.00	1.10	1.00	1.10	1.00
D	0.90	1.00	1.05	0.90	1.00	1.05
E	0.50	0.70	0.90	0.80	0.95	1.00
F	0.90	1.00	1.05	0.90	1.00	1.05
G	0.80	0.90	1.00	0.80	0.90	1.00
Overall factor	0.44			0.73		

Source: El-Dash, 2011

The low, most likely and high factor values were deduced from discussions with experts on performance and testing. The most likely value, corresponding to the traditional deterministic value, was expected to have a 50% confidence level. Meanwhile, the low and high values had a probability confidence level of 5% and 95% respectively (see Table 15).

The mean value of each factor was predicted using Eq-27 (Moser, 2004):

$$Mean = \frac{Low + 2.95 \times Most\ Likely + High}{4.95} \qquad \text{Eq-27}$$

The reference service life was 30 years. The result showed that buildings in coastal regions had a 95% probability of surviving >3 years and a 5% chance of surviving >23 years with a mean of 13 years. Buildings in near coastal regions had a 95% probability of surviving >15 years and a 5% chance of surviving >29 years with a mean of 22 years.

9.7.2 Regression analysis

Regression analysis has been used to estimate the service life of painted building surfaces (Silva, Gaspar & de Brito, 2015). This study used the so-called degradation curve, which represents the continuous process of deterioration of painted surfaces over time.

A quantitative degradation index, S_w, was used to describe the global performance of construction elements (Gaspar & de Brito, 2008b; Gaspar & de Brito, 2011; Silva, Dias, Gaspar & de Brito, 2013). S_w was defined as the ratio between the extent of the façade degradation, weighted as a function of the degradation level, the severity of the anomalies and the reference area.

$$S_w = \frac{\sum(A_n \times k_n \times k_{a,n})}{A \times k} \qquad \text{Eq-28}$$

where

S_w – normalised severity of degradation of façade (%)
A_n – area of coating affected by an anomaly (m^2)
k_n – anomaly's "n" multiplying factor, as a function of its condition (between 0 and 4)
$k_{a,n}$ – weighting coefficient corresponding to the relative importance of each anomaly ($k_{a,n}$ R^+) (if no instructions are provided, it is assumed $k_{a,n} = 1$)
k – weighting factor equal to the highest degradation level in the façade
A – total area of the cladding (m^2).

Table 16 shows how to define weighting factors for anomalies detected on concrete façades. These weighting factors were defined mainly according to their repair costs and to their propensity to cause other anomalies.

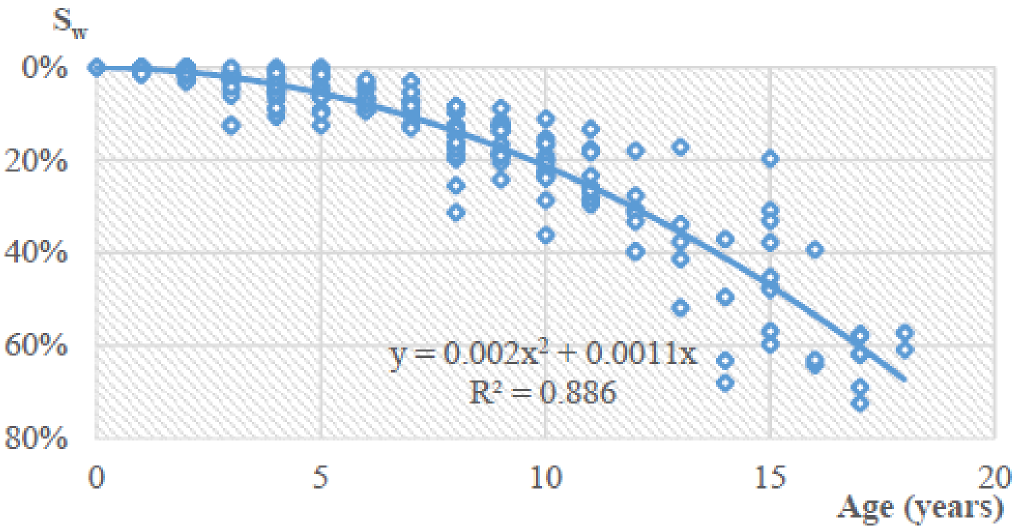
Data collected from field inspections of 220 painted building façades was used to establish degradation curves. Figure 16 shows a polynomial regression curve that represents the average sample degradation path. A maximum degradation level of 20% was used to define the service life of the painted building surface. The service life was then estimated to approximately 9.75 years.

This method has been used to predict the service life of architectural concrete façades based on visual inspection of 174 concrete buildings (Serralheiro, de Brito & Silva, 2017).

Table 16. Weighting factors according to the type of anomalies on concrete façades.

Aesthetical anomaly							
Dirt stain	Moisture stain	Corrosion stain	Efflorescence	Biological growth	Wear/Erosion	Bug hole	Graffiti
0.15	0.15	0.50	0.20	0.60	2.00	0.10	0
Mechanical anomaly							
Mapped cracking		Oriented cracking		Disaggregation		Spalling	
0.15		1.00		5.00		4.00	
Constructive anomaly							
Flatness defect	Honeycombing	Fastening mark		Dribbling	Crusts	Formwork incrustation	
0.10	0.30	0.10		0.10	0.10	0.10	

Source: Serralheiro, de Brito & Silva, 2017

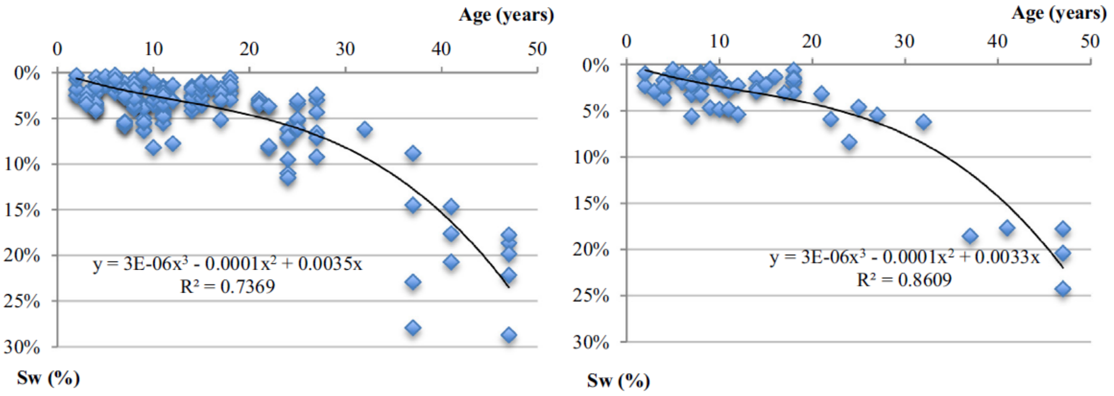


Source: Silva, Gaspar & de Brito, 2015

Figure 16. Average degradation curves obtained from 220 building degradation cases analysed.

With a maximum acceptable level of severity of degradation (S_w = 20%), the architectural concrete façades' service life was approximately 44 years (see Figure 17).

NP EN 1992-1 *Design of concrete structures; Part 1-1: General rules and rules for buildings* refers a design service life of 50 years for concrete structures. AS 3600 *Concrete structures* also states that concrete in maritime environments has an expected service life of 40–60 years. Other studies have shown that precast concrete wall systems and precast concrete slabs, when used as the building envelope, were expected to have a service life similar to the building, i.e. 50 years (Takahashi, Sekine, Horiike, Matsuoka & Hoshiro, 2008; Van Straaten, Straube & Alex Lukachko, 2016). It is reasonable to assume that the service life of structural concrete is approximately 50 years (Pakkala, Köliö, Lahdensivu & Kiviste, 2014). Meanwhile, the expected service life of architectural concrete can be slightly shorter than 50 years. Therefore, 44 years, as derived from this study, is acceptable for architectural concrete building surfaces.



Source: Serralheiro, de Brito & Silva, 2017

Figure 17. Degradation curve obtained: (left) from the 174 cases analysed in the fieldwork and (right) from the average degradation of the buildings analysed.

Multiple linear regression has been used to analyse the degradation of rendered façades (Silva, Dias, Gaspar & de Brito, 2013). The database composed of 100 sample rendered façades. The MLR analysis included a number of predictors that were related to the characteristics of the rendered façades (see Table 17).

Table 17. Independent variables analysed.

Render characteristics	**Independent variables**			
Render type	Cement and lime mortar	Monomass	Cementitious mortar	Marble agglomerate mortar
	0.90	1.25	1.18	1.38
Façade colour	White	Light colours	Dark colours	
	0.88	0.96	1.13	
Building height	≤9 m	>9 m, ≤14 m	≥14 m	
	0.96	1.02	1.11	
Building volume	Compact	Irregular		
	0.91	1.17		
Detailing/design level	Poor	Current	Good	
	1.02	0.99	1.41	
Eave protection	N	S		
	0.88	1.07		
Ground floor protection	N	S		
	0.99	1.00		
Platband copings	N	S		

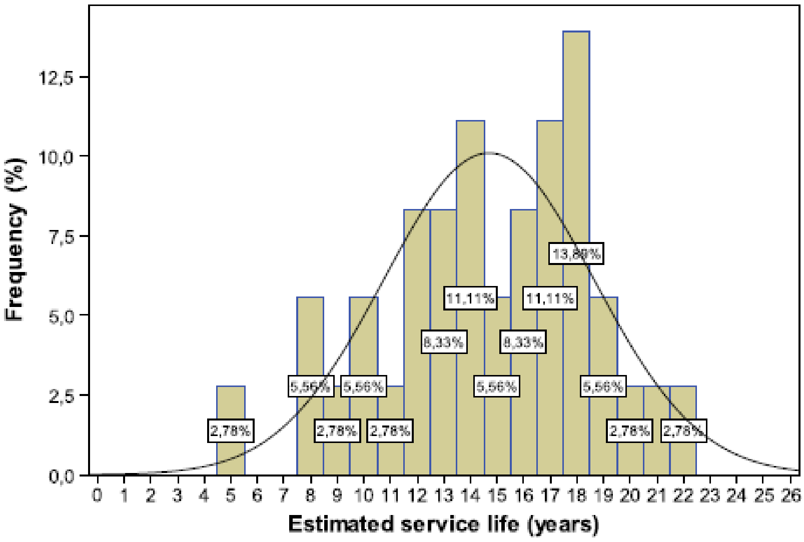
Render characteristics	Independent variables			
	0.92	1.14		
Balcony copings	N	S		
	0.94	1.31		
Façade orientation	NW/West	SW/South	SE/East	NE/North
	0.99	1.25	1.05	0.90
Distance from the sea	≤3.5 km	>3.5 km		
	0.95	1.02		
Exposure to damp	Unfavourable	Normal	Favourable	
	0.71	0.99	1.15	
Distance from pollution source	Unfavourable	Normal	Favourable	
	1.01	0.99	1.14	
Façade protection level	Poor	Average	Good	
	0.92	1.06	1.13	

Source: Silva, Dias, Gaspar & de Brito, 2013

A stepwise method was used to build the regression model, which only includes the statistically important predictors. The predictors of the dependent variables were introduced into the model in descending order of relevance. Of all the predictors initially selected, only four – render age, exposure to damp, render type and façade protection level – were finally included in the model.

The degradation severity, S_w, was described as a function of these four predictors.

$$S_{w,MLR} = 0.014 \times Render\ age - 0.132 \times Exposure\ to\ damp - 0.25 \times Render\ type - 0.239 \times Facade\ protection\ level + 0.662 \quad \text{Eq-29}$$



Source: Silva, Dias, Gaspar & de Brito, 2013

Figure 18. Histogram of the estimated service life using a MLR model.

Figure 18 shows the histogram of the estimated service life for the rendered façades determined using the MLR model. The average estimated service life was approximately 14.69 ± 3.95 years.

Logistic regression has also been used to predict the probability of timber claddings reaching the end of their service life over time (Silva & Prieto, 2020).

The degradation condition of 150 timber claddings has been evaluated through field survey. The severity of degradation was expressed as S_w, as shown in Eq-28.

The types of anomalies detected were classified according to five degradation levels (see Table 18).

Table 18. Degradation levels adopted for timber claddings.

Degradation level	Anomalies group	Anomalies description
Level A Very good $S_w \leq 1\%$		No visible degradation
Level B Good $1\% < S_w \leq 10\%$	Aesthetic	Staining or colour change (dirty surface)
		Wearing or detachment of the finishing layer
	Loss of integrity	Warping, swelling or other flatness deficiencies
Level C Slight degradation $10\% < S_w \leq 20\%$	Aesthetic	Staining or colour change (dirty surface)
		Wearing or detachment of the finishing layer
	Loss of integrity	Warping, swelling or other flatness deficiencies
		Cracking of elements and/or joints (possibly from substrate cracking)
		Moisture (Oxyde)/Biocostra
		Delamination
		Crumbling
Level D Moderate degradation $20\% < S_w \leq 40\%$	Aesthetic	Wearing or detachment of the finishing layer
	Loss of integrity	Warping, swelling or other flatness deficiencies
		Cracking of elements and/or joints (possibly from substrate cracking)
		Broken or splintered elements
		Detachment of elements from substrate (lack of adherence)
		Moisture (Oxyde)/Biocostra
		Rot
		Xylophage attack
		Delamination
		Crumbling
Level E	Loss of integrity	Broken or splintered elements

Degradation level	Anomalies group	Anomalies description
Severe degradation S_w >40%		Detachment of elements from substrate (lack of adherence)
		Rot
		Xylophage attack
		Delamination
		Crumbling

Source: Silva & Prieto, 2020.

In this study, the dependent variable corresponds to the question of whether the timber cladding reached the end of its service life, which has two mutually exclusive classes: "yes" and "no".

It is further assumed that a timber cladding reaches the end of its service life when it has a severity of degradation (S_w) of 20%.

The model proposed as Eq-30 was used to evaluate the probability of a timber cladding reaching the end of its service life according to its age.

$$P(Y = \text{End of service life}) = 1 - \frac{1}{1+e^{-18.200+0.539Age}} \qquad \text{Eq-30}$$

Case studies showed that the proposed model had a good classification capability – approximately 97.3% of the timber claddings were correctly classified.

Meanwhile, the influence of environmental exposure conditions on service life was studied (see Table 19) by introducing specific environmental variables into Eq-30.

Table 19. Probability of timber claddings reaching the end of their service life according to environmental exposure conditions.

Environmental exposure conditions		Age where a timber cladding reaches the end of its service life with a probability of:			
		50%	75%	90%	95%
Exposure to damp	High	32.8	34.6	36.4	37.5
	Medium	34.7	36.4	38.2	39.4
Façade orientation	N	32.6	34.3	36.1	37.2
	S	33.7	35.5	37.2	38.4
	W	34.4	36.5	38.3	39.4
	E	36.2	38.0	39.7	40.9
Exposure to wind-rain action	Unfavourable	33.2	35.3	37.4	38.8
	Current	34.5	36.6	38.7	40.1
Distance from the sea	<5 km	31.7	33.5	35.5	36.5
	>5 km	34.6	36.4	38.2	39.3

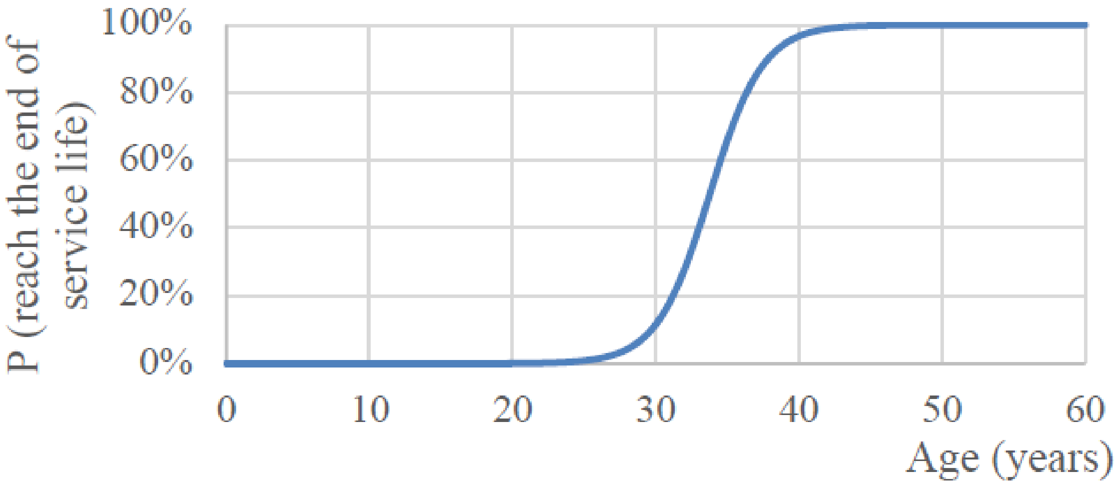
Source: Silva & Prieto, 2020.

These typically included:

- exposure to damp
- façade orientation
- wind-rain action
- exposure to sea salts.

Accordingly, the 150 timber claddings have a probability of having reached the end of its service life (see Figure 19):

- higher than 50% after 33.8 years
- higher than 75% after 35.8 years
- higher than 90% after 37.9 years.



Source: Silva & Prieto, 2020

Figure 19. Distribution of probability of timber claddings reaching the end of their service life over time.

9.7.3 Markov chain model

Continuous-time Markov chain models have been used to predict rendered façade deterioration.

The degradation condition of 100 rendered façades was characterised and classified, as shown in Table 20 (Silva, Neves, Gaspar & de Brito, 2016).

In this study, only the initial and final conditions (corresponding to the inspection date) were known. The optimised intensity matrix (Q) is shown below:

$$Q = \begin{bmatrix} q_{0,1} \\ q_{1,2} \\ q_{2,3} \\ q_{3,1} \end{bmatrix} = \begin{bmatrix} 0.4016 \\ 0.2819 \\ 0.0994 \\ 0.0761 \end{bmatrix} \quad \text{Eq-31}$$

The mean time of permanence in each degradation state, T_i, could be determined as Eq-32.

$$T_i = \frac{1}{q_{ij}} \quad \text{Eq-32}$$

The transitions between condition states occur faster for façades in better conditions. For example, the transition from level A to level B occurs after approximately 2.5 years.

The condition remains for a longer time period at higher degradation levels (levels C and D). The probabilistic distribution of the degradation condition shows that transition times are exponentially distributed (see Table 21).

Table 20. Proposed classification of degradation condition of render façade.

Condition	Physical and visual assessment	Severity of degradation (%)
Level A	Complete mortar surface with no deterioration. Surface even and uniform. No visible cracking or cracking ≤ 0.1 mm. Uniform colour and no dirt. No detachment of elements.	<1
Level B	Non-uniform mortar surface with likelihood of hollow localised areas determined by percussion, but no signs of detachment. Small cracking (0.25–1.0 mm) in localised areas. Change in the general colour of the surface. Eventual presence of microorganisms.	1–5
Level C	Localised detachments or perforations of the mortar. Hollow sound when tapped. Detachments only in the socle. Easily visible cracking (1.0–2.0 mm). Dark patches of damp and dirt, often with microorganisms and algae.	5–15
Level D	Incomplete mortar surface due to detachments and falling of mortar patches. Wide or extensive cracking (≥2 mm). Very dark patches with probable presence of algae.	15–30
Level E	Incomplete mortar surface due to detachments and falling of mortar patches. Wide or extensive cracking (≥2 mm). Very dark patches with probable presence of algae.	>30

Table 21. Probability of belonging to a condition level as a function of age.

Range (years)	Probability of belonging to a condition level (%)				
	Level A	Level B	Level C	Level D	Level E
[0:5]	45.87	31.82	19.14	2.91	0.28
[5:10]	4.70	22.26	49.57	19.07	4.40
[10:15]	0.63	7.17	44.57	33.06	14.56
[15:20]	0.08	1.99	31.41	38.14	28.38
[20:25]	0.01	0.52	20.26	36.48	42.73
[25:30]	0.00	0.13	12.62	31.52	55.72
[30:35]	0.00	0.03	7.75	25.61	66.60
[35:40]	0.00	0.01	4.74	20.00	75.25

Source: Silva, Neves, Gaspar & de Brito, 2016

Table 22 shows the maximum probability of belonging to degradation level D, the end of service life. These samples reach the maximum probability of 38.5% after 19 years. The probability at level D or E reaches 50% after approximately 14 years.

In coastal areas, this probability is reached after 10 years, while in inland areas, it takes approximately 23 years. Façades with severe exposure to damp reach the probability of 50% of belonging to level D or E after 10 years. This probability is reached after 17 and 11 years for façades with low and moderate exposure to damp, respectively.

Table 22. Analysis of the maximum probability of belonging to degradation level D (end of service life).

		Maximum probability of belonging to degradation level D (%)	**Age at which it reaches the maximum probability of belonging to degradation level D (years)**
	Overall sample	38.47	19
Distance from the sea (km)	>3.5	5.38	16
	≤3.5	46.85	16
Exposure to damp	Low	27.34	19
	Moderate	47.12	17
	Severe	62.83	22
Protection level of the façade	Poor	41.64	20
	Current	44.72	18
	Good	27.90	17
Exposure to pollutants	Unfavourable	52.04	18
	Normal	32.36	18
	Favourable	-	-

Source: Silva, Neves, Gaspar & de Brito, 2016

Façades with good protection reach the probability of 50% of being at degradation level D or E after 15 years. Façades with poor protection reach this probability after 14 years. This result seems to be different from normal expectation. It was supposed that the protection level has influences, direct and indirect, on environmental agents which may affect façade degradation.

Overall, this Markov chains model revealed that these rendered façades have a service life of approximately 15–16 years.

9.7.4 Artificial neural networks

Artificial neural network (ANN) with a back-propagation learning algorithm has been used to predict the service life of steel building components (Usman & Resdiansyah, 2008).

The variables fed into this model include (see Table 23):

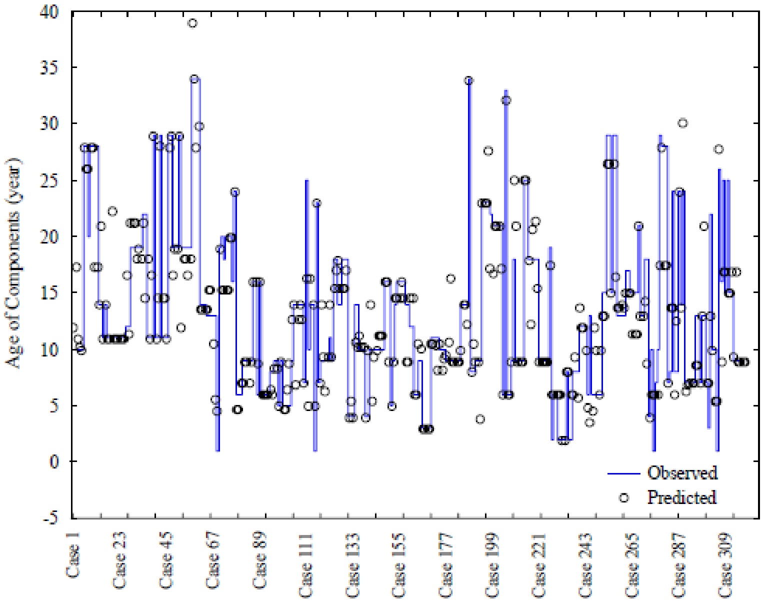
- building service load such as exposure, design, work quality, usage and maintenance
- building component performance rate
- environmental SO_2 level
- H^+ level
- time-of-wetness (ToW)
- zone where the assessed building is located.

The neural network model architecture used in this study had two hidden layers and one output layer. During the training process, this ANN model showed good correlation between the modelling output and the training target. Figure 20 shows the comparison between the observed data and the predicted value from the ANN model. The model was able to predict building component performance by relating the complexity of a large number of different parameters.

Table 23. Summary of variables for service life prediction of steel building components.

Variable	Minimum	Maximum	Variable	Minimum	Maximum
Age	1	44	Rating	1	4
Exposure	1	3	SO_2	2.17	57.44
Design	1	3	H^+	6.13	41.77
Work quality	1	3	ToW	0.707	0.890
Usage	1	3	Zone	1	6
Maintenance	1	3	Valid N	708	

Source: Usman & Resdiansyah, 2008



Source: Usman & Resdiansyah, 2008

Figure 20. Observed and predicted plot from neural network model result.

Multilayer perceptron (MLP) has been used to develop models to estimate the degradation severity of rendered façades based on approximately 100 field case studies (Silva, Dias, Gaspar & de Brito, 2013). MLP with one intermediate layer was considered, i.e. N-H-1 architectures. N is the number of cells in the input layer and H is the number of cells in the intermediate layer. Two ANN models were established.

In the first model, a 16-8-1 architecture was used. The 16 entries were grouped into four distinct sets of:

- building height (tall, current, short)

- façade orientation (north, south, east, west, northeast, northwest, southeast and southwest)
- render age
- render type (marble agglomerate, monomass, cement and lime mortar and cementitious mortar).

The output was degradation severity (S_w) that is correlated with the input variables according to the following equations.

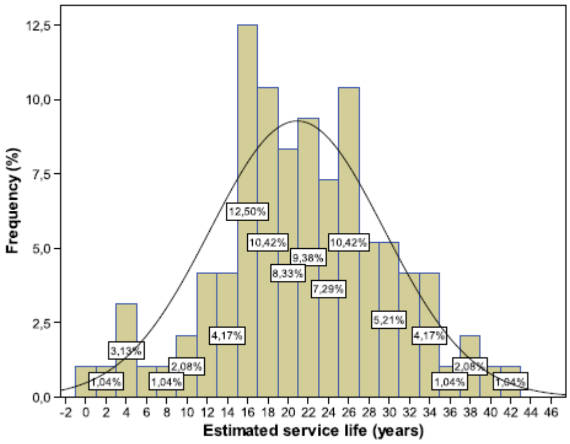
$$S_w = h_0 + \sum_{i=1}^{8} h_i H_i \qquad \text{Eq-33}$$

$$H_i = tanh(c_{i0} + \sum_{n=1}^{16} c_{in} V_n) \qquad \text{Eq-34}$$

where

V_1 – render age
V_2 – marble agglomerate
V_3 – monomass
V_4 – cement and lime mortar
V_5 – cementitious mortar
V_6 – a tall building
V_7 – a current building
V_8 – a short building
V_9 – a façade facing northwest
V_{10} – a façade facing south
V_{11} – a façade facing northeast
V_{12} – a façade facing southeast
V_{13} – a façade facing southwest
V_{14} – a façade facing north
V_{15} – a façade facing east
V_{16} – a façade facing west
h_0 to h_8 and c_{i0} to c_{i16} are coefficients.

Figure 21 shows the histogram of the service life estimated by this ANN model. The average service life is 20.91 ± 8.60 years.



Source: Silva, Dias, Gaspar & de Brito, 2013

Figure 21. Histogram of the estimated service life using the first model with a 16-8-1 architecture.

In the second model, an 11-4-1 architecture was developed with 11 entries of:

- age of the render
- type of render (marble agglomerate, monomass, cement and lime mortar and cementitious mortar)
- exposure to damp (favourable, normal, unfavourable)
- façade protection level (poor, average, good).

The output is also the degradation severity, as seen in Eq-35.

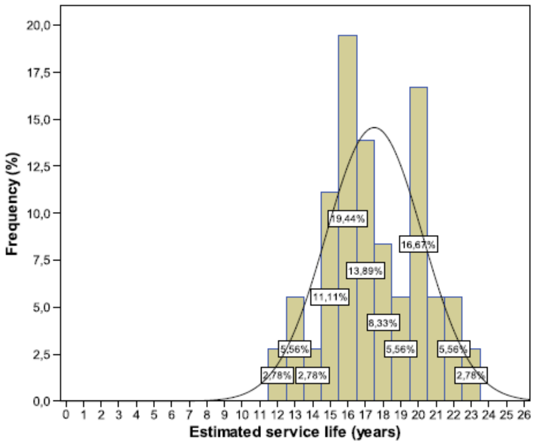
$$S_w = h_0 + \sum_{i=1}^{4} h_i\, H_i \qquad \text{Eq-35}$$

$$H_i = tanh\left(c_{i0} + \sum_{n=1}^{11} c_{in}\, V_n\right) \qquad \text{Eq-36}$$

where

V_1 – age of the render
V_2 – marble agglomerate
V_3 –monomass
V_4 – cement and lime mortar
V_5 – cementitious mortar
V_6 – a favourable exposure
V_7 – an unfavourable exposure
V_8 – a normal exposure
V_9 – a poor façade protection
V_{10} – a good façade protection
V_{11} – an average façade protection
h_0 to h_4 and c_{i0} a c_{i11} are coefficients.

Figure 22 shows the histogram of the service life estimated by this second model. The average service life is predicted to be 17.50 ± 2.74 years.



Source: Silva, Dias, Gaspar & de Brito, 2013

Figure 22. Histogram of the estimated service life using the second model with a 11-4-1 architecture.

The modelling results indicated that, when subjected to the same conditions, façades with bad exposure to damp have a shorter service life than those with less exposure. This is consistent with the findings from field observations.

9.7.5 Fuzzy logic model

The Takagi-Sugeno fuzzy model has been used for service life prediction of natural stone claddings (Silva, Vieira, de Brito & Gaspar, 2016). This model uses discriminant, precise functions as consequent variables, which are produced from the application of logic rules. Each function consists of the following rule:

Rule R_i

If x_1 is A_{i1} and … and x_n is A_{in}

then $y_i(x) = f_i(x)$, i = 1, 2, …, C Eq-37

where

f_i – consequent function for rule Ri
C – number of rules.

The activation degree of the i^{th} rule is given by:

$$\beta_i = \prod_{j=1}^{n} \mu_{A_{ij}}(x)$$ Eq-38

where $\mu_{A_{ij}}(x): R \rightarrow [0,1]$ is the membership function of the fuzzy set A_{ij}.

The model output, S_w (degradation severity), is calculated by:

$$S_w = \frac{\sum_{i=1}^{C} \beta_i \, f_i(x)}{\sum_{i=1}^{C} \beta_i}$$ Eq-39

Two models were proposed with the variables determined from field inspections with 140 and 203 façades:

- Type of stone finish (u_1) – smooth, value = -1; and rough, value = 1.
- Distance from the sea (u_2) – less than 5 km, value = 1; and more than 5 km, value = -1.
- Size/area of stone plates (u_3).
- Coating age (u_4) – the time period between the last major repair of the façade and the inspection date.

The fuzzy rules describing the input-output relation of model 1 are given as below:

Rule 1:

If u_1 is A_{11} and u_2 is A_{12} and u_3 is A_{13} and u_4 is A_{14}

then $y_1(k) = 4.35 \times 10^{-6} u_1 + 2.95 \times 10^{-3} u_2 - 5.63 \times 10^{-2} u_3 + 1.40 \times 10^{-3} u_4 + 2.76 \times 10^{-2}$ Eq-40

Rule 2:

If u_1 is A_{21} and u_2 is A_{22} and u_3 is A_{23} and u_4 is A_{24}

then $y_2(k) = 1.51 \times 10^{-2}u_1 + 1.16 \times 10^{-2}u_2 + 1.06 \times 10^{-1}u_3 + 5.07 \times 10^{-3}u_4 - 1.87 \times 10^{-1}$ Eq-41

The fuzzy rules describing the input-output relation of model-2 are given as below.

Rule 1:

If u_1 is A_{11} and u_2 is A_{12} and u_3 is A_{13} and u_4 is A_{14}

then $y_1(k) = 4.25 \times 10^{-4}u_1 + 6.00 \times 10^{-4}u_2 - 2.78 \times 10^{-2}u_3 + 1.38 \times 10^{-3}u_4 + 1.56 \times 10^{-2}$ Eq-42

Rule 2:

If u_1 is A_{21} and u_2 is A_{22} and u_3 is A_{23} and u_4 is A_{24}

then $y_2(k) = 1.04 \times 10^{-2}u_1 + 1.29 \times 10^{-2}u_2 + 1.09 \times 10^{-1}u_3 + 5.24 \times 10^{-3}u_4 - 1.96 \times 10^{-1}$ Eq-43

A stone cladding building of 42 years old, located more than 5 km from the sea has a rough finish and an area of 0.45 m^2. The degradation severity, S_w, was determined to be 6.1% in filed inspection. This gave:

- u_1 = 1 (rough stone finish)
- u_2 = -1 (more than 5 km from the sea)
- u_3 = 0.45 (area of the stone cladding element)
- u_4 = 42 (age of cladding).

The first rule was given by:

$y_1(k) = 4.25 \times 10^{-4} \times 1 + 6.00 \times 10^{-4} \times (-1) - 2.78 \times 10^{-2} \times 0.45 + 1.38 \times 10^{-3} \times 0.42 + 1.56 \times 10^{-2} = 0.060875$ Eq-44

The second rule was given by:

$y_2(k) = 1.04 \times 10^{-2} \times 1 + 1.29 \times 10^{-2} \times (-1) + 1.09 \times 10^{-1} \times 0.45 + 5.24 \times 10^{-3} \times 0.42 - 1.96 \times 10^{-1} = 0.07063$ Eq-45

Table 24. Service life of natural stone cladding predicted using the Takagi-Sugenon model.

Average reference service life	90.28 years
Median reference service life	71.00 years
Maximum reference service life	142.00 years
Minimum reference service life	62.00 years
Standard deviation of reference service life	31.23 years
95% confidence interval	±8.57 years

Source: Silva, Vieira, de Brito & Gaspar, 2016

The degradation severity, S_w, was then predicted with β_1=0.1579 and β_2=0.8688 from a fuzzy toolbox for MATLAB or graphical analysis to be 6.9%, which was similar to the observed value, 6.1%.

The two models were assessed using a test dataset, this representing 25% of the samples. Model 2 produced better service life estimation of natural stone claddings, as shown in Table 24.

The estimated service life values were predicted with a maximum acceptable degradation level of 20% and an average estimated service life of 90 years was obtained. This value is slightly higher than 72 years using multiple linear regression models and 80 years using ANN models (Silva, Dias, Gaspar & de Brito, 2011; Silva, de Brito & Gaspar, 2011).

9.7.6 Section summary

Service life prediction is very important to support informed decisions of building material/component specification and building maintenance. Essential information can be collected from field inspections, which allow identifying the effects of environments on material performance and the mechanisms behind material degradation. Meanwhile, service life prediction models, deterministic, stochastic or computational, can further explore this data to deliver better outputs such as:

- identification of patterns of degradation
- analysis of loss of performance over time
- estimation of service life.

Although the models discussed in this section are different, they seem to be able to provide service life estimations that are comparable to those derived from other studies.

However, every model has its own advantages and limitations. For example, ANN-based models have self-learning capability. However, they may require a large amount of structured data to develop and improve their prediction for situations not seen previously. Some models also require a good understanding of material degradation mechanisms and processes so that key variables and/or factors can be identified and/or quantified for the modelling process.

10. Service life expectation

10.1 Introduction

Trusted service life data is critical for specifying and using the right materials to construct the right buildings in the right places. Data that can be gathered and categorised for some typically used building materials includes:

- service life of products, based on experience or condition surveys
- maintenance intervals, based on experience
- information gained from accelerated or field testing.

The service life data found in publicly available literature can vary significantly. A good scientific understanding of material degradation mechanisms and the methodologies used to derive the relevant data must be achieved so that data and information can be used appropriately.

10.2 Degradation of building materials

A material will degrade when exposed to its in-service environment, resulting in changes in its chemical, physical, mechanical and/or functional properties over its service life, quickly or slowly. The behaviour and process of this degradation is material and/or environment dependent. A good understanding of the science behind degradation will form a solid basis for designing fit-for-purpose evaluation methodology and making quantitative predictions of service life. In this section, the environmental degradation of some building materials – metals, timbers, concretes and polymers – is briefly discussed.

10.2.1 Aluminium and its alloys

Aluminium and its alloys are commonly used in building and construction for window frames and roof claddings (Lyons, 2006).

Aluminium and its alloys are very active. However, they naturally exhibit a high passive state in many environments. This is because nascent aluminium can react rapidly with oxygen or water to form a thin and stable oxide film on its surface. This film can partially inhibit the reactions between the environment and the metal. However, it will dissolve in acid or alkaline media (Burleigh, 2003; de la Fuente, Otero-Huerta & Morcillo, 2007).

Long-term field exposure tests in rural, industrial, marine and urban atmospheres showed that aluminium had very low uniform corrosion rates (Fahy, 1980, 1983; Duncan & Cordner, 1991; Shreir, Jarman & Burstein, 1994; Escudero, Lopez, Otero, Bartolome & Gonzalez, 2007).

The major corrosion-related failure of aluminium and its alloys is localised attack such as pitting, intergranular corrosion, stress cracking corrosion and exfoliation. Pitting is the most frequently observed (Szklarska-Smialowska, 1999; Melchers, 2015). Pitting occurs in the regions of naturally grown passive oxide film with defects such as low thickness, partial damage, vacancies and areas with dislocations or impurities. Other factors such as corrosive salts (chloride) and gases in the atmosphere can significantly contribute to the loss of passive film stability, initialising pits (Lashermes, Guilhaudis, Reboul & Trentelivers, 1982; Blucher, Svensson & Johansson, 2006). However, the rate of pitting can gradually decrease with time (Shreir, Jarman & Burstein, 1994). Long-term exposure (20 years) testing with 1000, 3000, 5000 and 6000 series showed that the maximum pitting depth never exceeded 0.5 mm (Vargel, 2004). A 13-year testing in an industrial atmosphere showed the pitting depth did not exceed 0.2 mm.

Industrial atmospheres containing high concentrations of sulphur dioxide (SO_2) can accentuate the rate of attack. The combination of acidic sulphates and condensation experienced in some industrial conditions can lead to the formation of a particularly voluminous loose corrosion product on some aluminium alloys.

For long-term use of aluminium and its alloys in environments containing chlorides and sulphur dioxides, additional protection might be required, especially when the aesthetic quality needs to be retained. For most aluminium alloys, painting is desirable in aggressive atmospheres to reduce any risk of localised corrosion.

Filiform corrosion (also known as underfilm corrosion or wormtrack corrosion) could be a problem for painted aluminium alloys (Powers, 1991; Steele, 1994). Permeability (or porosity) and elasticity (or adhesion) of the paint coating, oxygen diffusion paths and surface presence of hygroscopic salt particles are the main contributing factors. The interface between metal and paint is critical as well and can be influenced by alloy chemical composition, method of chemical surface cleaning and/or type of chemical conversion coating applied before painting (Brown, Shimizu, Kobayashi, Thompson & Wood, 1993; Nordlien, Defrancq, Züst, Benmalek & Stuckart, 2000; Fedrizzi, Bianchi, Deflorian, Rossi & Bonora, 2002; Pereira, Pimenta & Dunn, 2008). It should be noted that this type of corrosion does not significantly weaken or destroy aluminium components but only affects aesthetic quality.

Anodisation is another way to protect aluminium from environmental attacks (Martínez-Viademonte, Abrahami, Hack, Burchardt & Terryn, 2020). In general, the anodised aluminium has very high corrosion resistance in rural, industrial and marine environments. The tests done with a 25-year exposure to the Madrid atmosphere (Spain) revealed a thickness loss of ≤0.15 μm/year, indicating a durability of >100 years for the usual thicknesses in architectural applications (Escudero Lopez, Otero, Bartolome & Gonzalez, 2007). Tests performed in New Zealand also confirmed that unsealed and completely sealed anodic coatings (>20 μm) could provide a service life longer than 100 years (Fahy, 1980, 1983). The long-term corrosion resistance depends on nature of the alloy, anodising/sealing conditions, film thickness and maintenance.

Aluminium and its alloys have good compatibility with common building and construction materials. However, aluminium can suffer from surface attacks when in contact with wet concrete (PCA, 1970). This process decreases rapidly with time, and the strength of the aluminium components will not be significantly affected. Some naturally acidic timbers such as oak, chestnut and western red cedar can attack aluminium but do not usually lead to serious problems. Direct contact with or leaching from timber treated with copper-based preservatives should be avoided.

When stainless steel (such as AISI 304) fasteners are used without a clearance hole and an isolating washer, rapid galvanic corrosion of aluminium can occur. This is particularly evident when the assembly is located in marine environments.

10.2.2 Copper and its alloys

Copper and its alloys can find applications as distinctive building elements including roof slopes, cladding, soffits, fascias, flashings, gutters and downpipes (Copper Concept, 2019).

Copper and copper alloys have a high atmospheric corrosion resistance due to the development of protective layers of corrosion products with highly varying compositions and microstructures on their surfaces (FitzGerald, Nairn, Skennerton & Atrens, 2006; Watanabe et al., 2007). In general, copper and its alloys will suffer from uniform corrosion, and the corrosion rate tends to decrease with time of exposure regardless of the atmosphere type (Odnevall Wallinder & Leygraf, 2001; Mendoza, Corvo, Gomez & Gomez, 2004; Fonseca, Picciochi, Mendonca & Ramos, 2004). Localised corrosion such as pitting or intergranular or transgranular penetration can happen on some copper alloys. Pitting with a maximum depth of 0.2 mm after 20 years of exposure has been observed on brasses and Cu-20Ni-20Mn (Shreir, 1976).

The combination of moisture and SO_2 have profound effects on copper corrosion (Oesch & Faller, 1997; Santana Rodriguez, Santana Hernandez & Gonzalez Gonzalez, 2003). When RH was less than 63%, there was little attack even in the presence of SO_2, but when RH was higher than 75%, corrosion became severe and increased with the concentration of SO_2. The co-presence of SO_2 and ozone (O_3) could provide synergistic effects and result in unexpectedly high corrosion rates.

A threshold for atmospheric salinity, ~20 $mg/m^2/day$ of Cl^-, seems to differentiate copper corrosion behaviour in marine atmospheres. Below this threshold, copper behaves as in rural atmospheres. Above this threshold, corrosion accelerates notably (Morcillo, Chico, Mariaca & Otero, 2000).

In urban areas, the deposition of fine dust particles may negatively influence the corrosion resistance of copper. Several lab tests have demonstrated that exposures to $(NH_4)_2SO_4$ produced patinas with at least some of the characteristics of naturally grown patina (Lobnig, Frankenthal, Siconolfi & Sinclair, 1993; Lobnig, Frankenthal, Siconolfi, Sinclair & Stratmann, 1994). The size of particles is also important. It has been shown that smaller particles resulted in a higher corrosion rate than larger particles at equal amounts of deposition, due mainly to the higher surface coverage of the smaller particles (Chen, 2005).

Rainwater run-off from copper may cause staining on adjacent materials and severe corrosion to other metals. Zinc, galvanised steel and non-anodised aluminium should not be used under copper. Specifically, copper should not be installed below exposed bitumen, bitumen paint or cedar wood shingles where leaching action producing acid solutions can cause localised attack on copper.

10.2.3 Zinc and its alloys

Bright zinc tarnishes in the air with the formation of zinc oxide and hydroxide, which is rapidly converted into zinc carbonate by the action of water and carbon dioxide (CO_2). These corrosion products can, to some extent, slow down environmental attack to the underlying metal substrate. However, due to the presence of various physical defects, zinc will still corrode slowly and steadily.

Zinc corrosion rate is dependent on the type of exposure (Leonard, 2003; Zhang, 2005; de la Fuente, Castano & Morcillo, 2007). In industrial areas, SO_2 in combination with excessive moisture prevents the formation of protective carbonate and leads to the formation of $Zn_4SO_4(OH)_6{\cdot}4H_2O$ and/or $Zn_4Cl_2(OH)_4SO_4{\cdot}5H_2O$. In environments heavily polluted with SO_2, the corrosion product layers can be partially dissolved. Under extreme conditions, this dissolution can reach such a point where practically no corrosion products are found on the metal surface, leading to abnormally high corrosion rates (Guttman, 1968).

The co-existence of NaCl particles and SO_2 on the surface can accelerate the initial atmospheric corrosion rate of zinc (Qu, Yan, Wan & Cao, 2002; Chen, Chung & Shih, 2006; Chen, Persson & Leygraf, 2008).

In the absence of NaCl, CO_2 in the atmosphere can accelerate zinc corrosion slightly. This is due to the acidification of the surface electrolyte, leading to a higher surface conductivity and an enhanced dissolution of surface films. In the presence of NaCl, CO_2 could slow down zinc corrosion. It has been reported that the corrosion rate of zinc at 22°C was 3–4 times smaller in air containing 350 ppm CO_2 compared with CO_2-free air in the presence of 70 $\mu g/cm^2$ NaCl particles (Chen, Persson & Leygraf, 2008).

Solid particulates can accelerate zinc corrosion, particularly via localised corrosion mechanisms (Almeida, Morcillo & Rosales, 2000; Qu et al., 2004; Qu, Li, Bai, Yan & Cao, 2005). Studies at 85% RH and 40°C showed that the mass loss decreased in the order of $NH_4Cl > NaCl > Na_2SO_4 > (NH_4)_2SO_4$. Obviously, chlorides were more corrosive than sulphates, and this was attributed to the greater hygroscopicity of chlorides compared to sulphates.

In New Zealand, the first-year corrosion rate of zinc coating on steel could vary from 0.1 to 20 μm/year, while after 10 years of exposure, the corrosion rate was much lower at 0.1–2.5 μm/year (Duncan & Cordner, 1991; Haberecht, Kane & Meyer, 1999). High corrosion rates were normally observed in severe marine and geothermal environments. In general, the corrosion rates of hot-dip galvanised zinc coatings in most New Zealand natural environments, particularly in zone B of the NZS 3604 exposure zone map, is low, while in zone C, its corrosion rate is variable and can be as high as ~2 μm/year.

Zinc can be used with aluminium or lead in some environmental conditions. However, it should not be in direct contact with copper or where water run-off from copper would discharge onto zinc. When in contact with steel or stainless steel, zinc must be the major component to minimise galvanic corrosion risks.

Zinc is not affected seriously by Portland cement mortars or concrete. However, it should be protected when contacting soluble salts from masonry or cement additives.

Direct contact between zinc and acidic timbers such as oak, chestnut and western red cedar should be avoided. If the timber is treated with preservatives containing a high quantity of copper such as copper azole (CuAz) and alkaline copper quaternary (ACQ), corrosion of zinc will be accelerated (Kear, Wu & Jones, 2009; Li, Marston & Jones, 2011b; Zelinka, 2013).

10.2.4 Stainless steels

Stainless steels have excellent environmental performance due to the presence of a chromium-rich passive film on their surfaces (Olsson & Landolt, 2003). This film can inhibit the reactions between the metallic substrate and the aggressive environment, resulting in a corrosion rate that will be several orders of magnitude lower (Uhlig, 1979; Sato, 1990; Hashimoto, Asami, Kawashima, Habazaki & Akiyama, 2007).

Surface finish has been found to exert significant influences on the corrosion performance of stainless steel upon atmospheric exposure (Asami & Hashimoto, 2003; Mameng, Wegrelius, Pettersson & Leygraf, 2015; Mameng, Pettersson & Leygraf, 2017; Mameng, 2019).

In general, stainless steel surface finishes can be divided into three main categories: mill, polished and special (Euro Inox, 2005).

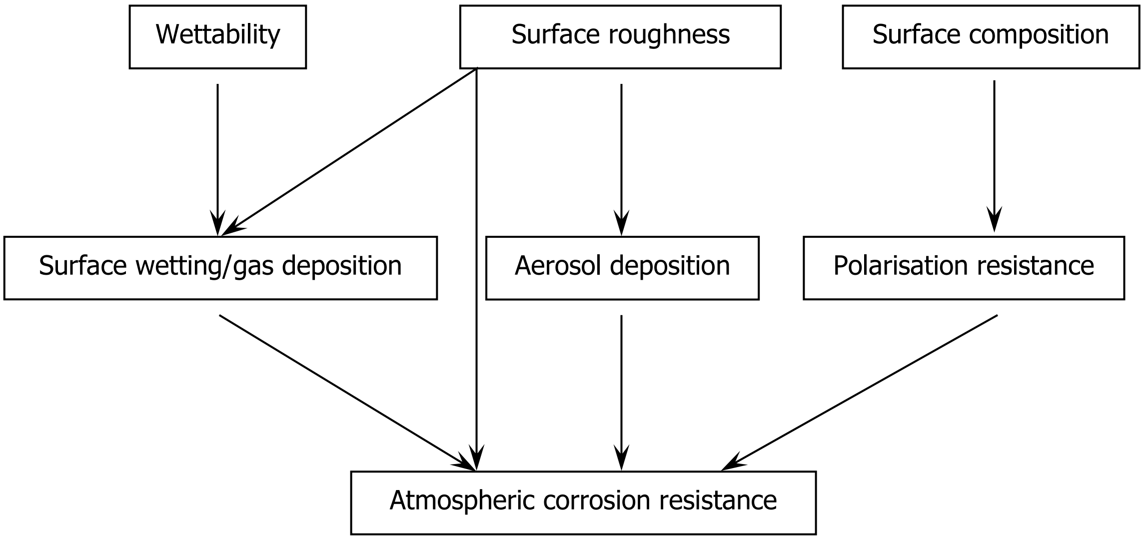
Mill finishes (hot or cold rolled), the basic surface condition, are used universally for architectural and building applications:

- **1D:** The hot rolled stainless steel is softened (annealed) with mill surface removed. This surface, slightly coarse with very low reflectivity, is commonly found on thick sheets and plates where uniformity and smoothness are not important.
- **2D:** The cold rolled stainless steel is heat treated and pickled to deliver a smooth surface of low reflective matt grain appearance.
- **2B:** The cold rolled stainless steel is annealed and de-scaled to receive a final light rolling using highly polished roll. This gives a smooth, reflective and grey sheen surface.
- **2R:** This is produced by cold rolling, de-scaling and final annealing done under oxygen-free conditions. The surface is very smooth and highly reflective.

Polishing can improve the appearance and consistency of stainless steel surfaces:

- **1G (hot rolled)/2G (cold rolled):** This is a uniform unidirectional finish with low reflectivity.
- **1J (hot rolled)/2J (cold rolled):** This is a unidirectional and non-reflective surface finish and is commonly used when an even matt ground surface is the main criterion for application.
- **1K (hot rolled)/2K (cold rolled):** This is a fine, smooth satin finish that has an attractive lustre and smooth texture. It is suitable for architectural applications since entrapment of debris and dirt can be minimised.
- **1P (hot rolled)/2P (cold rolled):** This is a highly reflective mirror polished surface.

Surface finish could affect several factors such as composition, roughness, wettability and inclusion that can contribute to atmospheric corrosion (see Figure 23).



Source: Wallinder, Odnevall Wallinder & Leygraf, 2003

Figure 23. Schematic illustration of the relationship between surface wettability, roughness, composition and atmospheric corrosion resistance of stainless steels.

It was generally believed that, the rougher the surface, the higher the probability that water, salt and dirt will stick to the surface (Johnson & Pavlik, 1982; Khanna & Gnanamoorthy, 1982). Micro-crevices on a rough surface may serve as initiation sites for pitting corrosion, and the time of wetness may increase on a rough surface as well. Therefore, a smoother surface finish will normally perform better since it tends to retain fewer contaminants and is more readily washed by rainwater. This improvement is typically observed when the surface roughness (R_a) is 0.5 µm or smoother.

Surface finishing processes may affect chromium (Cr) concentration in the surface film before atmospheric exposure (Asami & Hashimoto, 2003). For example, mechanical polishing with #600 grit abrasive paper in air could generate a considerable amount of heat through scrubbing or rubbing. This heat may cause surface enrichment of Cr. In comparison, bright annealing at a high temperature in hydrogen gas would not produce a surface film with a high Cr concentration. A surface finish that can enrich Cr could slow down corrosion if the environment is not very aggressive.

10.2.5 Timber

Durability of timbers and timber products can vary, according to species, hazards and in-service condition (Leicester, 2001; Evans et al., 2005; Morard et al., 2007; Goodell, Winandy & Morrell, 2020).

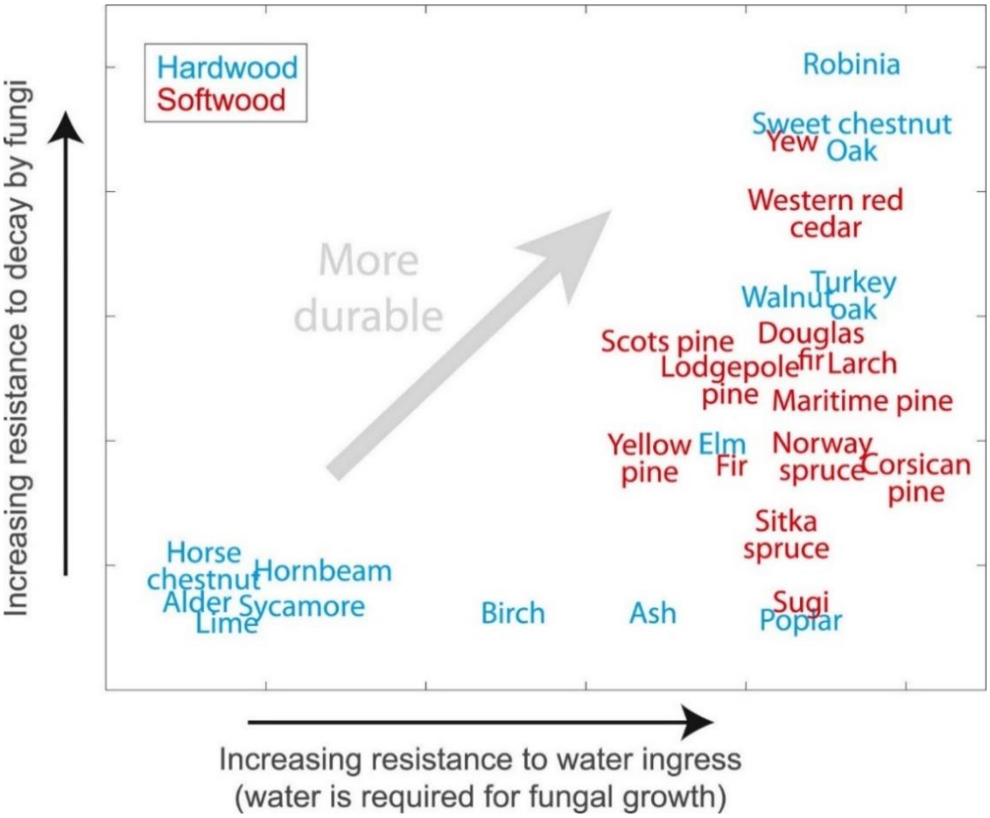
The following processes can contribute to timber degradation and therefore affect performance and durability:

- **Photodegradation:** Timber weathering associated with sunlight is the most common type of degradation occurring in exterior and above-ground applications (Derbyshire & Miller, 1981; Chang, Hon & Feist, 1982). The ultraviolet (UV) portion of the solar spectrum is most effective in this degradation and is responsible for a series of chemical changes, particularly dehydrogenation, dehydroxylation, dehydroxymethylation and demethoxylation of lignin. This energy transforms lignin into a variety of radical forms that transfer energy to hemicellulose and cellulose, which are then readily depolymerised. Photodegradation is a superficial phenomenon, but it can lead to surface fibre removal. The leaching of photodegraded lignin and hemicellulose fragments by rain is partly responsible for the characteristic grey colour of weathered timber.
- **Thermal degradation:** When heated at elevated temperatures, timber may lose its mechanical strength due to changes in its chemical components (Shafizadeh & Chin, 1977). Excessive heat has profound impacts on hemicelluloses, cellulose and lignin. Moisture in the presence of superficial solar heating may result in hydrolytic degradation of non-cellulosic components of timber.
- **Biodegradation:** Timber can be attacked by decay fungi, insects, termites, boring beetles, carpenter ants, marine borers and other organisms under favourable environmental conditions such as moisture, oxygen supply and temperature (Mindess, 2007; Reinprecht, 2016; Goodell, Winandy & Morrell, 2020). This leads to various microbiological degradations of lignocellulosic materials, which may reduce the density, strength and aesthetic properties of timber and its products.
- **Nail sickness:** Metallic fastening and fixing components are commonly used in timber structures. It is commonly observed that the surrounding timber may deteriorate slowly when the metal is corroding. The interactions between the corrosion products formed and the chemical components of the timber are responsible for this localised deterioration (Baker, 1974).

Durability can be enhanced by a variety of treatments – chemical or thermal (Rowell, 2005; Esteves & Pereira, 2009; Hill, Altgen & Rautkari, 2021). Good design details that minimise the exposure to moisture, solar irradiation and airborne contamination are also essential to achieve long durability.

Guidance on timber durability for decay by fungi and for insect attack has been given by BS EN 350-2[26] (see Figure 24). In general, wood species towards the top right of the graph are most durable.

It is interesting to note that not all hardwoods are more durable than softwoods.



Source: Ramage et al., 2017

Figure 24. Durability of heartwood of some wood species grown and tested in Europe according to EN 350-2.

10.2.6 Concrete

The American Concrete Institute defines the durability of concrete as its resistance to weathering action, chemical attack, abrasion and other degradation processes while maintaining its desired engineering properties (American Concrete Institute, n.d.).

Durability of concrete can be affected by the following.

Alkali-silica reaction

This is an expansive reaction between reactive forms of silica in aggregates and potassium and sodium alkalis in cement and/or aggregates, pozzolans, admixtures and

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[26] BS EN 350-2 Durability of wood and wood-based products – Natural durability of solid wood – Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe

mixing water (Grattan-Bellew & Mitchell, 2002; Farny & Kerkhoff, 2007; Pan et al., 2012). It can seriously damage the integrity of concrete and concrete structures due to the formation of crack networks, closed or spalling joints and/or movement of structural portions.

Sulphate attack

Sulphates can attack concrete through reactions with hydrated compounds in cement paste (Whittaker & Black, 2015). It can induce stresses sufficiently high to cause disintegration of concretes. Sulphate attack can be external or internal. Penetration by water containing dissolved sulphates such as sodium sulphate (Na_2SO_4), potassium sulphate (K_2SO_4) and magnesium sulphate ($MgSO_4$) can induce external attack.

A reaction front can be observed with polished samples. Behind the reaction front, some compositional and microstructural changes can be identified such as:

- cracking
- expansion
- loss of bond between cement paste and aggregate
- change in paste composition – mono sulphate phase converted into ettringite and then gypsum.

These changes will eventually result in a loss of concrete strength. Internal attack can occur when sulphate-rich aggregate and residual gypsum are incorporated into the concrete during mixing process.

Delayed ettringite formation (DEF)

This normally describes the reformation of ettringite in moist concrete, mortar or paste after destruction of primary ettringite at elevated temperatures (Thomas, Folliard, Drimalas & Ramlochan, 2008). When the ettringite crystals grow, they can exert an expansive force within the concrete, leading to damages. The formation of DEF may require high temperature of approximately 70–80°C and intermittent or permanent saturation with water after curing.

DEF correlates positively with some cement-related factors (Zhang, Olek & Diamond, 2002; Kurdowski, 2014) such as:

- high sulphate
- high alkali
- high MgO
- cement fineness
- high C3A
- high C3S.

Freezing and thawing

Repeated cycles of freezing and thawing are potentially destructive to the integrity and performance of concrete due mainly to the freezing of water and subsequent expansion in paste and/or aggregate particles (Šelih, 2010). The freezing and thawing resistance can be improved by adding air entrainment admixtures (Wang, Lomboy & Steffes, 2009). Microscopic air bubbles in the paste can provide enough spaces to accommodate the water displaced by ice formation during freezing. This action can relieve the hydraulic pressures generated, decreasing the normal disruptive processes.

10.2.7 Polymer

Degradation of polymers and polymer-based materials such as paints, sealants, adhesives and plastics may include embrittlement (surface cracking), discolouration and loss of transparency. UV light in the solar spectrum is the primary contributing factor, while others include heat, mechanical energy, moisture, ozone and microbial action (Yousif & Haddad, 2013; Kulkarni & Dasari, 2018; Chamas et al., 2020). The UV radiation of 290–400 nm has an energy of 415–300 kJ/mol – the same bond energy of many organic compounds.

Different polymers are sensitive to damage from different wavelengths of UV radiation, known as the activation spectra as detailed in Table 25. This is because different polymers may have different chemical structures.

Table 25. Reported activation spectra for polymers leading to different properties being changed upon exposure to UV radiation.

Polymer	Wavelengths (nm)	Property affected
Polycarbonate	281–290 308–330	Yellowness
Polyethylene	308–326	Mechanical properties
Polyethylene terephthalate	290–315	Mechanical properties
Polymethylmethacrylate	290–315	Mechanical properties
Polypropylene	360–380	Mechanical properties
Polyvinylchloride	300–318	Yellowness
Silicone rubber	320 & 365	Mechanical properties

Source: Marston & Jones, 2007

The potential for a polymer to undergo photo-induced degradation is controlled by its ability to absorb photons of a suitable energy and the availability of photochemical pathways that allow chemical reactions to use the energy absorbed.

In past BRANZ research, mechanical property data for different polymers was assessed against the calculated cumulative radiation dose at different locations across New Zealand. This process allowed the identification of a maximum irradiation dose, 50 MJ/m^2, before the polymer became mechanically non-viable. This dose can be applied to estimate the service life of other polymer-based materials in New Zealand.

10.3 Expected service life

The service lives of typical building materials, components and protective coating systems are summarised based on data collected from publicly available literature.

They can be useful for service life prediction of new materials using appropriate methods and/or models. For example, they can be used to provide guidance on reference service life issues and a means of determining the estimated service life using factor methods.

10.3.1 Timber

The durability of selected New Zealand-grown timbers has been assessed by in-ground contact (see Table 26). For exterior, out-of-ground contact, the species will shift up one class. All the timbers are effectively Class 1 rating (very durable) for interior uses.

Table 26. In-ground natural durability of the heartwood of New Zealand-grown timbers.

Class 1 **Very durable** **>25 years**	**Class 2** **Durable** **15–25 years**	**Class 3** **Moderately durable** **5–15 years**	**Class 4** **Non-durable** **<5 years**
Hardwoods			
E. cladcalyx Robinia	*E. amygdalina* *E. botryoides* *E. cornuta* *E. globoidea* *E. muellerana* *E. pilularis* *E. radiata* *E. saligna* European oak Hard beech Mountain beech Red beech Sweet chestnut	Black beech[2] Blackwood[2] *E. glogulus*[2] *E. sieberi*[2] Gleditsia[2] Southern rata *E. fastigata*[1] *E. delegatensis*[1] *E. fraxinoides*[1] *E. obliqua*[1] *E. pyrocarpa*[1] *E. viminalis*[1] *E. regnans*[1] Hinau[1] Mangeao[1] Pukatea[1] Silver beech[1]	*Pawlonia elongata* *Pawlonia tomentosa* Poplar Tawa Silver wattle
Softwoods			
Silver pine Totara		Japanese cedar[2] Kaikawaka[2] Kauri[2] Larch[2] Lawson cypress[2] Lusitanica[2] Macrocarpa[2] Matai[2] Redwood[2] Rimu[2] Tanekaha[2] Western red cedar[2] Douglas fir[1] Leyland cypress[1] (p) Miro[1]	*P. nigra*

Class 1 **Very durable** **>25 years**	**Class 2** **Durable** **15–25 years**	**Class 3** **Moderately durable** **5–15 years**	**Class 4** **Non-durable** **<5 years**
		Pinus contorta[1] *P. muricata*[1] *P. radiata*[1] *P. strobus*[1] *P. ponderosa*[1]	

1 – species with durability towards the lower end of the range.
2 – species with durability towards the upper end of the range.
(p) – provisional classification, species still in test.

Source: Page & Singh, 2014

The natural durability of timbers commonly used for window frames and aluminium window reveals is given in Tables 27 & 28 (Hedley & Page, 2004).

Table 27. Durability of timbers used for window frames and exterior reveals (years).

Common name	**Botanical name**	**Heartwood**			**Untreated sapwood**			**Treated sapwood**		
		50	**15**	**5**	**50**	**15**	**5**	**50**	**15**	**5**
Ash – Victorian	*Eucalyptus regnans*	×	✓	✓	×	×	✓	H3.2[1]	✓[2] (1)	✓ (1)
	Eucalyptus delegatensis	×	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Ash – NZ (messmate)	*Eucalyptus obliqua*	×	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Cedar – western red	*Thuja plicata*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Cherry – American	*Prunus serotina*	×	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Douglas fir, Oregon pine – North American	*Pseudotsuga menziesii*	×	×/✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Fastigata	*Eucalyptus fastigata*	×	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Hemlock	*Tsuga heterophylla*	×	×	✓	×	×	✓	×	✓ (1)	✓ (1)
	Abies amabilis	×	×	✓	×	×	✓	×	✓ (1)	✓ (1)
Iroko (African teak)	*Chlorophora excelsa*	✓	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Jarrah	*Eucalyptus marginata*	✓	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Jarrah – Pacific	*Sapotaceae*	×	×/✓	✓	×	×	✓	×	✓	✓

Common name	Botanical name	Heartwood			Untreated sapwood			Treated sapwood		
		50	15	5	50	15	5	50	15	5
									(1)	(1)
Karri	*Eucalyptus diversicolour*	✓	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Kauri – Island (Fijian kauri and dakua makadre)	*Agathis vitiensis*	×	×/✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Kwila (ipil and merbau)	*Intsia bijuga*	✓	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Lawson cypress	*Chamaecyparis lawsoniana*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Macrocarpa	*Cupressus macrocarpa*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Matai – NZ	*Prumnopitys taxifolia*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Matai – Pacific	*Podocarpus spicata*	×	×/✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Mexican cypress (Mexican pine)	*Cypress lustianica*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Oak – American	*Quercus alba*	×	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Oak – Tasmanian	*Eucalyptus delegatensis*	×	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Blackbutt	*Eucalyptus pilularis*	×/✓	✓	✓			✓	H3.2	✓ (1)	✓ (1)
Pine (radiata)	*Pinus radiata*	×	×/✓	✓	×	×	✓	✓[3] H3.2	✓ (2,6)	✓ (1,2)
South Island red beech	*Nothofagus fusca*	✓	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Redwood	*Sequoia sempervirons*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Rimu – NZ	*Dacrydium cupressinum*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Rimu – Pacific	*Decussocarpus vitiensis*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Saligna (Sydney blue gum)	*Eucalyptus saligna*	×	✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Silver beech	*Nothofagus menziesii*	×	×/✓	✓	×	×	✓	H3.2	✓ (1)	✓ (1)
Tawa	*Beilschmiedia tawa*	×	×	✓	×	×	✓	×	✓ (1)	✓ (1)

Common name	Botanical name	Heartwood			Untreated sapwood			Treated sapwood		
		50	15	5	50	15	5	50	15	5
Teak	*Tectona grandis*	✓	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Vitex	*Vitex cofassus*	✓	✓	✓	×	×	✓	×	✓ (1)	✓ (1)
Yaka	*Dacrydium nidulum*	×	✓	✓	×	×	✓	×	✓ (1)	✓ (1)

1 – technically feasible but, except for pines, not included in NZS 3640.

2 – internal exposure, i.e. internal timber reveals; 50 years: structural; 15 years: external window/door joinery; 5 years: internal window joinery.

3 – only species in the table approved for this use.

Sapwood treatment requirement:

(1) Boron, H1.2

(2) LOSP (IPBC, tributyltin), H1.2

(6) LOSP (tributyltin, azoles), H3.1.

Table 28. Assessment of timber reveal durability using BRANZ *Selecting timber*.

Common name	Botanical name	BRANZ durability note	Durability class in-ground
Ash – Victorian	*Eucalyptus regnans*	Non-durable and resistant to treatment	4
	Eucalyptus delegatensis	Heartwood low durability and hard to treat	4
Ash – NZ (messmate)	*Eucalyptus obliqua*	Moderately durable	3
Cedar – western red	*Thuja plicata*	Heart moderately durable Sapwood can be treated NZ grown less durable	2–3
Cherry – American	*Prunus serotina*		3–4
Douglas fir, Oregon pine – North American	*Pseudotsuga menziesii*	Non-durable and hard to pressure treat	3
Fastigata	*Eucalyptus fastigata*		3
Hemlock	*Tsuga heterrophylla*		4
	Abies amabilis		4
Iroko (African teak)	*Chlorophora excelsa*	Very durable	1–2
Jarrah	*Eucalyptus marginata*	Heartwood durable and resists treatment	2

Common name	**Botanical name**	**BRANZ durability note**	**Durability class in-ground**
Jarrah – Pacific	*Sapotaceae*		1–2, 3–4 depends on species
Kauri – Island (Fijian kauri and dakua makadre)	*Agathis vitiensis*	Moderately durable Can be treated with boron salts	3–4
Kwila (ipil and merbau)	*Intsia bijuga; Intsia palembancia*	Durable Resists treatment	1–2
Lawson cypress	*Chamaecyparis lawsoniana*	Heartwood moderately durable Takes boron but not pressure treatment	3
Macrocarpa	*Cupressus macrocarpa*	Heart moderately durable Sapwood takes diffusion treatment (boron H1?) Does not take pressure treatment	3
Matai – NZ	*Prumnopitys taxifolia*	Non-durable Difficult to pressure treat Susceptible to borer	3
Matai – Pacific	*Podocarpus spicata*		3–4 assuming it is dakua salusalu
Mexican cypress (Mexican pine)	*Cypress lustianica*	Heartwood moderately durable Does not pressure treat Can be boron treated by diffusion	3
Oak – American	*Quercus alba*	Moderately durable Resistant to treatment	2
Oak – Tasmanian; a group of timbers including alpine ash, blackbutt and messmate	*Eucalyptus delegatensis*	Heartwood low durability and hard to treat	4
	Eucalyptus pilularis	Heartwood durable Difficult to treat	2
Pine (radiata)	*Pinus radiata*	Non-durable but readily accepts all levels of chemical treatment	4
South Island red beech	*Nothofagus fusca*	Heartwood durable Sapwood difficult to treat with CCA	2

Common name	**Botanical name**	**BRANZ durability note**	**Durability class in-ground**
Redwood	*Sequoia sempervirons*	Heartwood moderately durable Sapwood non-durable but can be treated	3
Rimu – NZ	*Dacrydium cupressinum*	Heartwood durable Sapwood non-durable Difficult to pressure treat	3
Rimu – Pacific	*Decussocarpus vitiensis*		3–4
Saligna (Sydney blue gum)	*Eucalyptus saligna*	Heartwood moderately durable	3
Silver beech	*Nothofagus menziesii*	Non-durable in ground Resists borer Heartwood resists CCA	3
Tawa	*Beilschmiedia tawa*	Non-durable, but accepts CCA and diffusion treatments (except for black heartwood) Susceptible to borer	4
Teak	*Tectona grandis*		1–2
Vitex	*Vitex cofassus*		1–2
Yaka	*Dacrydium nidulum*		3

Class 1 – heartwood of timbers of the highest durability, 25 and up to 50 years.
Class 2 – heartwood of high natural durability, 15 to 25 years.
Class 3 – heartwood of only moderate durability, 5 to 15 years.
Class 4 – heartwood of low durability, up to 5 years.
All sapwood is rated Class 4.

10.3.2 Zinc-based coatings

Zinc-based coatings are normally produced by hot-dip galvanising, mechanically plating and electrochemical plating processes. They may differ from each other in terms of composition, microstructure, porosity, thickness and steel-coating interfacial structure.

Durability of zinc-based coatings has been given in AS/NZS 2312.2[27] Table 6.2 *Life of first maintenance for a selection of hot dip galvanized coating systems in a range of corrosivity categories* (reproduced as Table 36 in Appendix B). The service life is estimated in years before the first major maintenance and is given according to the atmospheric corrosivity category according to ISO 9223[28].

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[27] AS/NZS 2312.2 Guide to the protection of structural steel against atmospheric corrosion by the use of protective coatings. Part 2: Hot dip galvanizing

[28] ISO 9223 Corrosion of metals and alloys – Corrosivity of atmosphere – Classification, determination and estimation

10.3.3 Polymeric coatings

A guide has been developed to estimate the service lives of typical polymeric coatings from a practical maintenance approach. The estimated service life is not the time a coating system should be replaced but rather the time the maintenance painting sequence should begin (see Table 29) (Helsel & Lanterman, 2016, 2017).

Similarly, a service life estimation has been given in AS/NZS 2312.1[29] Table 6.3 *Paint systems for steel* (reproduced as Table 37 in Appendix B).

10.3.4 Building materials and components

The expected service lives of typical building materials and components are summarised in Table 30, based on information retrieved from a wide spectrum of sources.

Note that the service life is typically given without a description of the in-service environmental conditions, i.e. the atmospheric environment surrounding the building (corrosivity category or airborne pollution), micro-climate (industrial or geothermal) and micro-environments on the building (closed, sheltered and exposed). Maintenance is essential to service life. However, this is not always given within some sources.

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[29] AS/NZS 2312.1 Guide to the protection of structural steel against atmospheric corrosion by the use of protective coatings. Part 1: Paint coatings

Table 29. Estimated service life for practical maintenance coating systems for atmospheric exposure (in years before first maintenance painting).

Type	Coating system (primer/midcoat/topcoat)	Surface preparation[2]	Number of coats	DFT min. (mils)	Service life[3,4]			
					C2	C3	C5-I	C5-M
Acrylic	Acrylic waterborne/Acrylic WB/Acrylic WB	Hand/Power	3	6	12	8	5	5
	Acrylic waterborne/Acrylic WB/Acrylic WB	Blast	3	6	17	12	9	9
Alkyd	Alkyd/Alkyd	Hand/Power	2	4	6	3	2	2
	Alkyd/Alkyd/Alkyd (AWWA OCS-1C)	Blast	3	6	11	6	3	3
	Alkyd/Alkyd/Urethane Alkyd	Blast	3	6	12	7	4	4
	Alkyd/Alkyd/Silicone Alkyd (AWWA OCS-1D)	Blast	3	6	14	9	5	5
Epoxy	Surface-Tolerant Epoxy (STE)	Hand/Power	1	5	12	8	5	5
	Surface-Tolerant Epoxy (STE)	Hand/Power	2	10	17	12	9	9
	Surface-Tolerant Epoxy (STE)	Blast	2	10	21	15	12	12
	Surface-Tolerant Epoxy/Polyurethane	Hand/Power	2	7	17	11	6	6
	Surface-Tolerant Epoxy/Polyurethane	Blast	2	7	20	14	9	9
	Surface-Tolerant Epoxy/STE/Polyurethane	Hand/Power	3	12	23	17	12	12
	Surface-Tolerant Epoxy/STE/Polyurethane	Blast	3	12	26	20	15	15
	Epoxy 100% Solids Penetrating Sealer/Epoxy	Hand/Power	2	6	13	8	5	5
	Epoxy 100% Solids Penetrating Sealer/Polyurethane	Hand/Power	2	6	13	8	5	5
	Epoxy/Epoxy	Blast	2	6	18	12	9	9
	Epoxy/Epoxy	Blast	2	8	20	14	11	11
	Epoxy/Epoxy/Epoxy	Blast	3	10	23	17	14	14
	Epoxy/Polyurethane	Blast	2	6	17	11	8	8
	Epoxy/Epoxy/Polyurethane (AWWA OCS-5)	Blast	3	6	20	14	11	11

Type	**Coating system (primer/midcoat/topcoat)**	**Surface preparation**[2]	**Number of coats**	**DFT min. (mils)**	**Service life**[3,4]			
					C2	**C3**	**C5-I**	**C5-M**
	Epoxy Waterborne/Epoxy WB/Epoxy WB	Blast	3	9	18	12	9	9
	Epoxy Waterborne/Epoxy WB/Polyurethane WB (AWWA OCS-7)	Blast	3	6	18	12	9	9
	Coal Tar Epoxy/Coal Tar Epoxy	Blast	2	16	21	17	14	14
Epoxy zinc	Epoxy Zinc/Epoxy	Blast	2	7	24	17	12	12
	Epoxy Zinc/Epoxy/Epoxy	Blast	3	11	29	20	14	14
	Epoxy Zinc/Polyurethane	Blast	2	7	24	17	12	12
	Epoxy Zinc/Polyurethane/Polyurethane	Blast	3	11	29	20	14	14
	Epoxy Zinc/Epoxy/Polyurethane	Blast	3	9	29	20	14	14
Organic zinc	Organic Zinc/Acrylic Waterborne/Acrylic WB (AWWA OCS-3)	Blast	3	6	19	14	11	11
	Organic Zinc/Epoxy/Polyurethane (AWWA OCS-6)	Blast	3	6	27	18	12	12
	Organic Zinc/Polysiloxane	Blast	2	8	29	19	14	14
	Organic Zinc/Epoxy/Polysiloxane	Blast	3	12	30	21	15	15
	Organic Zinc/Polyaspartic	Blast	2	8	27	18	13	13
	Organic Zinc/Epoxy/Polyaspartic	Blast	3	12	29	20	14	14
Inorganic zinc	Inorganic Zinc (IOZ)	Blast	1	3	27	17	12	12
	IOZ/Epoxy	Blast	2	7	26	18	14	14
	IOZ/Epoxy/Epoxy	Blast	3	11	32	23	17	17
	IOZ/Polyurethane/Polyurethane	Blast	3	9	32	23	17	17
	IOZ/Epoxy/Polyurethane	Blast	3	11	30	21	15	15
	IOZ/Acrylic Waterborne/Acrylic WB	Blast	3	6	24	17	12	12
Metallising	Metallising (minimum 85% Zn)	Blast	1	8	33	22	16	16
	Metallising/Sealer	Blast	2	10	34	24	17	18

Type	Coating system (primer/midcoat/topcoat)	Surface preparation[2]	Number of coats	DFT min. (mils)	Service life[3,4]			
					C2	C3	C5-I	C5-M
	Metallising/Sealer/Polyurethane	Blast	3	13	39	27	22	22
Moisture curing polyurethane	MCU penetrating Sealer/MCU/MCU	Hand/Power	3	7	15	14	7	9
	Zn-rich MCU/Polyaspartic	Blast	2	11	25	20	14	14
	Zn-rich MCU/Polyurethane/Polyurethane	Blast	3	9	30	21	15	15
	Zn-rich MCU/MCU/MCU	Blast	3	9	29	21	14	15
Miscellaneous	Universal Primer/Epoxy	Hand/Power	2	6	12	8	5	5
	Universal Primer/Epoxy/Polyurethane	Hand/Power	3	8	14	9	6	6
	Epoxy/Polysiloxane	Blast	2	7	23	17	14	14
	Polyurethane 100% Solids Elastomeric	Blast	1	20	24	18	14	14
	Epoxy Zinc/Epoxy/Fluorinated polyurethane	Blast	3	10	30	2	17	17
	Polyurea (aliphatic)	Blast	1	20	24	18	16	16

1 – service life of hot-dip galvanising (4 mils minimum) as reported by American Galvanizers Association:

- Mild (rural): >100 years
- Moderate (industrial): 90 years
- Severe (heavy industrial): 72 years.

2 – surface preparation definitions:

- Hand/Power: Requires SSPC-SP3 Power Tool Cleaning or SP2 Hand Tool Cleaning
- Blast: Requires SSPC-SP6 Commercial Blast or SP10 Near White Blast.

3 – service life estimates: All estimates are for the practical life of the system. Practical life is considered to be the time until 5–10% coating breakdown occurs (SSPC-Vis 2 Grade 4) and active rusting of the substrate is present.

4 – service life environments per ISO 12944-2:

- C1: Very low – Atmospheres with very low pollution and time of wetness such as certain deserts
- C2: Low – Atmospheres with low levels of pollution; mostly rural areas
- C3: Medium – Urban and industrial atmospheres, moderate sulphur dioxide pollution; coastal areas with low salinity

Type	**Coating system (primer/midcoat/topcoat)**	**Surface preparation[2]**	**Number of coats**	**DFT min. (mils)**	**Service life[3,4]**			
					C2	**C3**	**C5-I**	**C5-M**

- C5-I: Very high, Industry – Industrial areas with high humidity and aggressive atmosphere
- C5-M: Very high, Marine – Coastal and offshore areas with high salinity.

Source: Helsel & Lanterman, 2016, 2017.

Table 30. Life expectancy of typical building materials and components.

Type	**Building material/component**	**Life expectancy (years)**				
		CRC	**BCIS**	**NAHB**	**BLP**	**Other**
Ground floor	Unreinforced concrete				>60	
	Reinforced concrete		30–90		60	
Frame	Reinforced concrete		47–100			81 (eTool)
	Steel					>100 (InterNACHI)
						83 (eTool)
	Timber		35–95			>100 (InterNACHI)
						69 (eTool)
	Laminated timber		32–100			65 (eTool)
	SIPs					>100 (InterNACHI)
Roof cladding	Butynol					>20 (Ardex)
	Bitumen		10–25	20		20 (InterNACHI)
						19 (eTool)
						15–20 (Florida Housing)
	EPDM rubber		15–30			15–25 (InterNACHI)
						25 (eTool)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
	Asphalt		20–50	20		20–30 (InterNACHI) 36 (eTool) 15–30 (Florida Housing)
	Clay tile		30–80	Lifetime		>100 (InterNACHI) >100 (Nauhaus)
	Concrete tile/slab			Lifetime	50	>100 (InterNACHI)
	Fibre cement		20–50	25		25 (InterNACHI)
	Timber shingle		50–100	30		30 (InterNACHI) 10 (Non-ventilated, Nauhaus) 50 (Back-ventilated, Nauhaus)
	Timber shake					20 (Non-ventilated, Nauhaus) 100 (Back-ventilated, Nauhaus)
	PVC		15–30			27 (eTool)
	Slate					>100 (Nauhaus)
	Galvanised steel	Marine: 5–15 (no maintenance) 10–15 (maintenance) Industrial: 10–15 (no maintenance) 20–30 (maintenance)	20–40 (PVF2 coated)			25 (Florida Housing)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
		Benign: 30–50 (no maintenance) >50 (maintenance)				
	Aluminium-zinc alloy coating (55 wt.% Al-Zn)	Marine: 5–15 (no maintenance) 20–30 (maintenance)				20–30 (no maintenance) (Build 147)
		Industrial: 20–30 (maintenance)				
		Benign: 20–30 (no maintenance)				
	Aluminium-zinc alloy coating (55 wt.% Al-Zn, 150 g/m^2) + Organic coating – ZinaCore					30 (Perforation, Zone B, ColorCote) 30 (Perforation, Zone C, ColorCote)
	Zinc-aluminium-magnesium alloy coating (200 g/m^2) + Organic coating – MagnaFlow					30 (Perforation, Zone B, ColorCote) 30 (Perforation, Zone C, ColorCote) 25 (Perforation, Zone D, ColorCote) 15 (Perforation, Zone E, ColorCote)
	Aluminium		20–50			37 (eTool)
						25 (Florida Housing)
						60–80 (no maintenance) (Build 147)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
	Aluminium (AA5005/5052) + Organic coating – AlumiGard					30 (Perforation, Zone B, ColorCote) 30 (Perforation, Zone C, ColorCote) 30 (Perforation, Zone D, ColorCote) 25 (Perforation, Zone E, ColorCote)
	Prepainted aluminium		22–47			
	Copper		30–80	Lifetime		>70 (InterNACHI) 63 (eTool) 50–75 (Florida Housing)
	Zinc		25–50			48 (eTool)
	Lead		20–35			72 (eTool)
	Stainless steel					50–75 (Florida Housing)
Rainwater goods (gutters & downspouts)	Aluminium		30–50 (powder coated)	20		20–>40 (InterNACHI) 40 (eTool) 10 (Florida Housing)
	Aluminium (AA5005/5052) + Organic coating – AlumiGard					12 (Perforation, Zone B, ColorCote) 12 (Perforation, Zone C, ColorCote) 12 (Perforation, Zone D, ColorCote) 10 (Perforation, Zone E, ColorCote)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
	Galvanised steel	Marine: <5 (no maintenance) 5-10 (maintenance)		20		20 (InterNACHI)
		Industrial: 5–10 (no maintenance) 10–15 (maintenance)				
		Benign: 10–15 (no maintenance)				
	Aluminium-zinc alloy coating (55 wt.% Al-Zn)	Marine: 5–10 (no maintenance) 15–20 (maintenance)				
		Industrial: 5–15 (no maintenance) 15–20 (maintenance)				
		Benign: 15–20 (no maintenance) 20–30 (maintenance)				
	Zinc-aluminium-magnesium alloy coating (200 g/m^2) + Organic coating – MagnaFlow					12 (Perforation, Zone B, ColorCote) 12 (Perforation, Zone C, ColorCote) 12 (Perforation, Zone D, ColorCote) 10 (Perforation, Zone E, ColorCote)
	Zinc		20–40			41 (eTool)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
	Copper			>50		50–100 (InterNACHI)
						50 (Florida Housing)
	PVCu		20–30		25	
	Lead		30–75			
Wall cladding	Timber weatherboard				>60	30 (eTool)
	Plywood					20 (Florida Housing)
	Plasterboard				60	
	Fibre cement		25–50			30–40 (Build 147)
	Stucco					>50 (InterNACHI)
						50 (Florida Housing)
						100 (Nuahaus)
	Profiled glass fibre sheet					27 (eTool)
	Profiled plastic sheet		17-32			
	Precast concrete		35–75			45 (Florida Housing)
	Galvanised steel	Industrial: 5–10 (no maintenance) 10–15 (maintenance)	25–50 (PVF2 coated)			
		Benign: 20–30 (no maintenance) 30–50 (maintenance)				
	Aluminium-zinc alloy coating (55 wt.% Al-Zn)					20–25 (no maintenance) (Build 147)

Type	**Building material/component**	**Life expectancy (years)**				
		CRC	**BCIS**	**NAHB**	**BLP**	**Other**
	Aluminium-zinc alloy coating (55 wt.% Al-Zn, 150 g/m^2) + Organic coating – ZinaCore					15 (Perforation, Zone B, ColorCote) 15 (Perforation, Zone C, ColorCote)
	Zinc-aluminium-magnesium alloy coating (200 g/m^2) + Organic coating – MagnaFlow					25 (Perforation, Zone B, ColorCote) 25 (Perforation, Zone C, ColorCote) 20 (Perforation, Zone D, ColorCote) 15 (Perforation, Zone E, ColorCote)
	Aluminium					40 (Florida Housing)
	Aluminium (AA5005/5052) + Organic coating – AlumiGard					25 (Perforation, Zone B, ColorCote) 25 (Perforation, Zone C, ColorCote) 20 (Perforation, Zone D, ColorCote) 20 (Perforation, Zone E, ColorCote)
	Zinc		30–60			
	Brick				>60	>100 (InterNACHI)
						86 (eTool)
						60 (Florida Housing)
						100 (Nauhaus)
	Natural stone					>100 (InterNACHI)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
	PVC		20–40			25–35 (Build 147)
	Curtain wall (Aluminium frame/Glass)		30–50			43 (eTool)
	EIFS					20 (Florida Housing)
	Western red cedar weatherboard					25–35 (Build 147)
Cavity wall tie	Galvanised steel	Marine: 10–20 (no maintenance)				25 (Nauhaus)
		Industrial: 10–15 (no maintenance)				
		Benign: >50 (no maintenance)				
	Stainless steel (AISI 316)	Marine: 30–50 (no maintenance)				>100 (Nauhaus))
		Industrial: >50 (no maintenance)				
		Benign: >50 (no maintenance)				
Window frame	Timber		20–40 (treated softwood) 30–60 (treated hardwood)		30	>30 (InterNACHI)
						36 (softwood) (eTool) 50 (hardwood) (eTool)
	Aluminium	Marine: 5–10 (no maintenance) 20–30 (maintenance)				15–20 (InterNACHI)
		Industrial:				44 (eTool)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
		20–30 (no maintenance) 20–30 (maintenance)				
		Benign: 20–30 (no maintenance) 30–50 (maintenance)				35 (Florida Housing)
	Colour coated aluminium	Marine: 20–30 (maintenance)				
		Industrial: 20–30 (maintenance)				
		Benign: 10–50 (no maintenance) 30–50 (maintenance)				
	Anodised aluminium					>20 (WGANZ)
	Polyester coated galvanised steel		30–60			
	PVCu					37 (eTool)
Flashing	Galvanised steel	Marine: <5–10 (no maintenance) 10–15 (maintenance)				25 (Nauhaus)
		Industrial: 5–15 (no maintenance) 20–30 (maintenance)				
		Benign: >50 (maintenance)				
	Stainless steel					>100 (Nauhaus)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
	Copper	Marine: >50 (no maintenance) >50 (maintenance)				>100 (Nauhaus)
		Industrial: >50 (maintenance)				
		Benign: >50 (no maintenance) >50 (maintenance)				
	Lead	Marine: 15-20 (no maintenance) 20–30 (maintenance)				
		Industrial: 20–30 (no maintenance) 30–50 (maintenance)				
		Benign: >50 (no maintenance) >50 (maintenance)				
Fastener	Galvanised nail	Marine/Hardwood: 10–15 (no maintenance) 10–15 (maintenance)				
		Industrial/Hardwood: 5–15 (no maintenance) 15–20 (maintenance)				
		Benign/Hardwood: >50 (maintenance)				

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
		Marine/Softwood: <5 (no maintenance) 20–30 (maintenance)				
		Industrial/Softwood: 5–15 (no maintenance) 10–15 (maintenance)				
		Benign/Softwood: 30–50 (no maintenance) >50 (maintenance)				
	Bolt – Brass	Marine/Hardwood: 5–10 (no maintenance)				
		Industrial/Hardwood: 15–20 (no maintenance)				
		Benign/Hardwood: 30–50 (no maintenance) >50 (maintenance)				
		Marine/Softwood: 5–10 (no maintenance) 10–15 (maintenance)				
		Industrial/Softwood: 30–50 (maintenance)				
		Benign/Softwood: 30–50 (no maintenance) >50 (maintenance)				
	Bolt – hot-dip galvanised	Marine/Hardwood:				

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
		20–30 (maintenance)				
		Industrial/Hardwood: 20–30 (maintenance)				
		Marine/Softwood: <5 (no maintenance) 20–30 (maintenance)				
		Industrial/Softwood: 15–20 (no maintenance)				
		Benign/Softwood: 30–50 (no maintenance) 30–50 (maintenance)				
Interior wall	Plywood			60		50 (CHH)
	Particle board			60		
	Plaster				60	50 (Florida Housing)
	Ceramic tile				60	30 (Florida Housing)
	Vinyl					10 (Florida Housing)
	Wallpaper					10 (Florida Housing)
	Paint				7	15 (Florida Housing)
Interior floor	Carpet			8–10		8–10 (InterNACHI) 13 (eTool) 7 (Florida Housing)
	Vinyl tile/sheet			50		25 (InterNACHI) 17–18 (eTool)

Type	Building material/component	Life expectancy (years)				
		CRC	BCIS	NAHB	BLP	Other
	Ceramic tile					20 (Florida Housing)
	Timber			Lifetime		
	Parquet					39 (eTool)
	Concrete			>50	60	>50 (InterNACHI) 75 (Florida Housing)
	Marble			>100		>100 (InterNACHI)
	Granite			>100		>100 (InterNACHI)
Ceiling	Plaster		20–50			50 (Florida Housing)
	Gypsum		20–50	Lifetime	60	Lifetime (Alltech)
	Aluminium	15–20 (commercial building, no maintenance)	15–35			
	Galvanised	20–30 (commercial building, no maintenance)				
	Steel	10–15 (commercial building, no maintenance)				

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Alltech: Alltech Home Inspection Services, LLC. http://www.alltechhomeinspections.com

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Building material/component</th><th colspan="5">Life expectancy (years)</th></tr>
<tr><th>CRC</th><th>BCIS</th><th>NAHB</th><th>BLP</th><th>Other</th></tr>
<tr><td colspan="7">Ardex New Zealand Ltd. (2008). Ardex: Butynol & EPDM membranes. http://www.butynol.net.nz/pdf/Ardex%20Butynol%20Manual.pdf</td></tr>
<tr><td colspan="7">Florida Housing. Estimated useful life tables. https://www.floridahousing.org/docs/default-source/programs/competitive/capital-needs-assessment-guide/cna-appendix-f---estimated-useful-life-(eul)-tables.pdf?sfvrsn=e8b71e7b_2</td></tr>
<tr><td colspan="7">InterNACHI. Typical life expectancy table for common building materials and systems. https://www.nachi.org/life-expectancy.htm</td></tr>
<tr><td colspan="7">eTool Global. Typical life expectancy of building components. http://etoolglobal.com/wp-content/uploads/2015/10/BuildingComponentLifeExpectancy.pdf</td></tr>
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<tr><td colspan="7">ColorCote: https://www.colorcote.co.nz/products/</td></tr>
</table>

11. Specialised weathering rig

11.1 Background

The degradation of a material is a result of its interactions with the environment. This is further complicated when it is installed on an actual building. The installation details may impact a number of factors such as deposition of airborne pollutants/particulate matters, wind-driven rain and time-of-wetness that can affect its degradation. Of particular significance are installation angle and the direction the material faces.

11.1.1 Inclination angle

When used on buildings and/or structures or when exposed for performance testing, a material or component is normally installed at a certain angle to the horizontal (Wypych, 2013):

- **0°:** This provides a long wet period and gives a high degree of dirt accumulation and is commonly used for testing with roof cladding materials.
- **5°:** This introduces some water drainage and slightly reduces dirt accumulation on the skyward surface.
- **45°:** This is the most commonly used configuration for performance testing.
- **90°:** This results in a low surface temperature, solar irradiation and wetting period and is commonly used for testing with wall cladding materials and window profiles.
- **Variable angle:** This allows samples to be exposed at an angle that can compensate for seasonal differences in the sun's position according to ASTM E782-95[30] and ASTM E881-92[31].

In practice, a variation in inclination angle may lead to the following changes:

- **Water (snow or ice in cold climate) retention:** This may lead to the formation of varying thicknesses of moisture and time-of-wetness on the material surface.
- Washing off from rainwater, which could change metal atmospheric corrosion mechanisms by affecting the morphology and microstructure of the growing corrosion products.
- **Surface deposition and retention:** This could change the gravitational settling of particles and then the quantity of solid media reaching and remaining on the material surface such as marine aerosol and particulate matter. This may also affect the dissolution of gas species into the moisture layer.

11.1.2 Direction the material faces

It is commonly observed that a material is performing differently when used on different walls of the same building. This is associated with the orientation effect, which may create micro-environments. In outdoor field testing, material samples are generally mounted at a specific angle and face the equator or the major close source of air contaminants (e.g. seawater or industrial emission). This provides a limited capability of assessing material durability under real in-service conditions on actual buildings.

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[30] ASTM E782-95 Standard practice for exposure of cover materials for solar collectors to natural weathering under conditions simulating operational mode

[31] ASTM E881-92 Standard practice for exposure of solar collector cover materials to natural weathering under conditions simulating stagnation mode

11.1.3 Effects on material degradation

The inclination angle has profound impacts on the weathering of polymeric materials. There is a strong positive correlation between the angle of exposure and yellowness index (Hardcastle, 2001). It may also have some impact on the behaviour and kinetics of metal atmospheric corrosion (Moroishi & Satake, 1973; Wade, Begbie & Trueman, 2003). Practically, both increase and decrease of metal corrosion rate with an increase of inclination angle have been observed (Spence, Lipfert & Katz, 1993; Vera, Rosales & Tapia, 2003; Morcillo, Chico, Díaz, Cano & de la Fuente, 2013; Santana, Cano, Vasconcelos & Souto, 2020). This is because the environmental factors related to inclination may interact with each other to exhibit synergistic effects on corrosion. These can be significantly different from common understandings.

A combination of orientation and inclination may lead to varying differences in solar irradiation received by a material and therefore affect its degradation behaviour, process and mechanism. It has been experimentally observed that an increase of solar irradiance could affect the corrosion rates of a number of metals (see Table 31).

Table 31. Effects of the increased solar irradiance on metal corrosion.

Material	Environment		Corrosion rate change	Reference
Aluminium Carbon steel Copper Silver Zinc	UV irradiation	Flowing fresh water	Increase	Burleigh, Ruhe & Forsyth, 2003
Electrodeposited nickel nanocrystalline foils		3.5% NaCl solution		Deng, Lu & Li, 2020
Polycrystalline copper		Urban environment		Graedel, Franey & Kammlott, 1984
Carbon steel		Atmospheric environment in Niigata, Japan	Decrease	Katoh, Yasukawa, Nishimura & Yasuda, 1981
Copper		Marine environment		Hidalgo, Vera, Rosales, Araya & Schrebler, 2008
Copper nanocrystalline foils		3.5% NaCl solution		Deng, Lu & Li, 2020
Copper	Visible light	Atmosphere	Increase	Liu, Chen et al., 2018

However, these observations also indicated that the mechanisms behind metal corrosion with an increased exposure to solar light were complicated.

Solar light illumination would affect the properties of the growing corrosion product layers through photoelectrochemical effect. This is because most corrosion products are semiconductors (such as n-type and p-type). In addition, solar irradiation may induce modifications of the composition and/or morphology of the corrosion products growing on the metal surface, making them more or less resistant to corrosion (Song, Ma, Chen & Hou, 2014; Song & Chen, 2014).

11.1.4 Salt deposition

Most cities in New Zealand are coastal, and many buildings are within 5 km of the sea. Chloride-containing salt particles and/or aerosols can affect the corrosivity of atmospheric environments and the durability of materials and buildings in large areas (Ballance & Duncan, 1985). These effects can be further complicated by other meteorological conditions and material installation details on buildings.

Consequently, the role of sea spray and salt deposition is an important consideration for atmospheric corrosion testing and durability evaluation of metallic materials in New Zealand areas with marine influences. Salt spray in a cabinet (ASTM B117) is commonly used to mimic marine environments and introduce salt into material degradation processes. However, continuous exposure to salt-laden media or environments does not adequately replicate the actual in-service conditions. Cyclic corrosion testing such as the Prohesion cycle (ASTM G85 Annex 5) attempts to address this issue with dry-off and/or humidity exposure (Cremer, 1996; Martin, Horstemeyer & Wang, 2010). Seawater spray has also been incorporated into field exposure to accelerate material degradation (Horton, Anderson, Sanders, Davis & Lemieux, 2017).

However, these are still not able to feature other important environmental and material factors to produce closer parallels to material degradation under real-world conditions.

11.2 Design principle

Outdoor field exposure testing provides data and information that are most closely relevant to the in-service performance of a material when used on a building. Meanwhile, it provides scientific understanding and technological evidence to support the development and verification of lab-based accelerated testing methodology (Xing & Taylor, 2011; Shimizu, Tokuta, Oishi, Kuriyama & Kunioka, 2016; Hooton, 2018).

There are several considerations related to the limitations of commonly used static exposure at a fixed angle:

- Develop field testing facilities that can feature some of the building micro-environmental factors critical to material degradation by controlling exposure details such as the direction and the angle of exposure. This ensures that data and information essential to durability evaluation and/or service life prediction will be collected. Sunlight tracking systems have been developed and used for testing of highly durable polymeric materials or organic coatings by maximising the amount of exposure (Qin et al., 2021).
- Perform experiments that can help better identify the factors (material and environmental) and investigate their primary effects, individual or combined, on material degradation.
- Ensure the testing facility can technically support some of the specific methods designed for material durability evaluation according to the procedure and scheme discussed in this study.

The weathering rig developed in this study will be able to investigate the interactions between a material and its environment by controlling main components of degradation appropriately. This is achieved by allowing material exposure details to be changed through controllable, systematic ways, particularly inclination angle, orientation and introduction of dominant air contaminants. This is a different approach from those using artificial or hypothetical simulations and therefore evaluates durability and predicts service life more closely.

11.3 Function

The weathering rig (see Figure 25) has the following functions in order to conduct accelerated field exposure experiments for material durability evaluation.

Figure 25. The weathering rig developed in this study.

Control rig position

It follows the time and azimuth of sunrise and sunset, i.e. angular motion starts at sunrise and stops at sunset. During this period, the rig moves uniformly. One hour after sunset, the rig moves back to its original state, i.e. the east, in 1 hour. It can also be faced steadily towards a certain direction such as north.

Control spray action

It has three spraying modes – continuous spray, cyclic spray and no spray. This gives an increased exposure to salt deposit and/or time of wetness when compared with conventional field exposure. Spray solution can be:

- deionised water
- natural seawater
- artificial seawater according to ASTM D1141[32]

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[32] ASTM D1141 Standard practice for the preparation of substitute ocean water

- 5 wt.% NaCl solution
- 0.31 g/L NaCl + 4.1 g/L $(NH4)_2SO_4$
- 0.5 wt.% NaCl + 0.1 wt.% $CaCl_2$ + 0.075 wt.% $NaHCO_3$
- 0.9 wt.% NaCl + 0.1 wt.% $CaCl_2$ + 0.25 wt.% $NaHCO_3$.

Control inclination angle

It has three individual sample installation frameworks, and each framework can be set to an angle between 0° and 90° manually.

11.4 Components

The weathering rig has the following electrical, mechanical and structural components to achieve the functions described above:

Control system

- Control programme
  - Web interface
    - Show current status and position
    - Set rotating parameters
    - Set parking angle parameters
    - Set arbitrary angle parameters
  - System time maintenance
    - Restore system time upon start-up
    - Periodic check that system time matches real time clock (RTC)
    - Synchronise RTC with internet time standard periodically
  - Log action
    - Record when parameters changed
    - Record spray operation
    - Record position
- Servomechanism

Spray system

- Compressor
- Pressured solution tank
- Pressure regulators
- Solenoid valves
- Spray feed control valve
- Spray feed dump valve
- Spray nozzles

At spray time run spray cycle according to spray parameters

- Atomising air on
- Water on
- Stop water on
- Spray time period
- Water off
- Open dump valve
- Stop water off
- Close dump valve
- Atomising air off

Rotation system

- Stepper motor
- Gear box

At rotation time, the system operates according to preset parameters

- Calculate sun angle
- Measure rig angle
- Adjust drive speed
- Drive to arbitrary angles set by user interface

Sample exposure system

- Sample installation frameworks
- Inclination angle adjustment mechanism

11.5 Experiments

A number of experiments are being designed to use this specialised weathering rig to evaluate the degradation of selected materials under more-controlled exposure conditions. Parallel experiments will also be conducted with stationary exposure racks located at a number of reference sites with a variety of air contaminants. Consequently, derived data can be used to investigate degradation mechanisms from various perspectives. These may include:

- Material
  - Mild steel vs weathering steel
  - Zinc vs zinc-aluminium vs zinc-aluminium-magnesium coatings
- Inclination
  - 0° vs 45° vs 90°
- Solar irradiation
  - Rotating vs fixed
- Salt deposit
  - Severe marine vs artificial spray vs light marine

It is expected that this improved understanding may help better evaluate the durability of materials on buildings under simulated conditions and in accelerated means.

12. Summary and outlook

Materials are core to buildings and their associated infrastructure services, and, as an example, they contribute approximately 16–24% of residential building development costs in New Zealand.

According to the performance-based NZBC, the durability of materials is one of the most important aspects in building and construction. It is pivotal to components, structures, buildings and infrastructural assets through:

- service life prediction and planning
- cost of maintenance, repair and refurbishment
- climate change resilience
- whole-of-life embodied carbon.

Consequently, materials durability is an everlasting research topic in the fields of materials science and engineering, building and construction and engineering science.

This study report contains an in-depth analysis and review of data, methods, models and standards used all over the world to evaluate material properties, performance and durability for service life prediction. Particularly, this study report highlights the following aspects:

- Durability requirements and pathways for NZBC compliance.
- Durability evaluation activities from both research and testing perspectives.
- A number of examples of relatively new materials and processes that are finding an increasing number of applications in New Zealand building and construction.
- Some representative methods, procedures and schemes – accelerated and non-accelerated – for materials performance assessment.
- National and international standards describing or specifying methods or procedures for the durability evaluation of building materials.
- Material-related factors and functional parameters that could be used to investigate material performance and to evaluate durability.
- Methods, tools and models used for the service life prediction of building and construction materials.
- Service life data of timber, metal and polymeric materials and components.

By integrating the most recent and relevant advances, a generic framework for durability evaluation of new building materials has been developed with two interconnected parts:

- A structurally phased durability evaluation procedure.
- A general approach for developing testing schemes using both top-down and bottom-up approaches within a material-component-environment paradigm.

On the technical side, a specialised weathering rig capable of rotating by following the sun, spraying specific solutions and controlling sample inclination has been designed, built and commissioned. It can be used to:

- conduct experiments that aim to better understand the degradation behaviours, processes and mechanisms of materials through their interactions with the environment
- evaluate the durability of building materials under more-controlled exposure conditions

- technically support some of the specific methods designed for material durability evaluation according to the approach and procedure discussed in this study report.

This study report can be expected to help develop dynamic processes for evaluating the properties, performance and durability of specific new building materials. However, there are still gaps. In particular, the following should be considered:

- Availability of baseline data is always one of the main concerns in assuming the success of performance and durability evaluation. Specifically, the strategies and technologies for the collection and transmission of monitoring and testing data have been challenged.
- Some of the technical methods, models and procedures currently available have been revealed to be not rigorous and, in fact, to be empirical. They might be limited to specific types of building materials used under specific environmental conditions.
- Increasingly, a systematic approach has been sought to assess the properties, performance and durability of new materials and/or components in specified building systems. This presents an unprecedented challenge, and it creates an immediate need for transformational advances in theoretical basis, methodology and technical tools.

Therefore, there is a need to:

- collect and manage more data, in a systematic manner, about a material’s fundamental characteristics, performance and service life
- interpret data for durability evaluation with a better understanding of environmental degradation mechanisms and material behaviour
- improve the interrelations between the core components to better correlate datasets from in-service monitoring, field inspection and lab testing.

This may help form a basis for further development and implementation of practical approaches to collect, integrate and interpret data and information for the purpose of achieving NZBC durability compliance.

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Appendix A: Test standards

Table 32. Material characterisation.

No	**Standard**		**Remarks**
Metallic coatings			
1	Requirement	AS 1397 *Continuous hot-dip metallic coated steel sheet and strip – Coatings of zinc and zinc alloyed with aluminium and magnesium*	• Zinc coating (Type Z, 99% zinc and >1% of minor additions of control elements) • Zinc coating converted to zinc/iron alloy (Type ZF) • Zinc/aluminium coatings (Type ZA, 3–15% aluminium and >1% of minor additions of control elements) • Zinc/aluminium/magnesium alloy coating (Type ZM, 5–13% aluminium, 2–4% magnesium and >1% of minor additions of control elements) • Aluminium/zinc alloy coating (Type AZ, 50–60% aluminium, 1–2% silicon and >1% of minor additions of control elements) • Aluminium/zinc/magnesium alloy coating (Type AM, 47–57% aluminium, 1–3% magnesium, 1–2% silicon and >1% of minor additions of control elements)
2		AS/NZS 4680 *Hot-dip galvanized (zinc) coatings on fabricated ferrous articles*	
3		ASTM A755/A755M *Standard specification for steel sheet, metallic coated by the hot-dip process and prepainted by the coil-coating process for exterior exposed building products*	Sheet material includes: • zinc-coated (galvanised) • aluminium-zinc alloy coated • aluminium coated. Top-coating material includes: • polyester • silicone polyester • acrylic

No	Standard		Remarks
			- fluoropolymer - plastisol - polyurethane.
4	Test method	AS 2331.0 *Methods of test for metallic and related coatings –Method selection guide*	- Local thickness - Average coating mass per unit area or for thickness - Corrosion and related property - Physical property
5		AS 2331.1.1 *Methods of test for metallic and related coatings – Local thickness tests – Micrographic examination of cross-sections*	Determine local thickness of metallic coatings, oxide layers, porcelain or vitreous enamel coatings by examining cross-sections using an optical microscope.
6		AS 2331.1.5 *Methods of test for metallic and related coatings Local thickness tests – Beta-backscatter method*	Determine coating thicknesses using beta-backscatter gauges. Applicable to metallic and non-metallic coatings on metallic and non-metallic substrates.
7		AS 2331.2.1 *Methods of test for metallic and related coatings –Tests for average coating mass per unit area or for thickness – Dissolution method – Strip and weigh, and analytical*	- Method A – strip and weigh (dissolution of coating) - Method B – strip and weigh (dissolution of base metal) - Method C – analytical
8		AS 2331.3.5 *Methods of test for metallic and related coatings – Corrosion and related property tests – Sulfur dioxide/hydrogen sulfide porosity tests*	
9		AS 2331.3.6 *Methods of test for metallic and related coatings – Corrosion and related property tests – Electrographic porosity test*	
10		AS 2331.3.9 *Methods of test for metallic and related coatings – Corrosion and related property tests – Metallic coatings – Porosity tests – Ferroxyl test*	
11		AS 2331.4.1 *Methods of test for metallic and related coatings Physical tests – Qualitative adhesion tests*	
12		ASTM A90/A90M *Standard test method for weight [mass] of coating on iron and steel articles with zinc or zinc-alloy coatings*	- Zinc - Zinc-5 % aluminium

No	Standard		Remarks
			- Zinc-aluminium-magnesium (including zinc-5 to 9 % aluminium-magnesium and zinc-9 to 13 % aluminium-magnesium) - 55 % aluminium-zinc
13		ASTM A428/A428M *Standard test method for weight [mass] of coating on aluminium-coated iron or steel articles*	
14		ASTM A751 *Test methods, practices, and terminology for chemical analysis of steel products*	
15		ASTM B487 *Standard test method for measurement of metal and oxide coating thickness by microscopical examination of cross section*	Determine local thickness of metal and oxide coatings by microscopical examination of cross-sections with an absolute measuring accuracy of 0.8 μm.
16		ASTM A754/A754M *Standard test method for coating weight (mass) of metallic coatings on steel by X-ray fluorescence*	- Zinc or zinc-iron coatings - Aluminium-zinc coatings - Zinc-aluminium coatings - Zinc-nickel coatings
17		ASTM B748 *Standard test method for measurement of thickness of metallic coatings by measurement of cross section with a scanning electron microscope*	Cross-sectional examination using a scanning electron microscope (SEM).
18		ASTM B809 *Standard test method for porosity in metallic coatings by humid sulfur vapor ("Flowers-of-Sulfur")*	
19		ASTM B571 *Standard practice for qualitative adhesion testing of metallic coatings*	
20		ASTM B905 *Standard test methods for assessing the adhesion of metallic and inorganic coatings by the mechanized tape test*	Four methods (A1, A2, B1 and B2), which can be used to assess the adhesion of metallic and inorganic coatings and other thin films on metallic and non-metallic substrates.
Paints			
21	Requirement	AS/NZS 2728 *Prefinished/prepainted sheet metal products for interior/exterior building applications – Performance requirements*	Six types according to their performance in respect to durability and aesthetics, in environments of varying corrosivity.

No	Standard		Remarks
22	Test method	AS 2331.1.7 *Methods of test for metallic and related coatings – Local thickness tests – Measurement of dry film thickness of thin coating systems particularly by coil coated products by destructive means using a boring device*	Only applicable for coatings of >90 µm thicknesses.
23		AS 2331.4.7 *Methods of test for metallic and related coatings – Physical tests – Resistance to scratching*	
24		ASTM D2197 *Standard test method for adhesion of organic coatings by scrape adhesion*	Applicable to paint, varnish and lacquer applied onto smooth, flat panel surfaces.
25		ASTM D3359 *Standard test methods for measuring adhesion by tape test*	Applying and removing pressure-sensitive tape over the purposely made cuts.
26		ASTM B916 *Standard test method for adherence of porcelain enamel coatings to sheet metal*	• Determine quantitatively the amount of enamel remaining after the porcelain enamel coating specimen has been deformed. • Standardise the deformation parameters for testing adherence of porcelain enamel to sheet metal. • Provide a quantitative adherence rating scale for comparison to reference standards.
27		ASTM D4541 *Standard test method for pull-off strength of coatings using portable adhesion testers*	• Protocol 1 (test to fracture) determines the greatest perpendicular force (in tension) that a surface area can bear before a plug of material is detached. • Protocol 2 (pass/fail) determines if the coated surface remains intact at a defined load criteria.
28		ASTM D2794 *Standard test method for resistance of organic coatings to the effects of rapid deformation (Impact)*	
29		ASTM D523 *Standard test method for specular gloss*	
30		ASTM D5324 *Standard guide for testing water-borne architectural coatings*	• Liquid paint properties • Coating application and film formation characteristics • Appearance of dry film • Properties of dry film • Coating analysis

Table 33. Environmental characterisation.

No	Standard	Remarks
1	AS 3580.8.1 *Methods for sampling and analysis of ambient air – Determination of hydrogen sulfide – Automatic intermittent sampling – Gas chromatographic method*	Applicable to airborne hydrogen sulphide with a concentration of approximately 0.003–2 ppm (5–3,000 mg/m^3).
2	ASTM G140 *Standard test method for determining atmospheric chloride deposition rate by wet candle method*	
3	ISO 4219 *Air quality – Determination of gaseous sulphur compounds in ambient air – Sampling equipment*	
4	ISO 4220 *Ambient air – Determination of a gaseous acid air pollution index – Titrimetric method with indicator or potentiometric end-point detection*	Applicable to concentrations higher than 30 µg/m^3.
5	ISO 4221 *Air quality – Determination of mass concentration of sulphur dioxide in ambient air – Thorin spectrophotometric method*	
6	ISO 6768 *Ambient air – Determination of mass concentration of nitrogen dioxide – Modified Griess-Saltzman method*	Applicable within the range 0.003 mg/m^3 to 2 mg/m^3 and for sampling times of 10–120 minutes
7	ISO 7996 *Ambient air – Determination of the mass concentration of nitrogen oxides – Chemiluminescence method*	Applicable to airborne nitrogen monoxide (up to approximately 12.5 mg/m^3) and nitrogen dioxide (up to approximately 19 mg/m^3) at 25°C and 101.3 kPa.
8	ISO 9223 *Corrosion of metals and alloys – Corrosivity of atmospheres – Classification, determination and estimation*	• Defines corrosivity categories for the atmospheric environments by the first-year corrosion rate of standard specimens. • Gives dose-response functions for normative estimation of the corrosivity category based on the calculated first-year corrosion loss of standard metals. • Makes possible an informative estimation of the corrosivity category based on knowledge of the local environmental situation.
9	ISO 9224 *Corrosion of metals and alloys – Corrosivity of atmospheres – Guiding values for the corrosivity categories*	It provides: • examples of calculated maximum corrosion attack after extended exposure (up to 20 years) for six standardised corrosivity categories • presumed average initial and steady-state corrosion rates of standard metals in intervals relative to six standardised corrosivity categories

No	Standard	Remarks
		- calculation procedure for corrosion attack of steels in regard to their composition.
10	ISO 9225 *Corrosion of metals and alloys – Corrosivity of atmospheres – Measurement of pollution*	It specifies methods for: - measuring the parameters required for corrosivity estimation used for atmospheric corrosivity classification by ISO 9223 - measuring the environmental parameters for normative corrosivity estimation based on the calculated first-year corrosion rates of standard metals, and informative corrosivity estimation based on characterisation of the exposure environment - measuring deposition rates of SO_2 and Cl^-.
11	ISO 9226 *Corrosion of metals and alloys – Corrosivity of atmospheres – Determination of corrosion rate of standard specimens for the evaluation of corrosivity*	It specifies methods that can be used to determine first-year corrosion rates of standard specimens. These corrosion rates can be used to classify atmospheric corrosivity according to ISO 9223 and also for informative evaluation of atmospheric corrosivity beyond the scope of ISO 9223.

Table 34. Durability evaluation.

No	Standard	Remarks
General		
1	AS 1580.452.2 *Paints and related materials – Methods of test – Resistance to corrosion – Salt droplet test*	
2	AS 2331.3.1 *Methods of test for metallic and related coatings, Method 3.1: Corrosion and related property tests – Neutral salt spray test (NSS test)*	Assess corrosion resistance of inorganic and organic coatings on metallic substrates.
3	AS 2331.3.2 *Methods of test for metallic and related coatings, Method 3.1: Corrosion and related property tests – Acetic acid salt spray test (ASS test)*	
4	AS 2331.3.3 *Methods of test for metallic and related coatings, Method 3.1: Corrosion and related property tests – Copper accelerated acetic acid salt spray test (CASS test)*	
5	AS 2331.3.12 *Methods of test for metallic and related coatings, Method 3.12: Corrosion and related property tests – Cyclic salt fog/UV exposure of organically coated metal*	Using alternating periods of exposure in two different cabinets, i.e. a cycling salt/dry cabinet and a fluorescent UV/condensation cabinet.
6	ASTM B117 *Standard practice for operating salt spray (fog) apparatus*	
7	ASTM B368 *Standard test method for copper-accelerated acetic acid-salt spray (fog) testing (CASS test)*	Assess corrosion performance of copper/nickel/chromium or nickel/chromium coatings on steel, zinc alloys, aluminium alloys and plastics and also anodised aluminium.
8	ASTM C1850 *Standard guide for improved laboratory accelerated tests to predict the weathering and for use in developing protocols to predict the design life of building sealant systems*	
9	ASTM D6491 *Standard practice for evaluation of aging resistance of prestressed prepainted metal in a dry heat test*	Assess resistance of prestressed prepainted metal panels to cracking, loss of adhesion or both, after accelerated, dry heat ageing.
10	ASTM D5894 *Standard practice for cyclic salt fog/UV exposure of painted metal (alternating exposures in a fog/dry cabinet and a UV/condensation cabinet)*	Use of a cycling salt fog/dry cabinet and a fluorescent UV/condensation cabinet.
11	ASTM D6577 *Standard guide for testing industrial protective coatings*	

No	Standard	Remarks
12	ASTM D6665 *Standard practice for evaluation of aging resistance of pre-stressed prepainted metal in a boiling water test*	Assess resistance of prestressed prepainted metal panels to cracking, loss of adhesion or both, after accelerated ageing by boiling water.
13	ASTM D7087 *Standard test method for an imaging technique to measure rust creepage at scribe on coated test panels subjected to corrosive environments*	
14	ASTM G7/G7M *Standard practice for atmospheric environmental exposure testing of nonmetallic materials*	
15	ASTM E632 *Standard practice for developing accelerated tests to aid prediction of the service life of building components and materials* (withdrawn 2005)	
16	ASTM F2832 *Standard guide for accelerated corrosion testing for mechanical fasteners*	
17	ASTM G60 *Standard practice for conducting cyclic humidity exposures*	
18	ASTM G85 *Standard practice for modified salt spray (fog) testing*	It set conditions for: • continuous acetic acid-salt spray • cyclic acidified salt spray • cyclic seawater acidified spray (SWAAT) • cyclic SO_2 salt spray • dilute electrolyte cyclic fog dry.
19	ASTM G87 *Standard practice for conducting moist SO_2 tests*	
20	ASTM G147 *Standard practice for conditioning and handling of nonmetallic materials for natural and artificial weathering tests*	
21	ASTM G149 *Standard practice for conducting the washer test for atmospheric galvanic corrosion*	
22	ASTM G151 *Standard practice for exposing nonmetallic materials in accelerated test devices that use laboratory light sources*	It covers: • procedures required to expose non-metallic materials in accelerated test devices that use laboratory light sources

No	Standard	Remarks
		• performance requirements for devices used for exposing non-metallic materials to laboratory light sources • information on the use and interpretation of data from accelerated exposure tests.
23	ISO 2810 *Paints and varnishes – Natural weathering of coatings – Exposure and assessment*	
24	ISO 9142 *Adhesives – Guide to the selection of standard laboratory ageing conditions for testing bonded joints*	
25	ISO/TR 16335 *Corrosion of metals and alloys – Corrosion tests in artificial atmospheres – Guidelines for selection of accelerated corrosion test for product qualification*	A guideline for selection of suitable accelerated corrosion tests based on a survey of different internationally standardised test methods. Aspects considered are: • categories of accelerated atmospheric corrosion tests • recommended fields of application for the different kinds of tests and their suitability • corrosivity of tests and relative corrosion rates of standard metals • requirements for test equipment, criteria for reproducibility and correlation with in-service performance • recommended procedures for product qualification.
26	ISO 7384 *Corrosion tests in artificial atmosphere – General requirements*	
27	ISO 11845 *Corrosion of metals and alloys – General principles for corrosion testing*	
28	ISO 17872 *Paints and varnishes – Guidelines for the introduction of scribe marks through coatings on metallic panels for corrosion testing*	Metallic panels can be made from: • steel • chemically treated steel • aluminium or aluminium alloy • chemically treated aluminium.
29	ISO/TR 20152-3 *Timber structures – Bond performance of adhesives – Part 3: Use of alternative species for bond tests*	

No	Standard	Remarks
Metals and metallic coatings		
30	AS 1247 *Metallic coatings – Rating of test specimens and manufactured articles subject to corrosion tests*	
31	AS 2309 *Durability of galvanized and electrogalvanized zinc coatings for the protection of steel in structural applications – Atmospheric*	
32	ISO 7441 *Corrosion of metals and alloys – Determination of bimetallic corrosion in outdoor exposure corrosion tests*	Standardised testing methods are described for: • rectangular plates • washers • wire on bolt.
33	ISO 9227 *Corrosion tests in artificial atmospheres – Salt spray tests*	Neutral salt spray (NSS) applicable to: • metals and their alloys • metallic coatings (anodic and cathodic) • conversion coatings • anodic oxide coatings • organic coatings. Acetic acid salt spray (AASS) applicable to: • copper/nickel/chromium coatings • nickel/chromium coatings • anodic and organic coatings on aluminium. Copper-accelerated acetic acid salt spray (CASS) applicable to: • copper/nickel/chromium coatings • nickel/chromium coatings • anodic and organic coatings on aluminium.
34	ISO 10062 *Corrosion tests in artificial atmosphere at very low concentrations of polluting gas(es)*	Applicable to: • metals and their alloys • metallic coatings (anodic and cathodic) • conversion coatings • anodic oxide coatings

No	**Standard**	**Remarks**
		• organic coatings.
35	ISO 11474 *Corrosion of metals and alloys – Corrosion tests in artificial atmosphere – Accelerated outdoor test by intermittent spraying of a salt solution (Scab test)*	Applicable to: • organic coatings • metallic coatings (anodic and cathodic) • chemical conversion coatings • metals and their alloys.
36	ISO 14993 *Corrosion of metals and alloys – Accelerated testing involving cyclic exposure to salt mist, "dry" and "wet" conditions*	Applicable to: • metals and their alloys • metallic coatings (anodic and cathodic) • conversion coatings • anodic oxide coatings • organic coatings.
37	ISO 16151 *Corrosion of metals and alloys – Accelerated cyclic tests with exposure to acidified salt spray, "dry" and "wet" conditions*	Method A applicable to: • metals and their alloys • metallic coatings (cathodic) • anodic oxide coatings • organic coatings. Method B applicable to: • steel coated with anodic coatings • steel coated with anodic coatings covered with conversion coatings.
38	ISO 16539 *Corrosion of metals and alloys – Accelerated cyclic corrosion tests with exposure to synthetic ocean water salt-deposition process – "Dry" and "wet" conditions at constant absolute humidity*	Method A applicable to: • metals and their alloys (including corrosion-resistance alloys). Method B applicable to: • metals and their alloys • metallic coatings (anodic or cathodic) • organic coatings • conversion coatings.

No	Standard	Remarks
39	ISO 16701 *Corrosion of metals and alloys – Corrosion in artificial atmosphere – Accelerated corrosion test involving exposure under controlled conditions of humidity cycling and intermittent spraying of a salt solution*	Includes a 6 hrs exposure to a slightly acidified 1 wt.% NaCl solution of twice weekly and a controlled humidity cycle between 95% RH and 50% RH at 35°C. It is applicable to: • metals and their alloys • metallic coatings (anodic or cathodic) • chemical conversion coatings • organic coatings.
40	ISO 17752 *Corrosion of metals and alloys – Procedures to determine and estimate runoff rates of metals from materials as a result of atmospheric corrosion*	
41	ISO 21207 *Corrosion tests in artificial atmospheres – Accelerated corrosion tests involving alternate exposure to corrosion-promoting gases, neutral salt-spray and drying*	Test method A simulates a moderately aggressive traffic environment and involves the following cycles: • Neutral salt spray using a 5 wt.% sodium chloride solution at 35°C for 2 hrs, followed by 22 hrs drying at a standard laboratory temperature. • 120 hrs exposure to an atmosphere containing a mixture of NO_2 (1.5×10^{-6} volumetric fraction) and SO_2 (0.5×10^{-6}) at 95% RH and 25°C, followed by 24 hrs drying at a standard laboratory temperature. Test method B simulates a more-severe industrial or traffic environment and involves the following cycles: • Neutral salt spray using a 5 wt.% sodium chloride solution at 35°C for 2 hrs, followed by 22 hrs drying at a standard laboratory temperature. • 48 hrs exposure to an atmosphere containing a mixture of NO_2 (10×10^{-6}) and SO_2 (5×10^{-6}) at 95% RH and 25°C. • Neutral salt spray using a 5 wt.% sodium chloride solution at 35°C for 2 hrs, followed by 22 hrs drying at a standard laboratory temperature. • 72 hrs exposure to an atmosphere containing a mixture of NO_2 (10×10^{-6}) and SO_2 (5×10^{-6}) at 95%RH and 25°C.

No	Standard	Remarks
Paint coatings		
42	AS/NZS 2312.1 *Guide to the protection of structural steel against atmospheric corrosion by the use of protective coatings – Paint coatings*	
43	AS/NZS 2728 *Prefinished/prepainted sheet metal products for interior/exterior building applications – Performance requirements*	
44	ASTM A755 / A755M *Standard specification for steel sheet, metallic coated by the hot-dip process and prepainted by the coil-coating process for exterior exposed building products*	
45	ISO 20340 *Paints and varnishes – Performance requirements for protective paint systems for offshore and related structures*	It includes: • test methods that can be used to determine the composition of the separate components of the protective paint system • laboratory performance test methods that can be used to assess the likely durability of the protective paint system • criteria that can be used to evaluate performance test results.
46	AS 1580.481.3 *Paints and related materials – Methods of test, Coatings – Exposed to weathering – Degree of corrosion of coated metal substrates*	
47	AS 2219.1.2 *Methods of test for vitreous enamel coatings Method 1.2: Chemical tests – Determination of resistance of vitreous enamel coatings to boiling water and water vapour*	
48	AS 2331.3.13 *Methods of test for metallic and related coatings, Method 3.13: Corrosion and related property tests – Wet (salt fog)/dry/humidity*	
49	AS/NZS 1580.457.1 *Paints and related materials – Methods of test – Resistance to natural weathering*	
50	AS/NZS 1580.481.1.5 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Change in gloss*	
51	AS/NZS 1580.481.1.6 *Paints and related materials – Methods of test, Coatings – Exposed to weathering – Degree of erosion*	• Method A – determination of film thickness decrease on metallic substrate as a percentage of the original dry film thickness.

No	Standard	Remarks
		- Method B – a visual examination to check for evidence of exposure or grinning through of an underlying substrate of contrasting colour.
52	AS/NZS 1580.481.1.7 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Degree of checking*	
53	AS/NZS 1580.481.1.8 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Degree of cracking*	
54	AS/NZS 1580.481.1.9 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Degree of blistering*	
55	AS/NZS 1580.481.1.10 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Degree of flaking and peeling*	
56	AS/NZS 1580.481.1.11 *Paints and related materials – Methods of test Coatings – Exposed to weathering – Degree of chalking*	
57	AS/NZS 1580.481.1.12 *Paints and related materials – Methods of test coatings – Exposed to weathering – Degree of colour change*	
58	ASTM D610 *Standard practice for evaluating degree of rusting on painted steel surfaces*	
59	ASTM D660 *Standard test method for evaluating degree of checking of exterior paints*	
60	ASTM D661 *Standard test method for evaluating degree of cracking of exterior paints*	
61	ASTM D714 *Standard test method for evaluating degree of blistering of paints*	
62	ASTM D772 *Standard test method for evaluating degree of flaking (scaling) of exterior paints*	
63	ASTM D1654 *Standard test method for evaluation of painted or coated specimens subjected to corrosive environments*	

No	Standard	Remarks
64	ASTM D2243 *Standard test method for freeze-thaw resistance of water-borne coatings*	
65	ASTM D4214 *Standard test method for evaluating degree of chalking of exterior paint films*	
66	ISO 3231 *Paints and varnishes – Determination of resistance to humid atmospheres containing sulfur dioxide*	
67	ISO 4623-1 *Paints and varnishes – Determination of resistance to filiform corrosion – Part 1: Steel substrates*	
68	ISO 4623-2 *Paints and varnishes – Determination of resistance to filiform corrosion – Part 2: Aluminium substrates*	
69	ISO 4628-2 *Paints and varnishes – Evaluation of degradation of coatings – Designation of quantity and size of defects, and of intensity of uniform changes in appearance – Part 2: Assessment of degree of blistering*	
70	ISO 4628-3 *Paints and varnishes – Evaluation of degradation of coatings – Designation of quantity and size of defects, and of intensity of uniform changes in appearance – Part 3: Assessment of degree of rusting*	
71	ISO 4628-4 *Paints and varnishes – Evaluation of degradation of coatings – Designation of quantity and size of defects, and of intensity of uniform changes in appearance – Part 4: Assessment of degree of cracking*	
72	ISO 4628-5 *Paints and varnishes – Evaluation of degradation of coatings – Designation of quantity and size of defects, and of intensity of uniform changes in appearance – Part 5: Assessment of degree of flaking*	
73	ISO 4628-6 *Paints and varnishes – Evaluation of degradation of coatings – Designation of quantity and size of defects, and of intensity of uniform changes in appearance – Part 6: Assessment of degree of chalking by tape method*	
74	ISO 4628-7 *Paints and varnishes – Evaluation of degradation of coatings – Designation of quantity and size of defects, and of intensity of uniform*	

No	Standard	Remarks
	changes in appearance – Part 7: Assessment of degree of chalking by velvet method	
75	ISO 4628-10 *Paints and varnishes – Evaluation of degradation of coatings – Designation of quantity and size of defects, and of intensity of uniform changes in appearance – Part 10: Assessment of degree of filiform corrosion*	
76	ISO 6270-1 *Paints and varnishes – Determination of resistance to humidity – Part 1: Condensation (single-sided exposure)*	
77	ISO 11997-1 *Paints and varnishes – Determination of resistance to cyclic corrosion conditions – Part 1: Wet (salt fog)/dry/humidity*	• Cycle A – specified in Japanese Automobile Standards JASO M 609 *Corrosion test method for automotive materials* and JASO M610 *Cosmetic corrosion test method for automotive parts*. • Cycle B – based on the VDA 621-415 cycle and has good correlations with natural weathering for thermosetting paints. • Cycle C – developed for use with water-soluble and latex paint systems and has good correlations with natural weathering. • Cycle D – specified in Japanese Standard JIS K 5621 *Anticorrosive paints for general use*.
78	ISO 11997-2 *Paints and varnishes – Determination of resistance to cyclic corrosion conditions – Part 2: Wet (salt fog)/dry/humidity/UV light*	
79	ISO 21227-1 *Paints and varnishes – Evaluation of defects on coated surfaces using optical imaging – Part 1: General guidance*	
80	ISO 21227-3 *Paints and varnishes – Evaluation of defects on coated surfaces using optical imaging – Part 3: Evaluation of delamination and corrosion around a scribe*	
81	ISO 21227-4 *Paints and varnishes – Evaluation of defects on coated surfaces using optical imaging – Part 4: Evaluation of filiform corrosion*	
Ceramic coatings		
82	ASTM C1624 *Standard test method for adhesion strength and mechanical failure modes of ceramic coatings by quantitative single point scratch testing*	Ceramic coatings may include: • carbides • nitrides

No	Standard	Remarks
		• oxides • diamond • diamond-like carbon (DLC).
Adhesives and sealants		
83	ISO 17194 *Structural adhesives – A standard database of properties*	
84	ISO 20152-1 *Timber structures – Bond performance of adhesives – Part 1: Basic requirements*	
85	ISO 20152-2 *Timber structures – Bond performance of adhesives – Part 2: Additional requirements*	
86	ASTM C1247 *Standard test method for durability of sealants exposed to continuous immersion in liquids*	
87	ASTM C1519 *Standard test method for evaluating durability of building construction sealants by laboratory accelerated weathering procedures*	
88	ASTM D1151 *Standard practice for effect of moisture and temperature on adhesive bonds*	
89	ASTM D1183 *Standard practices for resistance of adhesives to cyclic laboratory aging conditions*	
90	ASTM D2918 *Standard test method for durability assessment of adhesive joints stressed in peel*	Assess the durability of adhesive joints by using T-peel type specimens stressed in contact with air, air in equilibrium with solutions, water, aqueous solutions or other environments at temperatures. It may also be used to: • provide an accelerated screening test for assessing the durability of adhesive joints • measure durability of adhesive joints exposed to outdoor environments or environmental conditions experienced by adhesive joints in service • determine the effects of various surface preparations or substrates on durability of adhesive joints.

No	Standard	Remarks
91	ASTM D2919 *Standard test method for determining durability of adhesive joints stressed in shear by tension loading*	
92	ASTM D3434 *Standard test method for multiple-cycle accelerated aging test (automatic boil test) for exterior wet use wood adhesives*	
93	ASTM D3632 *Standard test method for accelerated aging of adhesive joints by the oxygen-pressure method*	
94	ASTM D3762 *Standard test method for adhesive-bonded surface durability of aluminium (wedge test)*	
95	ASTM D4502 *Standard test method for heat and moisture resistance of wood – Adhesive joints*	
96	ISO 10354 *Adhesives – Characterization of durability of structural adhesive assemblies – Wedge rupture test*	
97	ISO 14615 *Adhesives – Durability of structural adhesive joints – Exposure to humidity and temperature under load*	
Fasteners		
98	AS 1897 *Fasteners – Electroplated coatings*	Specifies dimensional and coating thicknesses requirements for electroplated fasteners of steel or copper alloy.
99	AS 3566.1 *Self-drilling screws for the building and construction industries. Part 1: General requirements and mechanical properties*	
100	AS 3566.2 *Self-drilling screws for the building and construction industries. Part 2: Corrosion resistance requirements (suspended)*	Also introduces a procedure to demonstrate corrosion resistance by exposure at an outdoor test site.
101	ASTM F1667 *Standard specification for driven fasteners: nails, spikes, and staples*	
102	ASTM F2329/F2329M *Standard specification for zinc coating, hot-dip, requirements for application to carbon and alloy steel bolts, screws, washers, nuts, and special threaded fasteners*	
103	ASTM F2833 *Standard specification for corrosion protective fastener coatings with zinc rich base coat and aluminium organic/inorganic type*	

No	Standard	Remarks
104	ASTM F3019/F3019M *Standard specification for chromium free zinc-flake composite, with or without integral lubricant, corrosion protective coatings for fasteners*	Requirements include: - appearance - adhesion - corrosion resistance - blisters - thread fit - hydrogen embrittlement - total coefficient of friction.
105	ASTM F1136/F1136M *Standard specification for zinc/aluminium corrosion protective coatings for fasteners*	
106	NZS 3604 *Timber-framed buildings*	Provides detailed performance requirements for fasteners commonly used in New Zealand residential buildings such as bolts, brackets, nail plates, nails and screws.
107	ASTM D6294/D6294M *Standard test method for corrosion resistance of ferrous metal fastener assemblies used in roofing and waterproofing*	
108	ASTM F680 *Standard test methods for nails*	Test methods are described as: - dimension - tension - conventional bend - impact bend - rockwell hardness - coating weight and adherence (for zinc-coated nails).
109	ASTM G198 *Standard test method for determining the relative corrosion performance of driven fasteners in contact with treated wood*	Two controlled environments: cyclic fog and steady-state moisture.
110	AWPA E12 *Standard method of determining corrosion of metal in contact with treated wood*	
Concrete		
111	ASTM D3744/D3744M *Standard test method for aggregate durability index*	Durability index is an indicator of the relative resistance of an aggregate to production of detrimental clay-like fines when subjected to the prescribed mechanical methods of degradation.

No	Standard	Remarks
112	CIA Z7/01 *Durability planning*	Describes how to make durability planning to achieve the required level of durability using appropriate tools and recommendations given in codes and recommended practices (such as CIA Z7/02-07).
113	CIA Z7/07 *Performance tests to assess concrete durability*	
114	ISO 16204 *Durability – Service life design of concrete structures*	Specifies principles and recommends procedures for the verification of the durability of concrete structures when exposed to: • known or foreseeable environmental actions that can cause material deterioration and ultimately lead to performance failure • material deterioration due to self-ageing The flow of decisions and the design activities needed in a rational service life design process with a chosen level of reliability is given. This standard is also useful for: • assessment of remaining service life of existing structures • design of service life of new structures provided quantified parameters on levels of reliability and design parameters are given in a national annex.
Timber		
115	ASTM D3345 *Standard test method for laboratory evaluation of solid wood for resistance to termites*	
116	BS EN 12037 *Wood preservatives – Field test method for determining the relative effectiveness of a wood preservative exposed out of ground contact. Horizontal lap-joint method*	
117	EN 330 *Wood preservatives – Determination of the relative protective effectiveness of a wood preservative for use under a coating and exposed out-of-ground contact – Field test: L-joint method*	
118	EN 350 *Durability of wood and wood-based products – Testing and classification of the durability to biological agents of wood and wood-based materials*	Applicable to individual wood species, batches of wood and processed wood-based materials, including heat-treated, preservative-treated wood and modified wood.

No	Standard	Remarks
119	EN 460 *Durability of wood and wood-based products – Natural durability of solid wood – Guide to the durability requirements for wood to be used in hazard classes*	
120	ISO 21887 *Durability of wood and wood-based products – Use classes*	
121	NZS 3602 *Timber and wood-based products for use in building*	
Rubbers and plastics		
122	ASTM D750 *Standard practice for rubber deterioration using artificial weathering apparatus*	
123	ISO 188 *Rubber, vulcanized or thermoplastic – Accelerated ageing and heat resistance tests*	
124	ISO 4611 *Plastics – Determination of the effects of exposure to damp heat, water spray and salt mist*	
125	ISO 4665 *Rubber, vulcanized or thermoplastic – Resistance to weathering*	Changes in colour, appearance and physical properties.
126	ISO 10640 *Plastics – Methodology for assessing polymer photoageing by FTIR and UV/visible spectroscopy*	
127	ISO/TS 19022 *Plastics – Method of controlled acceleration of laboratory weathering by increased irradiance*	
128	ISO 29664 *Plastics – Artificial weathering including acidic deposition*	• Method A uses a strong acid spray (pH 1.5) that is applied for a short time and is intended for the materials where surface degradation is very important. • Method B uses a weaker acid spray (pH 3.5) that is applied over a long time so that it can penetrate deeply into the material.

Table 35. Service life planning.

No	Standard	Remarks
Data analysis		
1	ASTM G16 *Standard guide for applying statistics to analysis of corrosion data*	
2	ASTM G166 *Standard guide for statistical analysis of service life data*	Discusses the Weibull life distribution model in detail.
3	ASTM G169 *Standard guide for application of basic statistical methods to weathering tests*	
4	ASTM G172 *Standard guide for statistical analysis of accelerated service life data*	It describes: • application of the Arrhenius equation to service life data • acceleration model used for multiple stress variables, i.e. the Eyring model • Weibull life distribution model.
5	ISO 14802 *Corrosion of metals and alloys – Guidelines for applying statistics to analysis of corrosion data*	
Service life planning		
6	ASTM E2136 *Standard guide for specifying and evaluating performance of single family attached and detached dwellings – Durability*	Provides relevant performance statements, performance tests and performance standards to evaluate the durability of building materials, components and systems for single family attached and detached dwellings. General conformance to this standard guide could provide reasonable assurance that the in-place materials, built elements and service subsystems of attached and detached dwellings will be serviceable through their service lives.
7	BS 7543 *Guide to durability of buildings and building elements, products and components*	Provides guidance and fundamental tools to assist decision making in terms of durability, design life, predicted service life, life cycle costs and whole-life carbon of buildings, constructed assets and their parts, both new and existing.
8	ISO 15686-1 *Buildings and constructed assets – Service life planning – Part 1: General principles and framework*	

No	Standard	Remarks
9	ISO 15686-2 *Buildings and constructed assets – Service life planning – Part 2: Service life prediction procedures*	
10	ISO 15686-3 *Buildings and constructed assets – Service life planning Part 3: Performance audits and reviews*	Deals with measures to ensure that the life care of a constructed asset is considered through its whole service life, including decision making from project conception and initial briefing, design and construction, occupancy, eventual disposal and reinstatement of the site. It provides a choice between formal independent audits carried out at key project stages and service life performance reviews carried out alongside existing internal project review procedures.
11	ISO 15686-4 *Building construction – Service life planning – Part 4: Service life planning using building information modelling*	Provides the basic procedures that are needed for the service life planning process of buildings with a suitable information management system. Practically, this means the use of building information modelling (BIM) systems. BIM is able to work with construction components and assemblies as objects that encapsulate both shape and other information about performance, delivery, operation and more. Performance can include information about durability and sustainability metrics. This offers powerful capabilities for dealing with these key areas of interest at every level from individual component to constructed facility.
12	ISO 15686-5 *Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing*	It intends to: • establish terminology and methodology for life cycle costing (LCC) • enable the practical, wide use of LCC in the construction industry • enable the application of LCC techniques and methodology for a wide range of procurement methods • help improve decision making and evaluation processes at relevant stages of any building and construction project • address concerns over uncertainties and risks and improve the confidence in LCC forecasting • make LCC and the underlying assumptions more transparent and robust • provide guiding principles, instructions and definitions for different forms of LCC and reporting • provide the framework for consistent LCC predictions and performance assessment

No	Standard	Remarks
		- provide a common basis for setting LCC targets during design and construction against which actual cost performance can be tracked and assessed over the asset life span - provide guidance on when to undertake LCC, to what level and what cost headings are appropriate for consideration - help unlock the real value of effectively doing LCC in construction by using service life planning - clarify the differences between life cycle costing and whole-life costing (WLC) - provide a generic menu of costs for LCC/WLC compatible with and customisable for specific national or international cost codes and data-structure conventions - provide cross-references to guidance on associated activities within the other parts of ISO 15686.
13	ISO 15686-6 *Buildings and constructed assets – Service life planning Part 6: Procedures for considering environmental impacts*	- Defines how and when to include environmental aspects into the design of a constructed asset. - Provides a procedure to assess the relative environmental impacts of design options. - Identifies the interface between environmental life cycle assessment (LCA) and service life prediction (SLP) and allows for consistent comparisons to be made between two or more design options taking the relevant factors from SLP into account.
14	ISO 15686-7 *Buildings and constructed assets – Service life planning – Part 7: Performance evaluation for feedback of service life data from practice*	Provides a framework to channel information collected as part of building performance surveys and assessments into structured data that can be used in various aspects of the service life planning process. The interactions and significance of initial inspection data, maintenance-driven inspections, changed performance expectations, performance surveys, service life predictions and service life planning are discussed.
15	ISO 15686-8 *Buildings and constructed assets – Service life planning – Part 8: Reference service life*	Provides guidance on reference service life (RSL) issues and a means of determining the estimated service life (ESL) using factor methods. The guidance for reference service life is structured into discussions regarding: - provision of RSL data utilising existing general data - selection of RSL data or general data

No	Standard	Remarks
		• formatting of general data into RSL data records.
16	ISO 15686-10 *Buildings and constructed assets – Service life planning – Part 10: When to assess functional performance*	It defines: • when to specify or verify functional performance requirements during the service life of buildings and building-related facilities • when to check the capability of buildings and facilities to meet identified requirements.

Appendix B: Service life expectation

Table 36. Life to first maintenance for a selection of hot-dip galvanised coating systems in a range of corrosivity categories.

Coating system	Reference standard and specification		Minimum thickness		Durability – years to first maintenance			
			g/m^2	µm	C3	C4	C5	CX
Hot-dip galvanising	AS/NZS 4680	HDG390	390	55	26–78	13–26	6–13	2–6
		HDG500	500	70	33–100	16–33	8–16	2–8
		HDG600	600	85	40–100	20–40	10–20	3–10
		HDG900	900	125	60–100	30–60	15–30	5–15
Hot-dip galvanised sheet	AS 1397	Z350	140	20	10–29	5–10	2–5	1–2
		Z450	180	25	12–36	6–12	3–6	1–3
Electro galvanised tube	AS 4750	ZE100	100	14	6–20	3–6	1–3	0–1
		ZE300	300	42	20–60	10–20	5–10	1–5
Hot-dip galvanised tube	AS/NZS 4792	ILG100/ZB100/100	100	14	6–20	3–6	1–3	0–1
		ILG140/ZB140/140	140	20	10–29	5–10	2–5	1–2
		ILG300/ZB300/300	300	42	20–60	10–20	5–10	1–5
Mechanical plating	AS 5056		55	8	4–11	2–4	1–2	0–1
			175	25	12–36	6–12	3–6	1–3
Electroplated coatings	AS 1897	Fe/Zn 8c	55	8	4–11	2–4	1–2	0–1
		Fe/Zn 25c	175	25	12–36	6–12	3–6	1–3

Source: AS/NZS 2312.2:2014 *Guide to the protection of structural steel against atmospheric corrosion by the use of protective coatings. Part 2: Hot dip galvanizing*

Table 37. Paint systems for steel.

Type	Surface preparation	Coating system: Type/DFT (µm)			DFT (µm)	Durability – Years to first maintenance					
		1st	2nd	3rd		C1	C2	C3	C4	C5-I	C5-M
Acrylic – latex, single pack	St 3	Alkyd/40	Acrylic/40	Acrylic/40	120	15+	5–15	2–5			
	Sa 2.5	Zinc-rich/75	Acrylic/40	Acrylic/40	155	25+	15–25	10–15	5–10	2–5	2-5
	Sa 2.5	Zinc-rich primer/75	High build epoxy/125	Acrylic/40	240		25+	15–25	10–15	5–10	5–10
	Sa 2.5	High build epoxy/250	Acrylic/40		290	25+	15–25	10–15	5–10	2–5	2–5
Acrylic – solvent borne, two pack	St 3	Epoxy mastic/125	Acrylic 2 pack/50		175	25+	10–25	5–10	2–5		
	Sa 2.5	Epoxy primer/75	Acrylic 2 pack/50		125	25+	15–25	10–15	5–10	2–5	2–5
	Sa 2.5	Epoxy primer/75	High build epoxy/125	Acrylic 2 pack/50	250		25+	15–25	10–15	5–10	5–10
	Sa 2.5	Zinc-rich primer/75	High build epoxy/125	Acrylic 2 pack/50	250		25+	15–25	10–15	5–10	5–10
	Sa 2.5	Zinc-rich primer/75	High build epoxy/200	Acrylic 2 pack/50	325		25+	25+	25+	5–10	15–25
Alkyd	St 3/Sa 2	Alkyd primer/40			40	5+	0–5				
	St 3/Sa 2	High build alkyd primer/75	Alkyd gloss/40		115	15+	5–15	2–5			
	St 3/Sa 2	Alkyd primer/40	Alkyd MIO/40	Alkyd MIO/40	120	25+	10–25	5–10	2–5		
Epoxy – very high build	Sa 2.5	Very high build epoxy/250			250	25+	15–25	10–15	5–10	2–5	2–5
	Sa 2.5	Very high build epoxy/400			400		25+	15–25	10–15	5–15	5–15
	Sa 2.5	Epoxy primer/75	Very high build epoxy/400		475		25+	15–25	10–15	5–15	5–15
Epoxy – high build	Sa 2.5	Epoxy primer/75	High build epoxy/200		275		15–25	10–15	5–10	2–5	2–5
	Sa 2.5	Zinc-rich primer/75	High build epoxy/200		275		25+	15–25	10–15	5–10	5–10
	Sa 2.5	Epoxy primer/75	Epoxy MIO/125	Epoxy MIO/125	325		25+	15–25	10–25	10–15	10–15

Type	Surface preparation	Coating system: Type/DFT (µm)			DFT (µm)	Durability – Years to first maintenance					
		1st	2nd	3rd		C1	C2	C3	C4	C5-I	C5-M
	Sa 2.5	Zinc-rich primer/75	Epoxy MIO/125	Epoxy MIO/125	325		25+	25+	25+	10–15	15–25
Epoxy mastic – surface tolerant	St 3	Epoxy mastic/75	Epoxy mastic/75		150	25+	10–25	5–10	2–5		
	St 3	Epoxy mastic/200	Epoxy mastic/200		400		15–25	10–15	5–10	2–5	2–5
Inorganic zinc silicate – solvent borne	Sa 2.5	IZS/75			75	25+	25+	15–25	10–15	2–5	5–10
	Sa 2.5	IZS/75			75	25+	25+	15–25	10–15	2–5	5–10
	Sa 2.5	IZS/125			125	25+	25+	25+	15–25	5–10	10–15
	Sa 2.5	IZS/125			125	25+	25+	25+	15–25	5–10	10–15
Moisture cured urethane	St 3	MCU sealer primer/50	MCU MIO/75	MCU finish coat/75	200		10–15	10–15	5–10	2–5	2–5
	Sa 2.5	Zinc rich MCU primer/75	MCU MIO/75	MCU finish coat/75	225		25+	15–25	10–15	5–10	10–15
Polysiloxane	Sa 2.5	Zinc rich primer/75	Organic polysiloxane/125		200		15–25	15–25	10–15		
	Sa 2.5	Zinc rich primer/75	High build epoxy/175	Organic polysiloxane/75	325		25+	25+	25+	15–25	15–25
	Sa 2.5	Epoxy primer/75	High build epoxy/175	Organic polysiloxane/75	325		25+	25+	15–25+	15–25	10–15
Polyurethane – two pack, solvent borne	St 3	Epoxy mastic/125	Polyurethane gloss/50		175		10–15	5–10	2–5		
	Sa 2.5	Epoxy primer/75	Polyurethane gloss/50		125	25+	10–25	5–10	2–5		
	Sa 2.5	Zinc rich primer/75	High build polyurethane gloss/75		150	25+	15–25	10–15	5–10	2–5	2–5
	Sa 2.5	Epoxy primer/75	High build epoxy/125	Polyurethane gloss/50	250		25+	15–25	10–15	5–10	5–10
	Sa 2.5	Zinc rich primer/75	High build epoxy/125	Polyurethane gloss/50	250		25+	15–25	10–15	5–10	5–10

Type	Surface preparation	Coating system: Type/DFT (µm)			DFT (µm)	Durability – Years to first maintenance					
		1st	2nd	3rd		C1	C2	C3	C4	C5-I	C5-M
	Sa 2.5	Zinc rich primer/75	High build epoxy/200	Polyurethane gloss/50	325		25+	25+	25+	15–25	15–25
	St 3	Epoxy mastic/75	High build epoxy/75	High build polyurethane/75	225		15–25	10–15	5–10	2–5	2–5
	Sa 2.5	Epoxy zinc primer/75	High build epoxy/75	High build polyurethane/75	225		25+	15–25	10–15	5–10	5–10

Source: AS/NZS 2312.1:2014 *Guide to the protection of structural steel against atmospheric corrosion by the use of protective coatings. Part 1: Paint coatings*